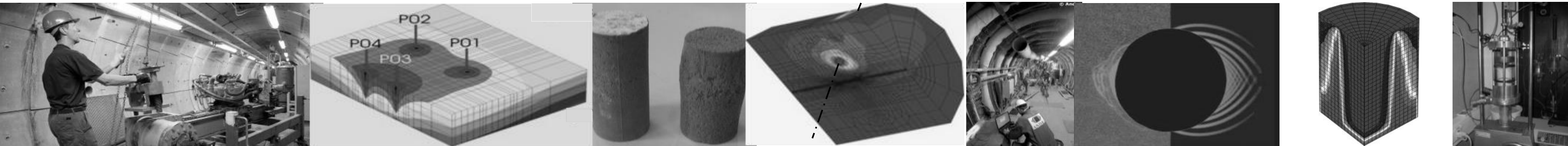
UEE
Urban & Environmental Engineering

Réseau International – ADAPTCLIM
Réseau international sur l'évaluation des risques et l'adaptation climatique d'ouvrages en génie civil et bâtiments

Modélisation hydromécanique de quelques problèmes de géotechnique dans le cadre des changements climatiques

F. Collin [1] – P. Kotronis [2] – S. Ahayan [1,2] – G. Jouan [1,2] – B. Cerfontaine [1] – J. Hubert [1]

[1] Université de Liège – Dept. ArGEnCo - UEE
[2] Ecole Centrale de Nantes – Laboraoire GeM



Collaboration Université de Liège – Ecole Centrale de Nantes

- Gwendal Jouan (post-doc) – Elément 2nd gradient couplé / Interface cohésive

- Sanae Ahayan (Co-tutelle) – Fondation éolienne off-shore

- Projet ITN – Sustain (Soil strUcture interaction reSearch TrAIning Network: innovative integrated design approaches for infrastructures and sustainable urban development)

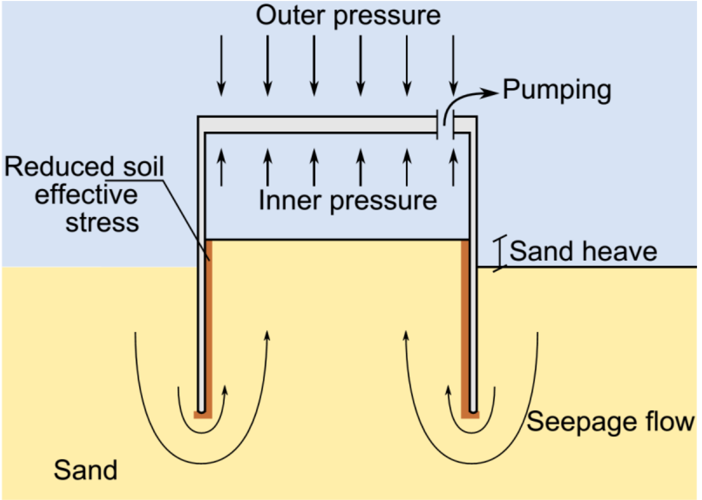
- Julien Hubert (doctorant) – Modélisation de la fissuration au séchage

Hydromechanical modelling of interfaces

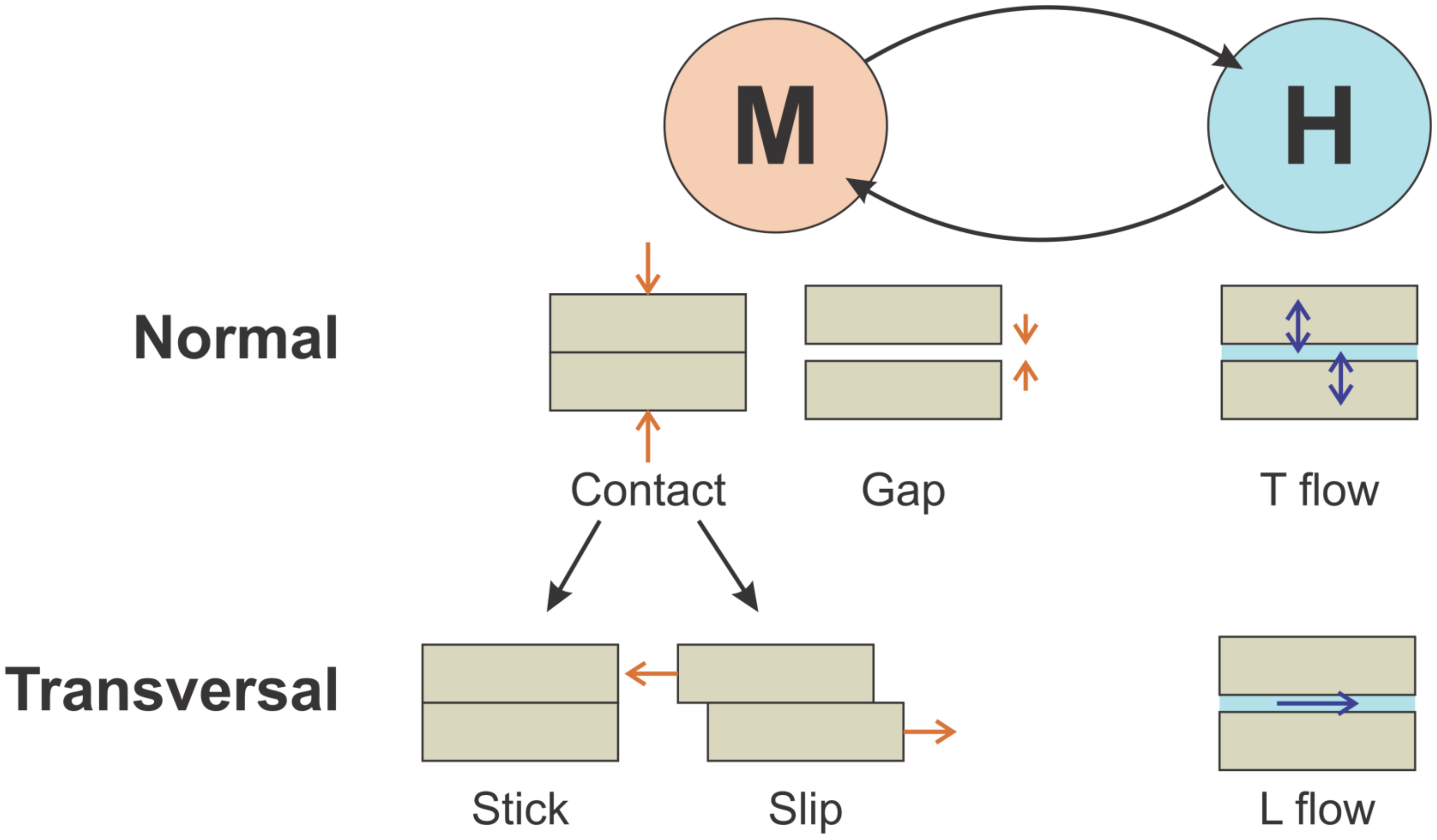
WHY AN INTERFACE ELEMENT

- Suction caisson

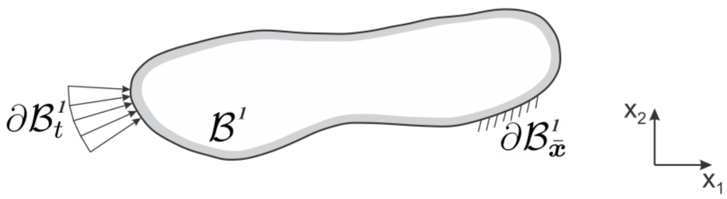
(DONG Energy)



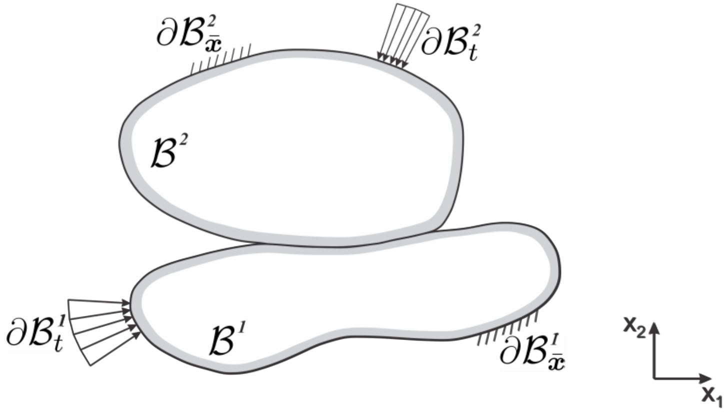
What an interface element



GOVERNING EQUATIONS

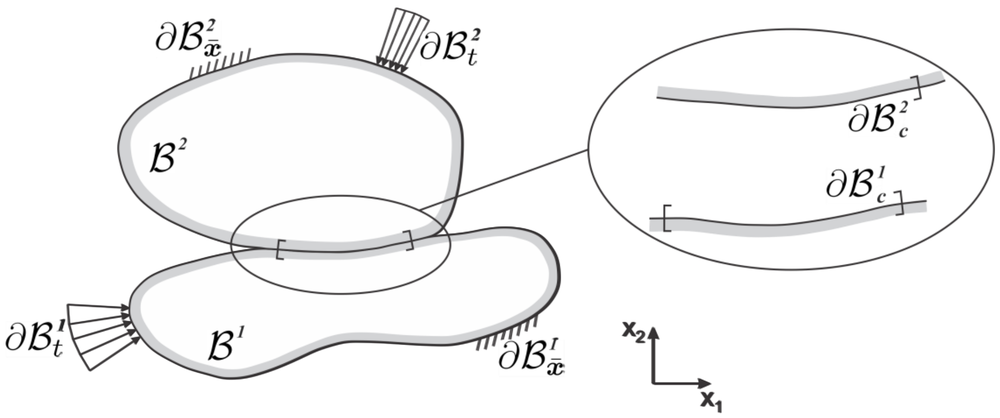


Governing equations



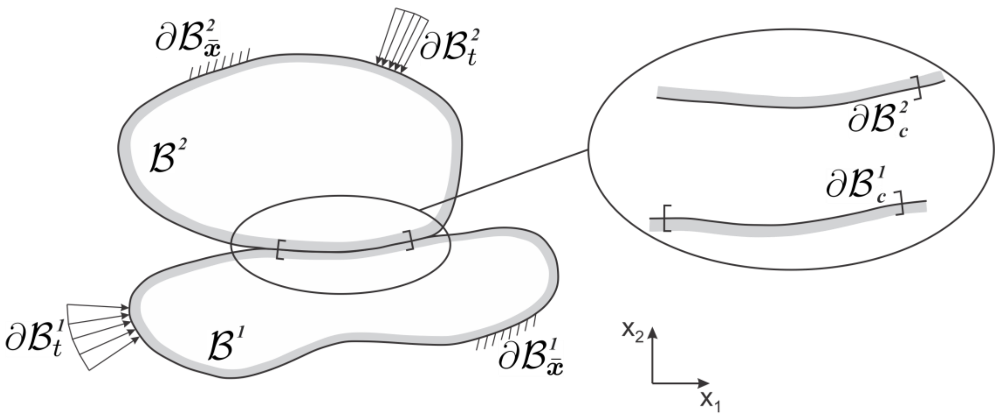
- $\partial\mathcal{B}^i_c$: boundary where contact is likely to happen

Governing equations



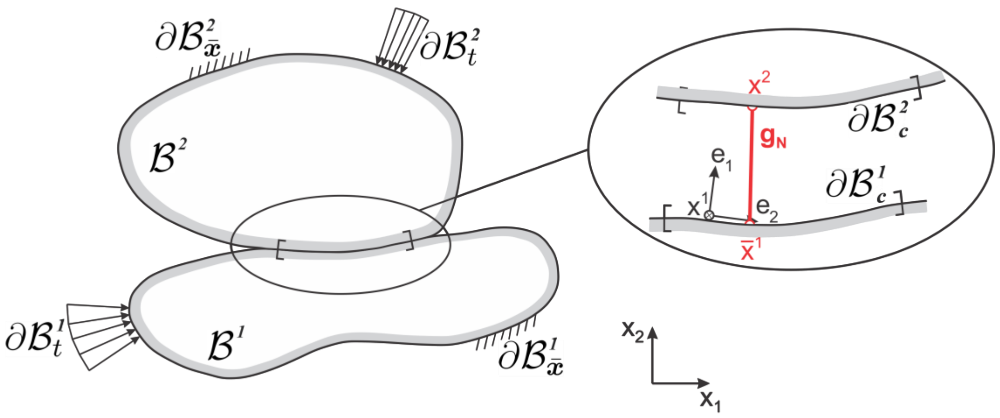
- $\partial\mathcal{B}_c^i$: boundary where contact is likely to happen
- Governing equations:
  1. Definition of a gap function
  2. Normal contact constraint
  3. Tangential contact constraint

Governing equations: Definition of a gap function



- Local system of coordinate along the mortar side

Governing equations: Definition of a gap function



- Local system of coordinate along the mortar side

- Gap function: $\boxed{g_N = (\boldsymbol{x}^2 - \overline{\boldsymbol{x}}^1)} \cdot \overline{\boldsymbol{e}}_1$

With $\overline{\boldsymbol{x}}^1$ = closest point projection of $\boldsymbol{x}^2$

GOVERNING EQUATIONS: DEFINITION OF A GAP FUNCTION

- Relative tangential displacement: no meaning in the field of large displacements!

  ➔ Use of velocities

$$\dot{g}_T = \frac{d}{dt}\left[\bar{e}_2 \cdot \left(\boldsymbol{x}^2 - \overline{\boldsymbol{x}}^1\right)\right]$$

Governing equations: Definition of a gap function

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  ➔ Use of velocities

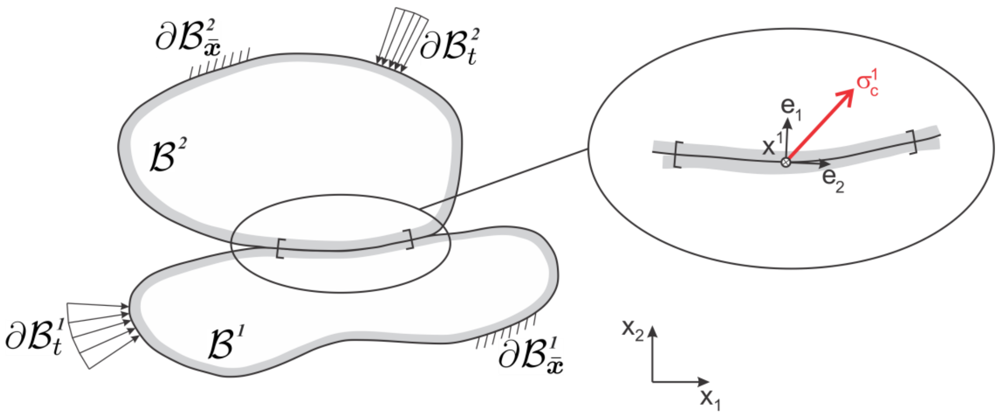
$$\dot{g}_T = \frac{d}{dt}[\bar{e}_2 \cdot (\boldsymbol{x}^2 - \bar{\boldsymbol{x}}^1)]$$

- Vector of variation of normal and tangential displacements:

$$\boxed{\dot{g} = \dot{g}_N \boldsymbol{e}_1 + \dot{g}_T \boldsymbol{e}_2}$$

GOVERNING EQUATIONS: NORMAL CONTACT CONSTRAINT

- Normal contact constraint: two solids in contact cannot overlap



- Contact stress vector: $\boldsymbol{\sigma_c} = -p_N\boldsymbol{e}_1 + \tau\boldsymbol{e}_2 = [-p_N \quad \tau]^T$

- Hertz-Signorini-Moreau condition:

$$\boxed{g_N \geq 0 \qquad \text{and} \qquad p_N \geq 0 \qquad \text{and} \qquad p_N \cdot g_N = 0}$$

Governing equations: Tangential Contact constraint

- When solids are in contact:
  - Stick: no relative tangential displacement ($\dot{g}_T = 0$)
  - Slip: relative tangential displacement ($\dot{g}_T \neq 0$)

Governing equations: Tangential Contact constraint

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$$\boxed{\dot{g}_T^{sl} \geq 0 \quad \text{and} \quad f_c(\boldsymbol{\sigma_c}, \boldsymbol{q}) \leq 0 \quad \text{and} \quad \dot{g}_T^{sl} \cdot f_c(\boldsymbol{\sigma_c}, \boldsymbol{q}) = 0}$$

with $\dot{g}_T = \mathrm{sign}(\dot{\tau})\, \dot{g}_T^{sl}$

GOVERNING EQUATIONS: TANGENTIAL CONTACT CONSTRAINT

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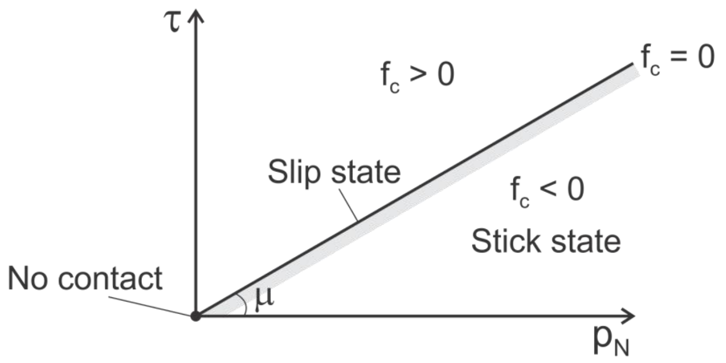
- Threshold criterion $f_c(\boldsymbol{\sigma_c}, \boldsymbol{q})$:

  → Simplest: Mohr criterion



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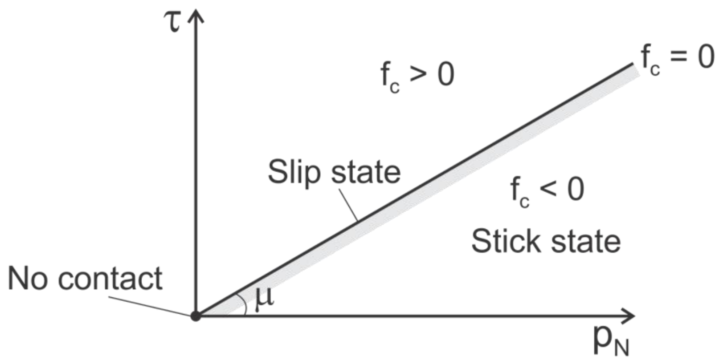


FINITE ELEMENT FORMULATION

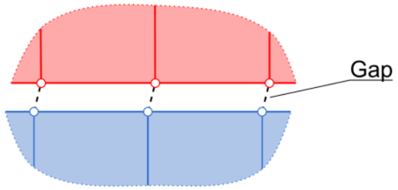
- Discretisation of the contact area between solids

→ How to compute the gap function ?

