Friction modifies poroelasticity of a yeast clog

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$$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$$

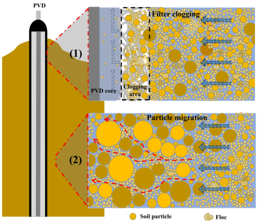
InterPore – May 19-22nd, 2026

What is (bio)clogging ?

Definition of **clogging**

Accumulation of particles at the solid surface of a porous media flowed by a suspension.

- Environment
  - **Soil remediation**
- Industry
  - **Filtration**, buried resources



Zhang *et al.* (2024)

From cerahelix.com

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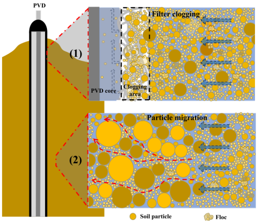

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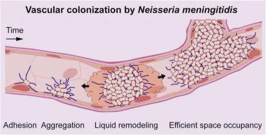
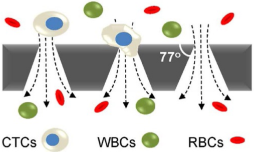
Bioclogging: clogging with biological objects

> Bio-medicine
  - **Brain diseases**
  - **Diagnostic**

> Food industry
  - Yeast filtration (beer, ...)

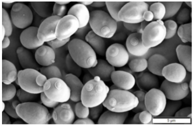


Bonazzi *et al.* (2018)



Tang *et al.* (2014)

> Well-known **mechanical properties**
- Ovoid, polydisperse in size



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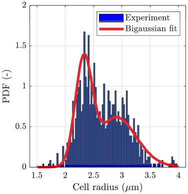
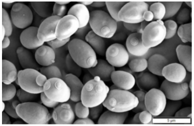


From T. Desclaux thesis

Saccharomyces cerevisiae, a model biological object

> Well-known **mechanical properties**
- Ovoid, polydisperse in size
- Specific adhesion/friction mechanism
- Pressurized elastic shell



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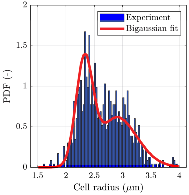

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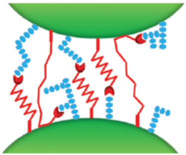
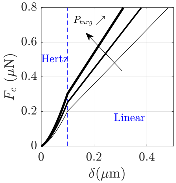


From El-Kirat Chatel *et al.* (2014)



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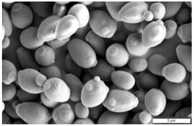

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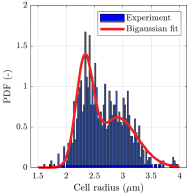

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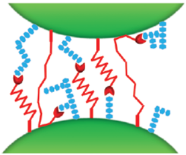
> Well-controlled **biological behaviour**
- Cells collected in exponential growing phase
- Add of antibiotic to **stop proliferation**



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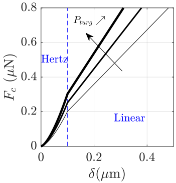

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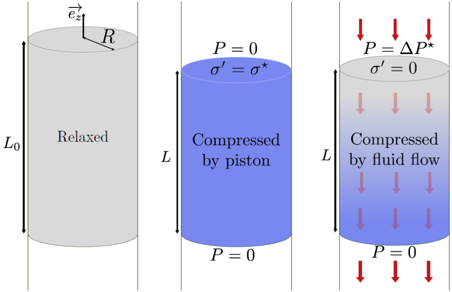
(Poro)mechanics of a yeast clog

> A yeast clog is...
- a soft porous media
- in a confined environment



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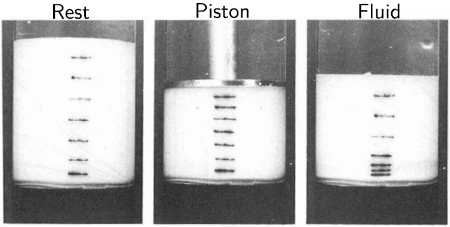

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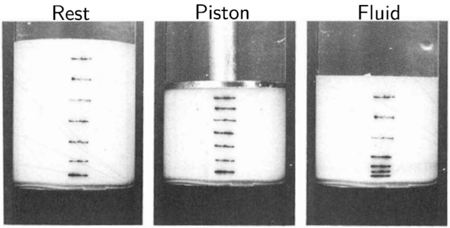
- Few studies of yeast clog mechanics
  - Ben Hassan *et al.* (2014): no compression
  - Valencia *et al.* (2022): decompression



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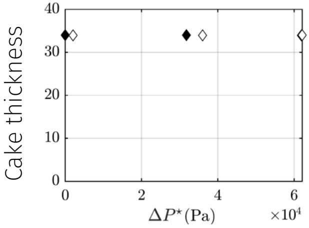

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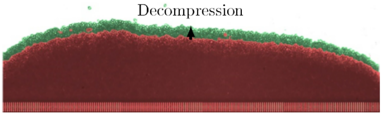

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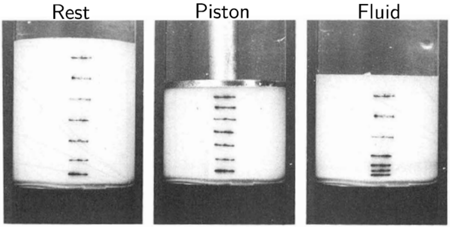

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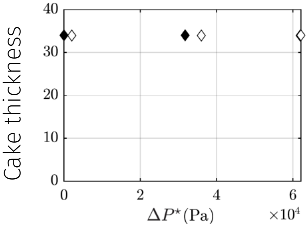

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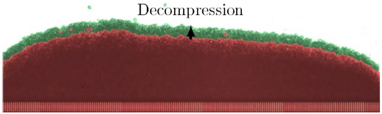
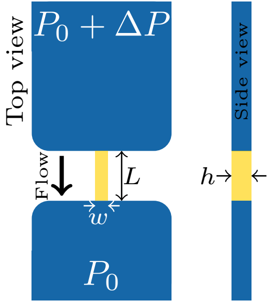


Could confinement explain these differences ?

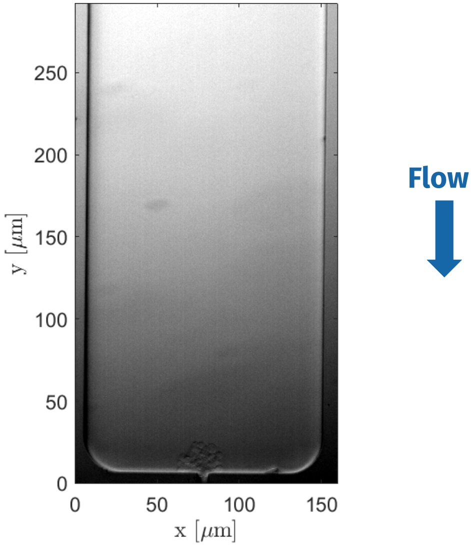
- Microfluidic silicon-glass channels



Dimensions

- Depth: $h = 6.5\,\mu$m
- Width: $w = 6\,\mu$m
- Length: $L = 50\,\mu$m
- Yeast: $\oslash \approx 4.5\,\mu$m

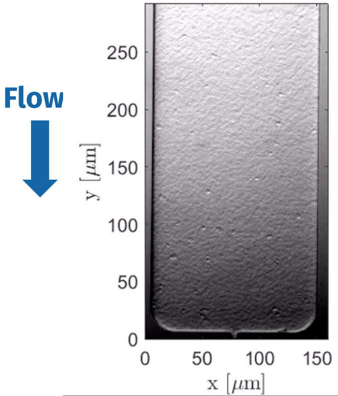
- Clog generation by accumulation, speed up 25×

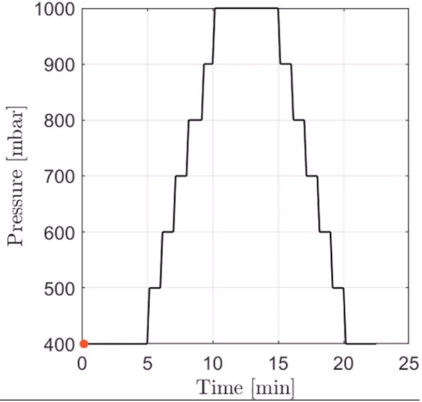


How to measure the mechanical properties of a yeast clog ?

