Gravity fingering in infiltration: A microfluidics study across scales

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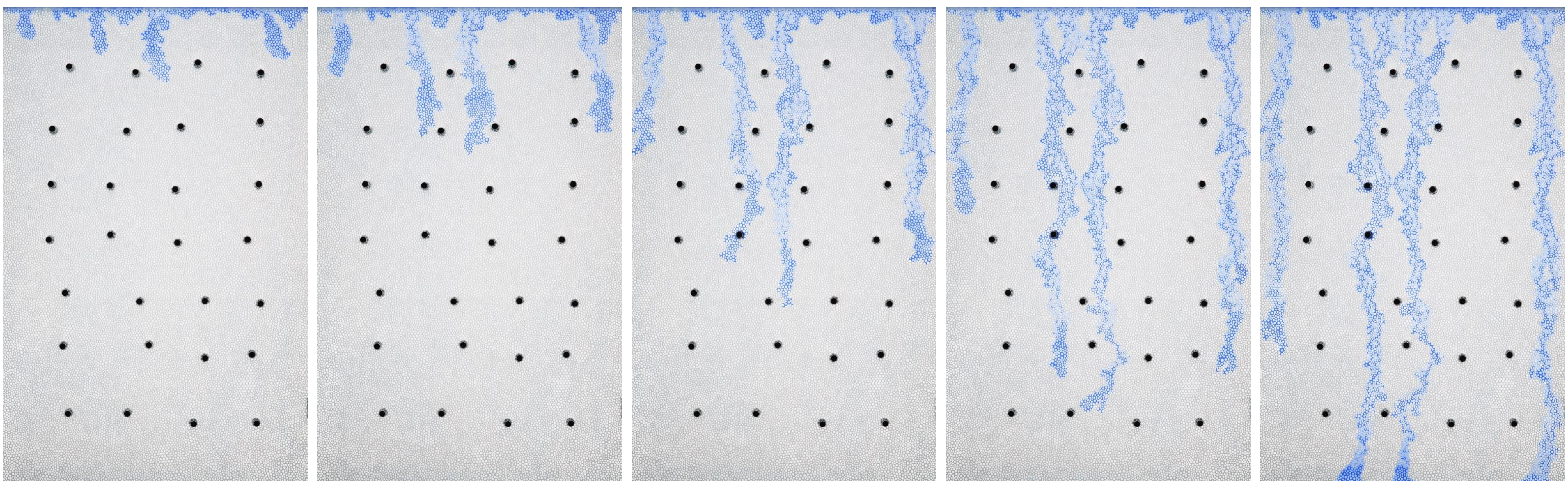

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Motivation

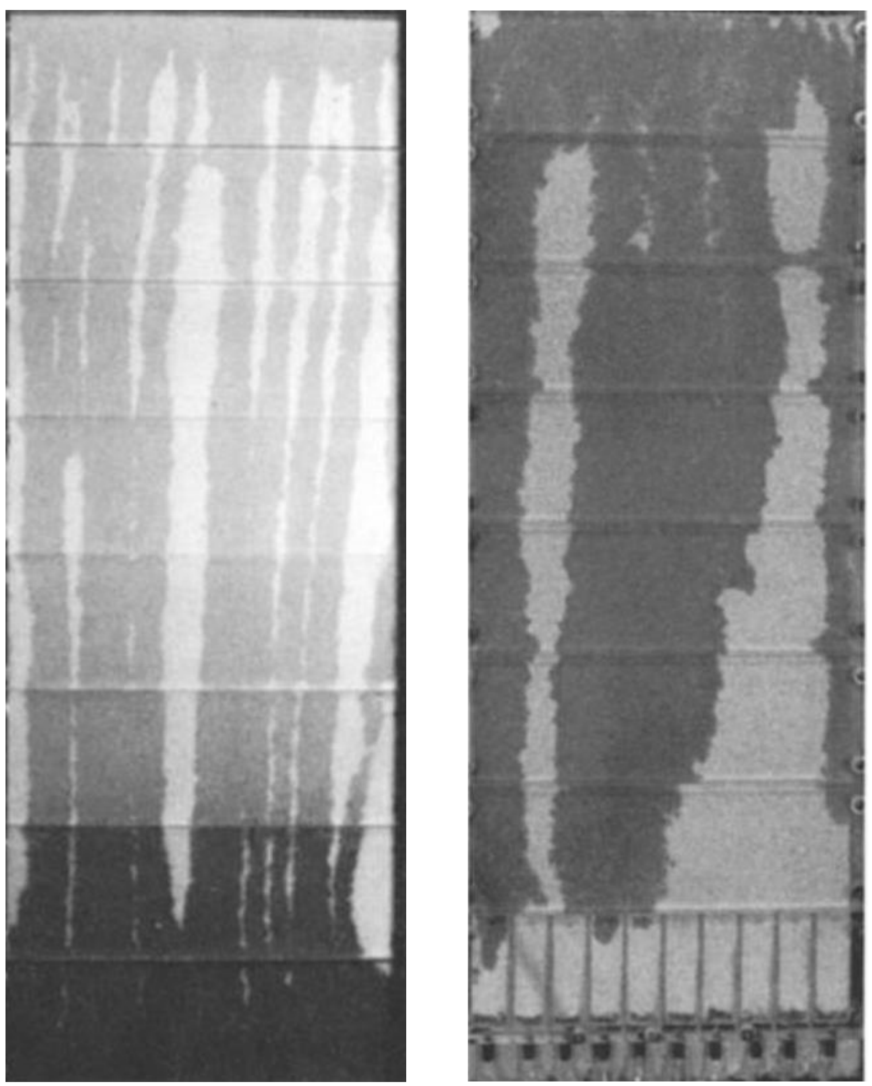
- The ecology and water budget of arid and semi-arid ecosystems depend critically on the dynamics of soil water.
- Water infiltration in dry soil exhibits a gravity-driven hydrodynamic instability termed gravity fingering.
- Gravity fingering could affect plant ecology, groundwater recharge, and nutrient cycling at the regional and global scales.

An Acacia tree in the Kenyan desert

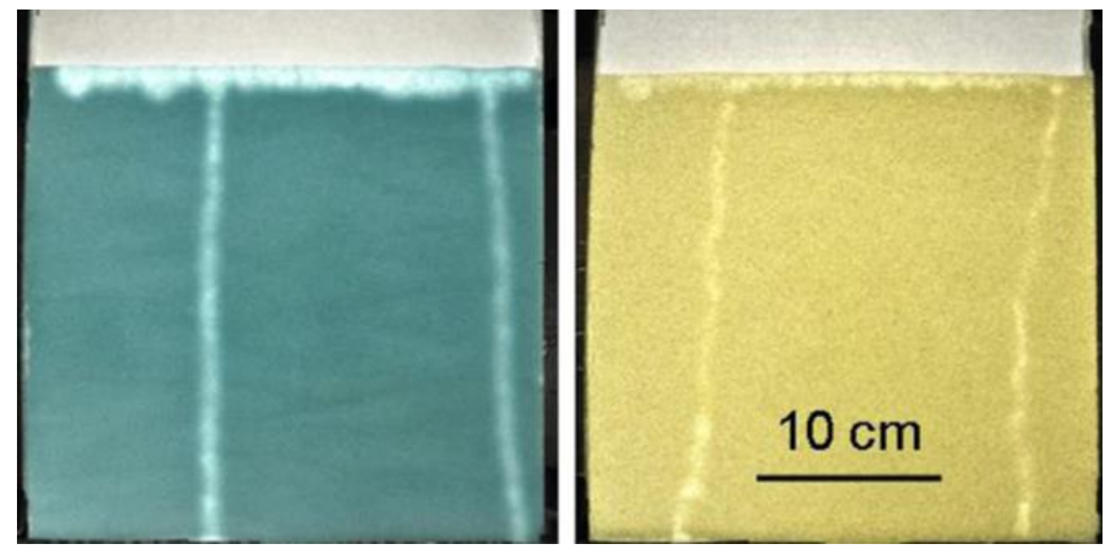
An infiltration experiment with dyed water

