# 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**

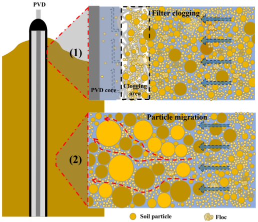
# What is (bio)clogging ?



## 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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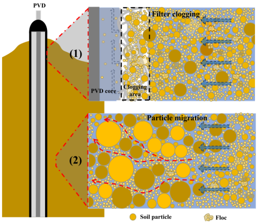


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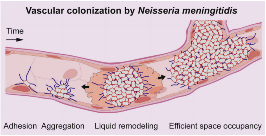
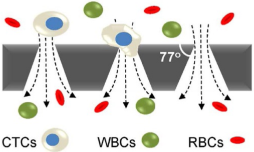
**Bioclogging: clogging with biological objects**

- Bio-medicine
  - **Brain diseases**
  - **Diagnostic**
- Food industry
  - Yeast filtration (beer, ...)

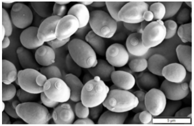



Bonazzi *et al.* (2018)




Tang *et al.* (2014)

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



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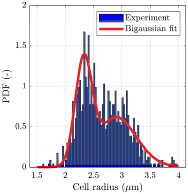
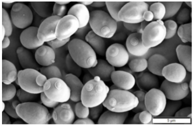



From T. Desclaux thesis

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



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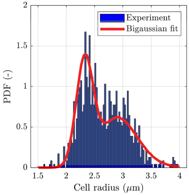


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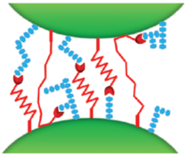
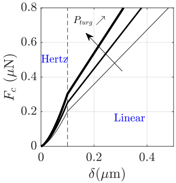


From El-Kirat Chatel *et al.* (2014)




From Vella *et al.* (2021)
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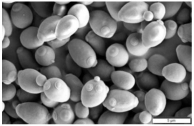
# *Saccharomyces cerevisiae*, a model biological object

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



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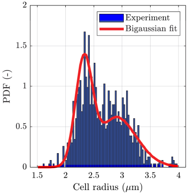
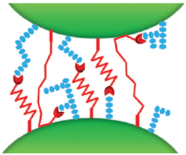



From T. Desclaux thesis

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



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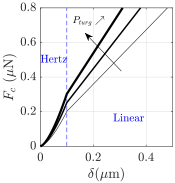


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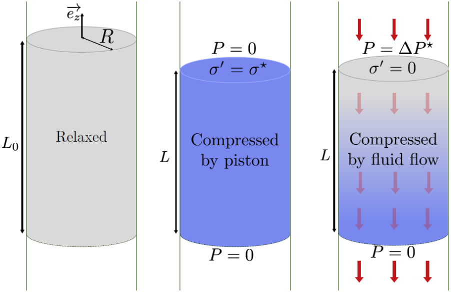
> A yeast clog is...
- a soft porous media
- in a confined environment



# (Poro)mechanics of a yeast clog



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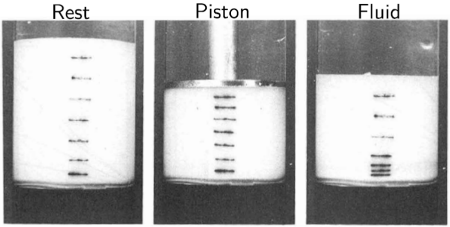


From Parker (1987)

# (Poro)mechanics of a yeast clog



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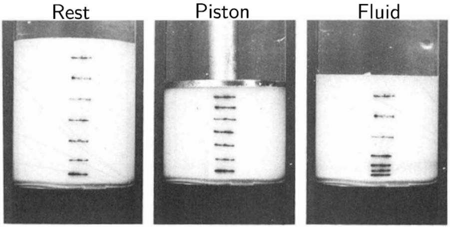
> Few studies of yeast clog mechanics
- Ben Hassan *et al.* (2014): no compression
- Valencia *et al.* (2022): decompression

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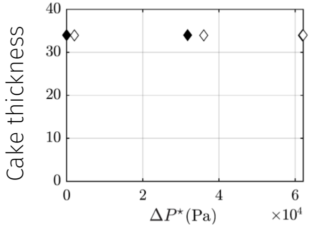


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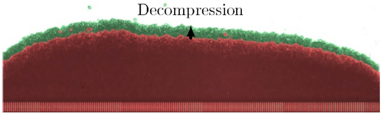

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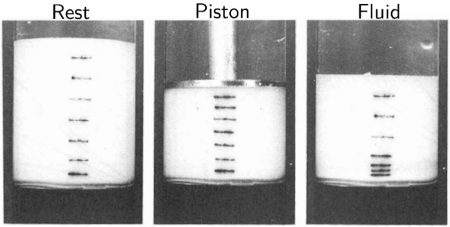


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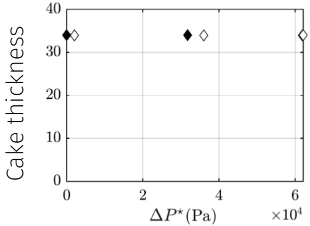


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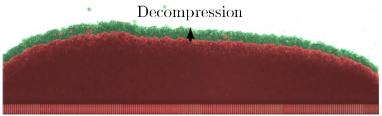
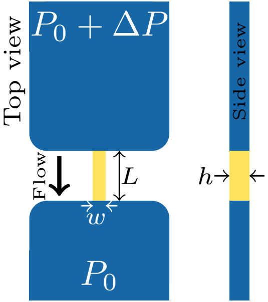



**Could confinement explain these differences ?**

# Bioclogging in a microfluidic chip



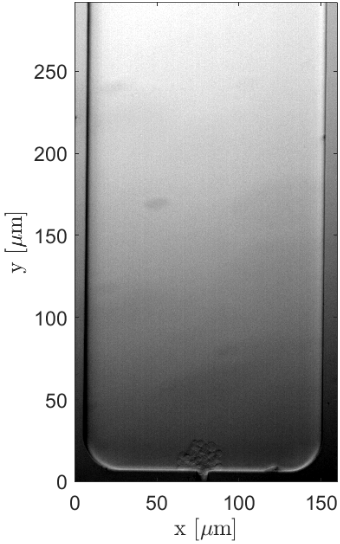
- Microfluidic silicon-glass channels




## 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×



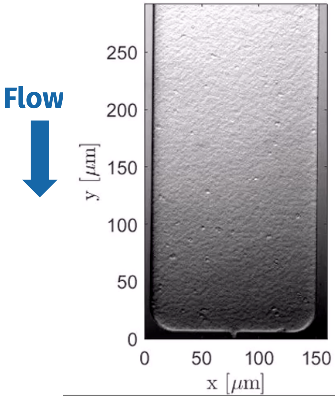

**Flow**

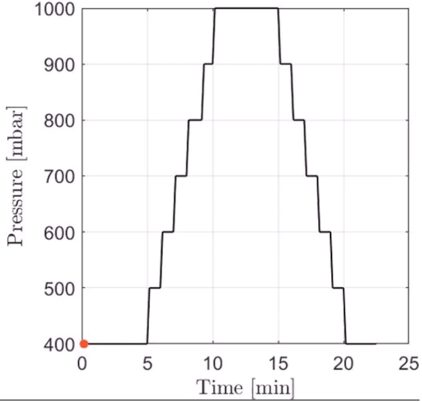
# How to measure the mechanical properties of a yeast clog ?