1. Node-to-node approach:

☺ Simplest

☹ Small relative displacements only



Finite element formulation

- Discretisation of the contact area between solids

  → How to compute the gap function ?

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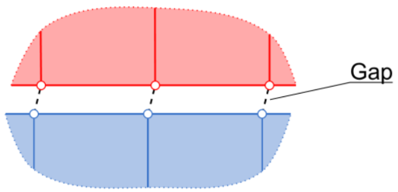
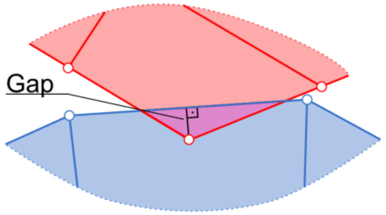


☺ Simplest
☹ Small relative displacements only

2. Node-to-segment approach



☺ Large displacements
☹ Sensitive to sudden changes in projection direction

FINITE ELEMENT FORMULATION

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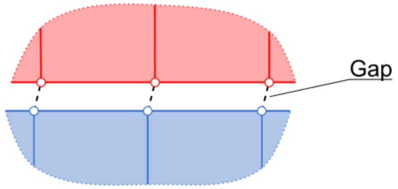

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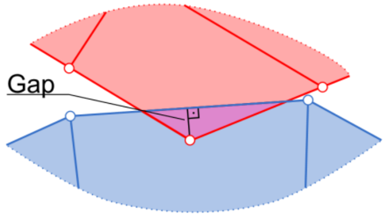
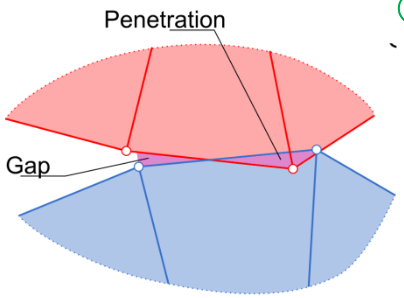


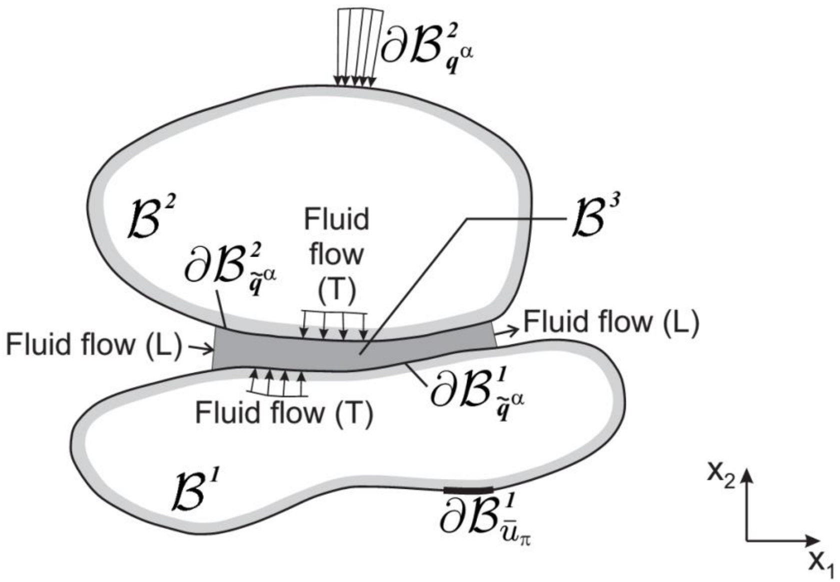
☺ Large displacements
☹ Sensitive to sudden changes in projection direction

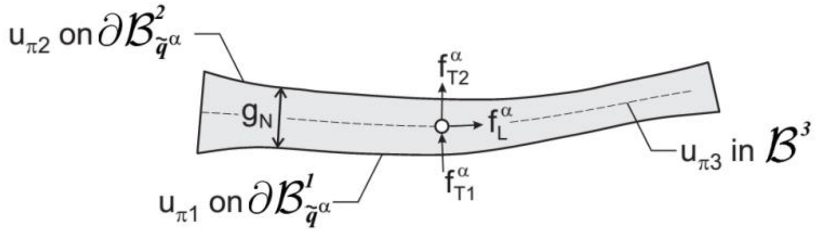
3. Segment-to-segment approach



☺ Large displacements

Finite element formulation : HM modelling





- Interface = new volume $\mathcal{B}^3$ → equivalent porous medium
- Flow of water transversally and longitudinally

Finite element formulation : HM modelling

- Longitudinal fluxes: generalized Darcy's law

$$\boxed{f_{wL} = -\frac{k_{wL}}{\mu_w}\left(\nabla_{e_2} u_w - \rho_w g \nabla_{e_2} x_2\right)\rho_w}$$

  - k_{wL}: longitudinal permeability (cubic law)

$$k_{wL} = \begin{cases} \dfrac{D_0^2}{12}, & g_N \leq 0 \\ \dfrac{(D_0 + g_N)^2}{12}, & \text{oherwise} \end{cases}$$

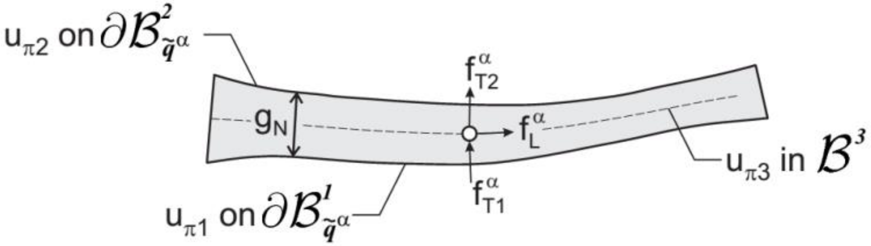
  - ∇_{e_2}: gradient in the direction e_2

Finite element formulation : HM modelling

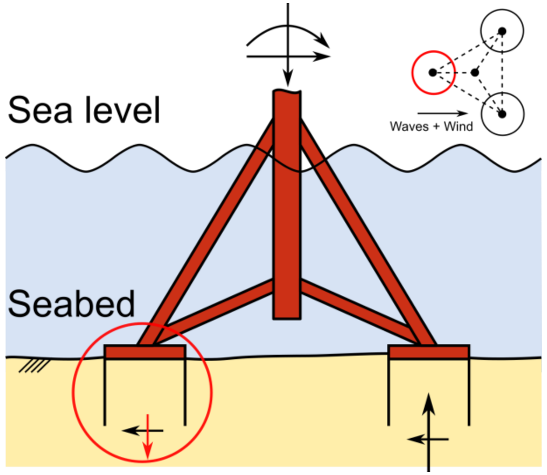
- Transversal fluxes
  - Analogy with generalized Darcy's law
  - Zero-thickness → Flux proportional to a pressure drop

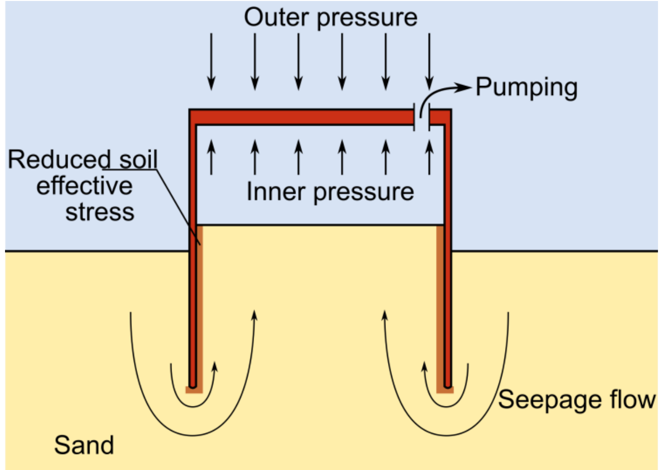
$$f_{wT1} = T_{wT1}(u_{w1} - u_{w3})\rho_w$$

$$f_{wT2} = T_{wT1}(u_{w3} - u_{w2})\rho_w$$



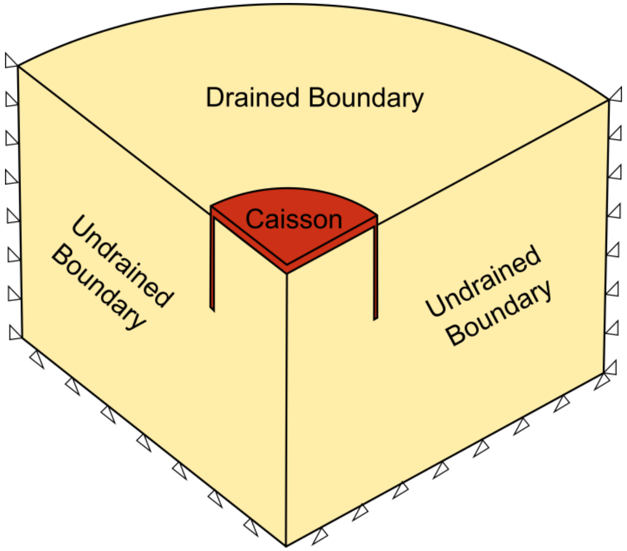
Application

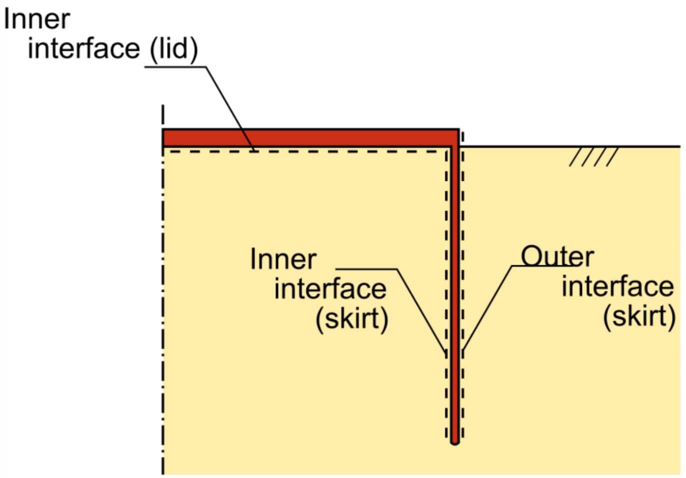




- Foundation for offshore structures
- Hollow cylinder open towards the bottom
- Installation by self-penetration + suction
- Importance of interfaces

SUCTION CAISSONS: INITIALISATION



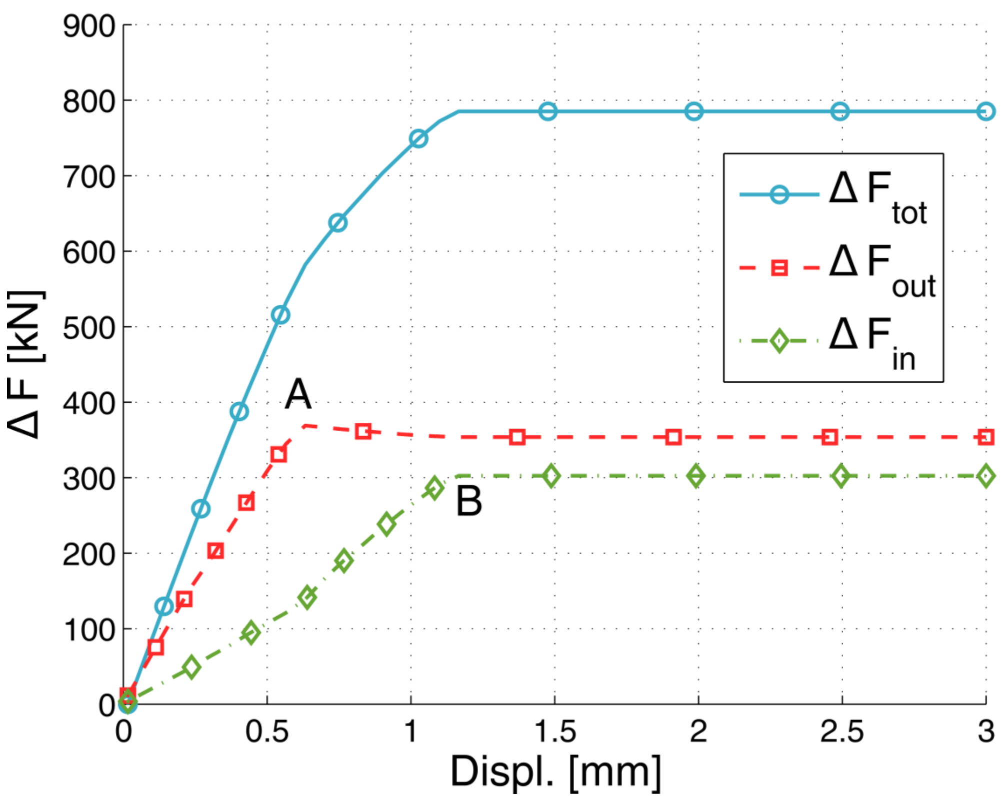


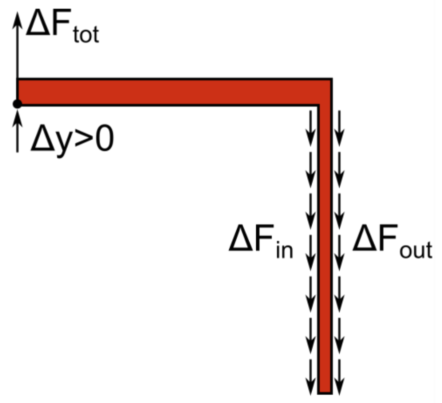
- Diameter 7.8m
- Length 4m
- Sand-steel friction 0.58

- Soil permeability 10^{-11}m^2
- $K_0 = 1$
- Sand & steel elastic

- Tw = 10^{-8}m/Pa/s
- $D_0 = 10^{-5}$ m

Suction caissons: drained uplift (mechanical problem)





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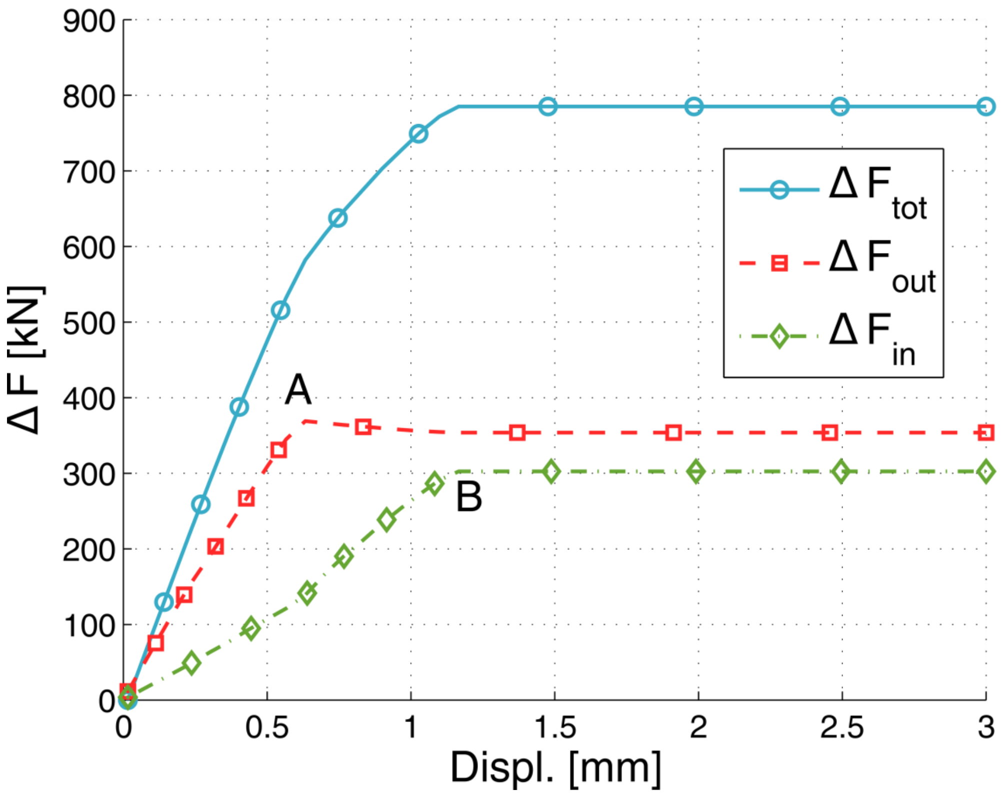