Literature review

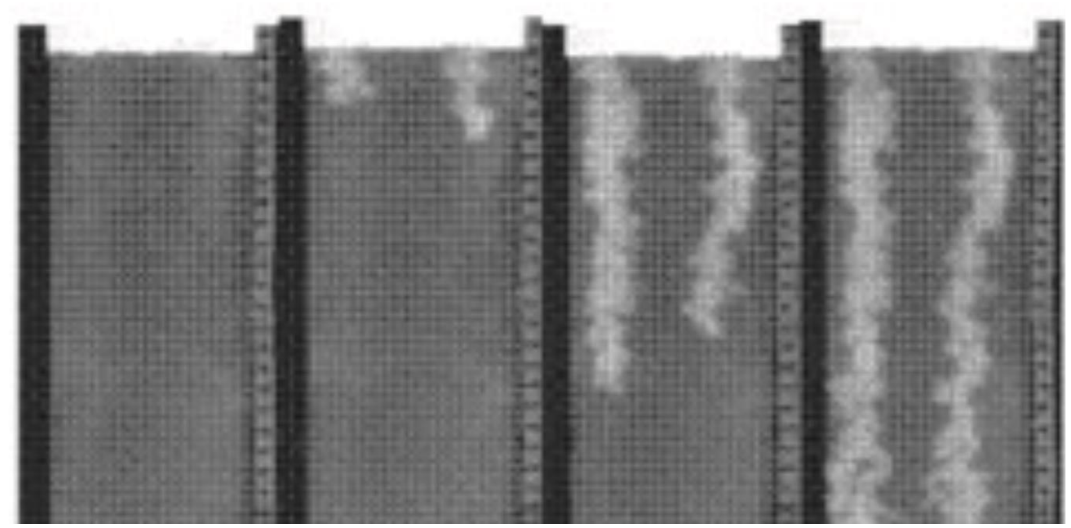
- Gravity fingering in infiltration has been extensively investigated via bench-scale experiments.
- Existing experiments use flow cells packed with glass beads/sand particles.



Glass et al., *Water Resour. Res.*, 1989



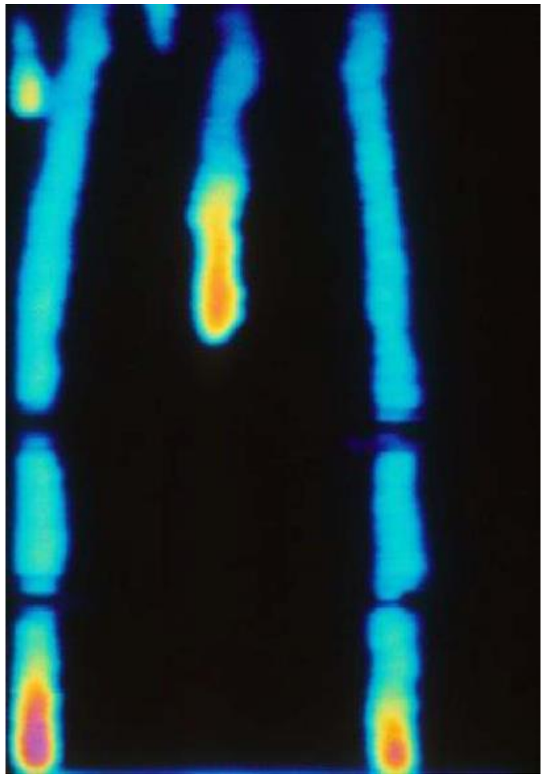
Wei et al., *Phys. Rev. Applied*, 2014



Annaka & Hanayama, *Soil Sci. Plant Nutr.*, 2010

Literature review

- Existing experimental studies have found
  - Fingering instability occurs in infiltration in dry porous media.
  - Increasing the infiltration flux increases finger velocity and finger width.
  - Increasing the infiltration flux decreases finger separation.
  - Saturation overshoot – the fingertip exhibits the highest saturation and saturation decreases in the upstream direction.



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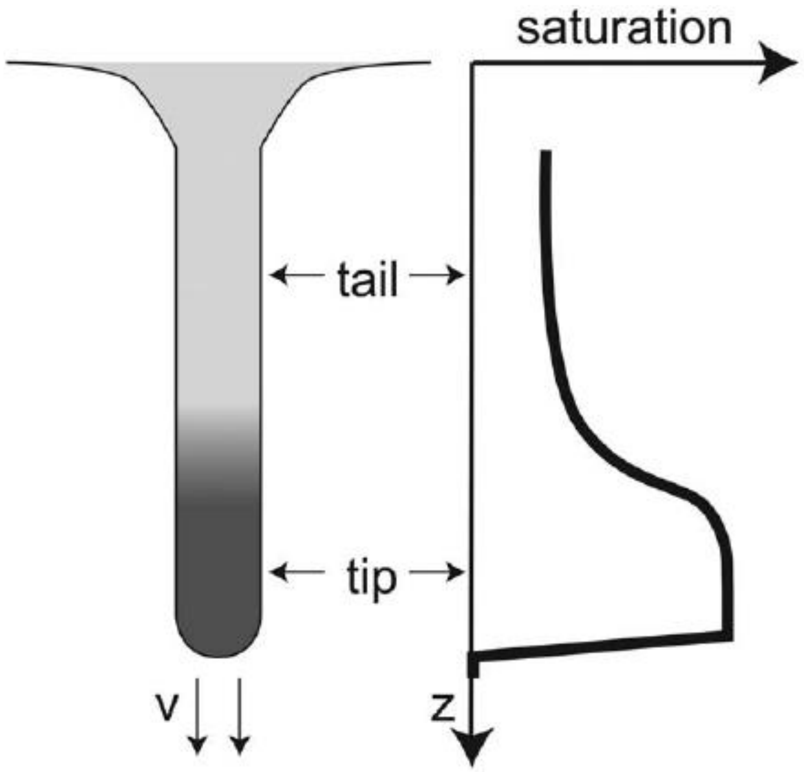
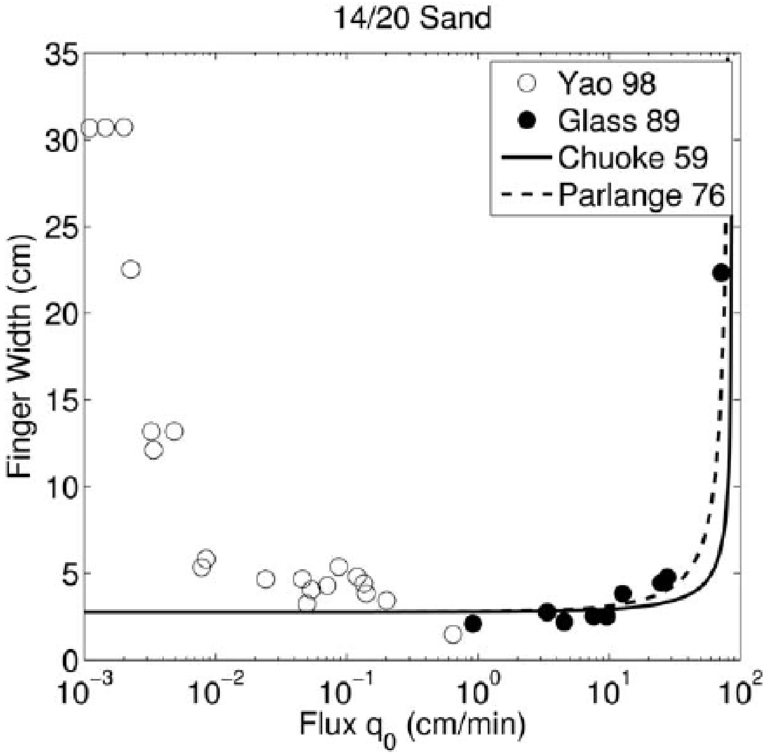