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

Fluid-driven solicitation



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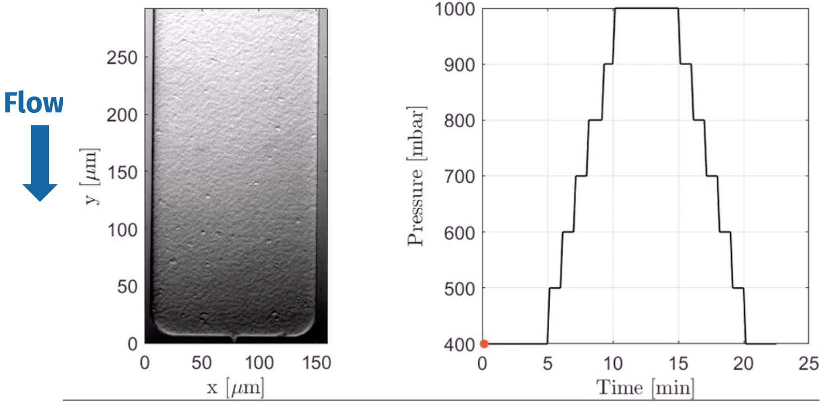
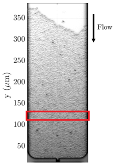
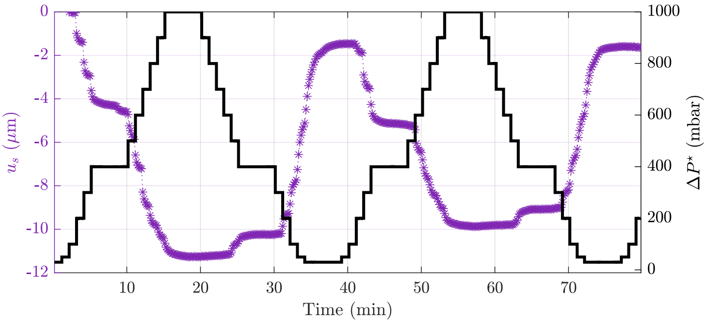



**Relation stress/deformation**

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



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# Displacements time-evolution



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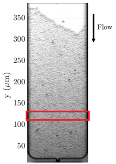


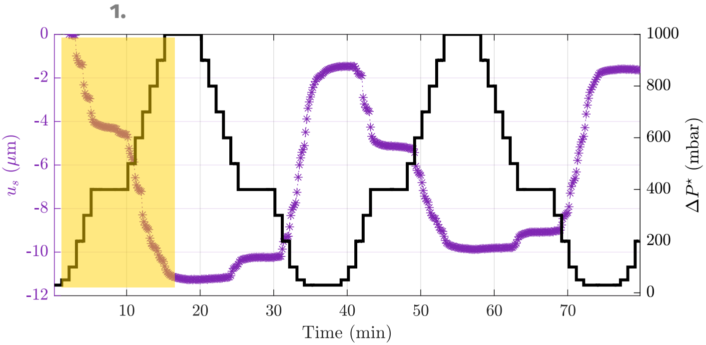


1. Compression: large displacements

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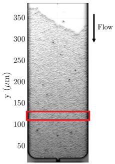


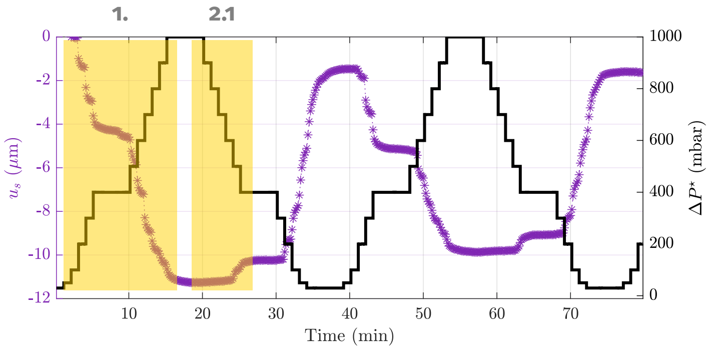


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2. Decompression:
   2.1 High $\Delta P^\star$: small displacements

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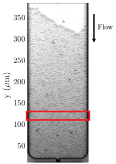


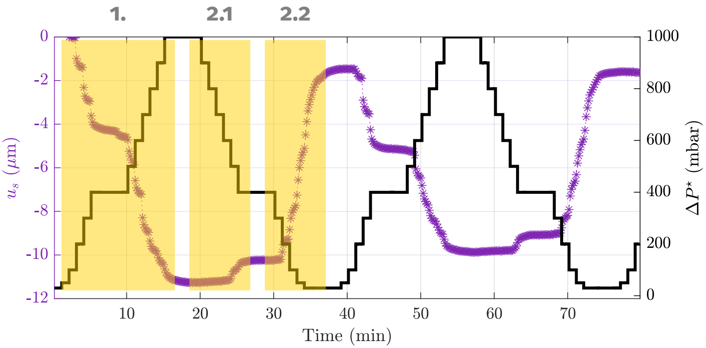


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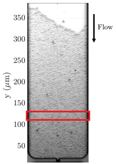


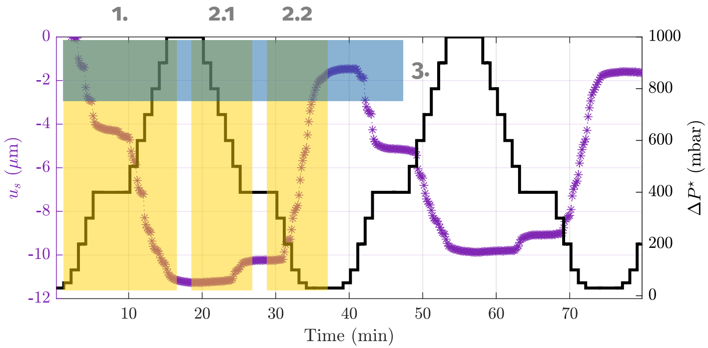


1. Compression: large displacements
2. Decompression:
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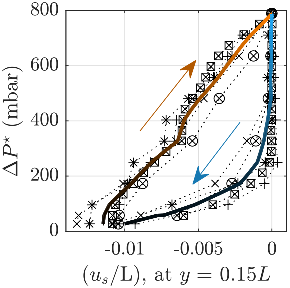
   - 2.2 Low $\Delta P^\star$: high displacements
3. Few plasticity (internal rearrangements)

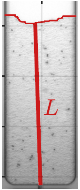
$$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$$

# Displacements vs Pressure



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



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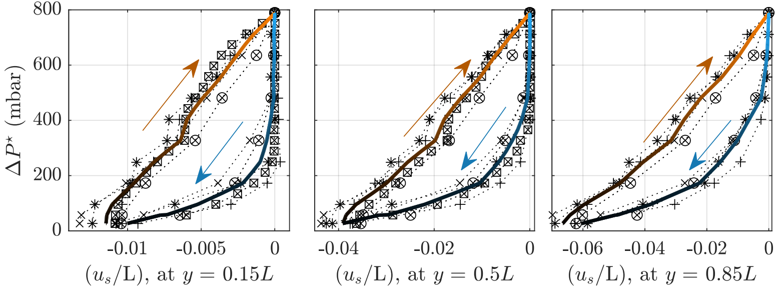
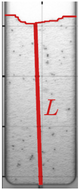



- Relative hysteresis cycle area higher close to the pore



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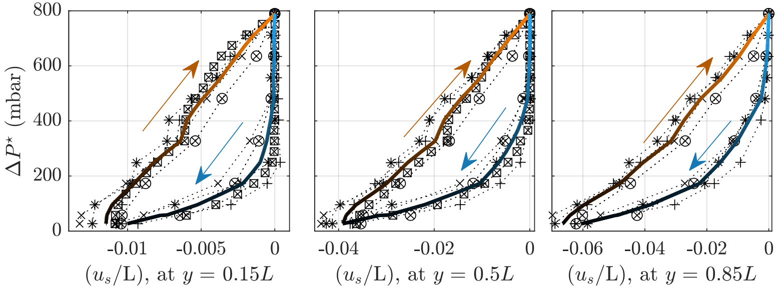
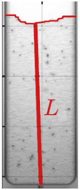



- Relative hysteresis cycle area higher close to the pore
- **Which origin for this energy dissipation and elastic energy storage ?**