- Use of **microfluidics**: controlled environment, confinement, direct visualization
- Quasi-2D yeast assembly

Fluid-driven solicitation





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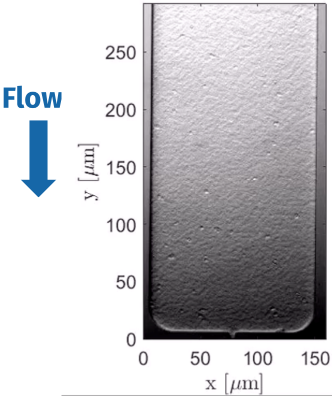
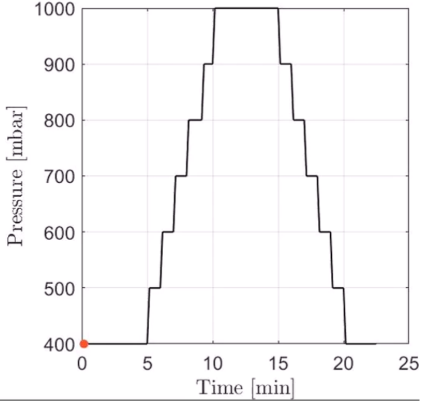
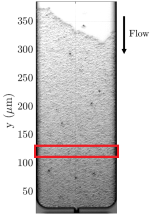
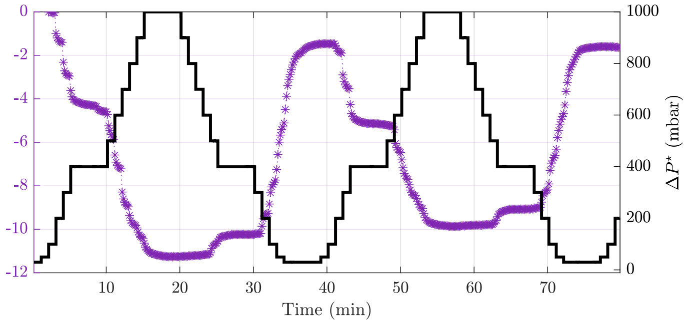




Relation stress/deformation

Time-evolution at $y = 120\,\mu$m from the pore





$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

Displacements time-evolution

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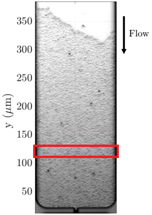

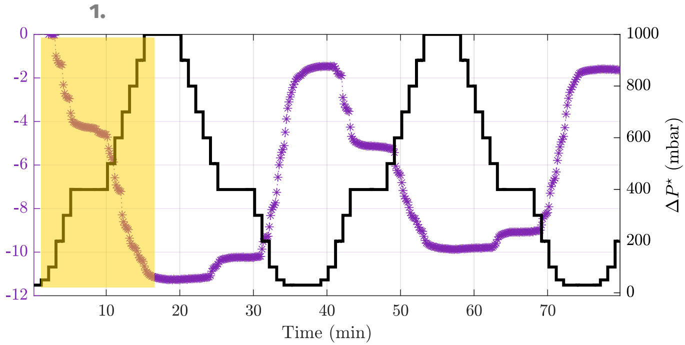

1. Compression: large displacements

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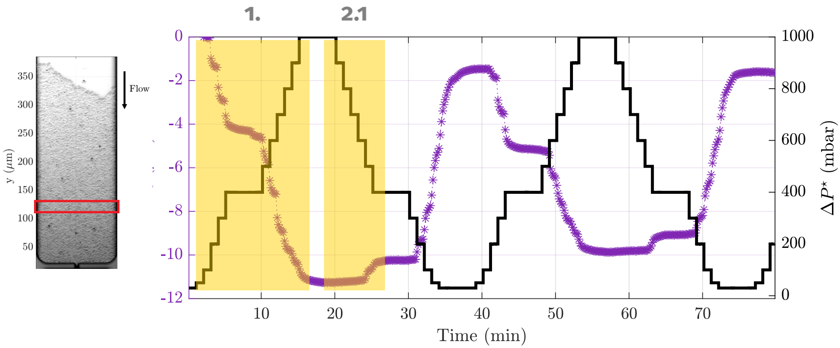

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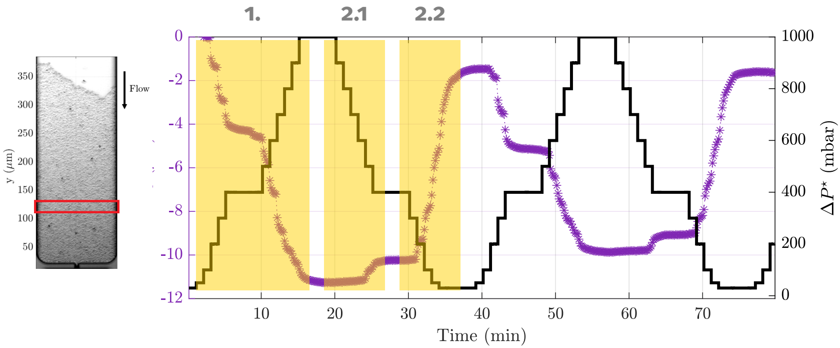

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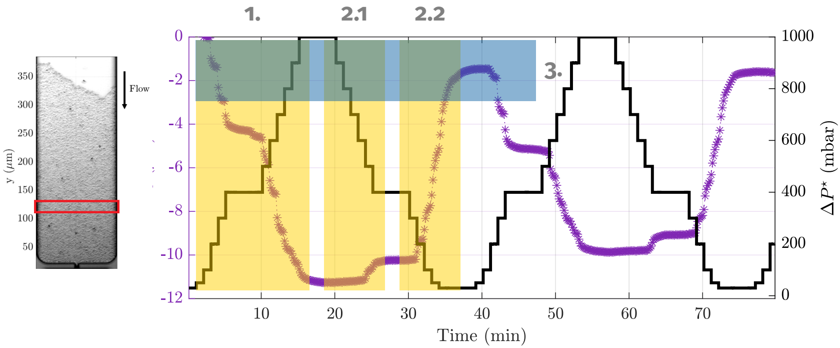
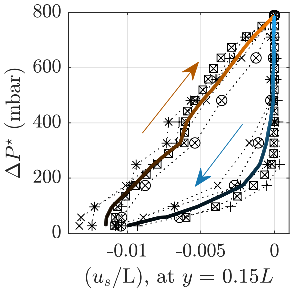
Time-evolution at $\boldsymbol{y} = 120\ \mu$m from the pore

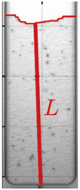


1. Compression: large displacements
2. Decompression:
   - 2.1 High $\Delta P^{\star}$: small displacements
   - 2.2 Low $\Delta P^{\star}$: high displacements
3. Few plasticity (internal rearrangements)

Displacements vs Pressure

- Good reproducibility
- Hysteretic behaviour
- Signature of energy dissipation during the process





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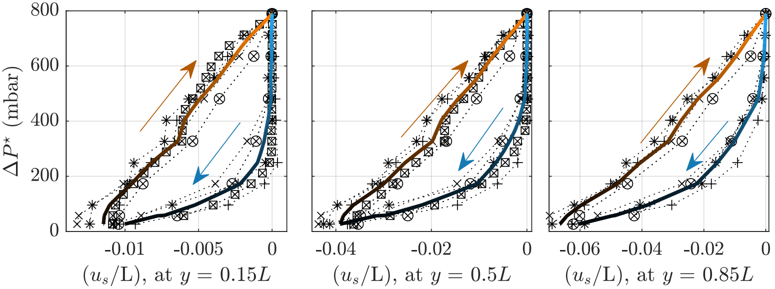
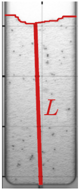


- Relative hysteresis cycle area higher close to the pore



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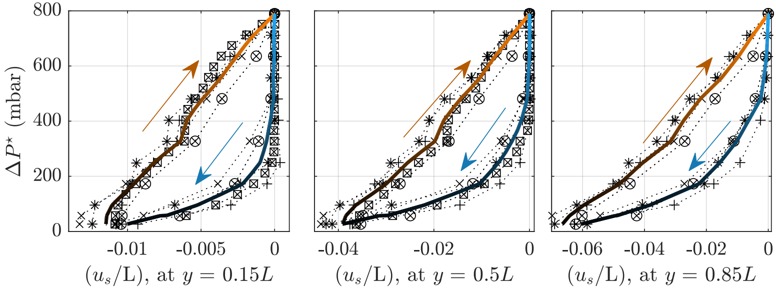
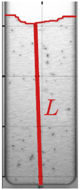
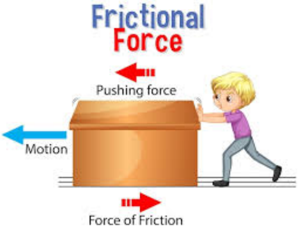