DiCarlo., *Water Resour. Res.*, 2013



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Literature review

- Existing experimental studies have found
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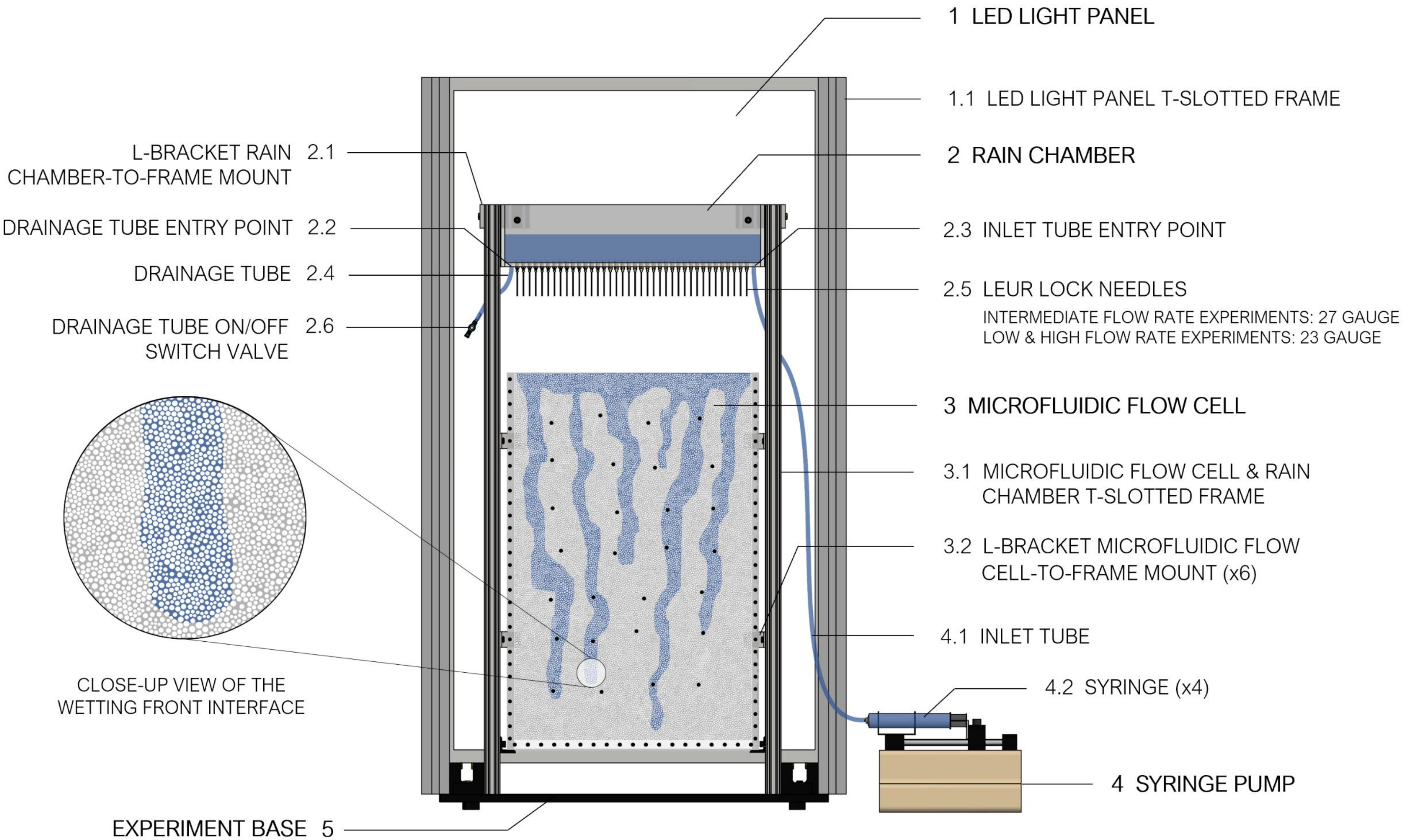
  - Increasing the infiltration flux increases finger velocity and finger width.
  - Increasing the infiltration flux decreases finger separation.
  - Saturation overshoot – the fingertip exhibits the highest saturation and saturation decreases in the upstream direction.
- However, existing experiments lack direct observation of pore-scale phenomena in gravity fingering.

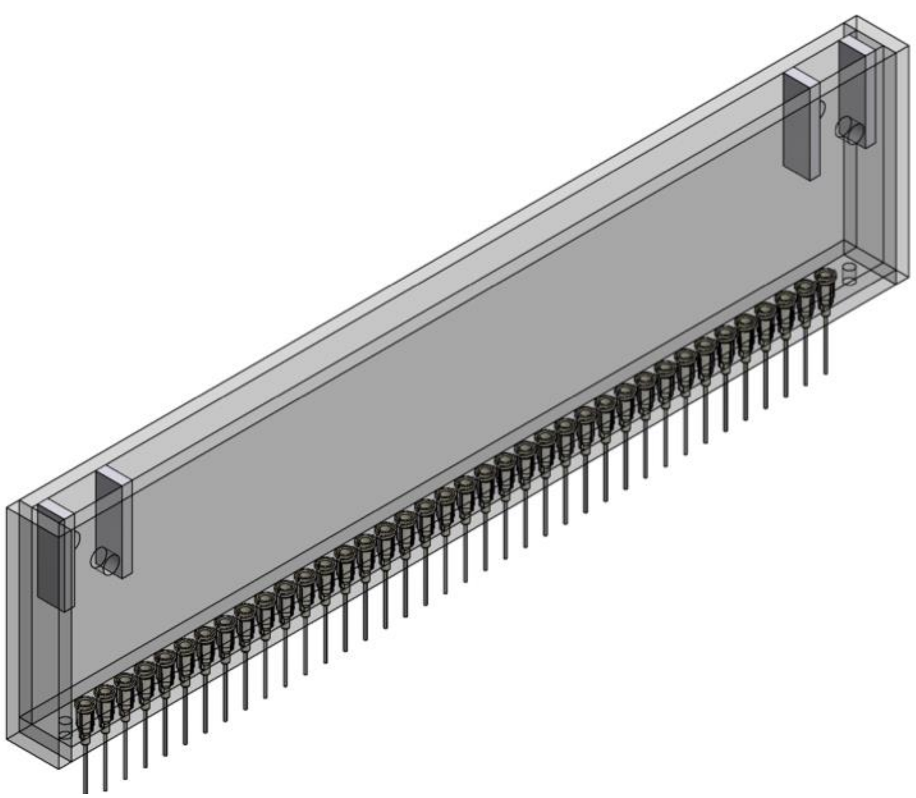
Experimental setup

- We study gravity fingering experimentally in a large microfluidic flow cell that enable simultaneous visualization of the macroscopic infiltration front and the pore-scale interfaces.