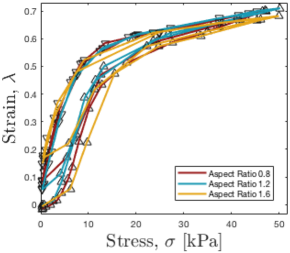


# A well-hidden suspect



- 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)

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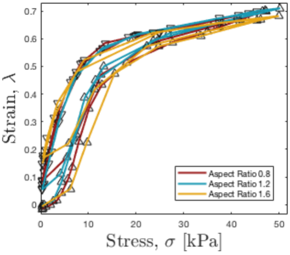
  - **Yet**, biological cells are slippery on glass/silicon

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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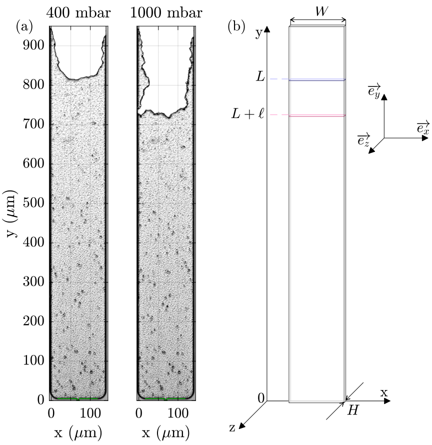
# Let's take a closer look at friction



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



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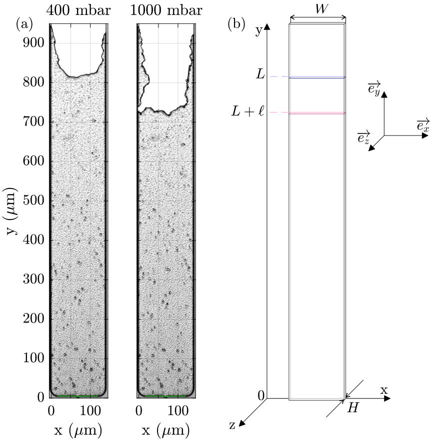

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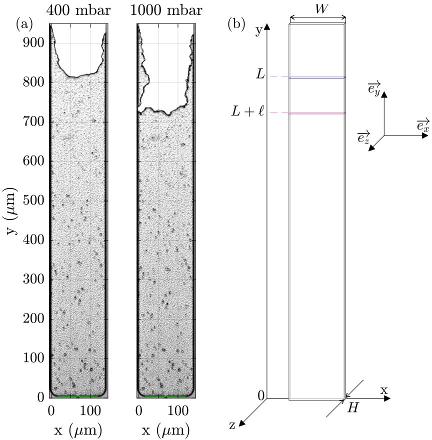

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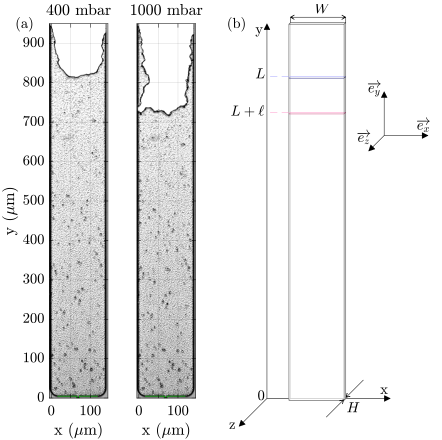

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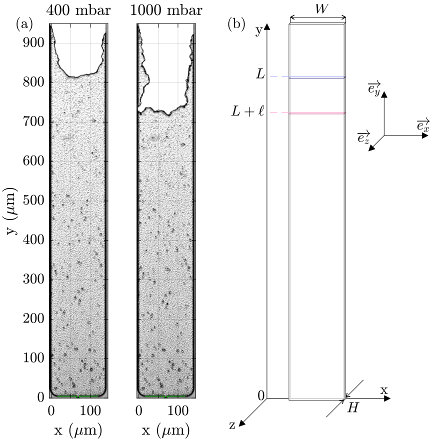

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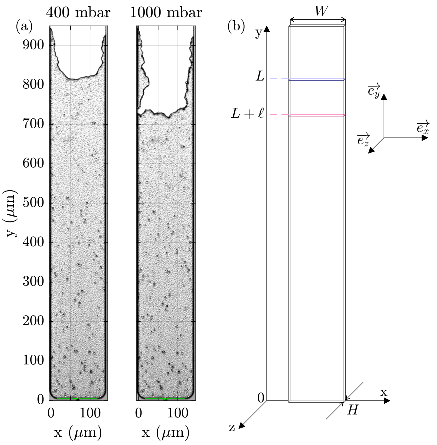

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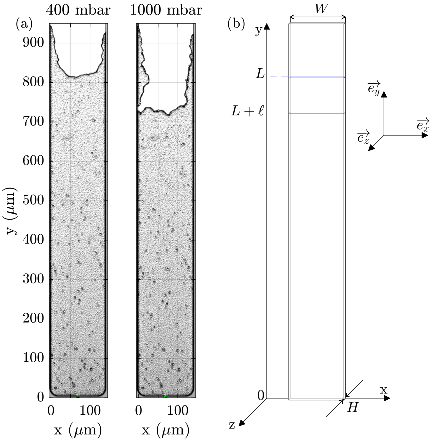
Wall stress ($\sigma'_F$)

Depth of the device ($H$)



# Let's take a closer look at friction



> Couloumb's law: $|\sigma'_F| \leq \mu\, |\sigma'_{zz}|$ (Friction coefficient: $\mu$)

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

> Porous medium with Darcy flow

> Solid: linear elastic, incompressible
- Oedometric modulus: $\mathcal{M} = f(E,\nu)$

> Terzaghi decomposition of stress:

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

> Mechanical equilibrium:

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

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Depth of the device ($H$)

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Friction coefficient ($\mu$)

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

Janssen parameter ($K$)

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⇒ 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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(Friction forces: $F_f$; Applied forces: $F_a$)

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Wall stress

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

Depth of the device

Friction coefficient

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Applied forces

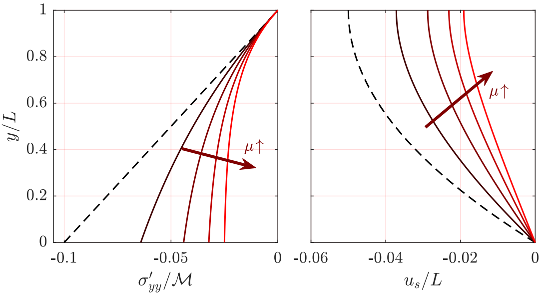
**Device aspect ratio is a key parameter**

# Model behaviour



Fluid-driven compression:

- Stress profile ≠ linear
- Displacements no longer quadratic
- Hysteresis on stress/deformation relation

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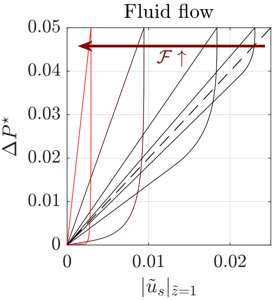



- Dashed lines: frictionless case

# Reproduction of fluid-driven experiments

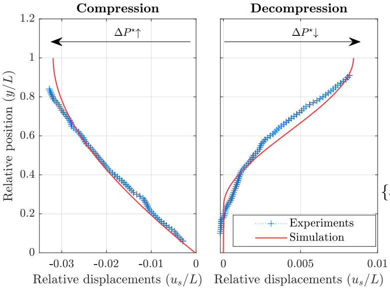


**Calibration:**

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

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

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

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> $\mu = 0.012$, $\mathcal{M} = 0.5$ MPa

- Consistent with yeast mechanics and on-glass friction

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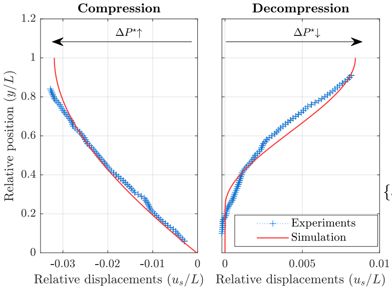