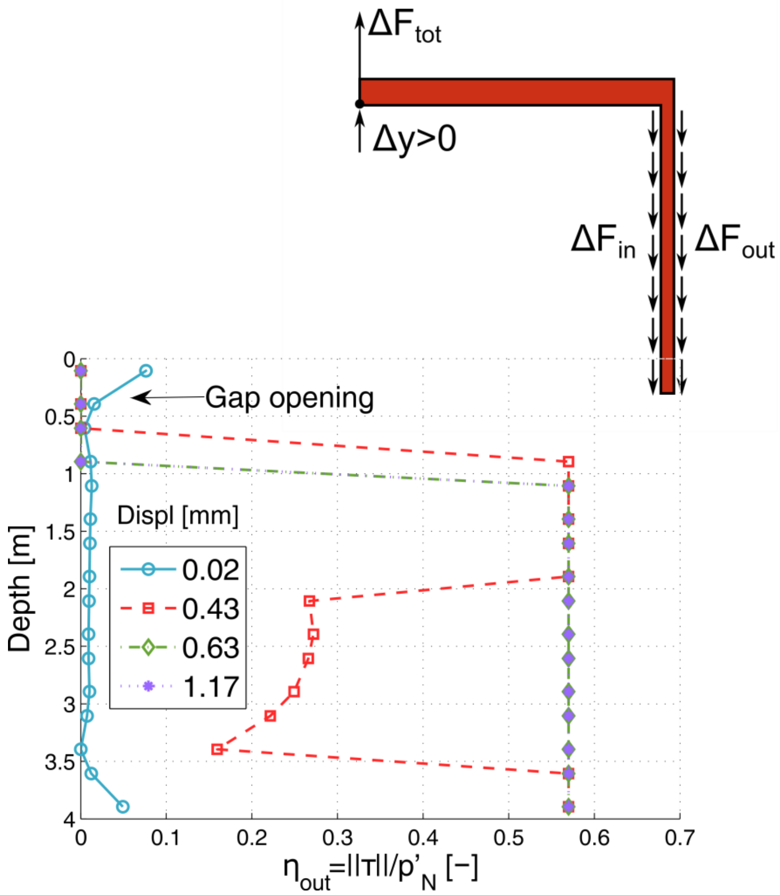

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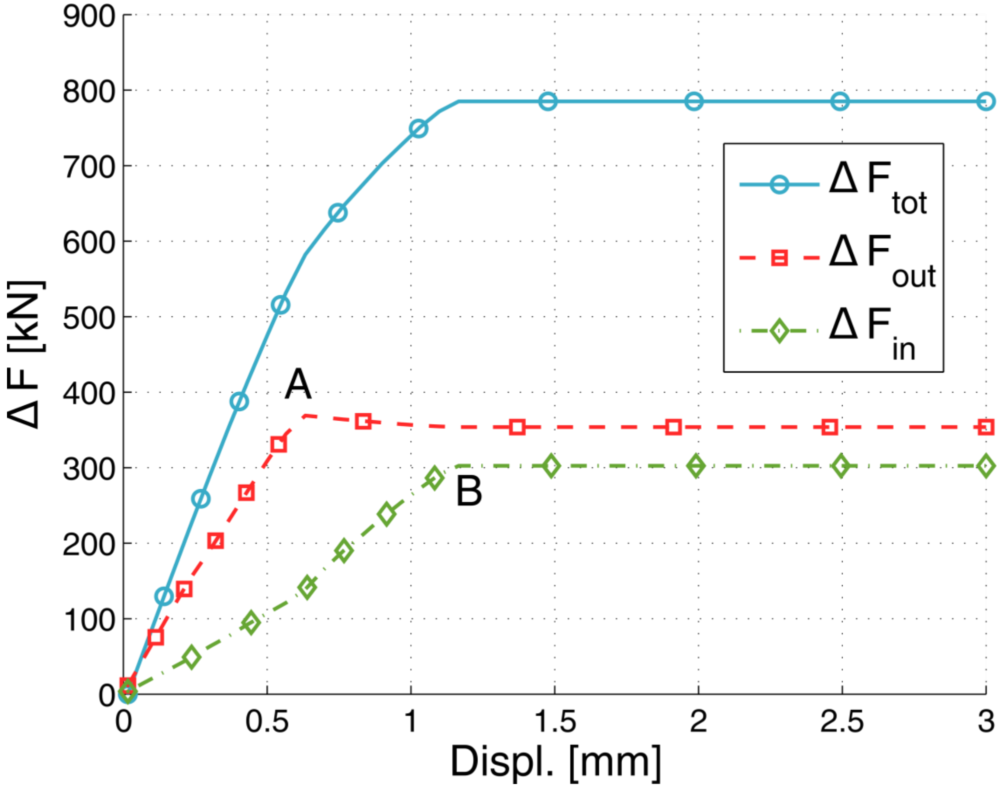
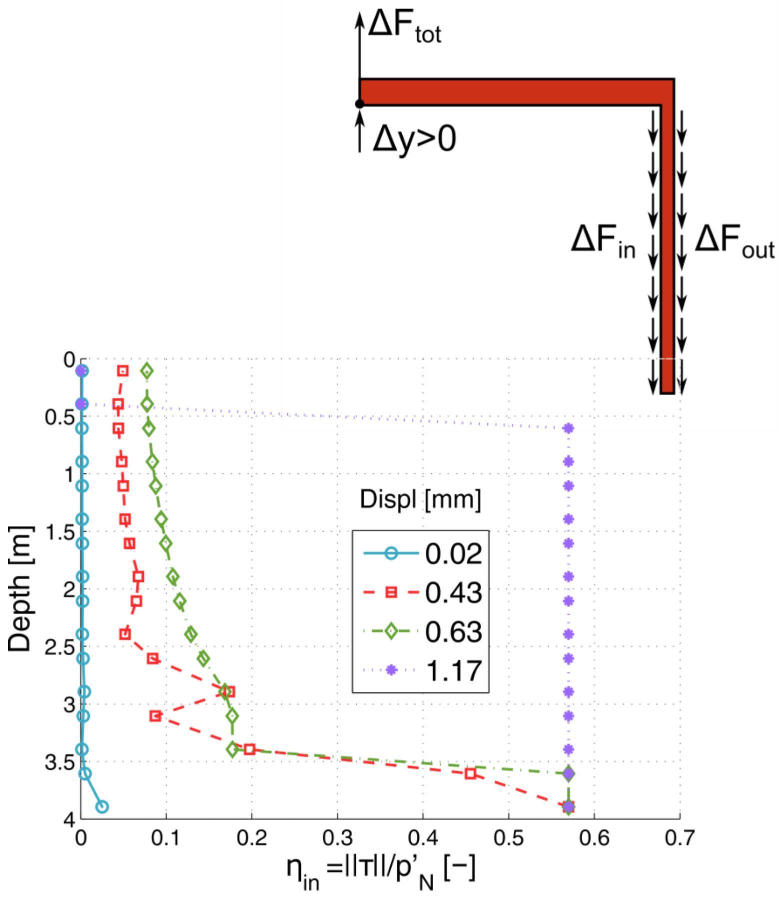
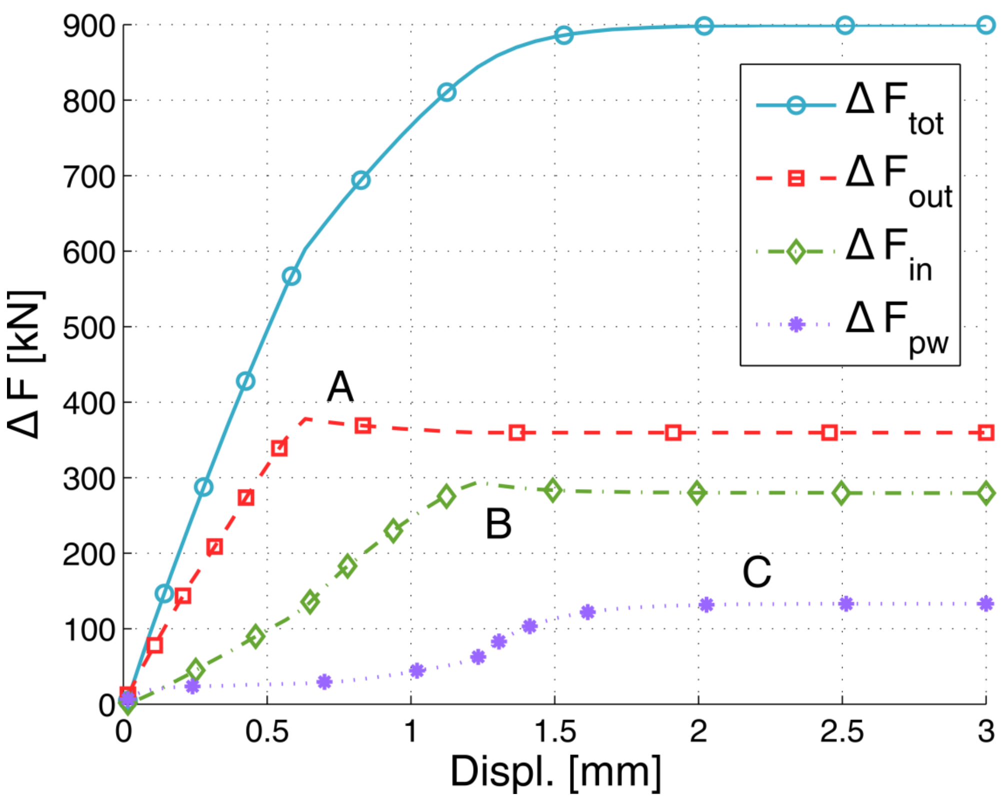
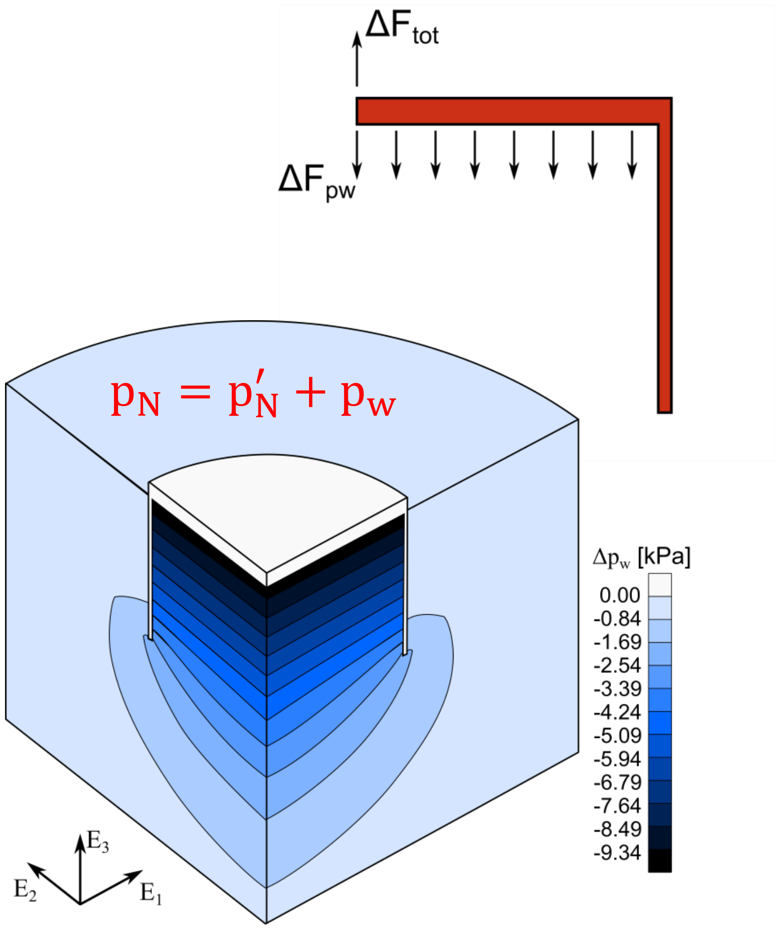


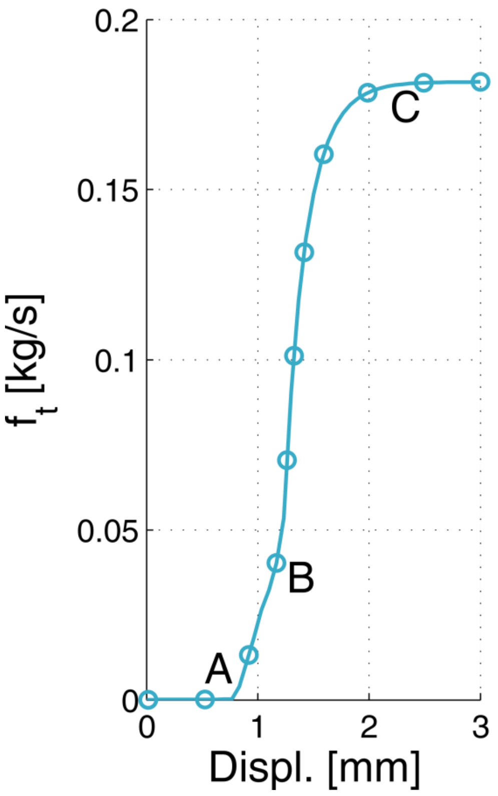


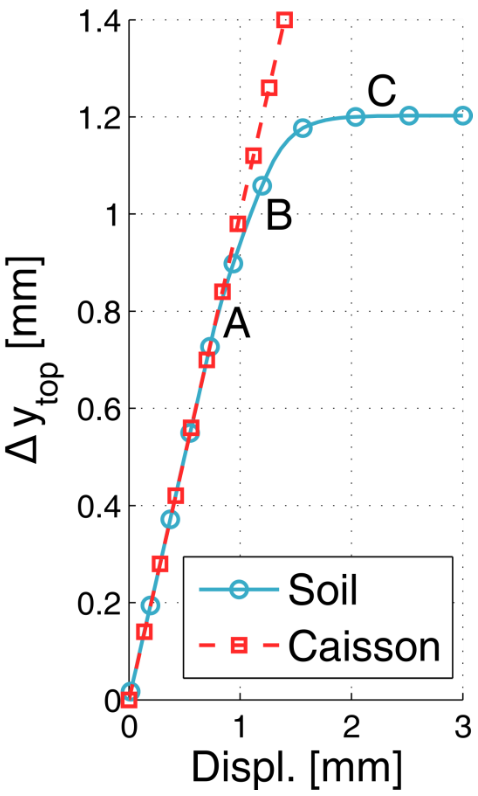
Suction caissons: Partially drained uplift (Coupled problem)

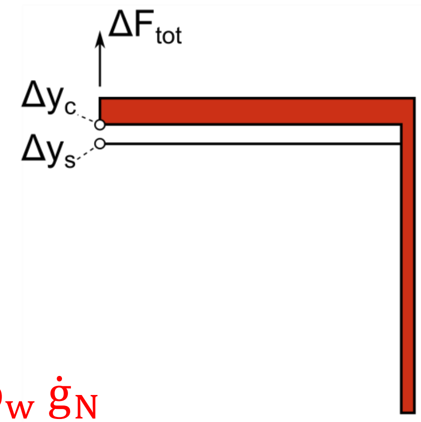




Suction caissons: Partially drained uplift (Coupled problem)



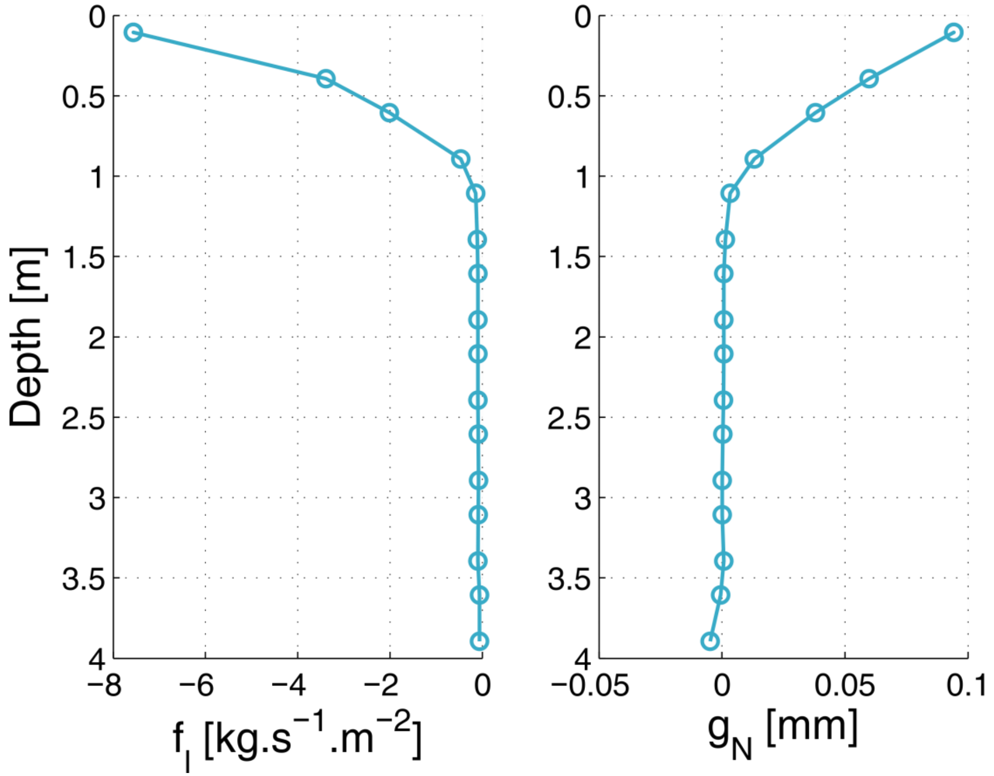


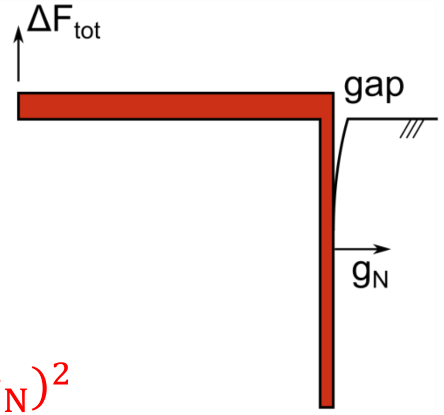


$\dot{S} = \rho_w \, \dot{g}_N$

- Inverse consolidation process
- Stabilisation of p_w
- Purely transient

SUCTION CAISSONS: PARTIALLY DRAINED UPLIFT (COUPLED PROBLEM)