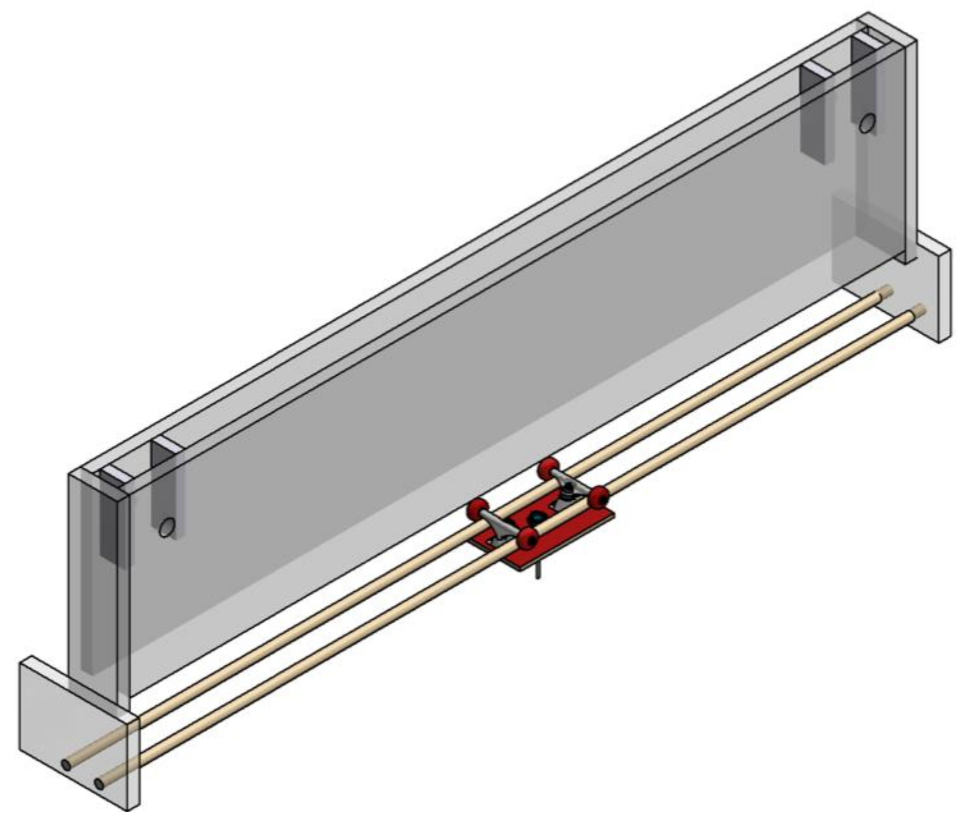


Experimental setup

- We study gravity fingering experimentally in a large microfluidic flow cell that enable simultaneous visualization of the macroscopic infiltration front and the pore-scale interfaces.
- We vary the infiltration flux over a wide range of flow rates (i.e., 6, 146, and 940 mL/hr).