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**Full hysteresis cycle reproduced**

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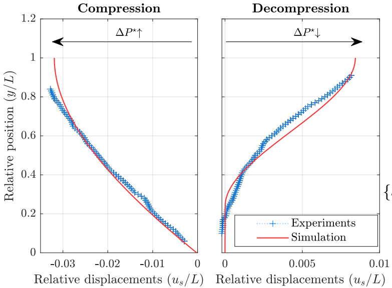


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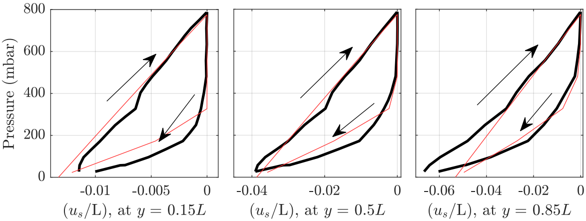
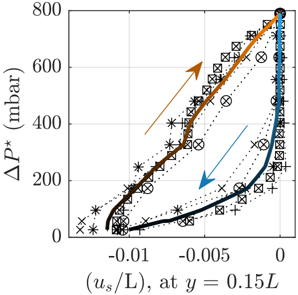


$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

# Take-home messages



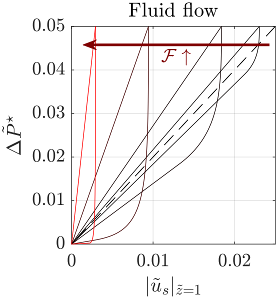



- **Wall friction modifies poroelasticity of a yeast clog**

- **Friction number** involves aspect ratio

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

- **Good agreement** with experimental results



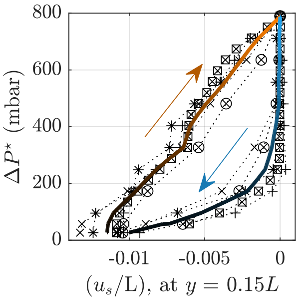
# Take-home messages

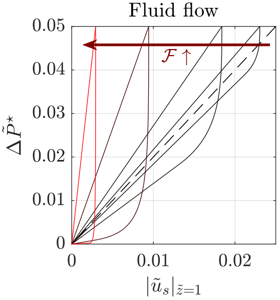


- Highly non-linear mechanics
  - Hysteretic stress-deformation characteristics
- **Friction** with the wall is the key
  - Even for slippery materials
  - Aspect ratio drives the intensity of friction

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

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



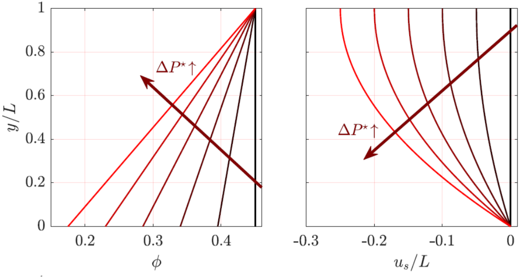



# What does poromechanics theory foresee ?



**Fluid-driven compression**

- Stress gradient in the medium
- Porosity ($\phi$) gradient
- Quadratic displacements ($u_s$)



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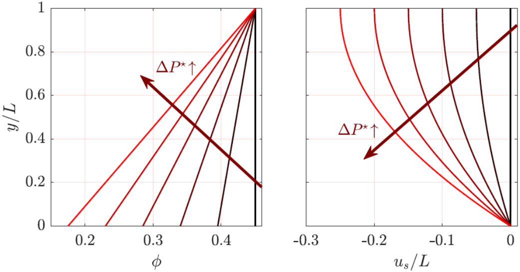
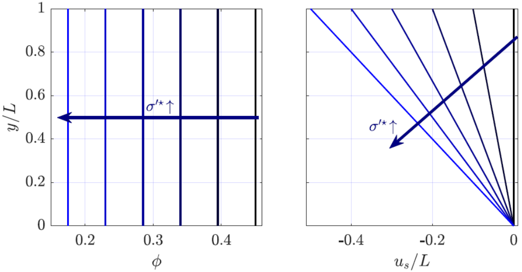


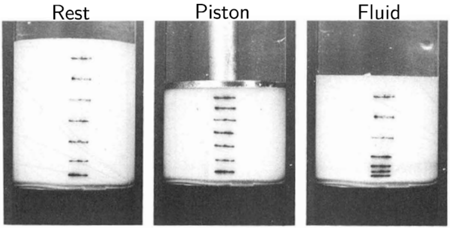

**Piston-driven compression**

- Stress uniformly transmitted
- Uniform porosity ($\phi$)
- Linear displacements ($u_s$)



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

> Fluid flow → Darcy's law



From Parker *et al.* (1987)

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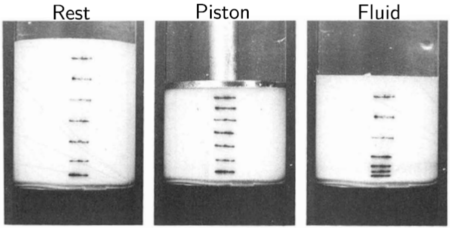
Poroelasticity framework (see MacMinn *et al.* (2015, 2016))

- > Fluid flow → Darcy's law
- > Solid mechanical properties → linear elastic

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

- Fluid flow → Darcy's law
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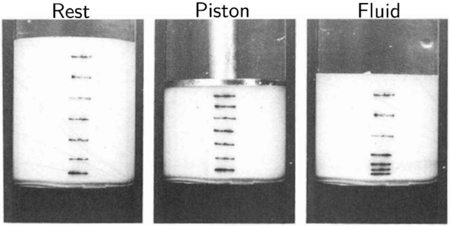


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- > Fluid flow → Darcy's law
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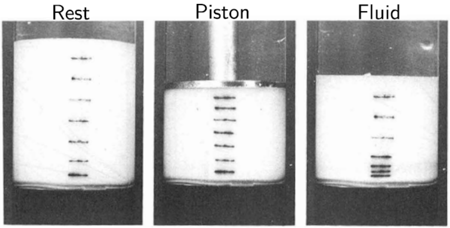


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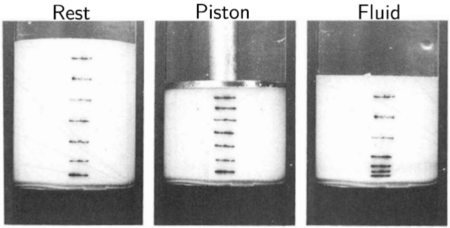


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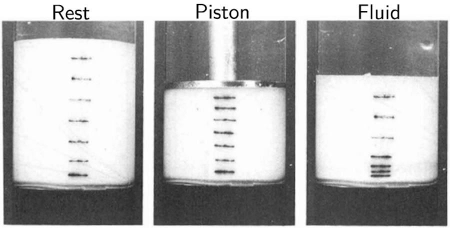


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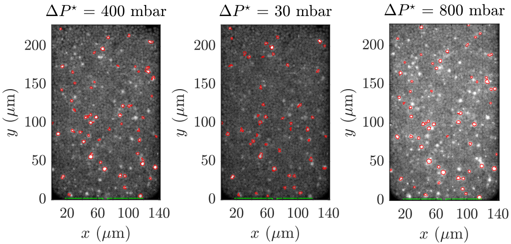
**Fluorescent hydrogel probes:**

- Added to the yeast suspension
- Fluorescence increases with compression



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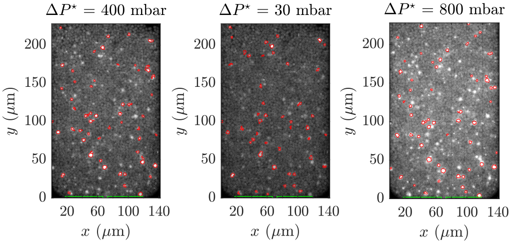