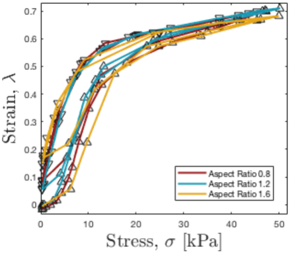
- Relative hysteresis cycle area higher close to the pore
- **Which origin for this energy dissipation and elastic energy storage ?**

A well-hidden suspect

- Could the friction to the walls be an ideal suspect ?
  - Started to be investigated for non-granular soft porous media



From freepik.com



Lutz's thesis (2021)

A well-hidden suspect

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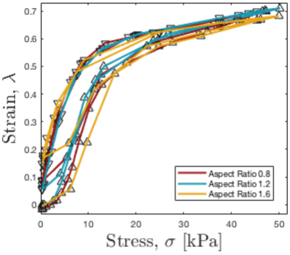
  - **Yet**, biological cells are slippery on glass/silicon

From freepik.com

Coulomb's friction coef. $\sim 0.03 - 0.06$

For human endothelial cells on glass
Dunn *et al.* (2007)

From physioextra.ca



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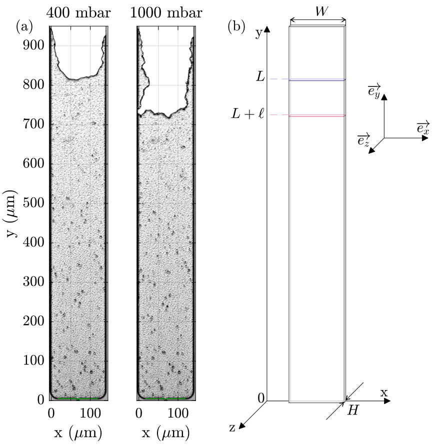
Let's take a closer look at friction

> 2D problem
- All quantities uniform over $\overrightarrow{e_x}$



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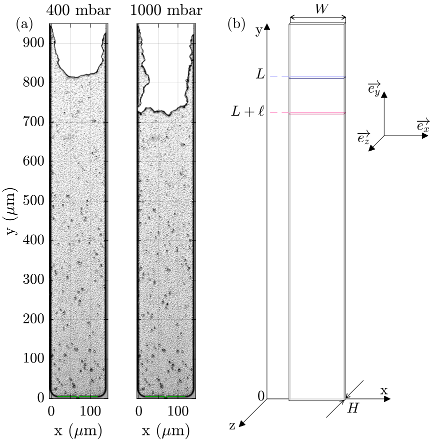

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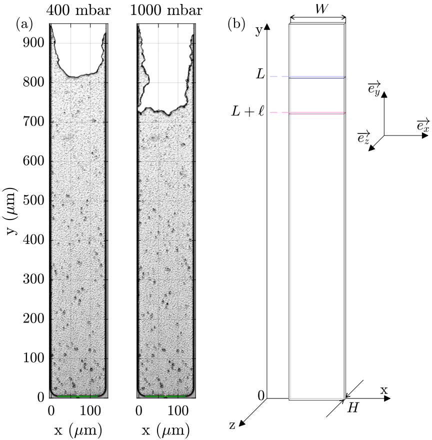

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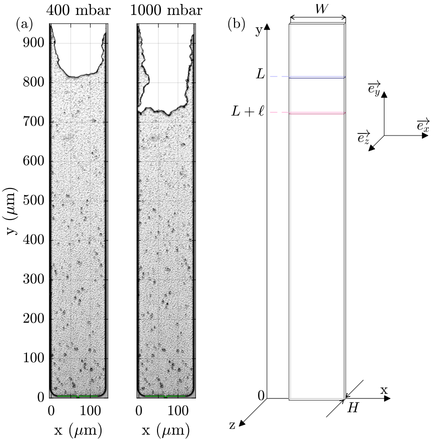

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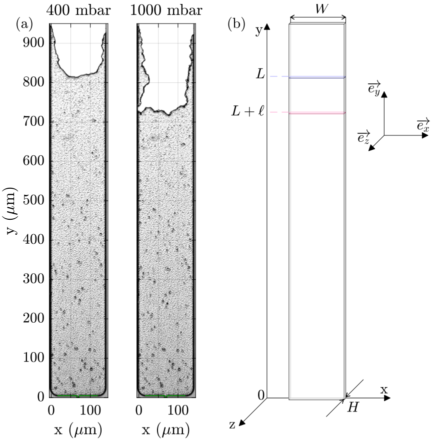

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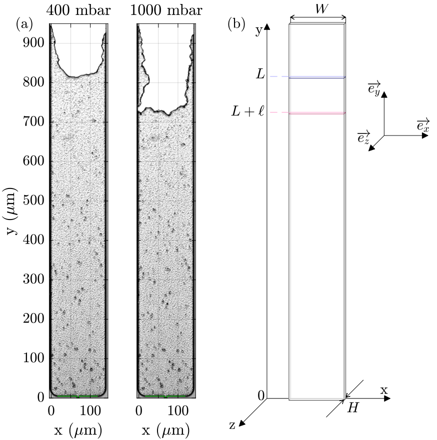

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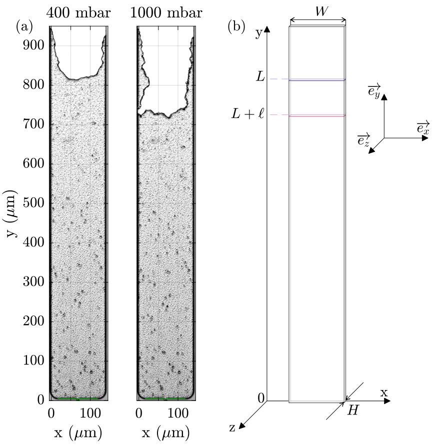
Wall stress (σ'_F)

Depth of the device (H)



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$$\underbrace{\boldsymbol{\sigma}}_{\text{Total stress}} = \overbrace{\boldsymbol{\sigma}'}^{\text{Effective stress}} - \underbrace{P}_{\text{Fluid pressure}} \boldsymbol{I}$$

- Mechanical equilibrium:

$$\int_0^H (\nabla \cdot \boldsymbol{\sigma})\, dz = \vec{0} \Rightarrow \partial_y \sigma'_{yy} + \frac{2\sigma'_F}{H} = \partial_y P$$

Wall stress: σ'_F

Depth of the device: H

- Couloumb's law: $|\sigma'_F| \leq \mu \, |\sigma'_{zz}|$

Friction coefficient: μ

Let's take a closer look at friction

- 2D problem
  - All quantities uniform over $\vec{e_x}$
- Porous medium with Darcy flow
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Wall stress (σ'_F)

Depth of the device (H)

- Couloumb's law: $|\sigma'_F| \leq \mu\, |\sigma'_{zz}|$

Friction coefficient (μ)

- Redirection of stress: $\sigma'_{zz} = K \sigma'_{yy}$

Janssen parameter (K)

Let's take a closer look at friction

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Wall stress (σ'_F); Depth of the device (H)

- Couloumb's law: $|\sigma'_F| \leq \mu\, |\sigma'_{zz}|$ (Friction coefficient: μ)
- Redirection of stress: $\sigma'_{zz} = K\sigma'_{yy}$ (Janssen parameter: K)

⇒ Adimension. (friction fully mobilized):

$$\partial_{\tilde{y}} \tilde{\sigma}'_{\tilde{y}\tilde{y}} + \frac{2\mu K L}{H} \tilde{\sigma}'_{\tilde{y}\tilde{y}} = \partial_{\tilde{y}} \tilde{P}$$

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⇒ Importance of friction controlled by:

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Friction forces: F_f; Applied forces: F_a

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⇒ Importance of friction controlled by:

$$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$$

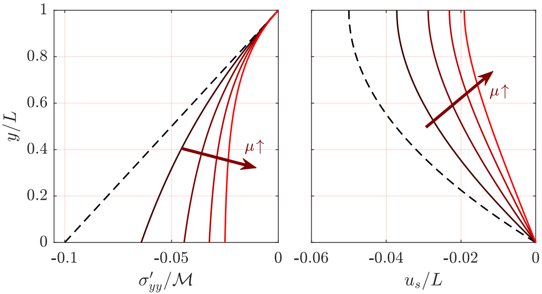
Friction forces (F_f); Applied forces (F_a)

Device aspect ratio is a key parameter

Model behaviour

Fluid-driven compression:

- Stress profile $\neq$ linear
- Displacements no longer quadratic
- Hysteresis on stress/deformation relation