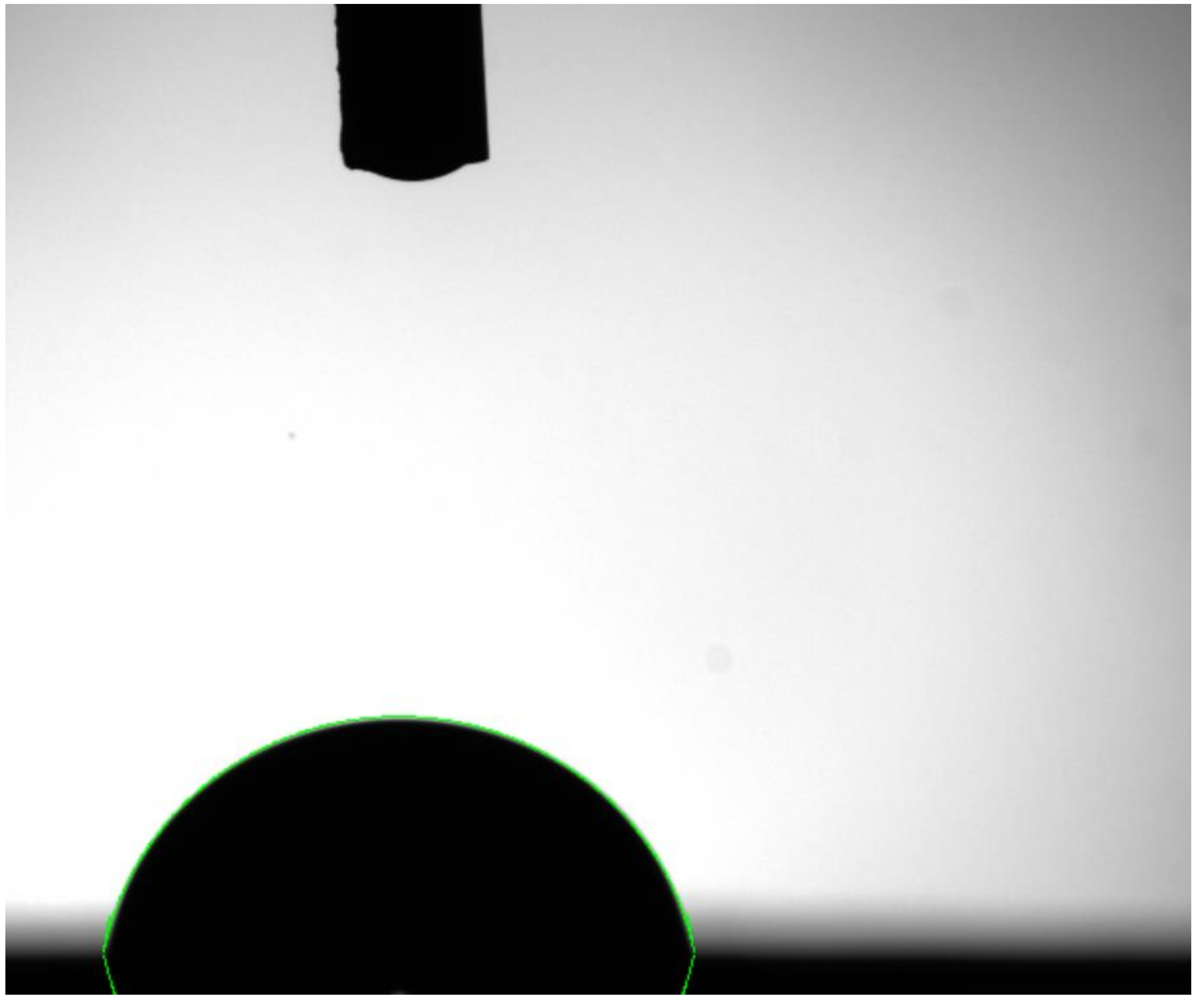
146 mL/hr and 940 mL/hr



6 mL/hr

Experimental setup

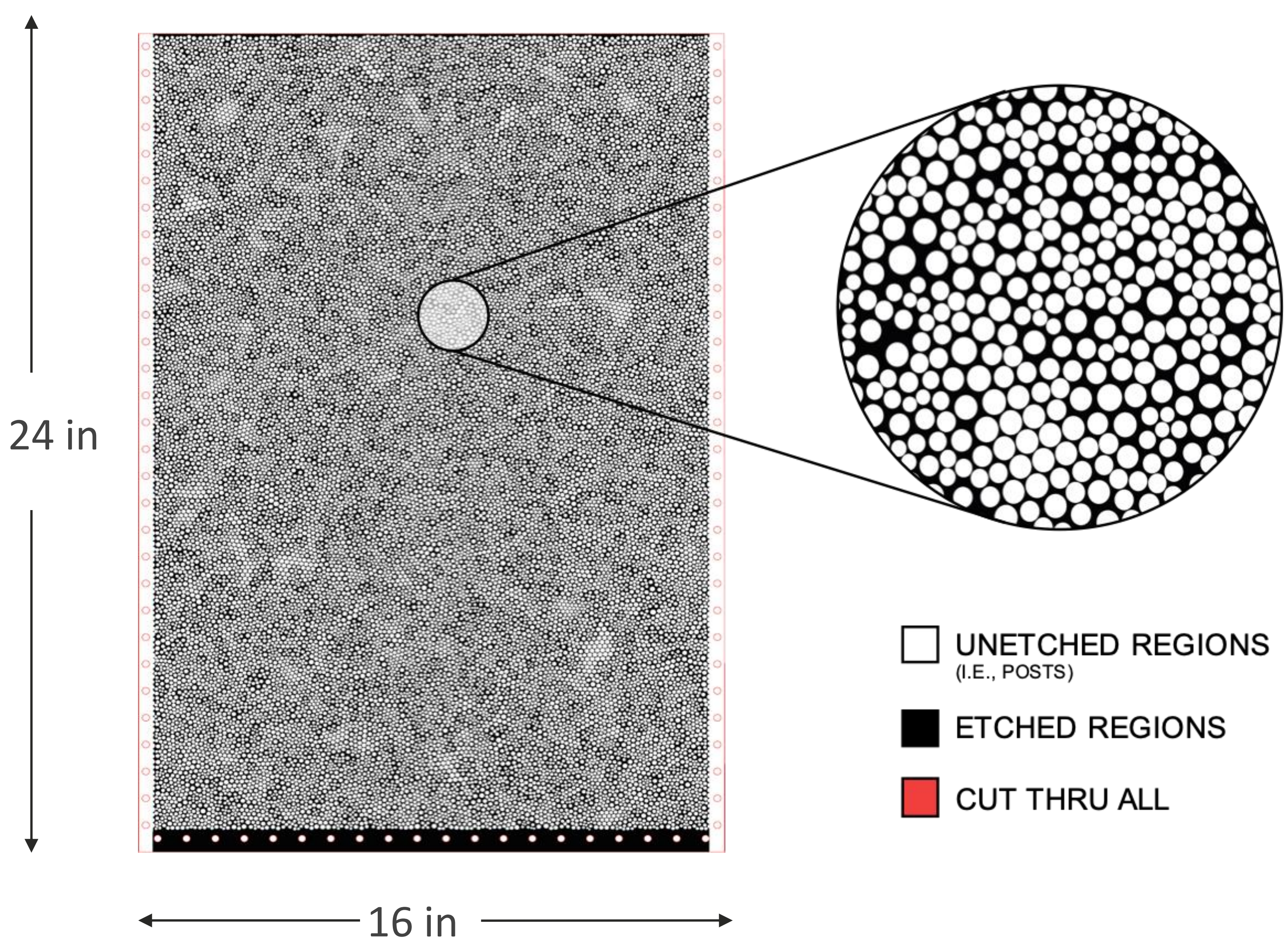
- The microfluidic cell is a quasi-2D acrylic flow cell patterned with ~25,300 500 µm-high cylindrical posts using a laser cutter.

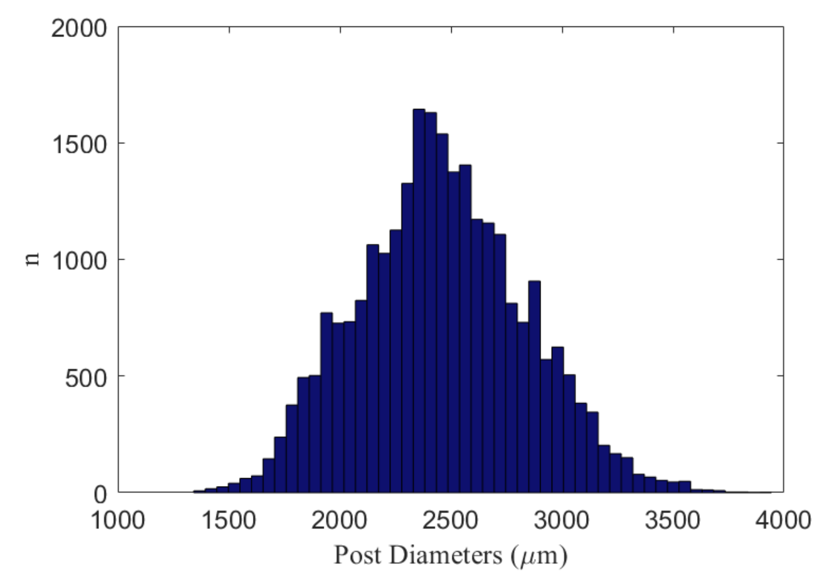


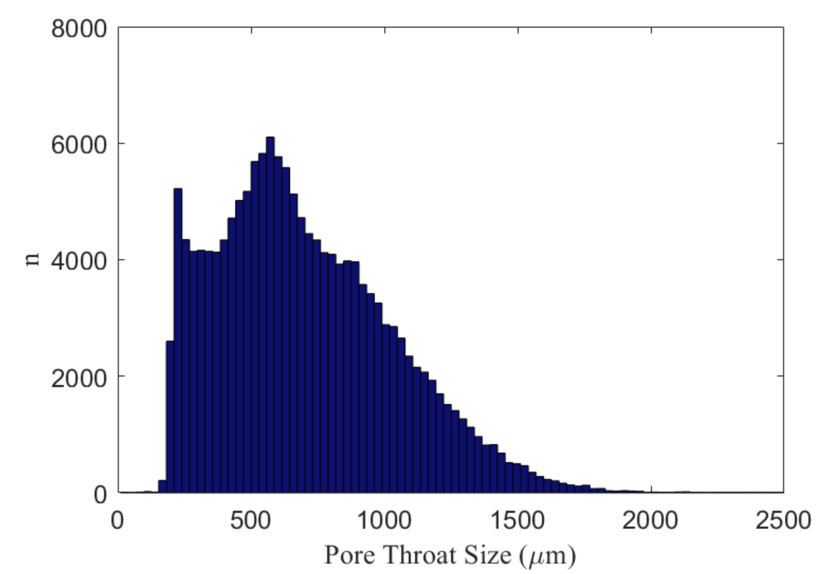
Contact Angle, θ = 78.9 degrees

Experimental setup

- The microfluidic cell is a quasi-2D acrylic flow cell patterned with ~25,300 500 μm-high cylindrical posts using a laser cutter.
- The post pattern contains disorder locally, but it is macroscopically homogeneous at the scale of the flow cell with porosity, Φ = 0.46.