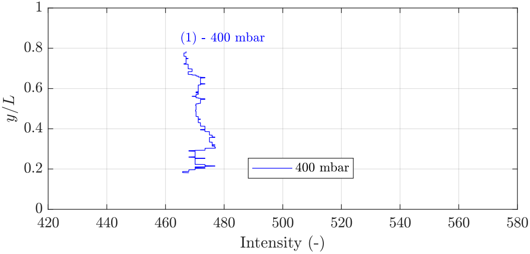

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# Stress repartition



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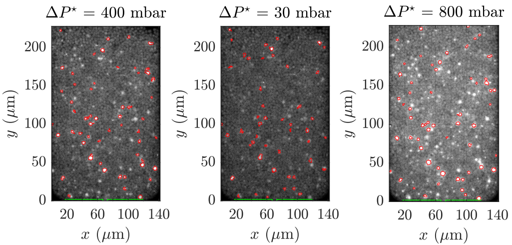


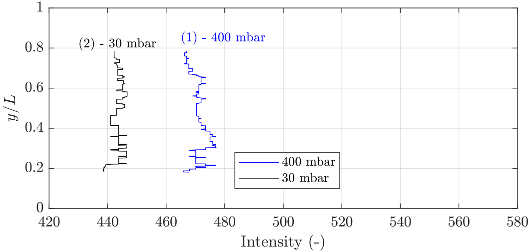

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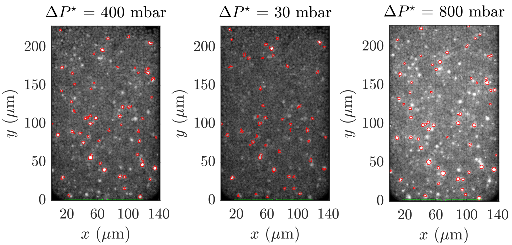


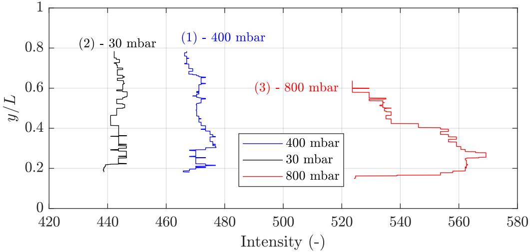

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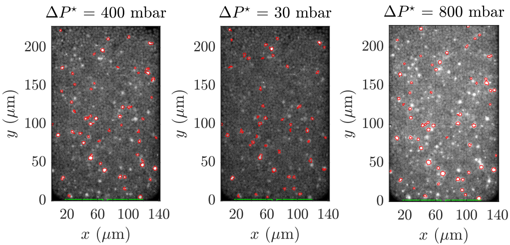


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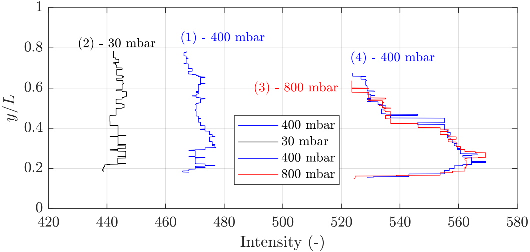

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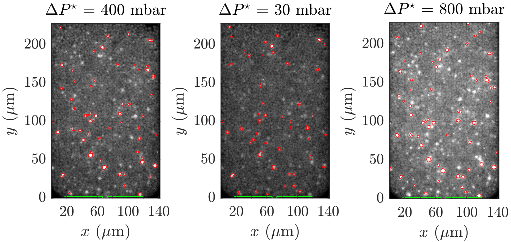


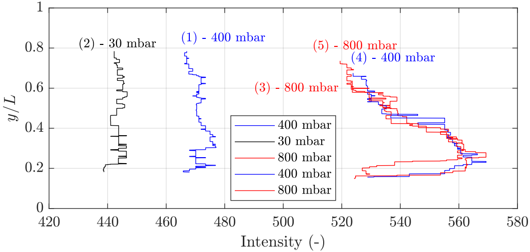

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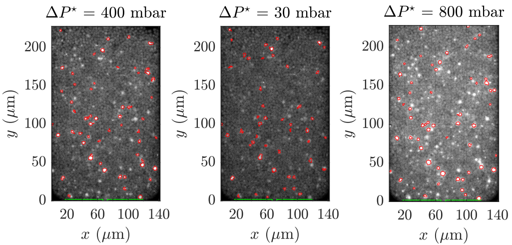


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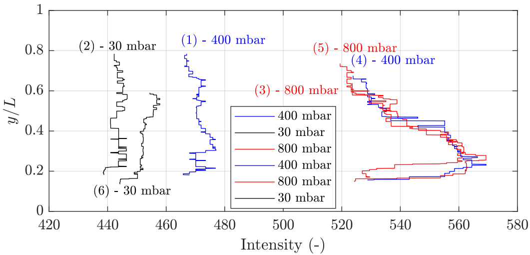

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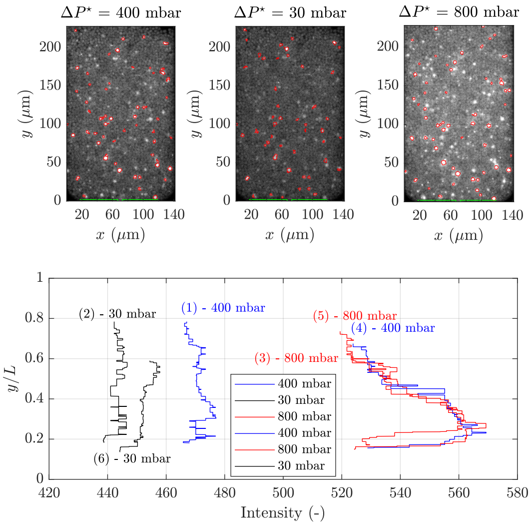

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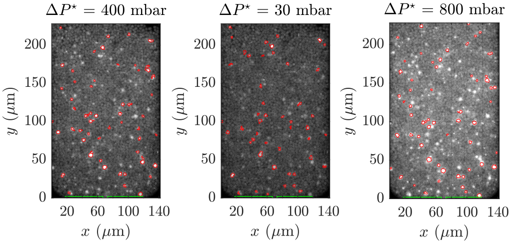


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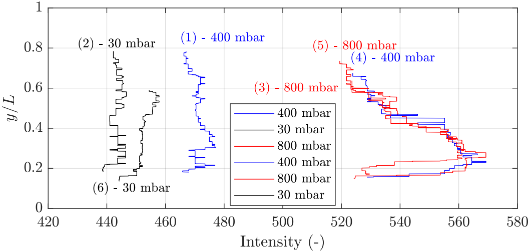


Which origin for this energy dissipation and elastic energy storage ?

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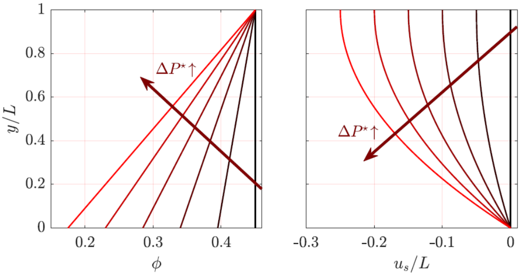
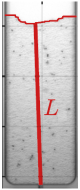
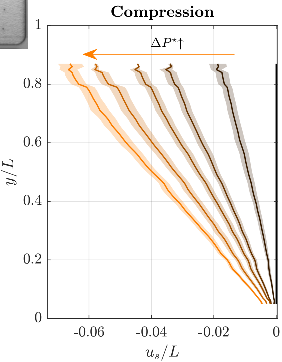


## Compression

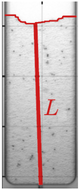
- Staggered displacement steps
- Non quadratic profile