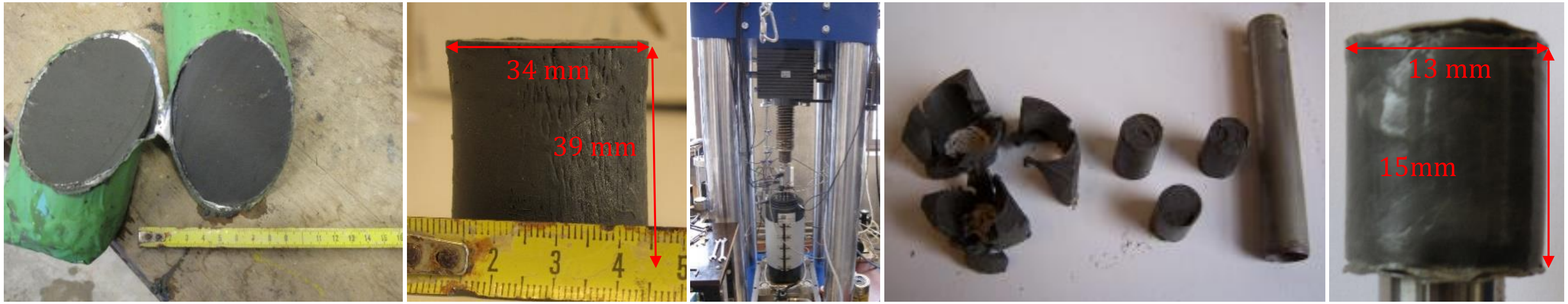
$$k = \frac{(D_0 + g_N)^2}{12}$$

- Increase drainage

Convective drying modelling

EXPERIMENTAL CAMPAIGN

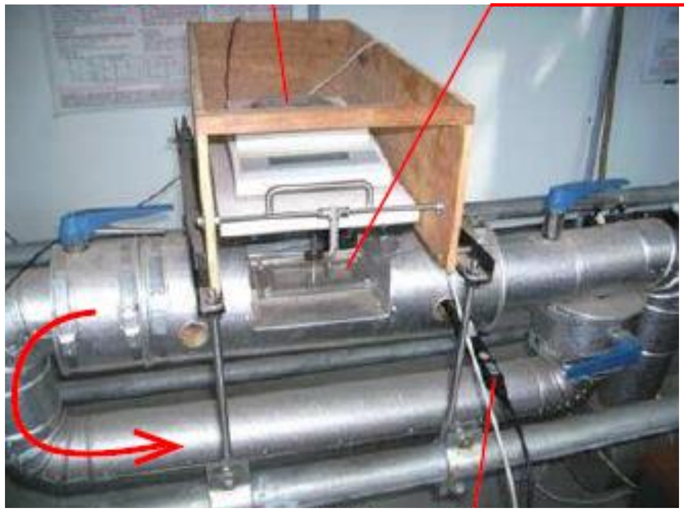
- Samples preparation

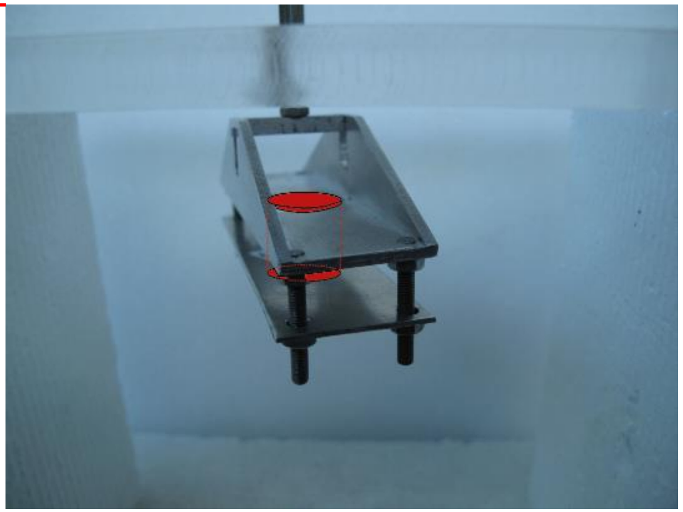


Initial core | Extracted samples | Saturation | Optimization | Finished samples

EXPERIMENTAL CAMPAIGN

- Convective drying tests

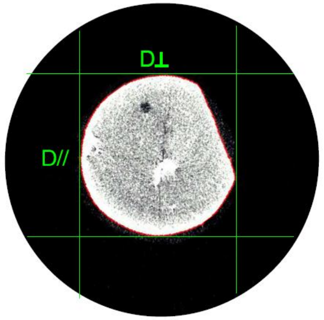


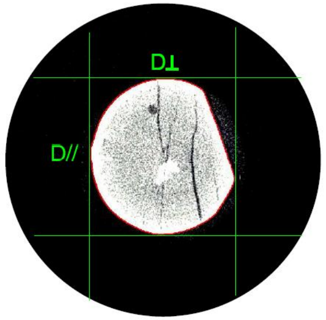


Drying conditions	
Temperature	25°C
Humidity	3,5 %
Air flow	0,8 m/s

EXPERIMENTAL CAMPAIGN

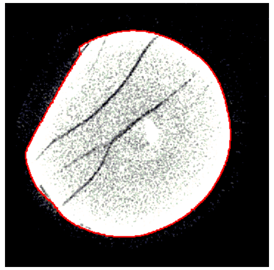
- Data acquisition



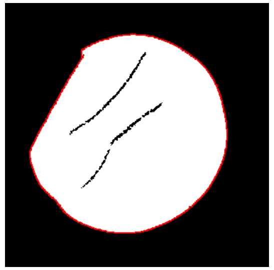


Identification of the bedding direction → Dimensions at saturated state → Dimensions until dry state

Skyscan 1172



Hole filling and binarization

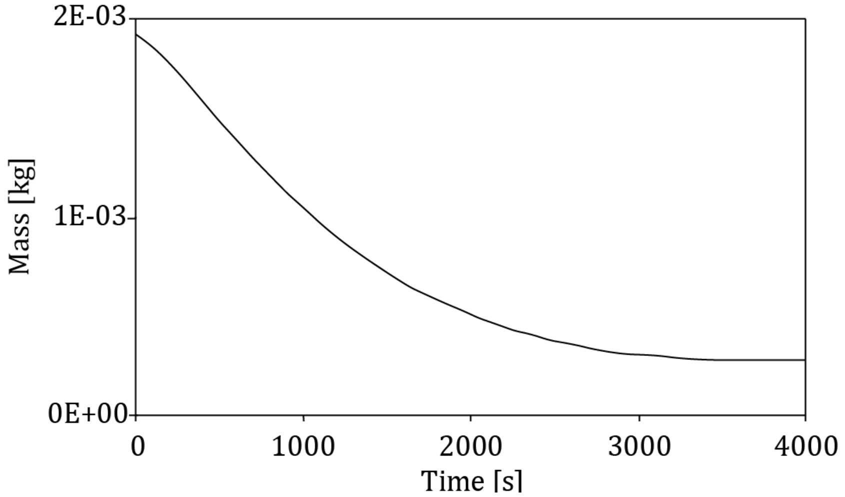


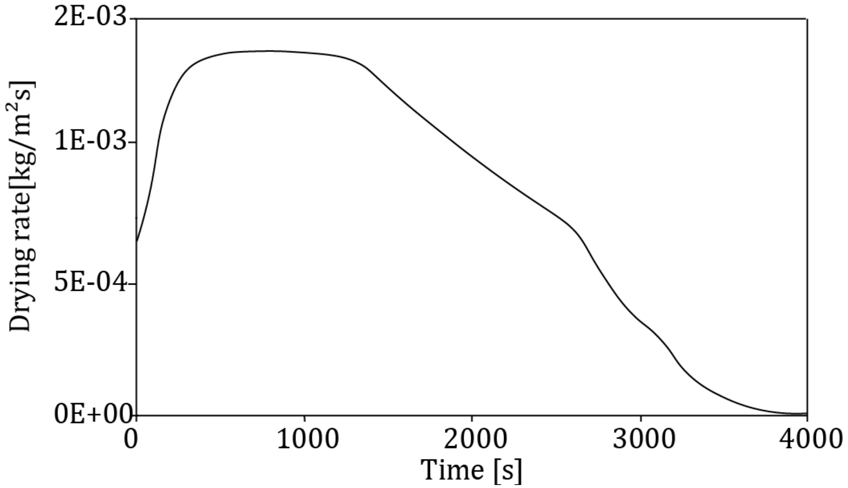
SUMMARY OF THE PRESENTATION

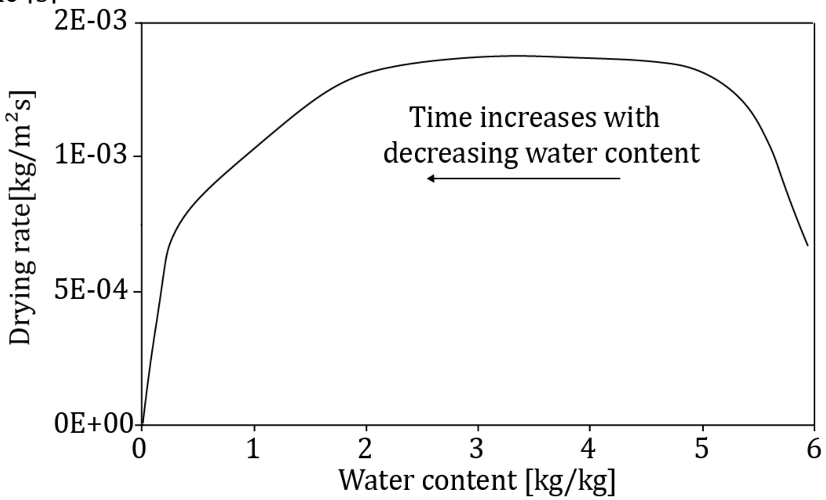
- Material and method
- Experimental results
- Model
- Numerical results
- Conclusion

DRYING KINETICS

- Theory of porous media convective drying

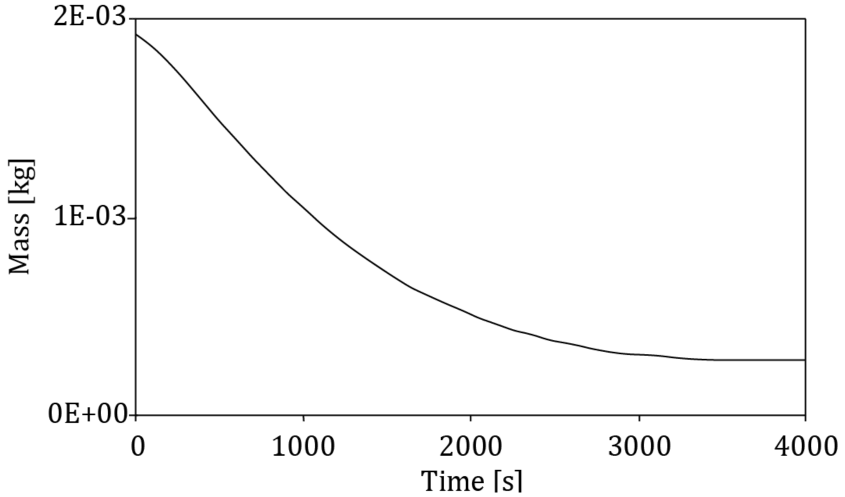


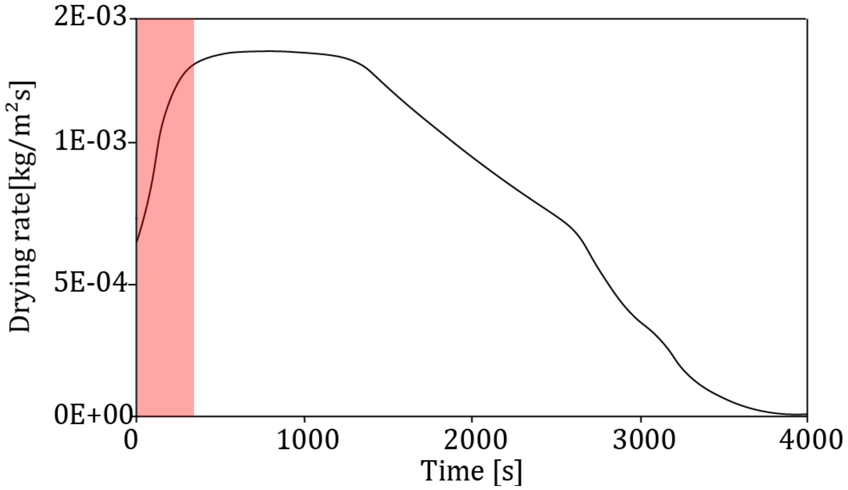


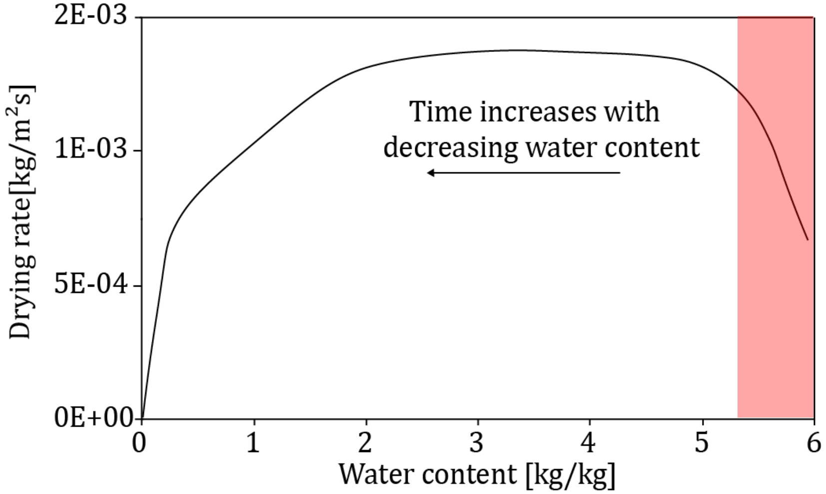


Drying kinetics

- Theory of porous media convective drying







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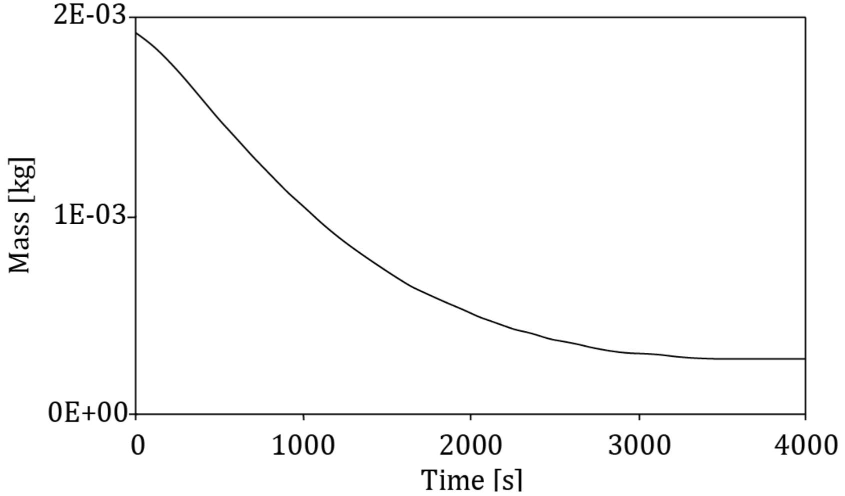
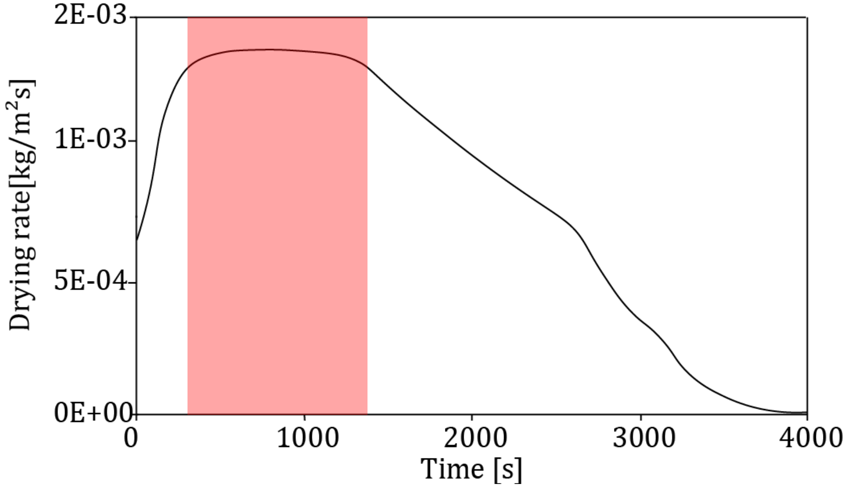
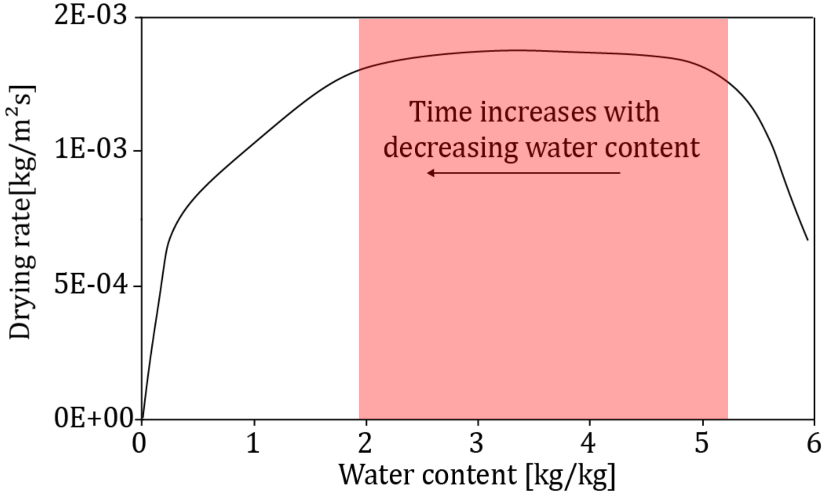
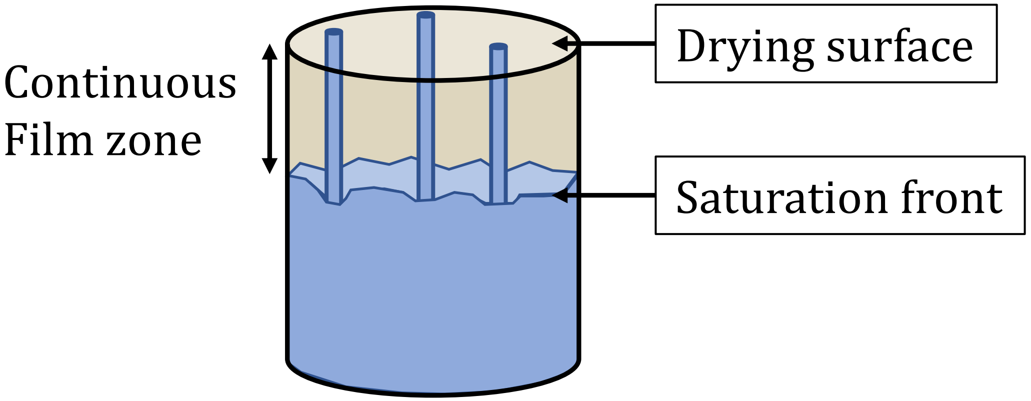