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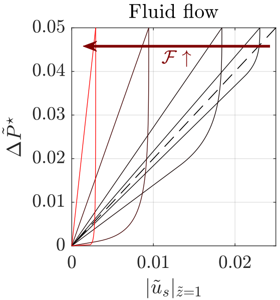


- Dashed lines: frictionless case

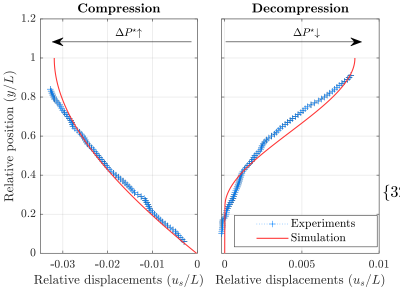
Reproduction of fluid-driven experiments

Calibration:

- Two free parameters (μ, $\mathcal{M}$)
- Two $\boldsymbol{u_s}$ profiles used (blue)

$\Delta P^\star_{\text{ref}} =$ 325 mbar

$\Delta P^\star \in \{480, 635, 775\}$ mbar



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Reproduction of fluid-driven experiments

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Results:

- $\mu = 0.012$, $\mathcal{M} = 0.5$ MPa
  - Consistent with yeast mechanics and on-glass friction

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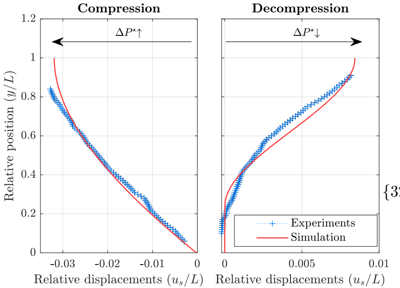

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  - Consistent with yeast mechanics and on-glass friction
- Other u_s profiles reproduced

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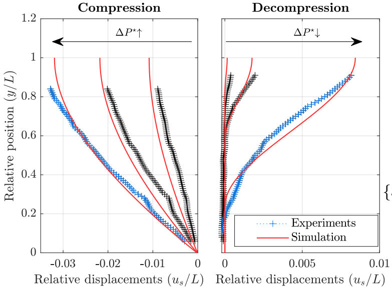

$\Delta P^\star_{\text{ref}} =$ 775 mbar

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$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

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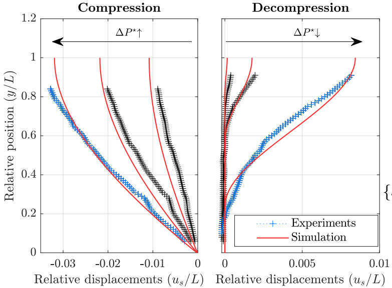

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Calibration:

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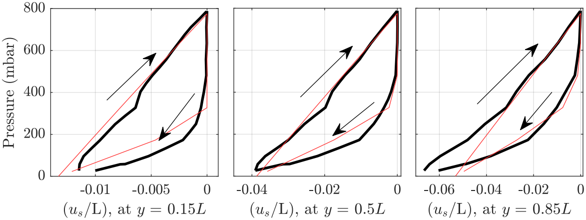
- Two u_s profiles used (blue)

Results:

- $\mu = 0.012$, $\mathcal{M} = 0.5$ MPa
  - Consistent with yeast mechanics and on-glass friction
- Other u_s profiles reproduced
- Full hysteresis cycle reproduced



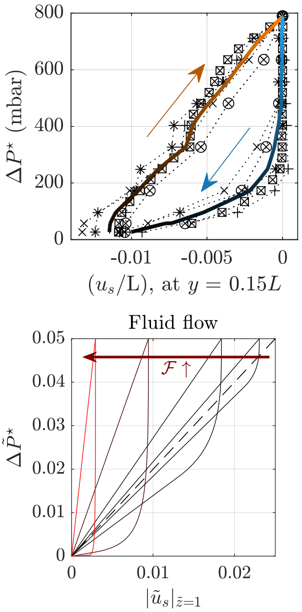
Take-home messages

> **Wall friction modifies poroelasticity of a yeast clog**

> **Friction number** involves aspect ratio

$$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$$

> **Good agreement** with experimental results

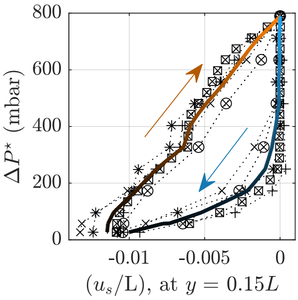


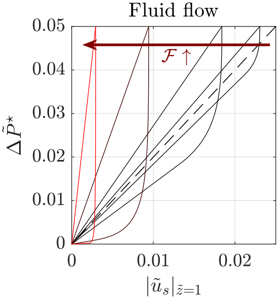
> Highly non-linear mechanics
- Hysteretic stress-deformation characteristics

> **Friction** with the wall is the key
- Even for slippery materials
- Aspect ratio drives the intensity of friction

$$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$$

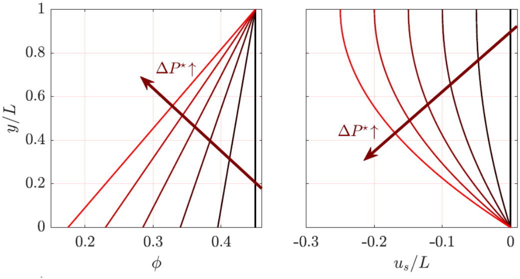
> A faithful reproduction of experimental results
- Fair estimation of friction coeff. and elastic modulus
- Captures the hysteresis for fluid-driven forcing





Fluid-driven compression

- Stress gradient in the medium
- Porosity (ϕ) gradient
- Quadratic displacements (u_s)



$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

What does poromechanics theory foresee ?

Fluid-driven compression

- Stress gradient in the medium
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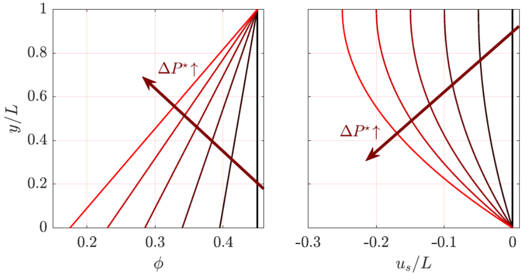
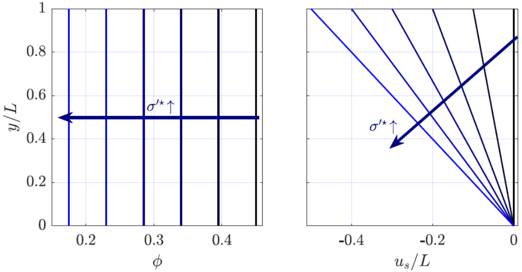


Piston-driven compression

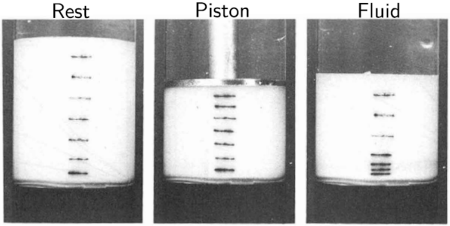
- Stress uniformly transmitted
- Uniform porosity (ϕ)
- Linear displacements (u_s)



What does poromechanics theory foresee ?

Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

> Fluid flow → Darcy's law

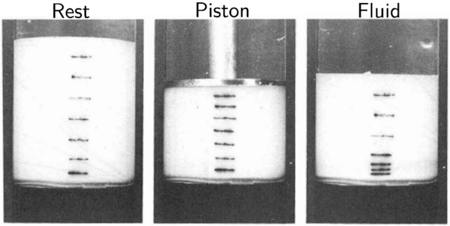


From Parker *et al.* (1987)

What does poromechanics theory foresee ?

Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

- Fluid flow $\longrightarrow$ Darcy's law
- Solid mechanical properties $\longrightarrow$ linear elastic



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Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

- Fluid flow → Darcy's law
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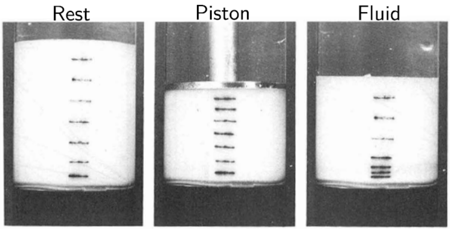
- Permeability → uniform



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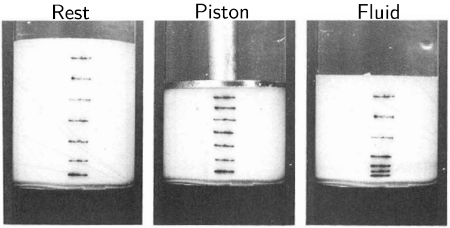
Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

- > Fluid flow $\rightarrow$ Darcy's law
- > Solid mechanical properties $\rightarrow$ linear elastic
- > Permeability $\rightarrow$ uniform
- > Fluid-solid stress coupling $\rightarrow$ Terzaghi



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- Fluid flow → Darcy's law
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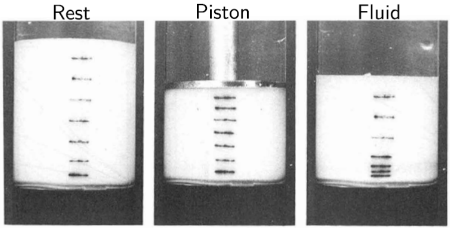
- Fluid-solid stress coupling → Terzaghi
- Incompressibility of both phases



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- Solid mechanical properties → linear elastic
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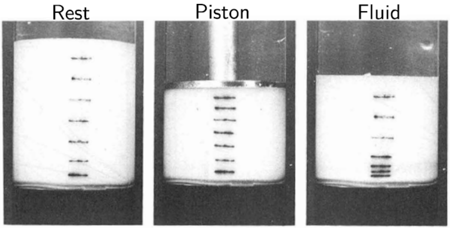
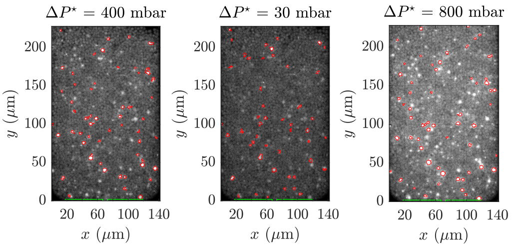
- Fluid-solid stress coupling → Terzaghi
- Incompressibility of both phases
- Mechanical equilibrium



From Parker *et al.* (1987)

Fluorescent hydrogel probes:

- Added to the yeast suspension
- Fluorescence increases with compression



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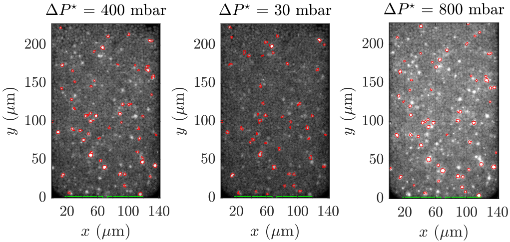
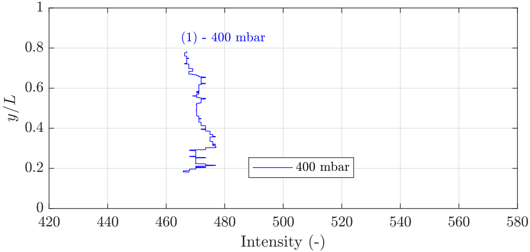


Results:



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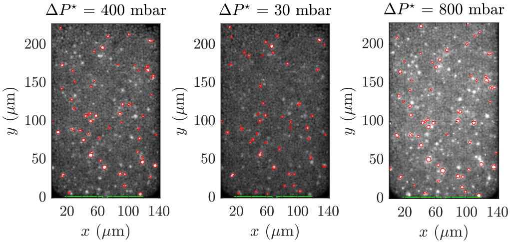

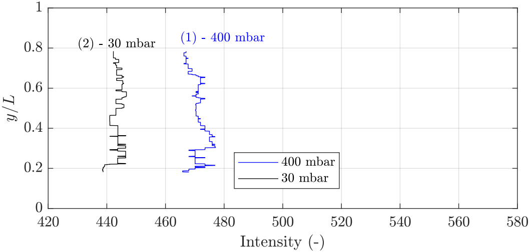

Stress repartition

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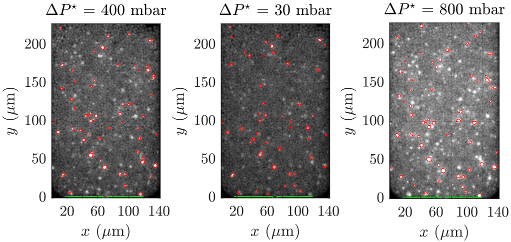

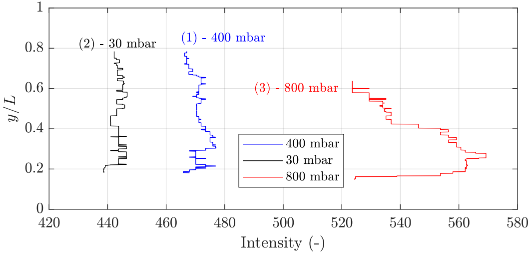

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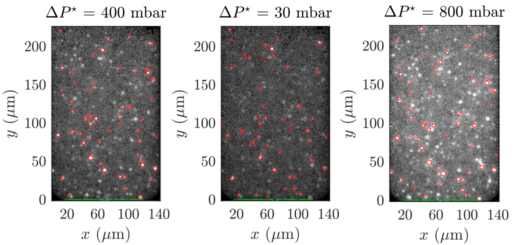

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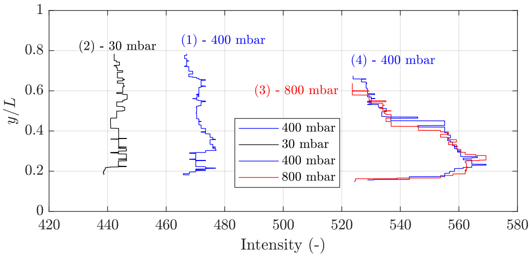

$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

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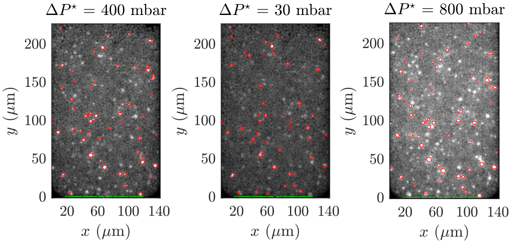

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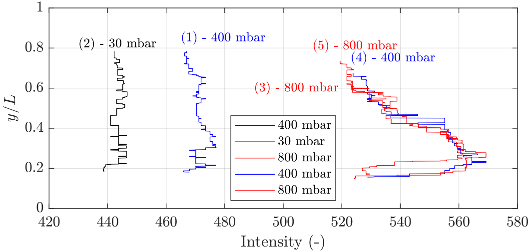

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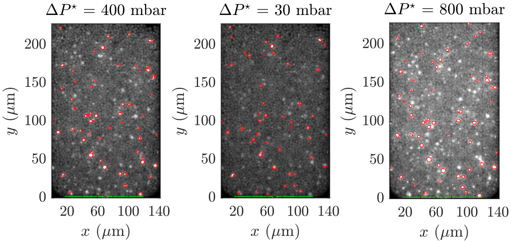

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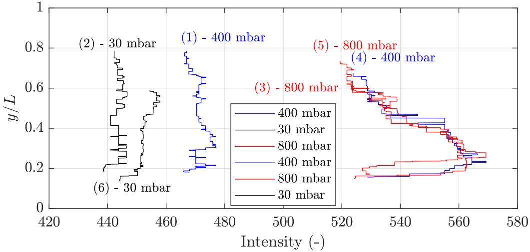

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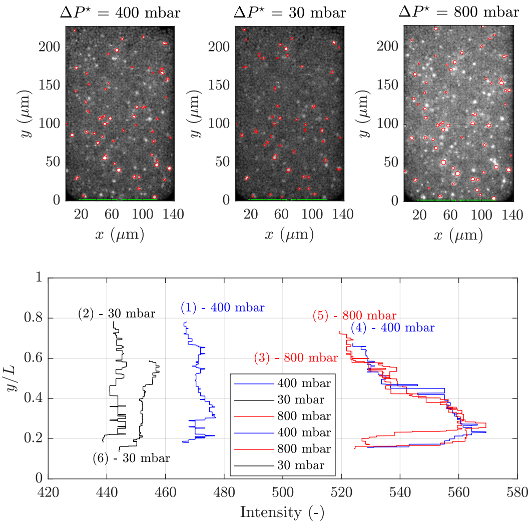
Results:

- Stress gradient through the clog
- Clog remains compressed at intermediate decompression



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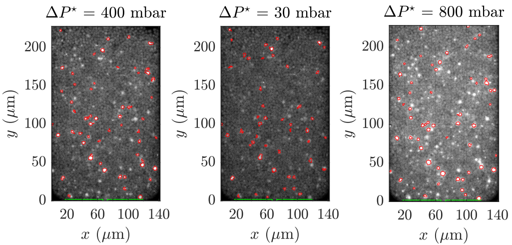
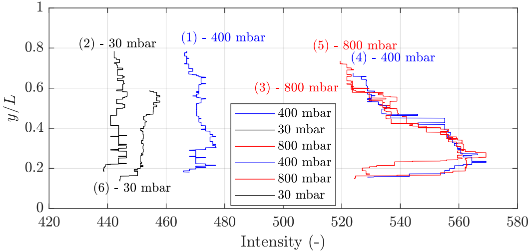


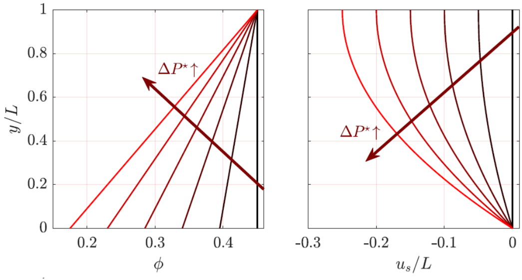


Which origin for this energy dissipation and elastic energy storage ?