# Relative displacement profiles



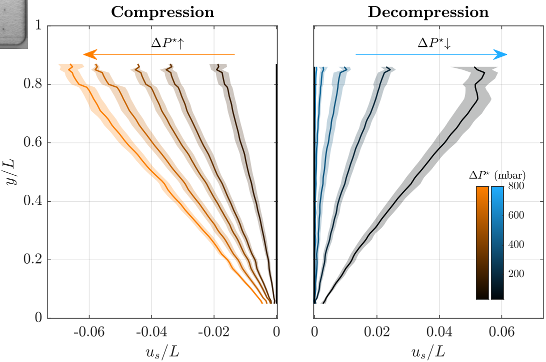



**Compression**

- Staggered displacement steps
- Non quadratic profile

**Decompression**

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



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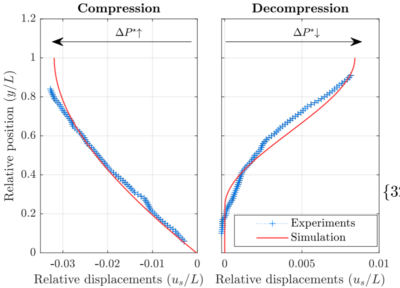


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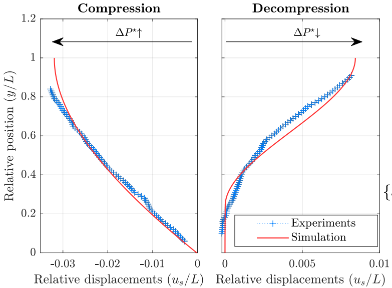


$\Delta P^\star_{\text{ref}} =$ 775 mbar

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# Reproduction of fluid-driven experiments



**Calibration:**

- Two free parameters ($\mu$, $\mathcal{M}$)
- 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

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

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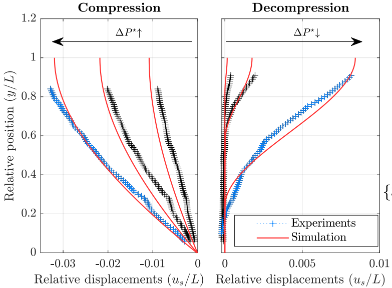


$\Delta P^\star_{\mathrm{ref}} =$ 775 mbar

$\Delta P^\star \in \{325, 480, 635\}$ mbar

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

# Reproduction of fluid-driven experiments



## Calibration:

- Two free parameters ($\mu$, $\mathcal{M}$)
- 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

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

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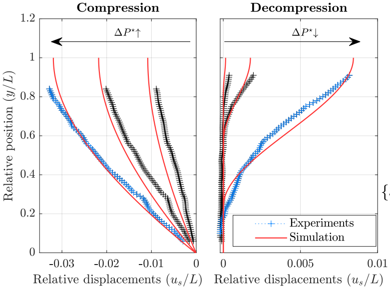


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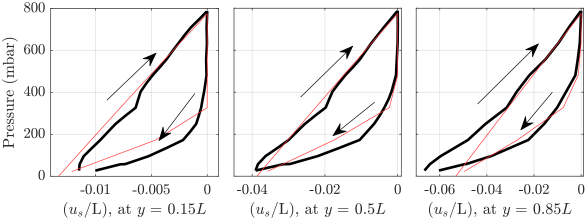
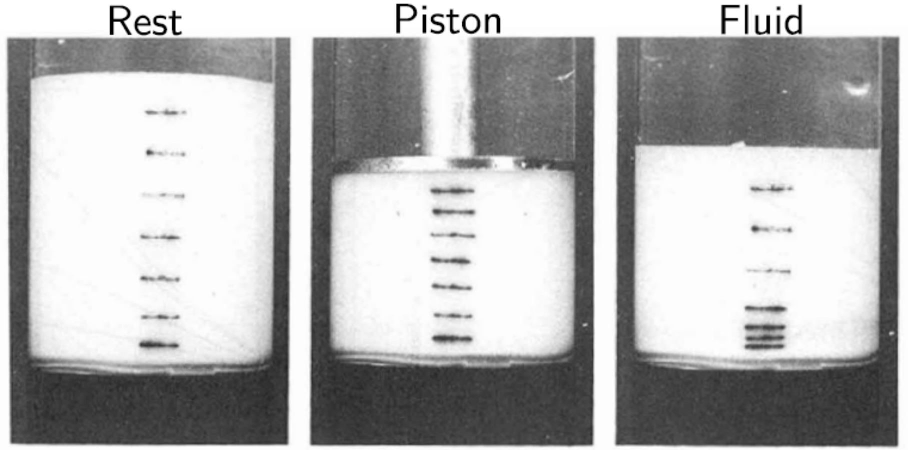


# What does poromechanics theory foresee ?



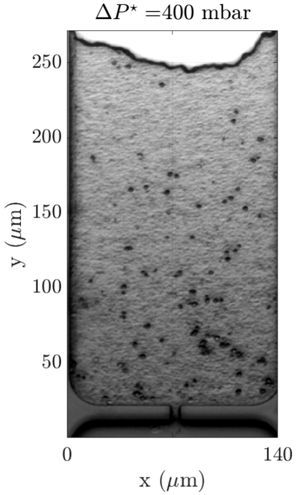



From Parker *et al.* (1987)

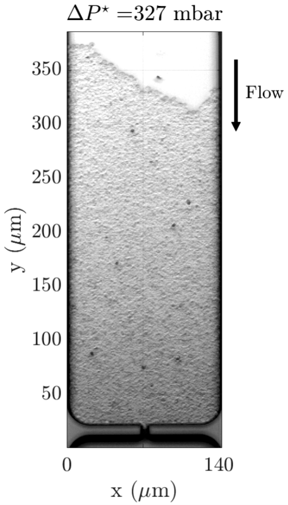
# How to measure the mechanical properties of a yeast clog ?



Piston-driven solicitation
(using an air bubble)




Fluid-driven solicitation



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

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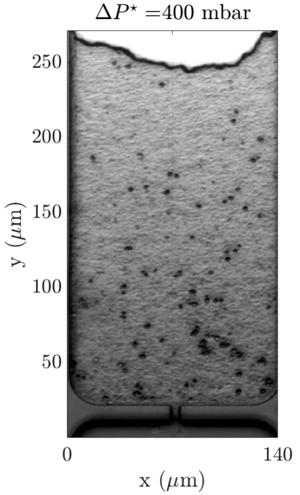
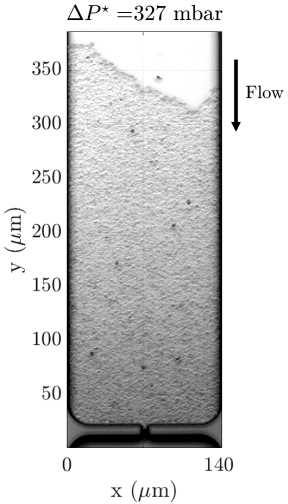