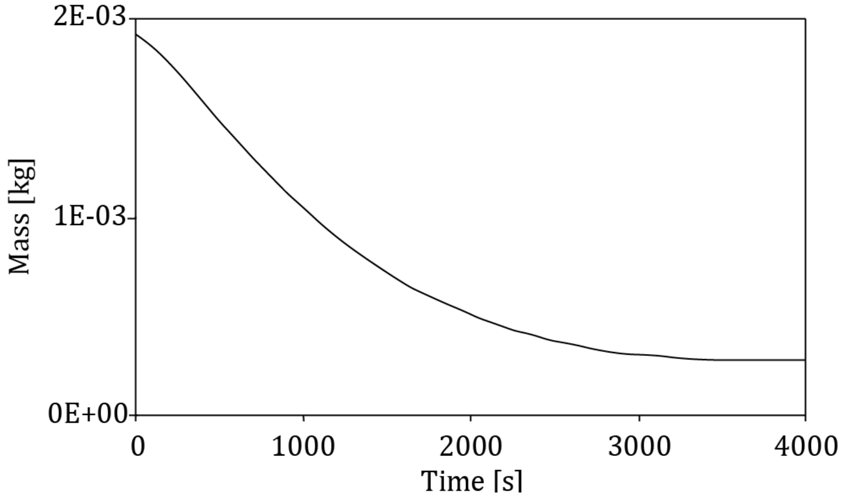


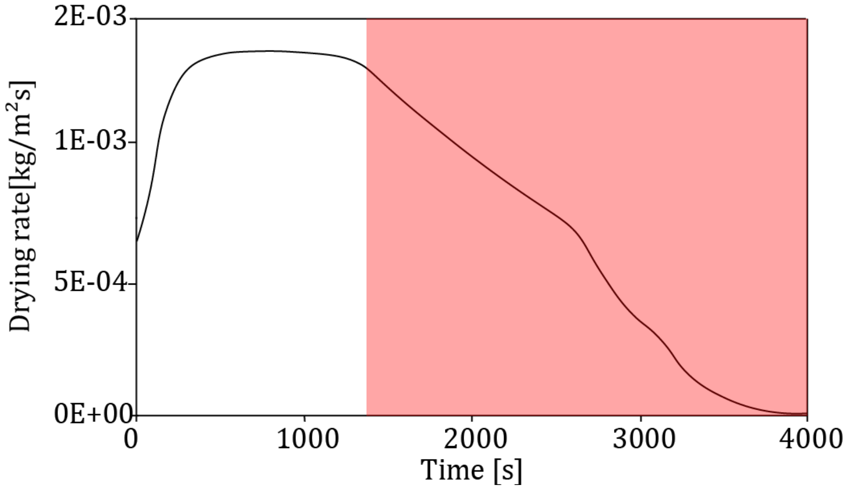


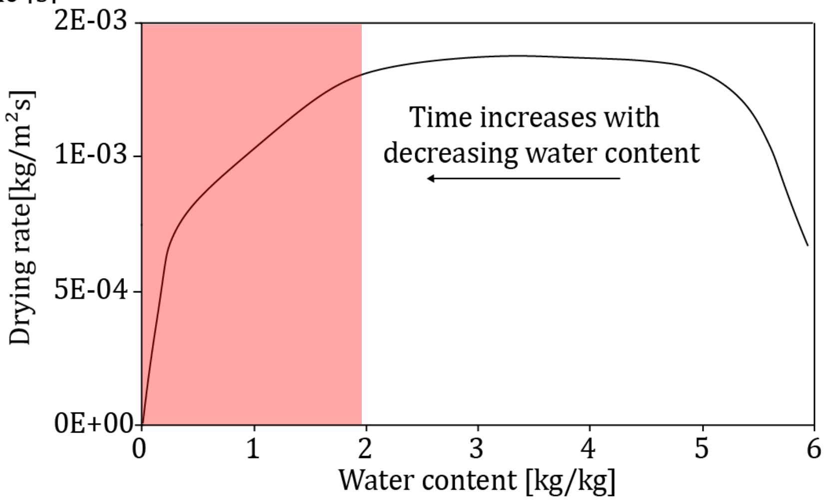


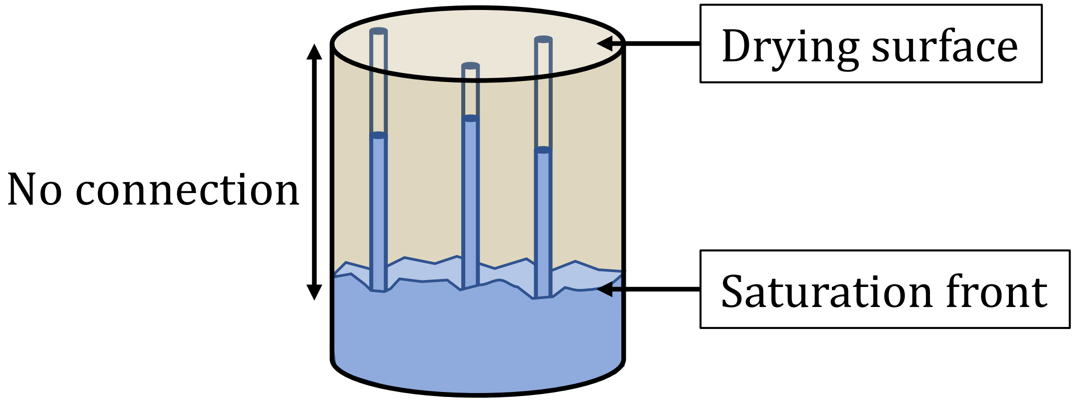
DRYING KINETICS

- Theory of porous media convective drying



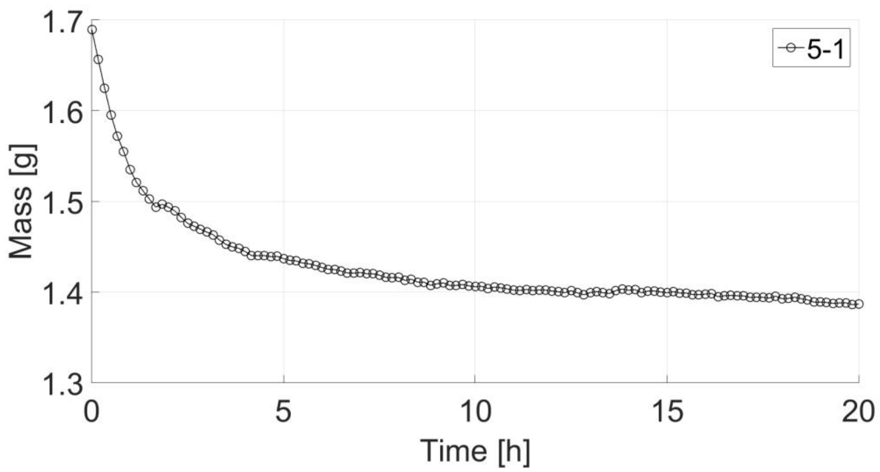


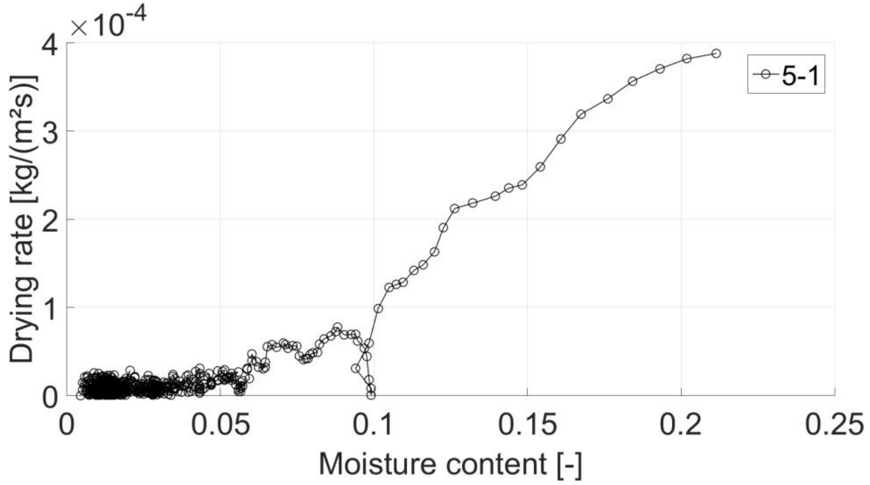


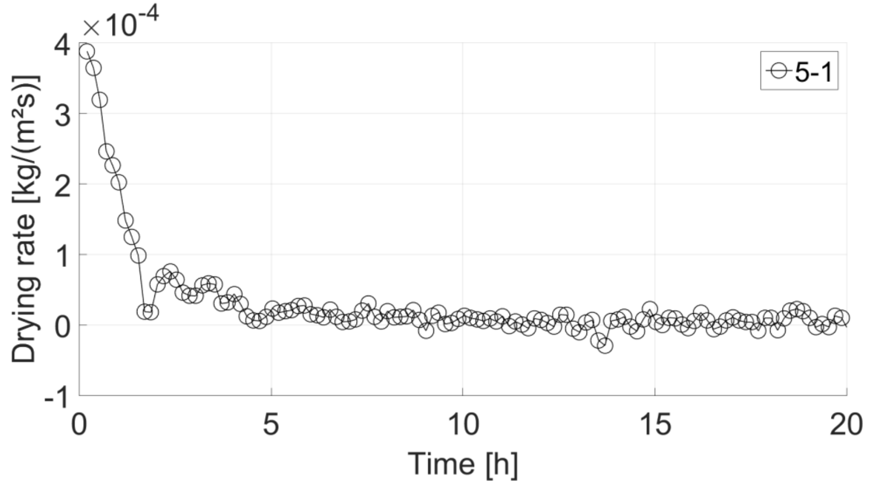


Experimental results

- Drying kinetics

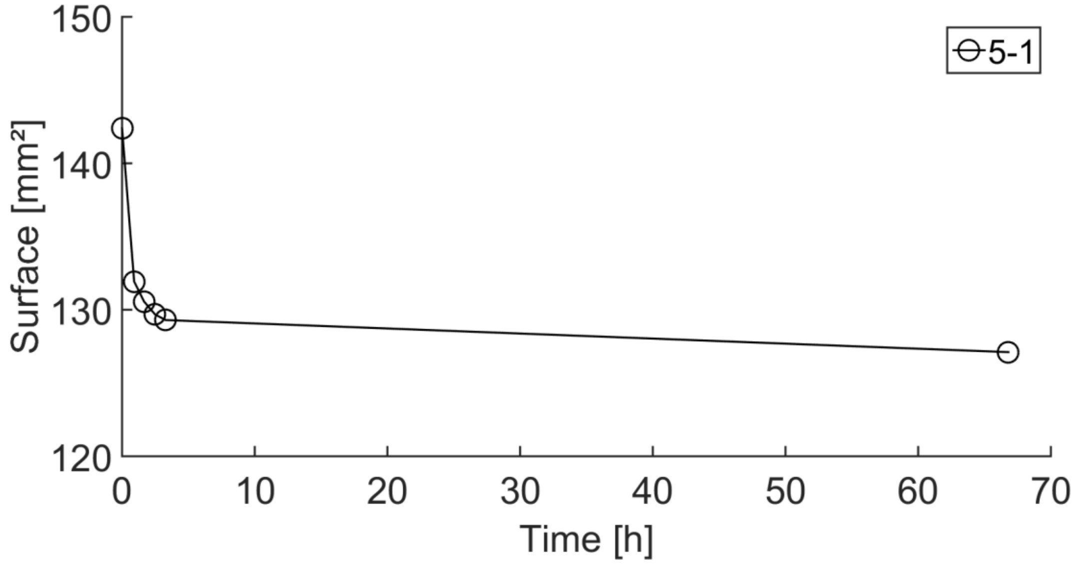


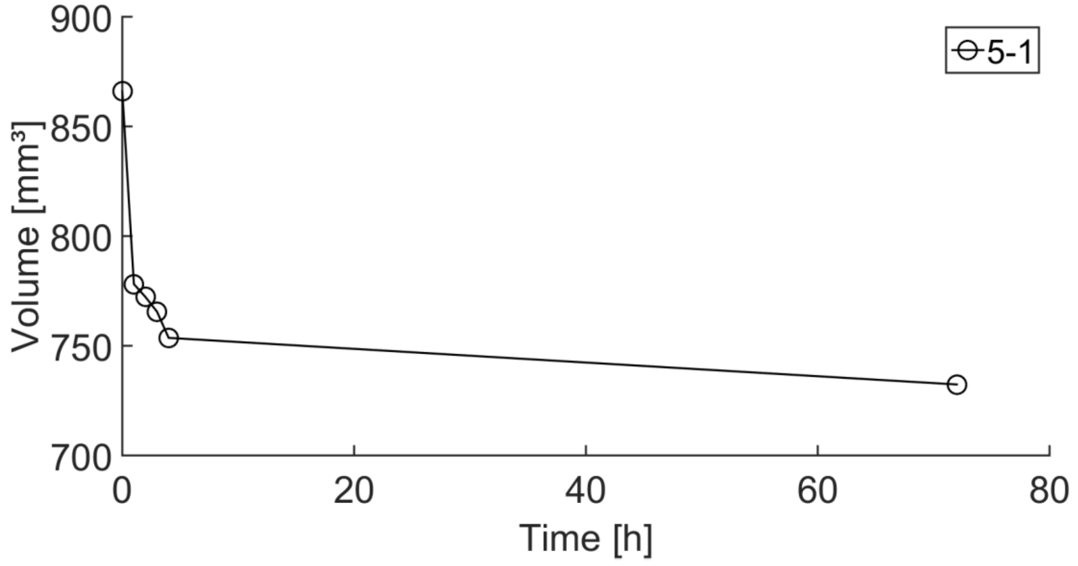




Experimental results

- Shrinkage



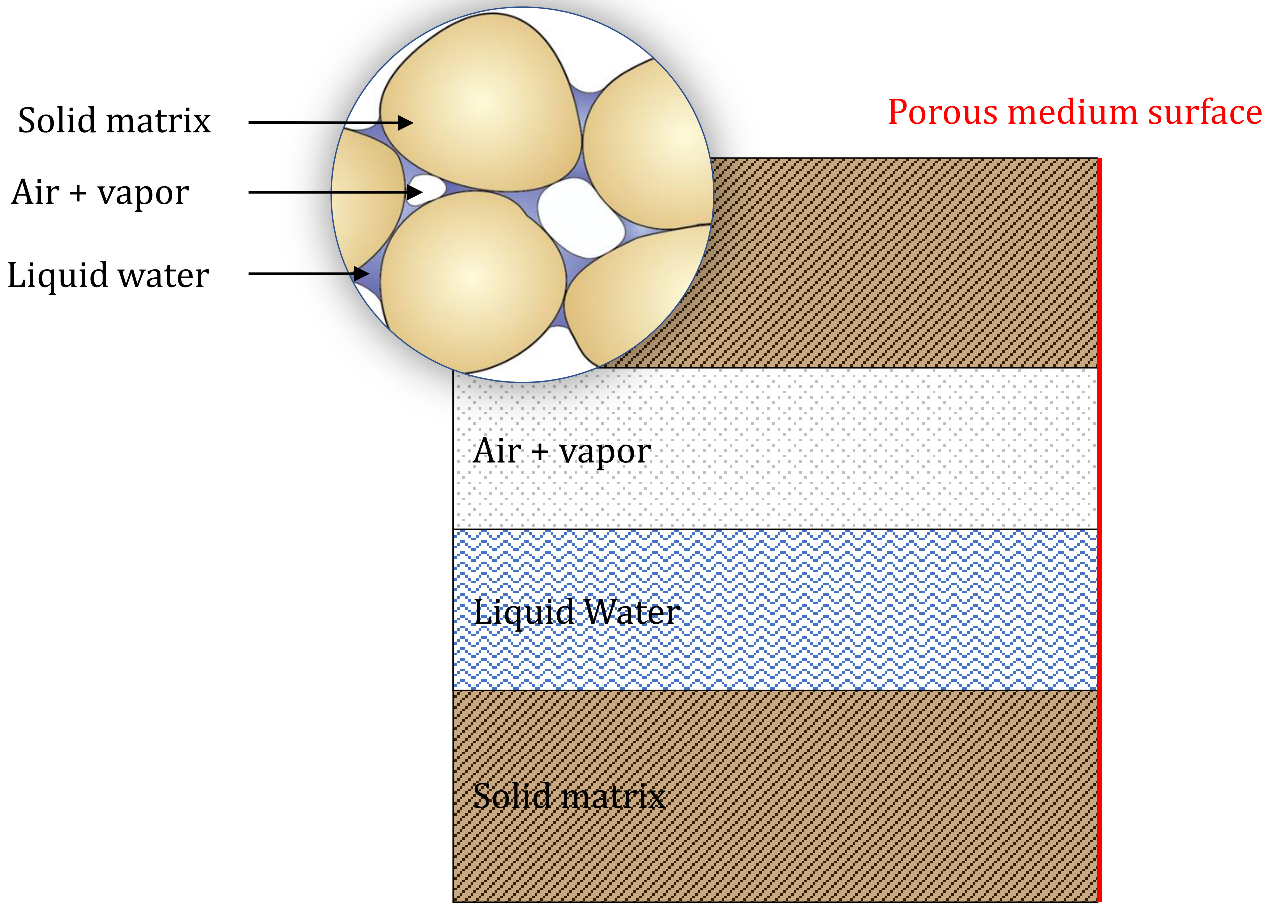


Summary of the presentation

- Material and method
- Experimental results
- Model
- Numerical results
- Conclusion