What does poromechanics theory foresee ?

Fluid-driven compression

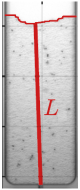
- Stress gradient in the medium
- Porosity (ϕ) gradient
- Quadratic displacements (u_s)

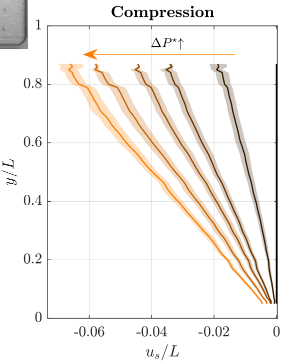


Relative displacement profiles

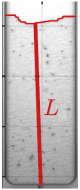
Compression

- Staggered displacement steps
- Non quadratic profile





Relative displacement profiles

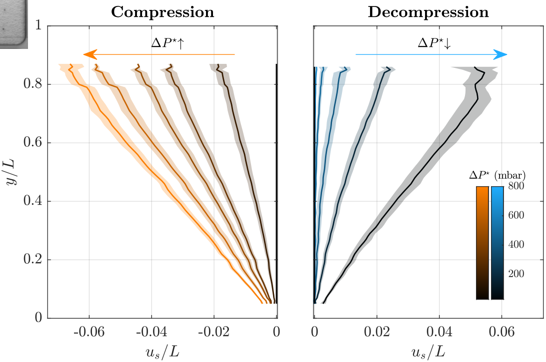


Compression

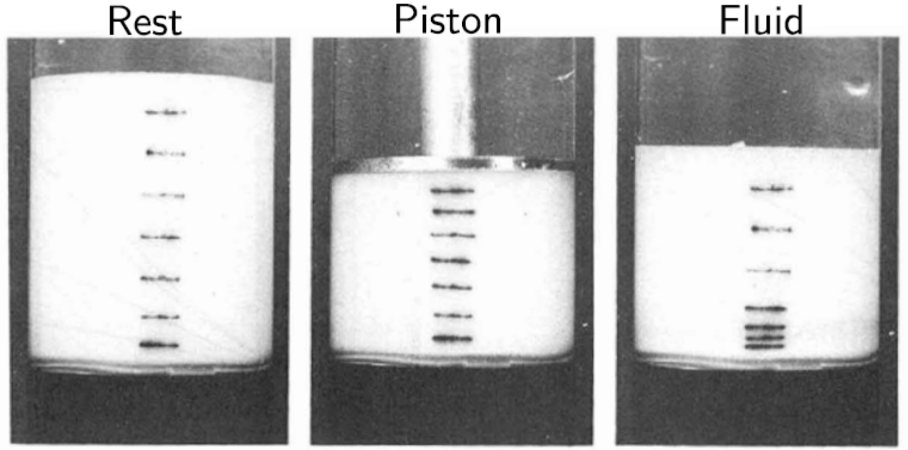
- Staggered displacement steps
- Non quadratic profile

Decompression

- Non quadratic profile
- No displacement at decompression start
- Large displacements at the end



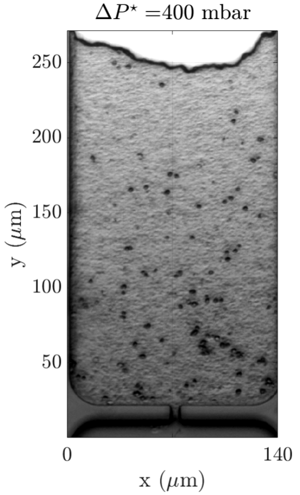
What does poromechanics theory foresee ?



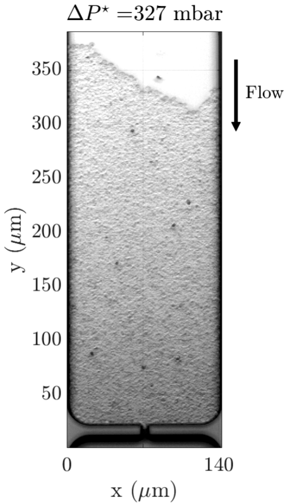
From Parker *et al.* (1987)

How to measure the mechanical properties of a yeast clog ?

Piston-driven solicitation
(using an air bubble)

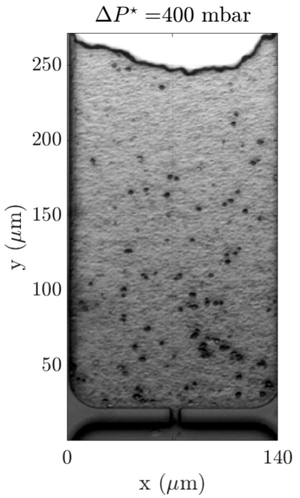


Fluid-driven solicitation

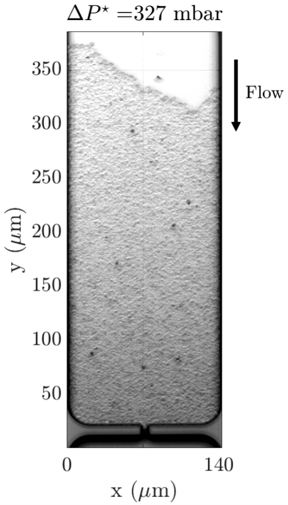


How to measure the mechanical properties of a yeast clog ?

Piston-driven solicitation
(using an air bubble)



Fluid-driven solicitation



Relation stress/deformation → Focus on fluid-driven case

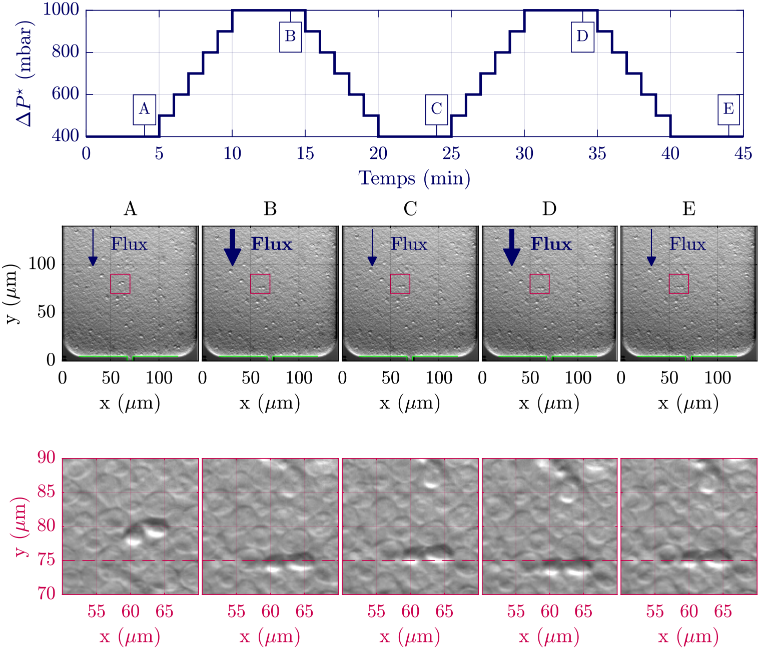
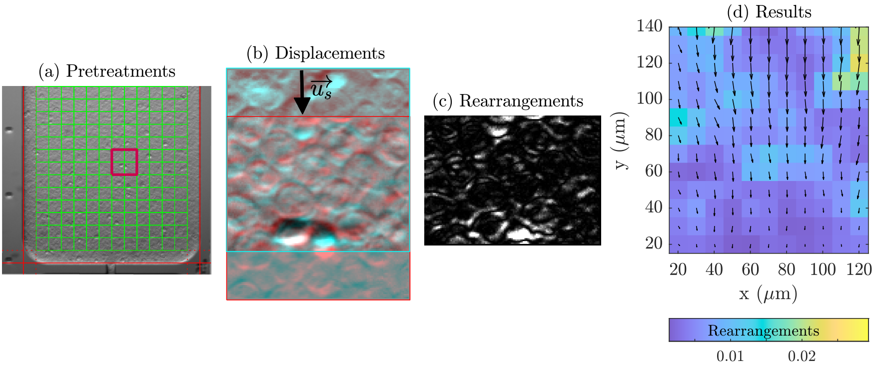