Fluid-driven solicitation

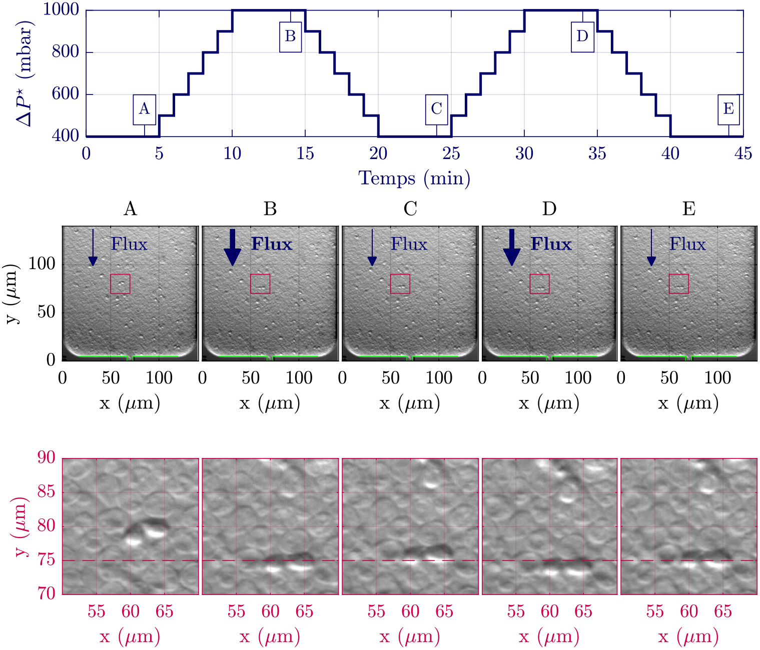



**Relation stress/deformation → Focus on fluid-driven case**

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

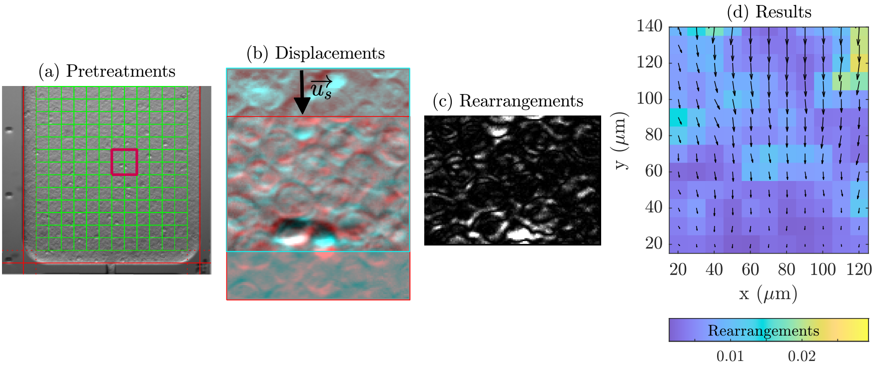
# Mechanical solicitation vs. displacement





# Image processing



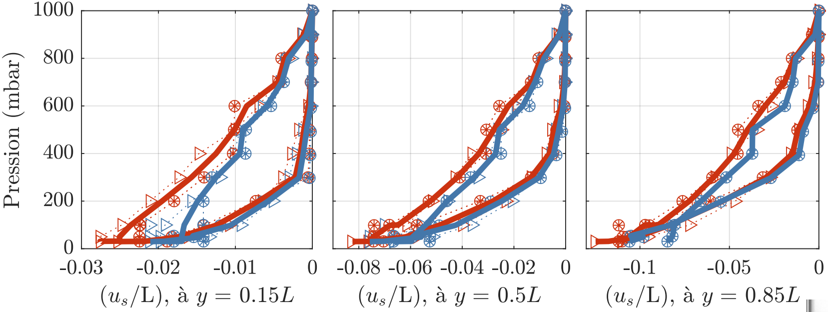


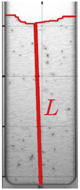

- Method adapted from Cerbino *et al.* (2021)
- First step similar to Particle Image Velocimetry

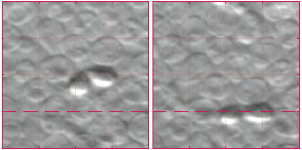
# Influence of local rearrangements of yeasts ?



> Weak irreversibility due to rearrangements



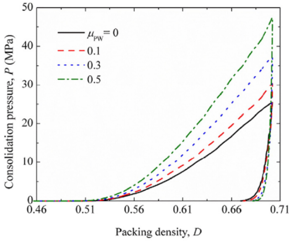


- Could the hysteresis be due to local rearrangement ?

# A well-hidden suspect



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

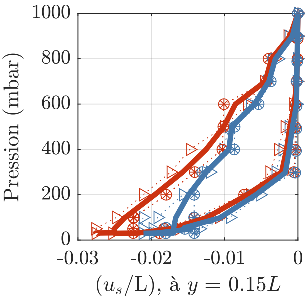



He *et al.* (2018)

# 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



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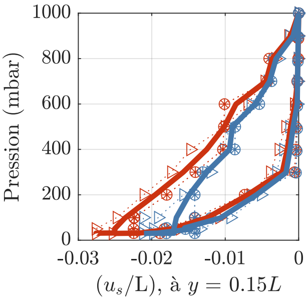


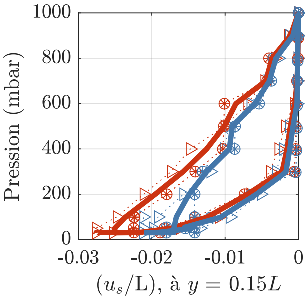

> Could the friction to the walls be an ideal suspect ?


From freepik.com

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

# A well-hidden suspect



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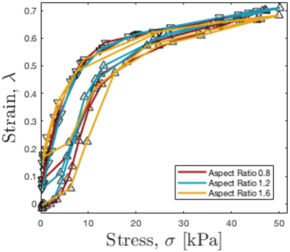


Lutz *et al.* (2021)

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

# A well-hidden suspect

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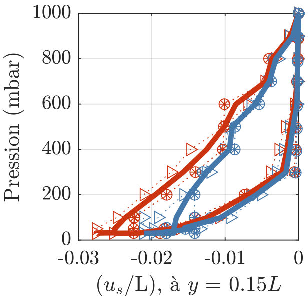



> Could the friction to the walls be an ideal suspect ?
- Started to be investigated for non-granular soft porous media
- **Yet**, biological cells are slippery on glass/silicon

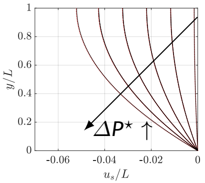
| Coulomb's friction coef. $\sim 0.03 - 0.06$ |
|---|

For human endothelial cells on glass

Dunn *et al.* (2007)

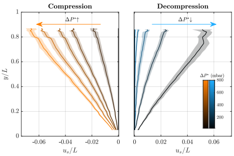
## Theory (poromechanics)

> Quadratic profile of displacements




## Experiments (yeast clog)

> **Linear profile** of displacements



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

# Comparison of poromechanics theory to experiments

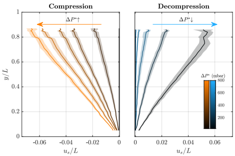


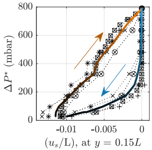
## Theory (poromechanics)

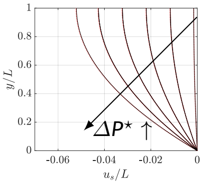
- Quadratic profile of displacements
- Elastic behaviour expected

## Experiments (yeast clog)

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



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# Comparison of poromechanics theory to experiments

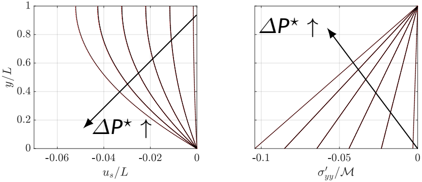


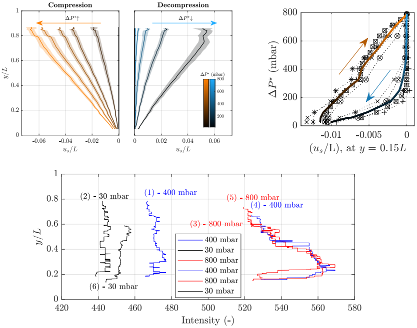
## Theory (poromechanics)

- 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



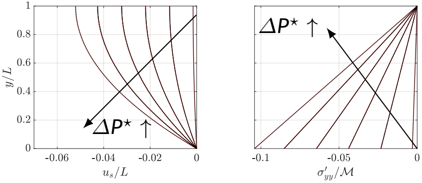



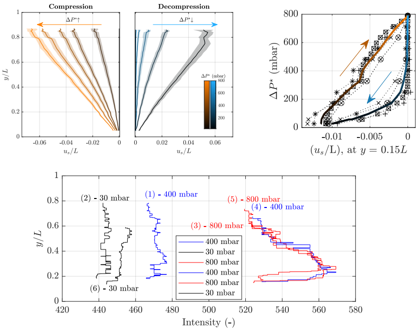
## Theory (poromechanics)