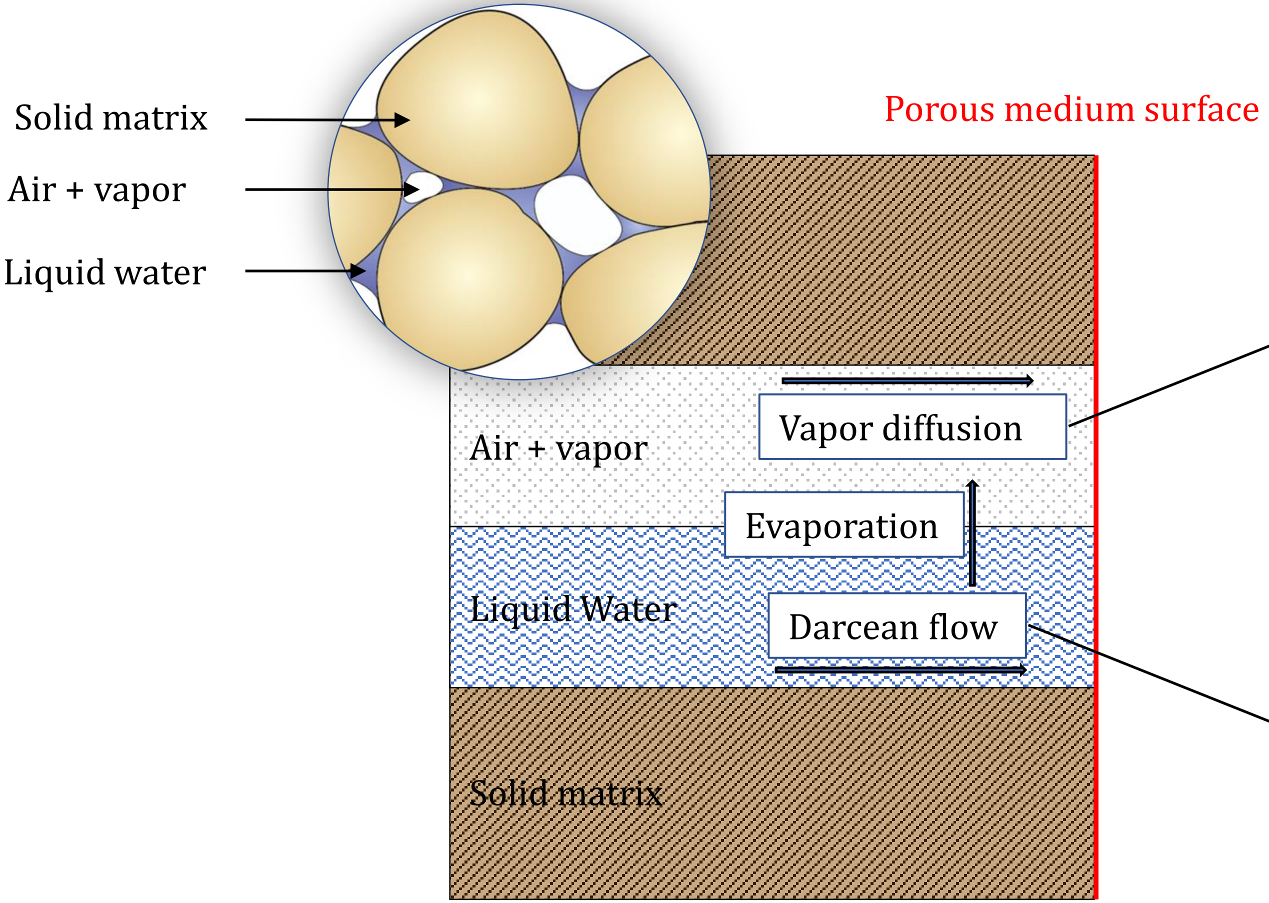
Model

- Porous medium



Model

- Internal Water transfer



Fick's law

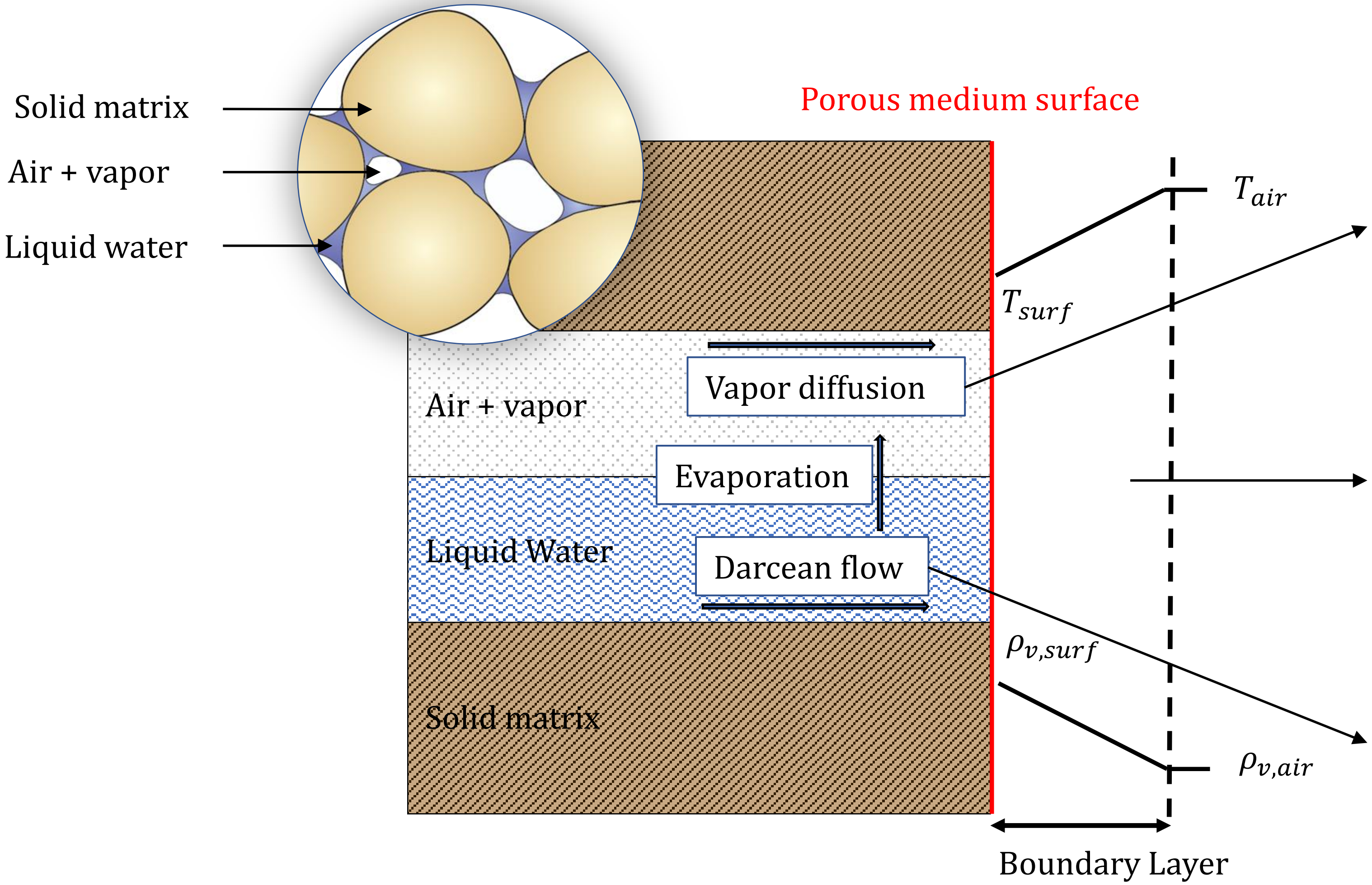
$$\underline{i}_v = -D_{atm} \tau_v n S_{r,v} \nabla(\rho_v)$$

Darcy's law

$$\underline{f}_w = -\frac{k_{rel}\left(S_{r,w}\right) k_{sat}}{\mu_w}\left(\underline{\nabla}(p_w) + \rho_w g \underline{\nabla}(z)\right)$$

Model

- Boundary layer model



Fick's law

$$\underline{i}_v = -D_{atm}\tau_v n S_{r,v} \nabla(\rho_v)$$

Boundary layer model

$$\underline{q}_h = L\underline{q} - \boldsymbol{\beta}(T_{air} - T_{surf})$$

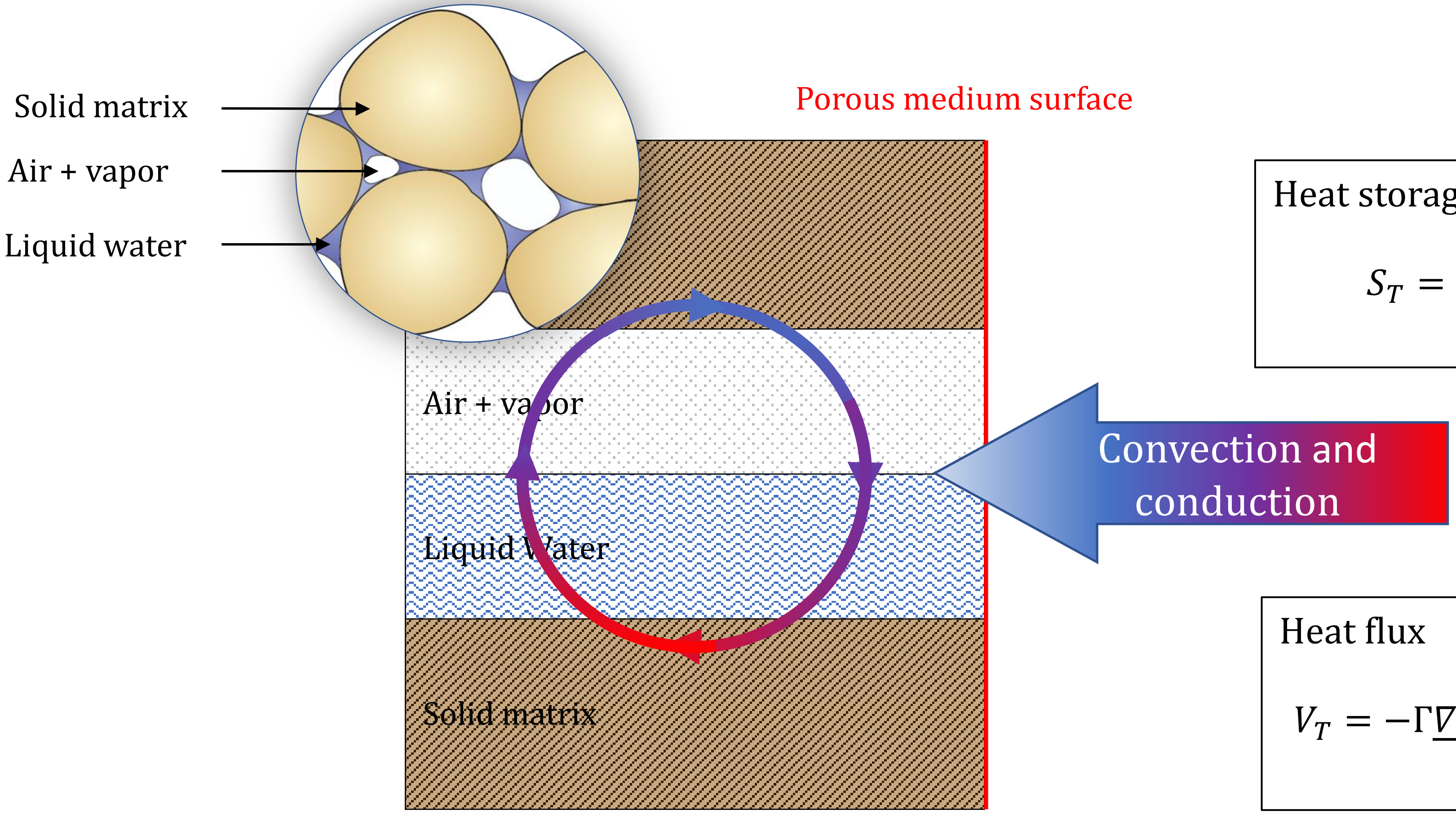
$$\underline{q} = \boldsymbol{\alpha}(\rho_{v,surf} - \rho_{v,air})$$

Darcy's law

$$\underline{f}_w = -\frac{k_{rel}(S_{r,w})k_{sat}}{\mu_w}\left(\underline{\nabla}(p_w) + \rho_w g \underline{\nabla}(z)\right)$$

Model

- Thermal model



Heat storage

$$S_T = nS_{r,i}\rho_i c_{p,i}(T - T_0) + nS_{r,g}\rho_v L$$

Heat flux

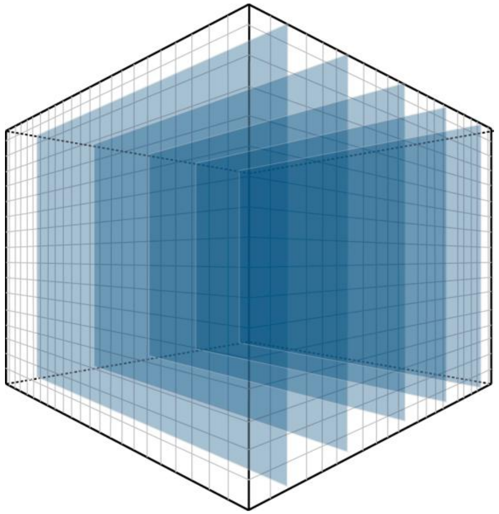
$$V_T = -\Gamma \underline{\nabla} T + c_{p,i}\rho_i \underline{f_i}(T - T_0) + (\rho_v f_v + i_v)\mathrm{L}$$

MODEL

- Mechanical model
  - Expressed in effective stress

$$\sigma'_{ij} = \sigma_{ij} - p_g\delta_{ij} + S_{r,w}(p_g - p_w)\delta_{ij}$$

  - 3D orthotropic elastic model



- Non linear elasticity :

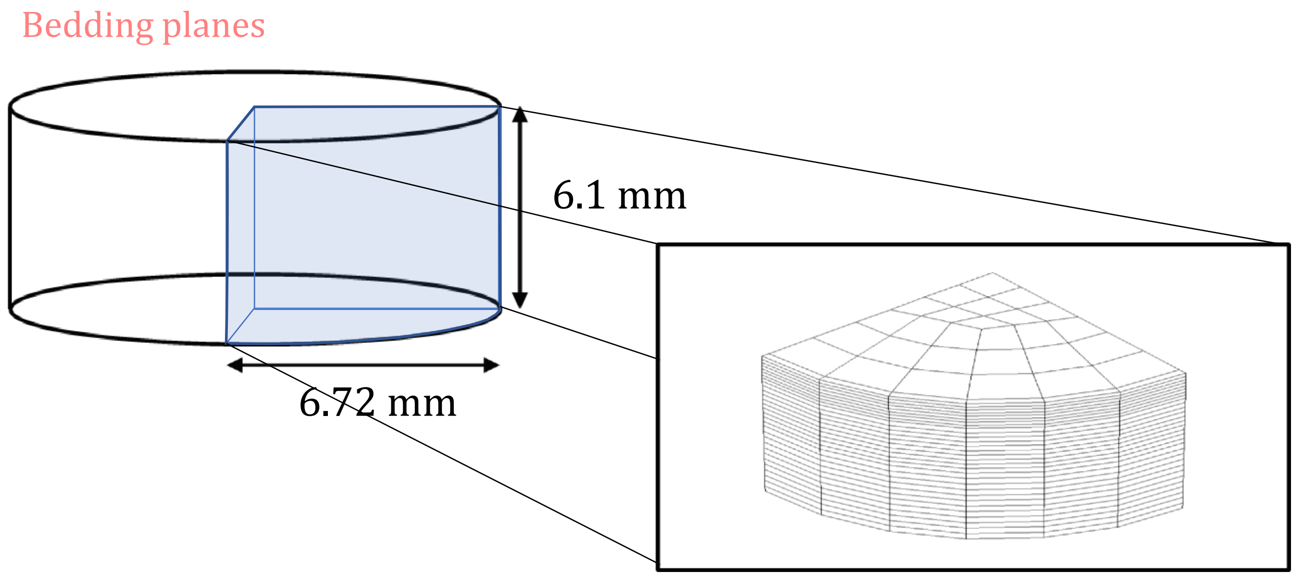
$$E = E_0 + E_{ref}\left(\frac{p'}{p_{ref}}\right)^b$$

$$\epsilon_{ij} = \mathrm{D}^{\mathrm{e}}_{\mathrm{ijkl}}\sigma'_{ij}$$

$$\mathrm{D}^{\mathrm{e}}_{\mathrm{ijkl}} = \begin{pmatrix} \frac{1}{E_\parallel} & -\frac{\nu_{\perp,\parallel}}{E_\perp} & -\frac{\nu_{z,\parallel}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{\parallel,\perp}}{E_\parallel} & \frac{1}{E_\perp} & -\frac{\nu_{z,\perp}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{\parallel,z}}{E_\parallel} & -\frac{\nu_{\perp,z}}{E_\perp} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{\parallel,\perp}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{\parallel,z}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{\perp,z}} \end{pmatrix}$$