1000
800
600
400
ΔP* (mbar)
A
B
C
D
E
0
5
10
15
20
25
30
35
40
45
Temps (min)
A
B
C
D
E
Flux
Flux
Flux
Flux
Flux
y (μm)
100
50
0
0
50
100
x (μm)
90
85
80
75
70
55
60
65

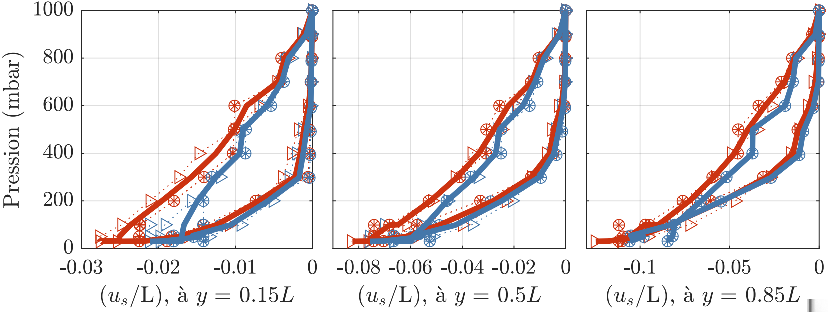
Image processing

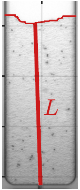


- Method adapted from Cerbino *et al.* (2021)
- First step similar to Particle Image Velocimetry

Influence of local rearrangements of yeasts ?

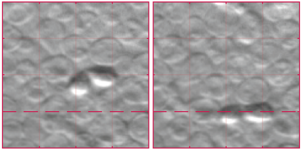
> Weak irreversibility due to rearrangements





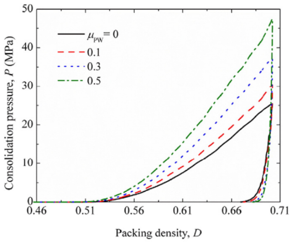
A well-hidden suspect

- Could the hysteresis be due to local rearrangement ?



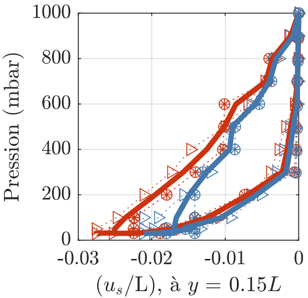
A well-hidden suspect

> Could the hysteresis be due to local rearrangement ?
  - Classical observation in dry granular media mechanics



He *et al.* (2018)

- Could the hysteresis be due to local rearrangement ?
  - Classical observation in dry granular media mechanics
  - **But**, still hysteretic for the second cycle



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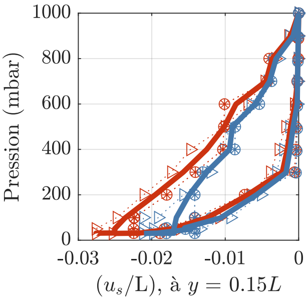
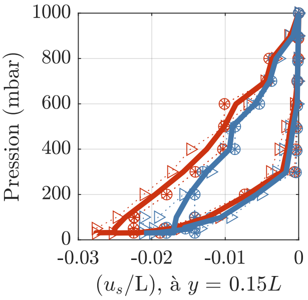


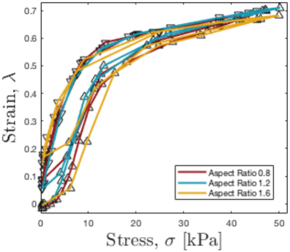
- Could the friction to the walls be an ideal suspect ?

From freepik.com

> Could the hysteresis be due to local rearrangement ?
  - Classical observation in dry granular media mechanics
  - **But**, still hysteretic for the second cycle



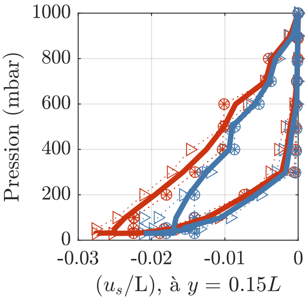
> Could the friction to the walls be an ideal suspect ?
  - Started to be investigated for non-granular soft porous media



Lutz *et al.* (2021)

A well-hidden suspect

- Could the hysteresis be due to local rearrangement ?
  - Classical observation in dry granular media mechanics
  - **But**, still hysteretic for the second cycle



- Could the friction to the walls be an ideal suspect ?
  - Started to be investigated for non-granular soft porous media
  - **Yet**, biological cells are slippery on glass/silicon

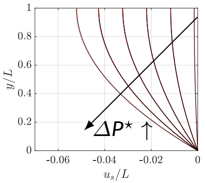
Coulomb's friction coef. $\sim 0.03 - 0.06$

For human endothelial cells on glass

Dunn *et al.* (2007)

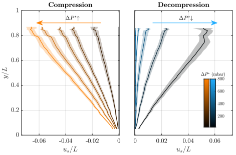
Theory (poromechanics)

> Quadratic profile of displacements



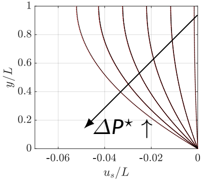
Experiments (yeast clog)

> **Linear profile** of displacements



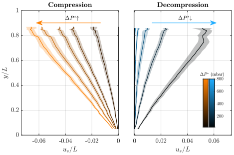
Theory (poromechanics)

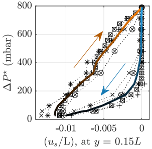
- Quadratic profile of displacements
- Elastic behaviour expected



Experiments (yeast clog)

- **Linear profile** of displacements
- **Hysteresis** with energy dissipation

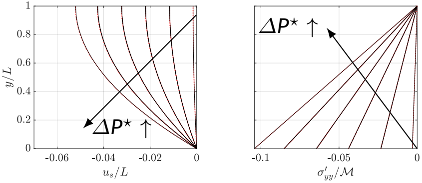




Comparison of poromechanics theory to experiments

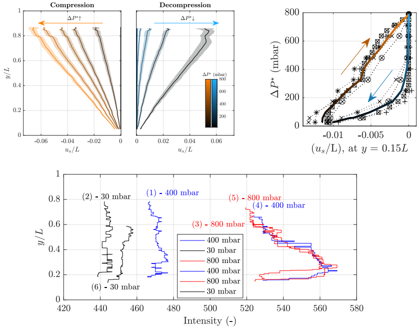
Theory (poromechanics)

- Quadratic profile of displacements
- Elastic behaviour expected
- Stress gradient under compression



Experiments (yeast clog)

- **Linear profile** of displacements
- **Hysteresis** with energy dissipation
- Stress gradient under compression

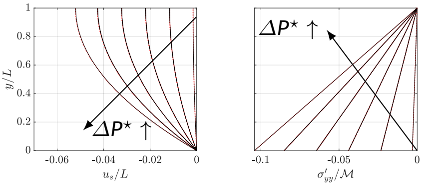


$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

Comparison of poromechanics theory to experiments

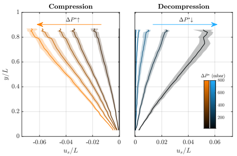
Theory (poromechanics)

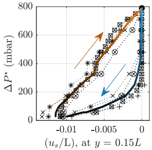
- Quadratic profile of displacements
- Elastic behaviour expected
- Stress gradient under compression
- No potential energy storage

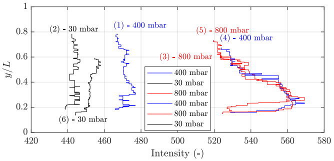


Experiments (yeast clog)

- **Linear profile** of displacements
- **Hysteresis** with energy dissipation
- Stress gradient under compression
- Potential **energy storage**