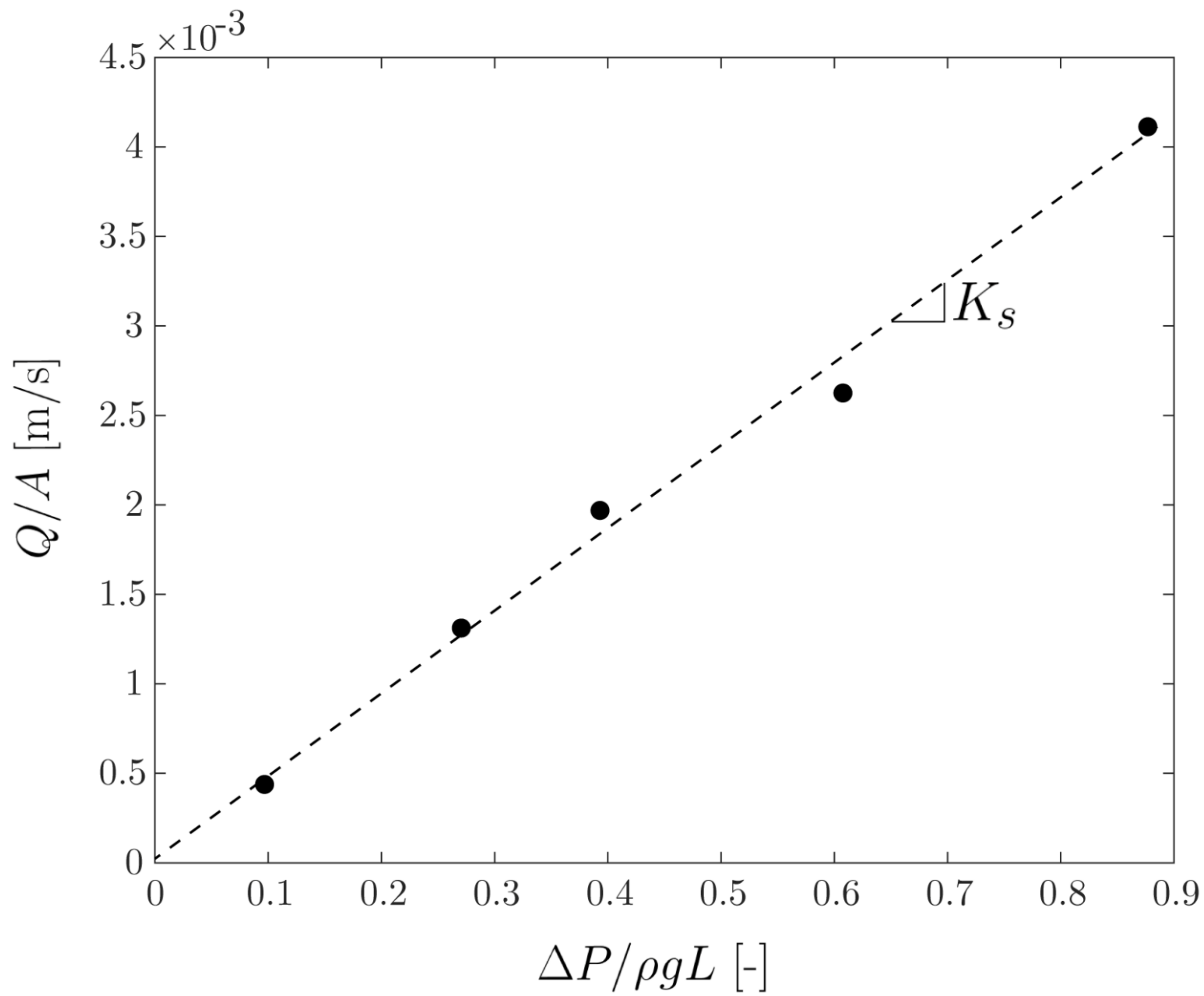






Hydraulic conductivity measurement

- We measure the saturated hydraulic conductivity of the microfluidic flow cell via single-phase flow of water at different imposed flow rates.