Numerical modeling

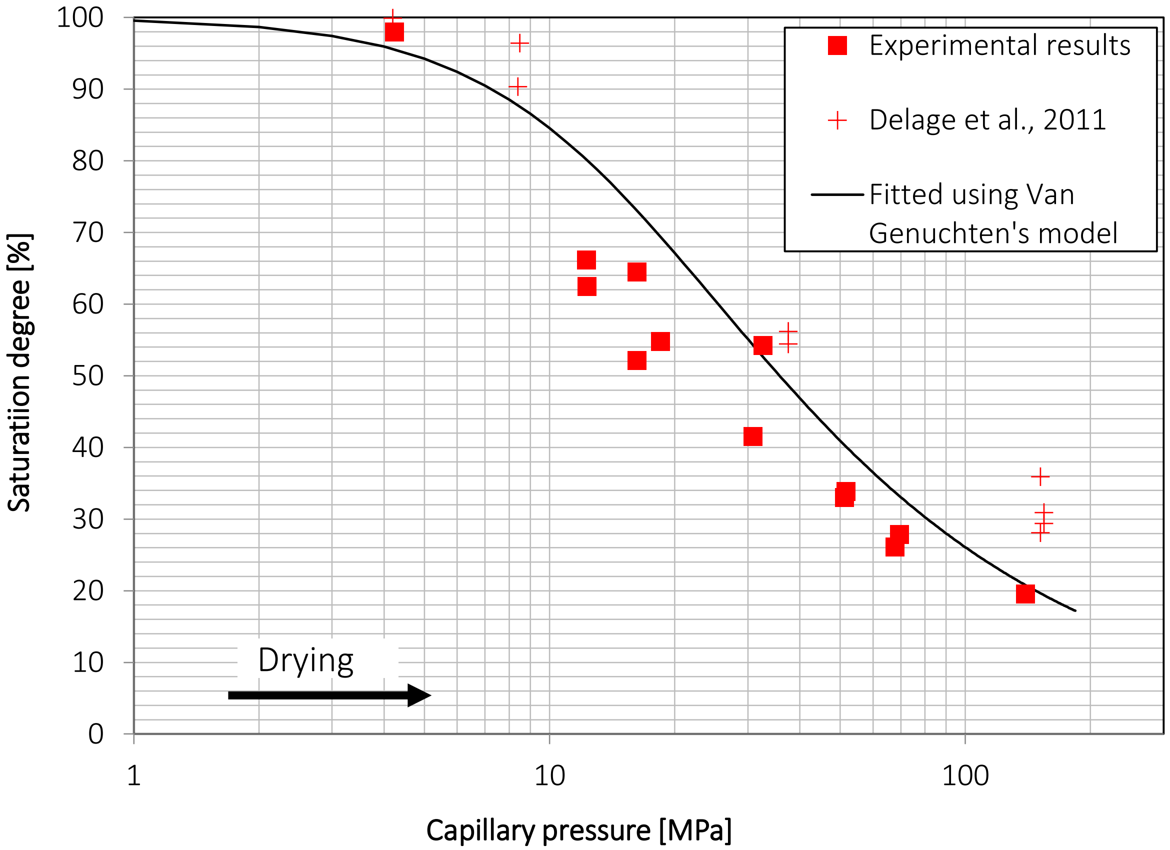
- Meshing and parameters



Parameters	Values	Units
Hydraulic Parameters		
$k_{sat,\perp}$	6.10^{-12}	$[m/s]$
$k_{sat,\parallel}$	3.10^{-12}	$[m/s]$
n	0.39	$[-]$
Mechanical Parameters		
$E_{\parallel,ref}$	350	$[MPa]$
$E_{\perp,ref}$	175	$[MPa]$
$E_{z,ref}$	300	$[MPa]$
$\nu_{\parallel\perp}$	0.125	$[-]$
$\nu_{\parallel z}$	0.0625	$[-]$
$\nu_{\perp z}$	0.0625	$[-]$
$G_{\parallel\perp}$	140	$[MPa]$
$G_{\perp z}$	140	$[MPa]$
ρ_s	2670	$[kg/m^3]$
Thermal Parameters		
$c_{p,s}$	2080	$[J/kg/K]$
ρ_s	2670	$[kg/m^3]$
$c_{p,w}$	4185	$[J/kg/K]$
ρ_w	1000	$[kg/m^3]$
$c_{p,a}$	1004	$[J/kg/K]$
ρ_a	1.2	$[kg/m^3]$
$c_{p,v}$	1864	$[J/kg/K]$
ρ_v	0.59	$[kg/m^3]$

WATER RETENTION CURVE

- Samples put into chamber with controlled suction (saline solution)
- Water content measured ⇒ saturation degree deduced



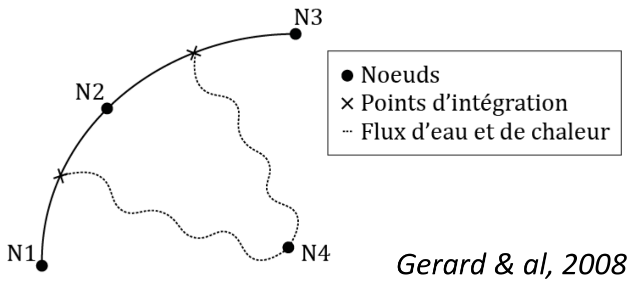
Van Genuchten formulation :

$$S_{r,w} = S_{res} + (S_{sat} - S_{res})\left[\left(1 + \frac{p_c}{\alpha}\right)^{n_{vG}}\right]^{-m_{vG}}$$

VAN GENUCHTEN FORMULATION		
S_{res}	0	[-]
S_{sat}	1	[-]
α_{vg}	15	$[MPa]$
m_{vg}	0.449	[-]
n_{vg}	1.70	[-]

NUMERICAL MODELING

- Boundary layer model in FEM code:



Gerard & al, 2008

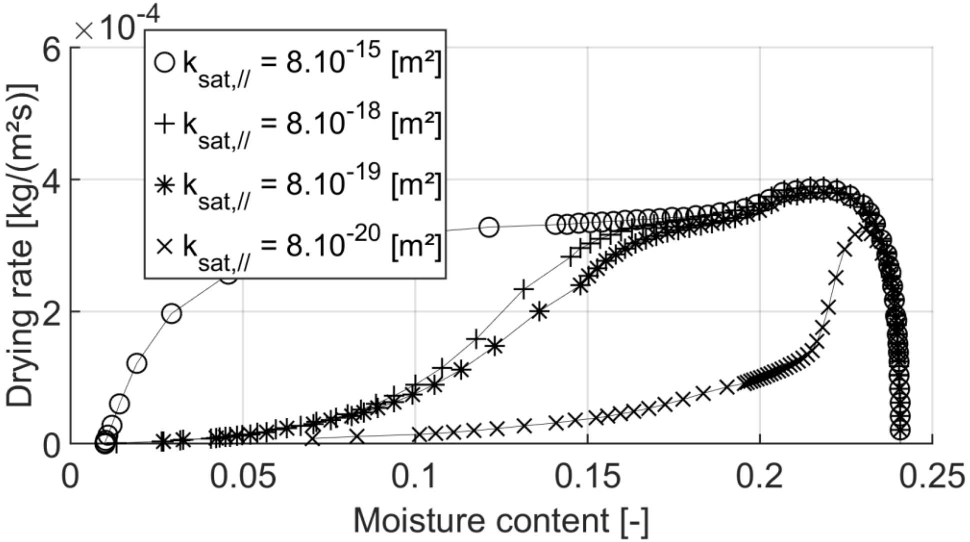
- Water pressure at the environmental node n_4: $p_c = -\frac{\rho RT}{M} ln(HR)$
- Temperature at the environmental node n_4 : $T \;= 25°C$
- Transfer coeffcients:

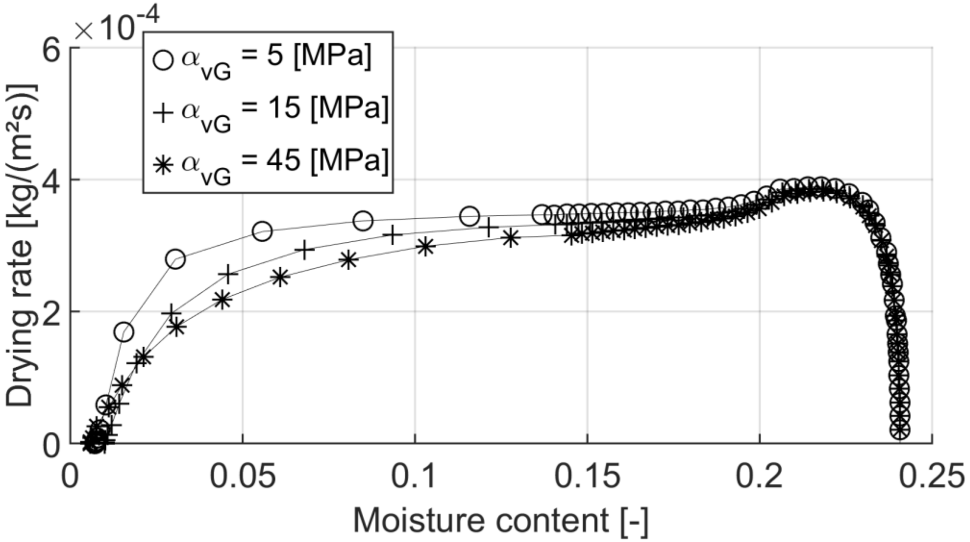
$\boldsymbol{\alpha}$ $[\boldsymbol{m/s}]$	$\boldsymbol{\beta}$ $[\boldsymbol{W/m^2/K}]$
0.048	53

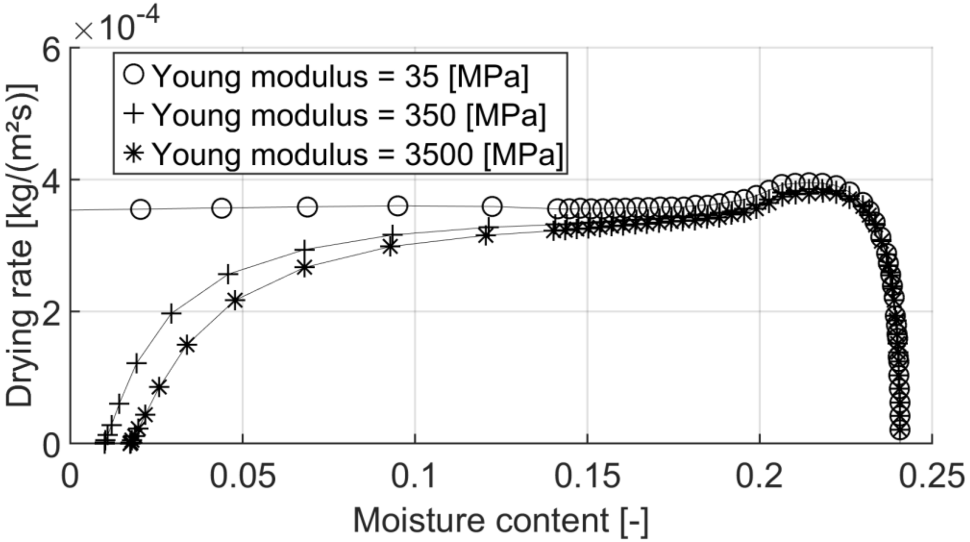
SUMMARY OF THE PRESENTATION

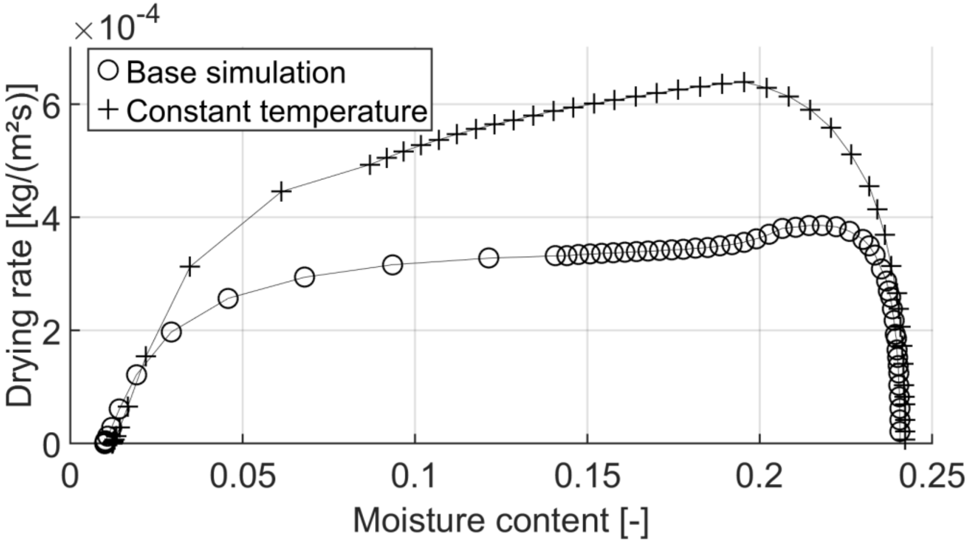
- Material and method
- Experimental results
- Model
- Numerical results
- Conclusion