Summary of the model for resolution

Name	Equation
Mass conserv. (fluid)	$\partial_t \phi + \partial_y(\phi v_f) = 0$
Definition of q	$q = \phi v_f + (1-\phi) v_s$
Mass conserv. (solid)	$\partial_y q = 0$
Darcy	$\phi \times (v_f - v_s) = -\frac{k}{\eta}\partial_y P$
Solid constit. law	$\sigma'_{yy} = \mathcal{M}\frac{\phi - \phi_0}{1-\phi_0}$
Mechanical equil.	$\partial_y \sigma'_{yy} + \frac{2\sigma'_F}{H} = \partial_y P$
Coulomb's law	$\begin{cases} \sigma'_F = \text{sgn}(v_s)\mu K \sigma'_{yy} & \Longleftrightarrow \quad \lvert v_s \rvert > 0 \\ \sigma'_F = -\frac{H\eta}{2k}q - \frac{H}{2}\partial_y \sigma'_{yy} & \Longleftrightarrow \quad \left\lvert \frac{H\eta}{2k}q + \frac{H}{2}\partial_y \sigma'_{yy} \right\rvert \leq \mu K \left\lvert \sigma'_{yy} \right\rvert \end{cases}$

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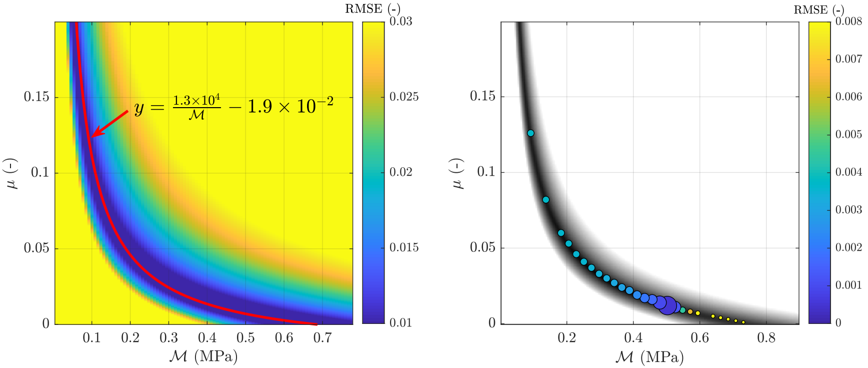
- Can be solved analytically in some specific cases
- In general case, a numerical resolution is necessary

Experiment best fits

> RMSE: Root Mean-Square Error



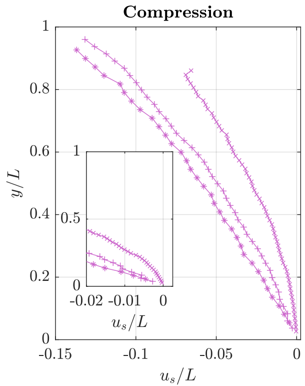
> One sweep on a compression profile

> One sweep on a decompression profile based on compression results

$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

What do we get for piston-driven solicitation ?

- Linear displacement profiles
- Less reproducibility

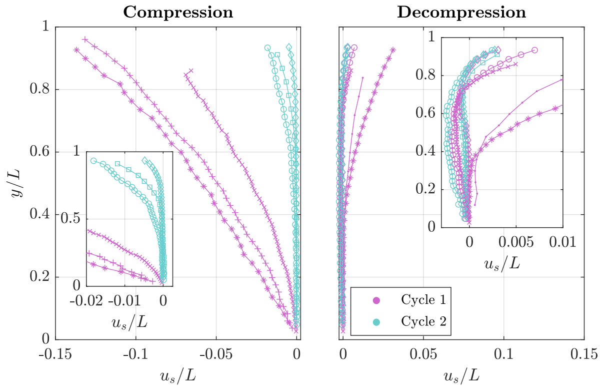


$\mathcal{F} = \frac{2\mu KL}{H} \sim \frac{F_f}{F_a}$

What do we get for piston-driven solicitation ?

- Linear displacement profiles
- Less reproducibility

- Decompression: very weak displacements
- Exotic behaviour at decompression



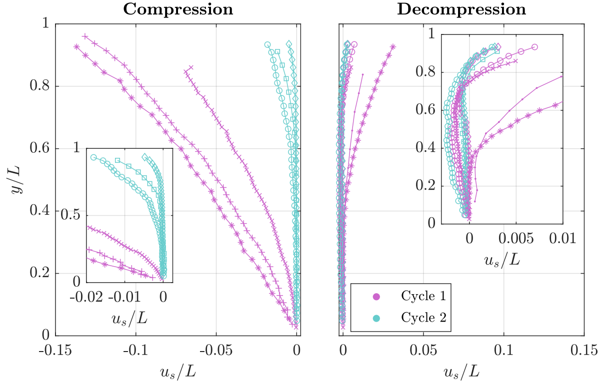
$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

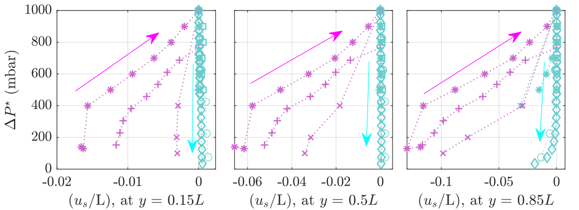
What do we get for piston-driven solicitation ?

- Linear displacement profiles
- Less reproducibility

- Decompression: very weak displacements
- Exotic behaviour at decompression

- Energy dissipation by hysteresis
- Strong differences between the cycles



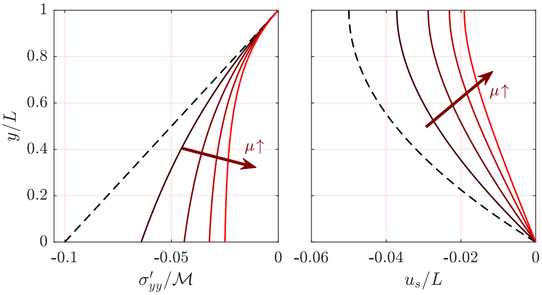


$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

Model behaviour

Fluid-driven compression:

- Stress profile $\neq$ linear
- Displacements no longer quadratic



$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

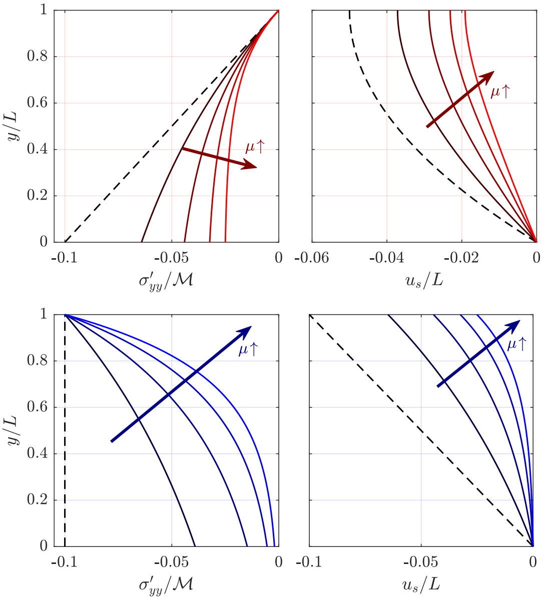
Model behaviour

Fluid-driven compression:

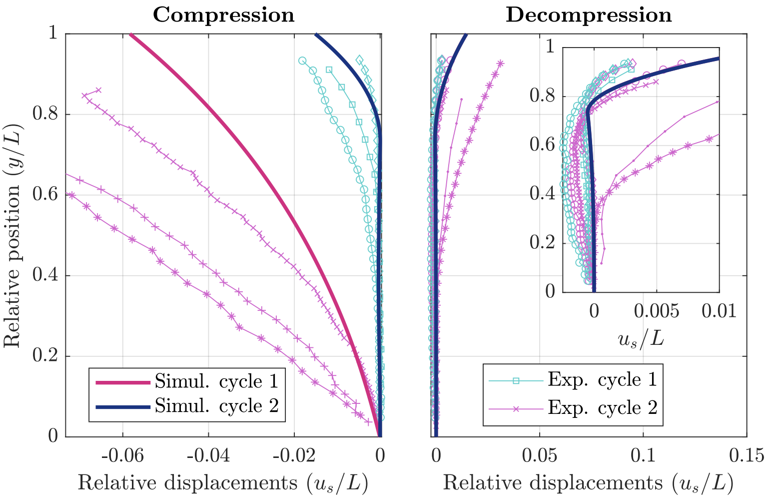
- Stress profile ≠ linear
- Displacements no longer quadratic

Piston-driven compression:

- Stress exponentially damped
- Displacements exponentially damped



Model comparison to piston-driven experiments



> Acceptable agreement with experimental data

> Exotic behaviour at decompression is validated by the model