$$\boxed{K_s = 0.0046 \text{ m/s}}$$

❖ Darcy's law

$$\frac{Q}{A} = \boxed{K_s} \frac{\Delta P}{\rho g L}$$

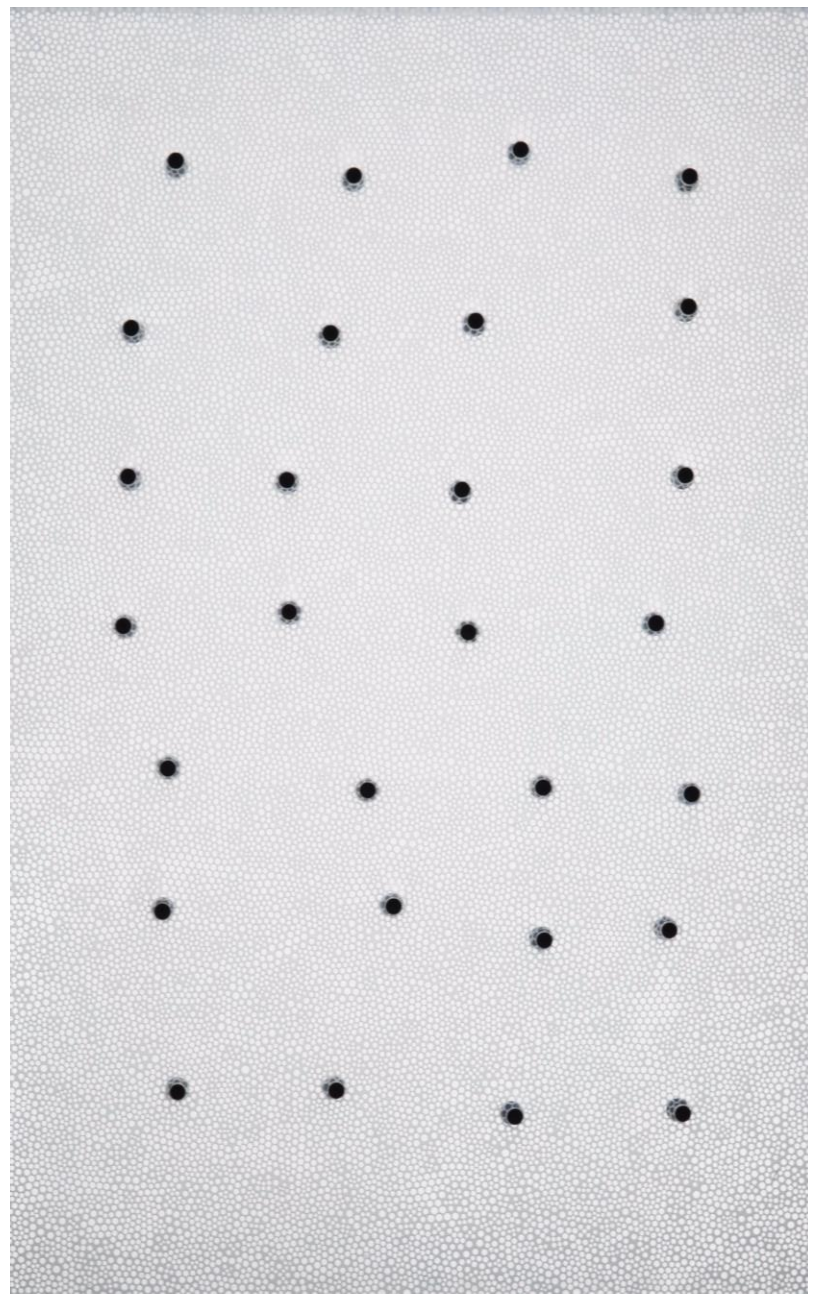
saturated hydraulic conductivity

❖ Normalized infiltration flux

$$R_s = \frac{q_i}{K_s}$$

A typical experiment

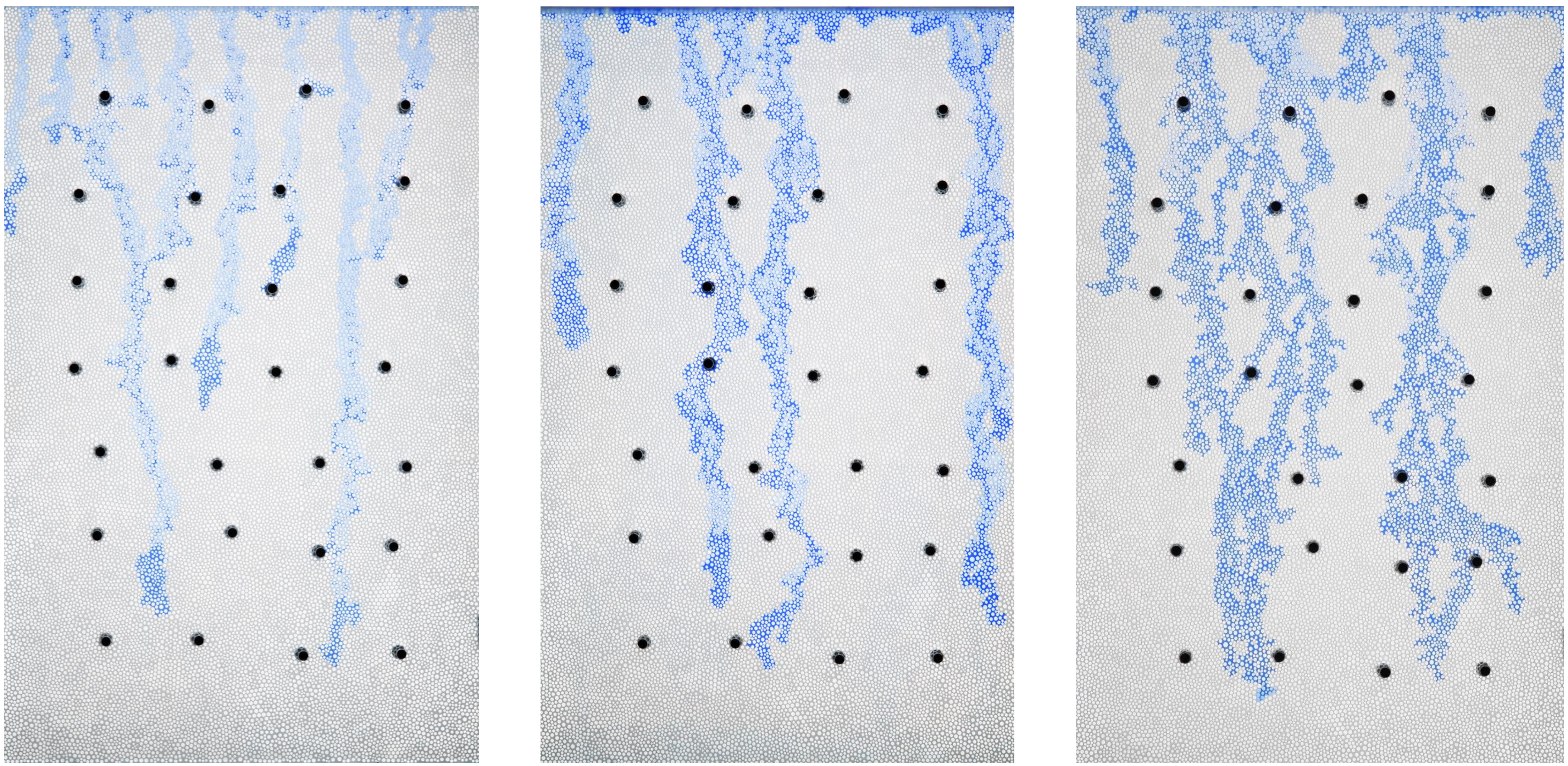
0.0 min



$R_s = 0.002$

Experimental phase-diagram

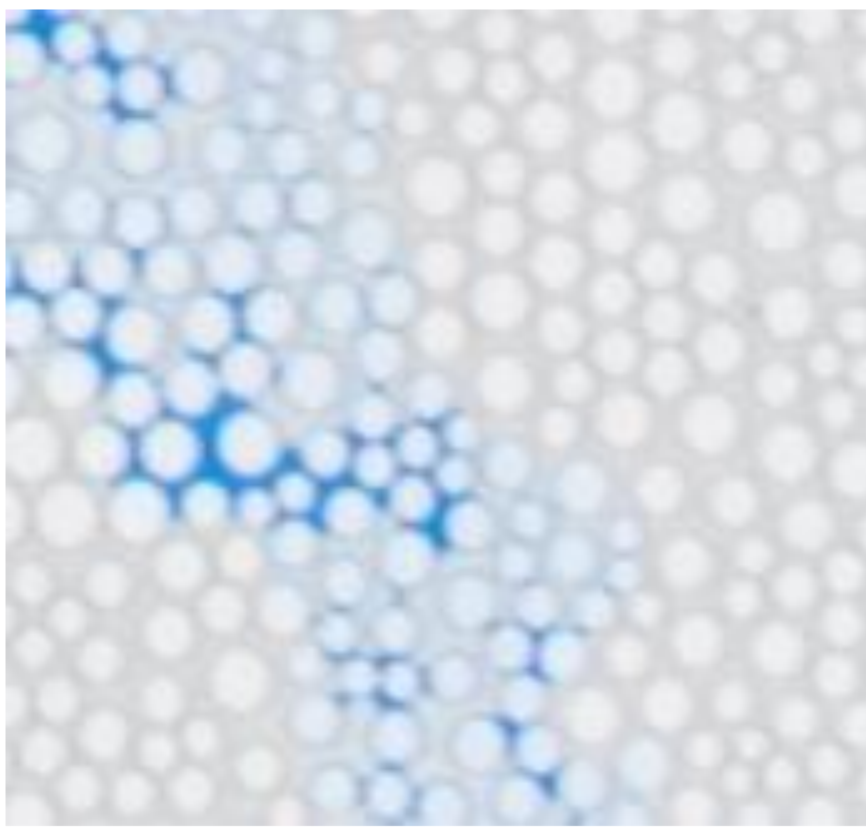
- We observe different behaviour in finger morphology,
  as well as saturation distribution as we increase the infiltration rate.



$R_s = 0.002$ $R_s = 0.046$ $R_s = 0.294$

Pixel intensity vs saturation

- We identify 3 distinct pixel intensities and their corresponding water saturation.