Sensitivity study



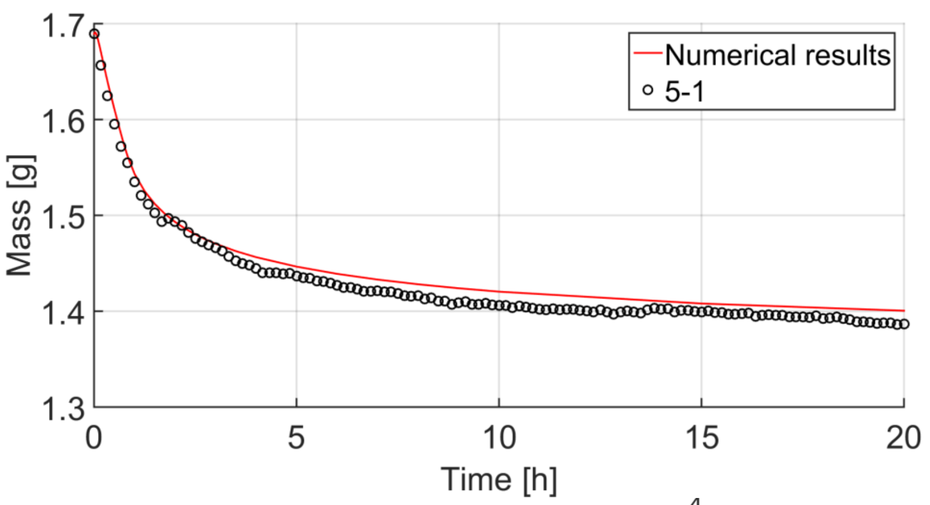


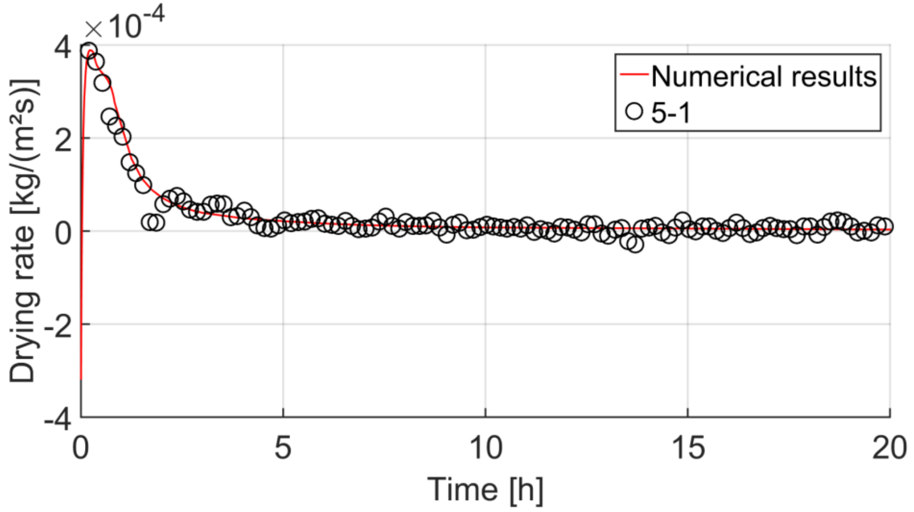


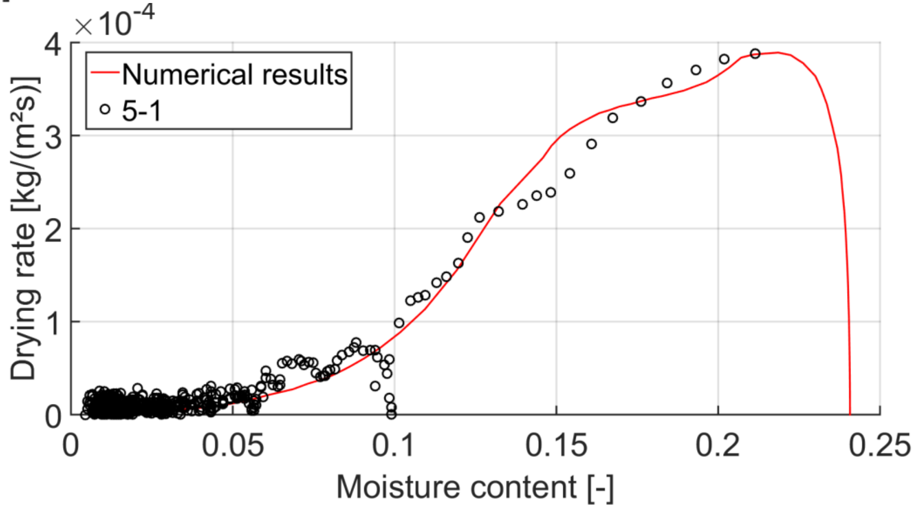


NUMERICAL RESULTS

- Drying kinetics

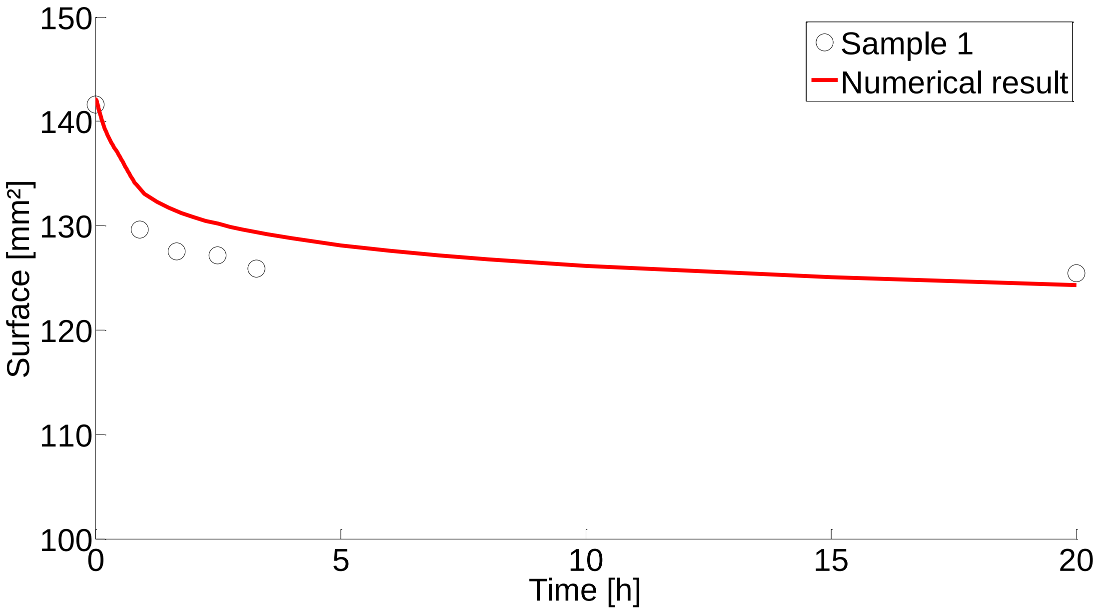


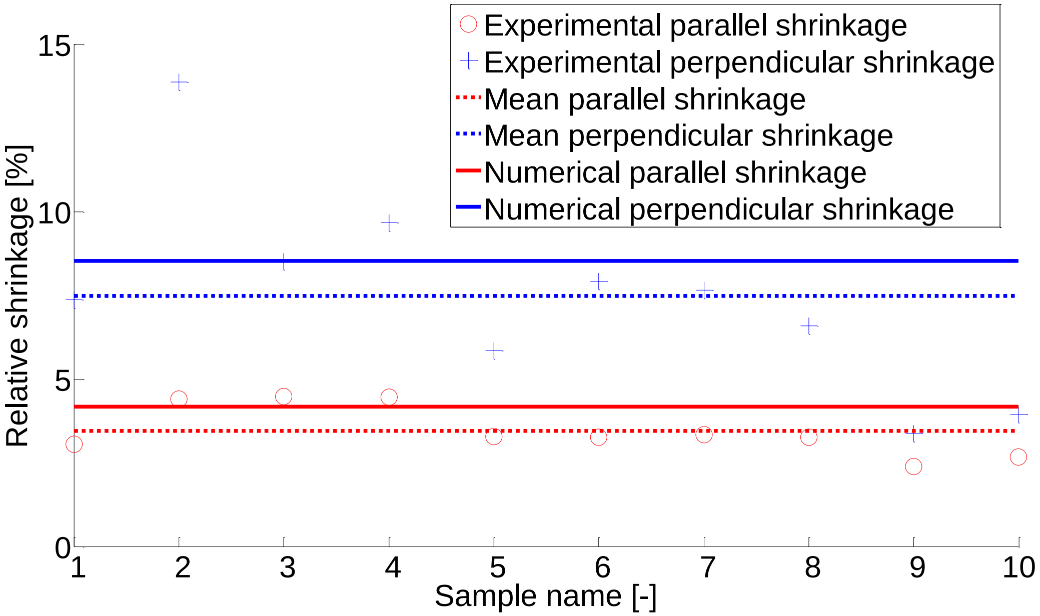




Numerical results

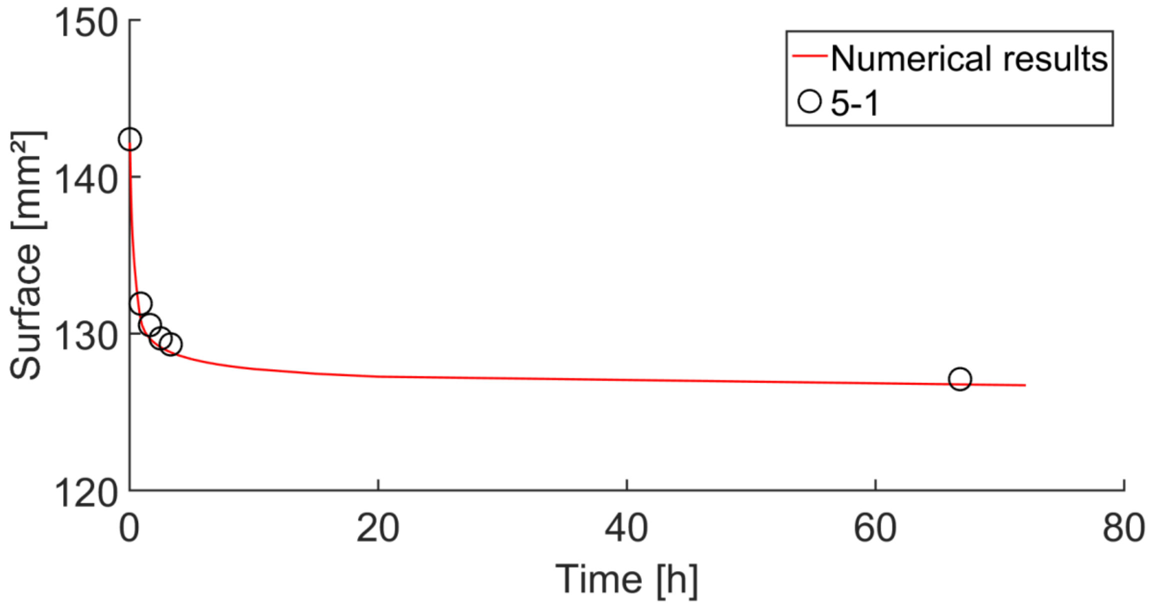
- Shrinkage (linear elasticity)

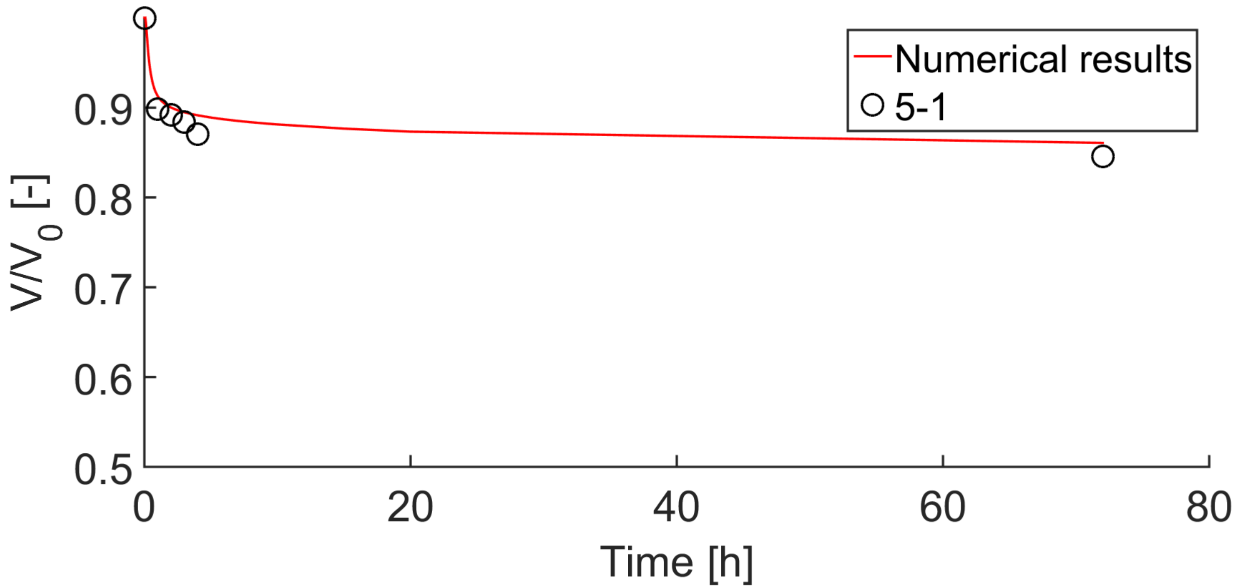




NUMERICAL RESULTS

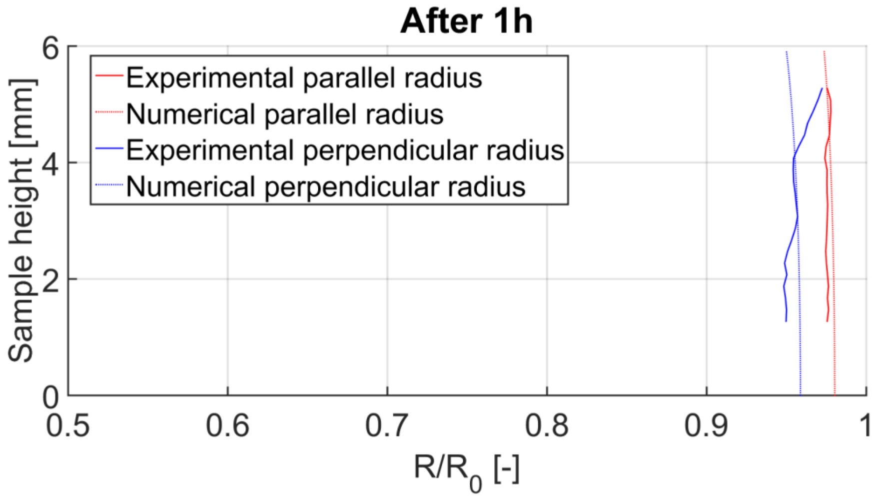
- Shrinkage (non linear elasticity)

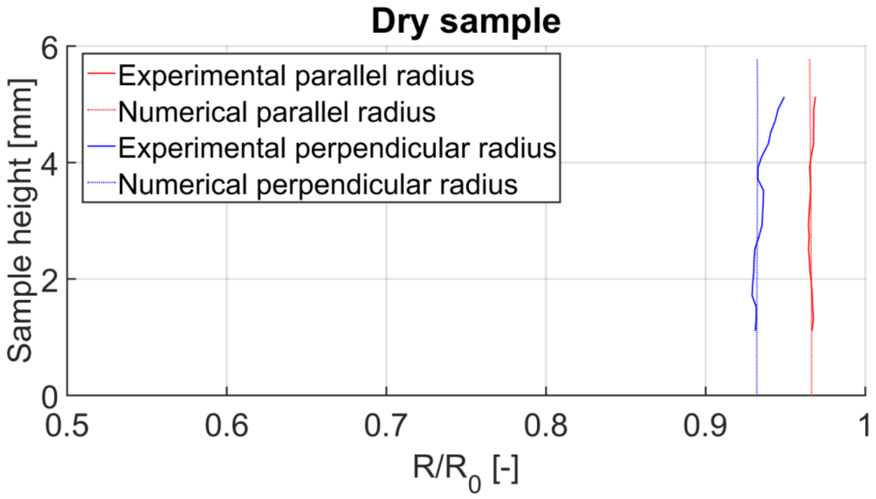


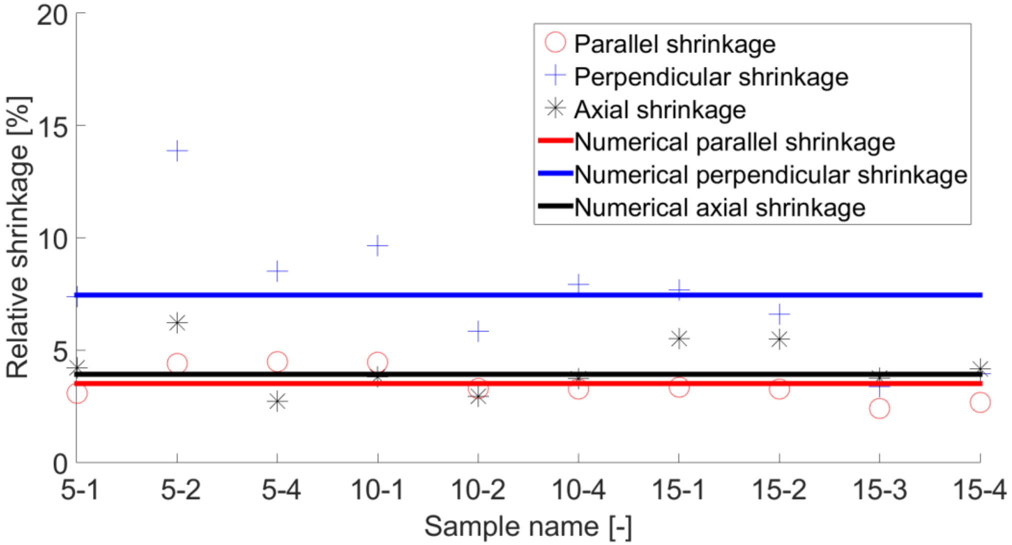


NUMERICAL RESULTS

- Shrinkage

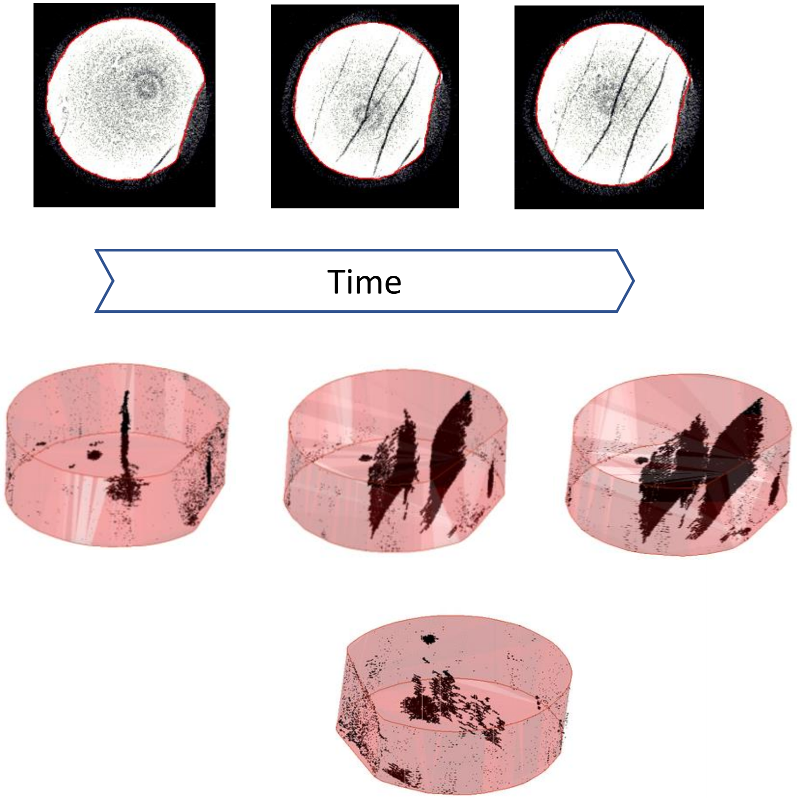


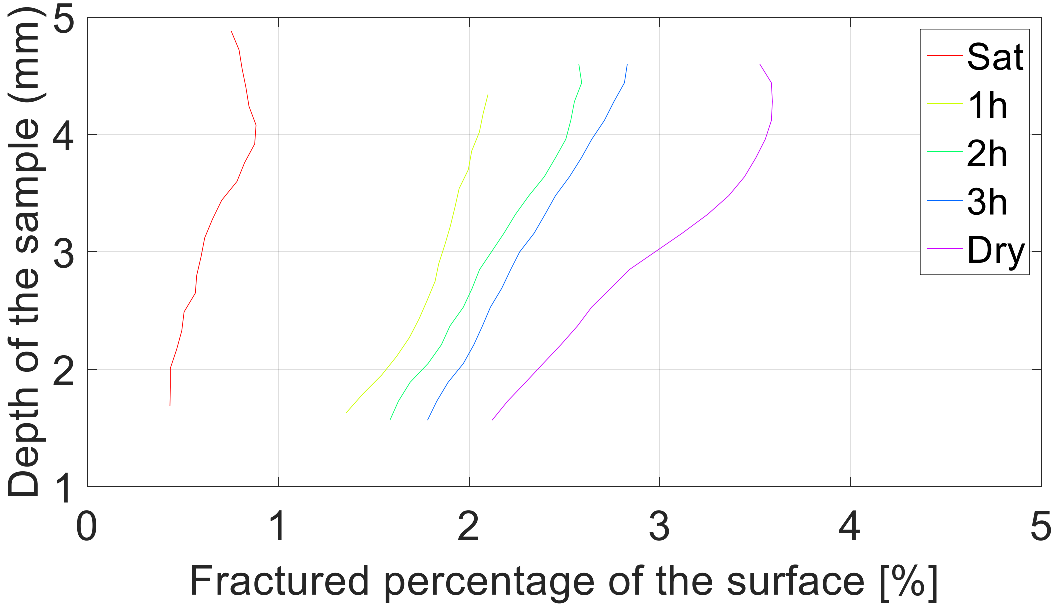




Conclusion

- Dessication cracking





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BOOM CLAY COMPOSITION

Composition minéralogique en [%]	*Al-Mukhtar et al., 1996*	*Wouters et Vandenberghe, 1994*	*Decleer et al., 1983*	*Horseman et al., 1986*
Quartz	20-25	20	23.8-58.3	30
Interstratifié illite-smectite	33	40-50		
Illite	16	25-35	3-23	19
Smectite			19-42	22
Kaolinite	13	15-25	1-9	29
Feldspaths:		5-10		
Microcline	4-5		6.5-11.3	
Plagioclase	4-5		3.2-6.2	
Chlorite		5-10		
Pyrite	4-5	1-5	0.7-2.5	
Carbonates	traces	1-5	0.0-4.3	
Matières organiques		1-5		

Tableau 3 : Revue bibliographique de la composition minéralogique de l'Argile de Boom

Materials and methods

- X-Ray tomography characteristics
  - Cross section acquisition using a X-Ray microtomography

Skyscan 1172

Source Voltage = 100 kV	Filter = Al 0.5 mm	4x4 binning = 900x666 pixel radiograms
Pixel size = 27.27 µm	Exposure time = 510 ms	Rotation Step (deg)= 0.65
180° rotation	2 vertically-connected scans	Scan duration = 8 minutes

EXPERIMENTAL RESULTS

- Numerical filter