- 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 | $\begin{cases} \sigma'_F = \mathrm{sgn}(v_s)\mu K \sigma'_{yy} & \iff \lvert v_s \rvert > 0 \\ \sigma'_F = -\frac{H\eta}{2k} q - \frac{H}{2}\partial_y \sigma'_{yy} & \iff \left\lvert \frac{H\eta}{2k} q + \frac{H}{2}\partial_y \sigma'_{yy} \right\rvert \leq \mu K \left\lvert \sigma'_{yy} \right\rvert \end{cases}$ |

# Summary of the model for resolution



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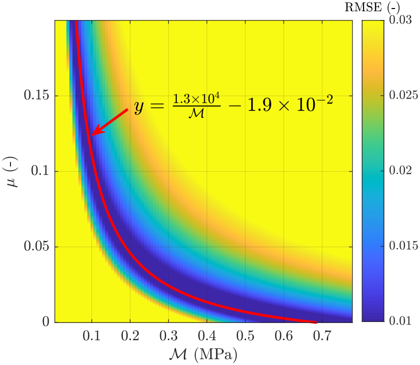
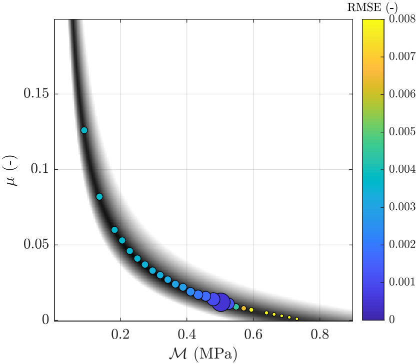
- Can be solved analytically in some specific cases
- In general case, a numerical resolution is necessary

> RMSE: Root Mean-Square Error




> One sweep on a compression profile

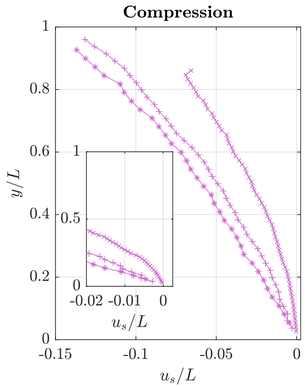
> One sweep on a decompression profile based on compression results

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

# What do we get for piston-driven solicitation ?



- Linear displacement profiles
- Less reproducibility



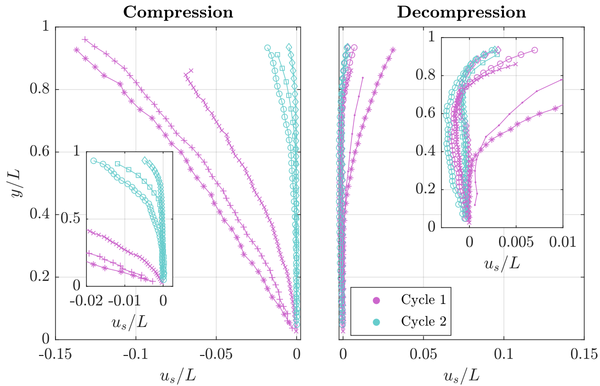
$\mathcal{F} = \frac{2\mu K L}{H} \sim \frac{F_f}{F_a}$

# What do we get for piston-driven solicitation ?



- Linear displacement profiles
- Less reproducibility

- Decompression: very weak displacements
- Exotic behaviour at decompression



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

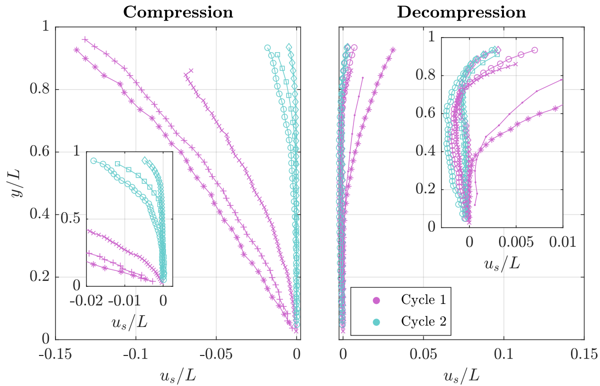
# What do we get for piston-driven solicitation ?

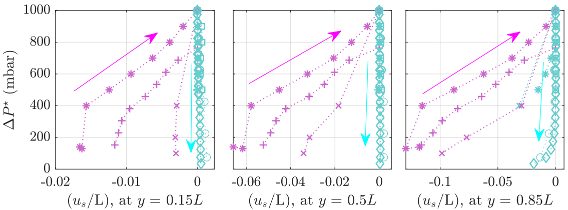


- Linear displacement profiles
- Less reproducibility

- Decompression: very weak displacements
- Exotic behaviour at decompression

- Energy dissipation by hysteresis
- Strong differences between the cycles



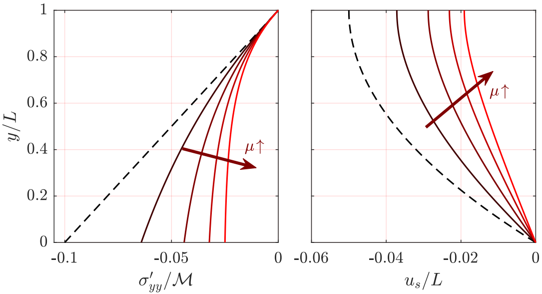



# Model behaviour



Fluid-driven compression:

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



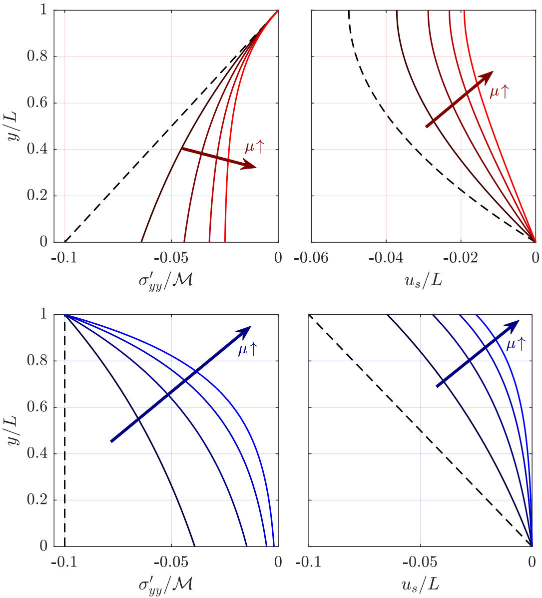
# Model behaviour

Fluid-driven compression:

- Stress profile ≠ linear
- Displacements no longer quadratic

Piston-driven compression:

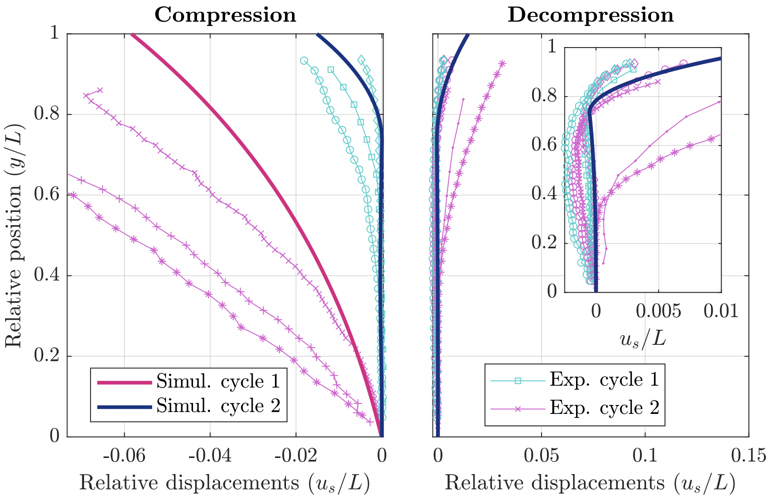
- Stress exponentially damped
- Displacements exponentially damped



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

# Model comparison to piston-driven experiments






- Acceptable agreement with experimental data
- Exotic behaviour at decompression is validated by the model