Unsaturated zone 1
(i.e., etched region, air only)
Water thickness: 0 μm

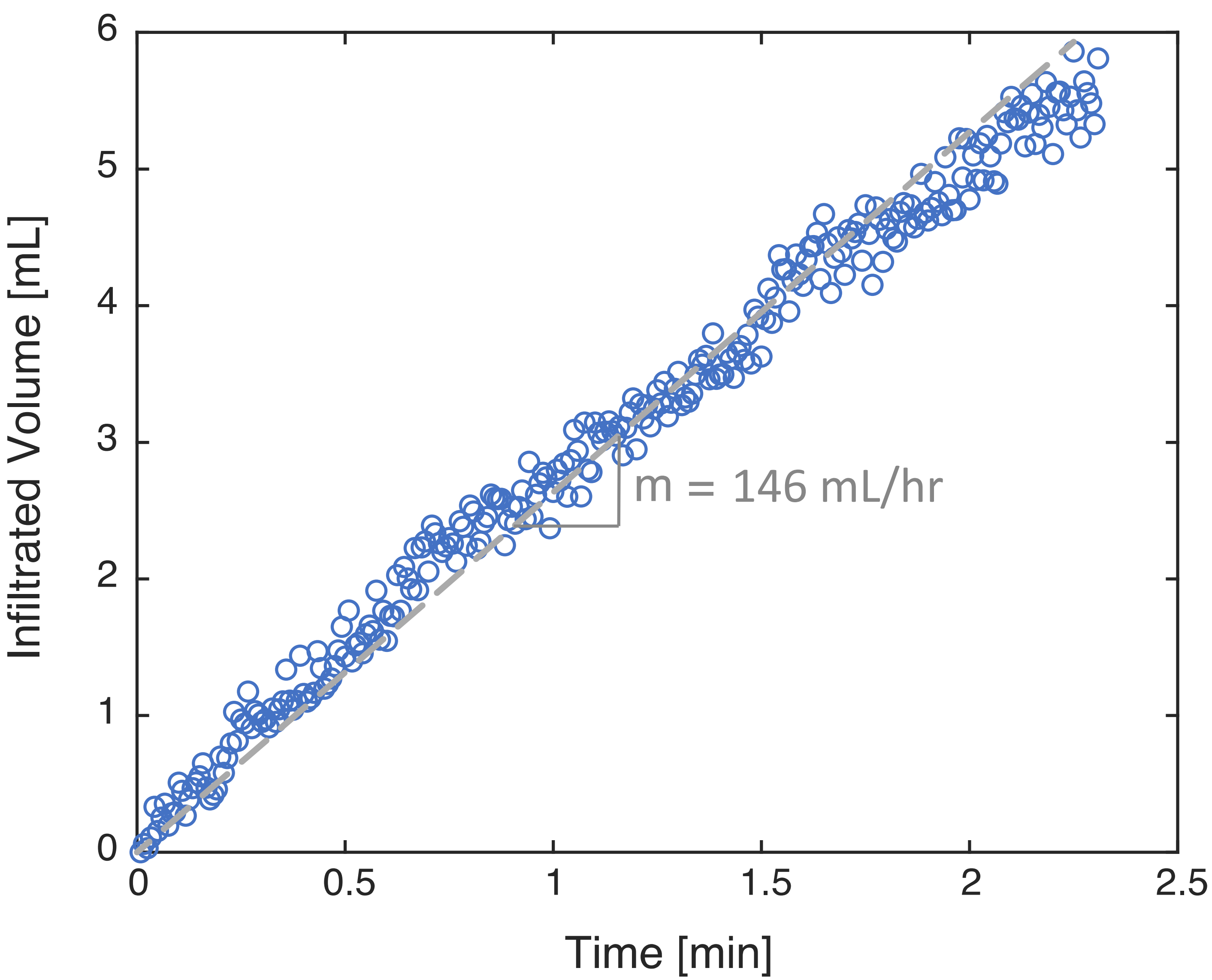
Fully saturated region
Water thickness: 500 μm

Partially saturated thin film region
Water thickness: 20 μm

** Intensity corresponding to posts were not included.

Pixel intensity vs saturation

- We identify 3 distinct pixel intensities and their corresponding water saturation.



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Fully saturated region
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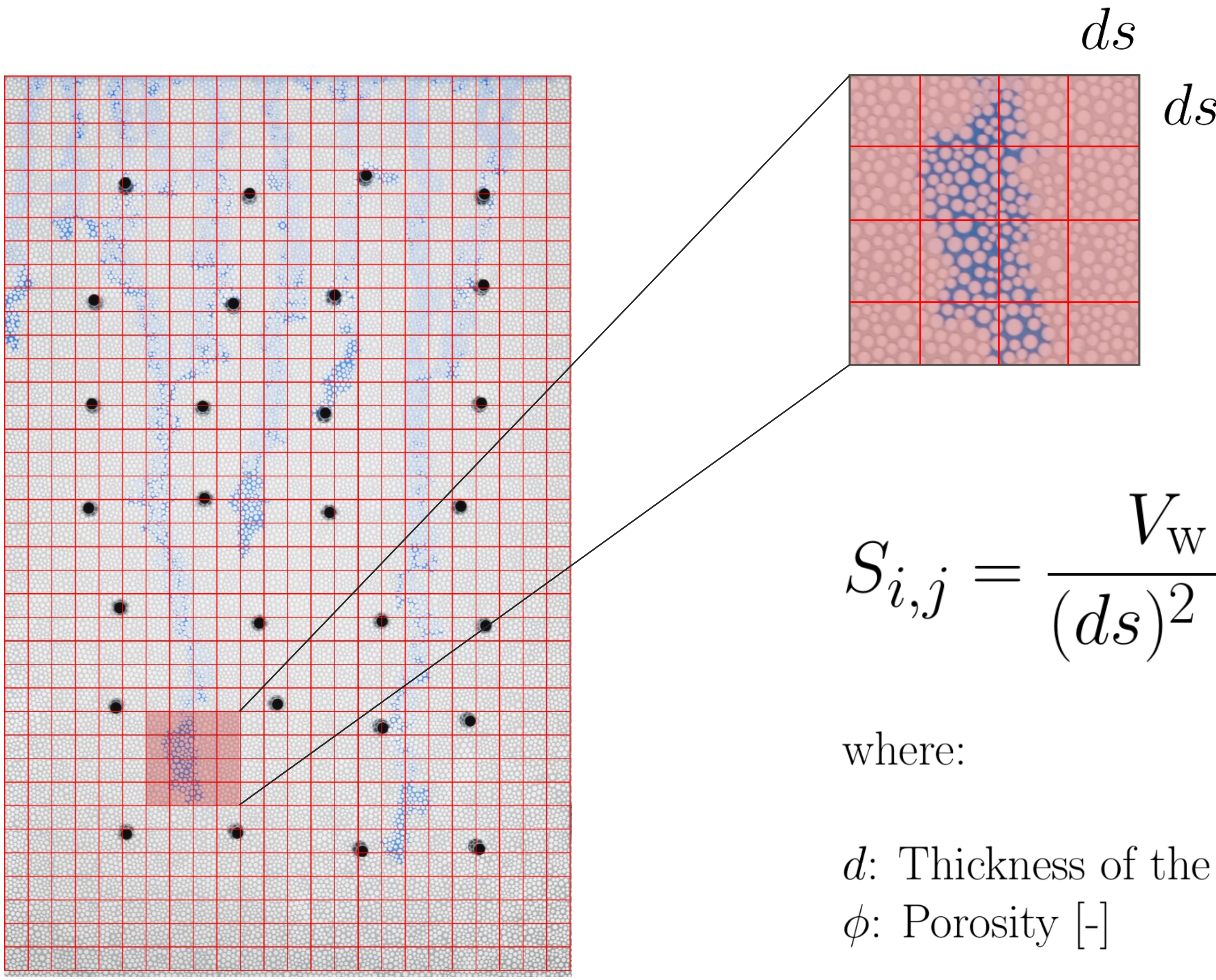
Partially saturated thin film region
Water thickness: 20 μm

A downscaling exercise (2D)

- We downscale the saturation distribution from the microfluidic experiments to a coarser resolution.



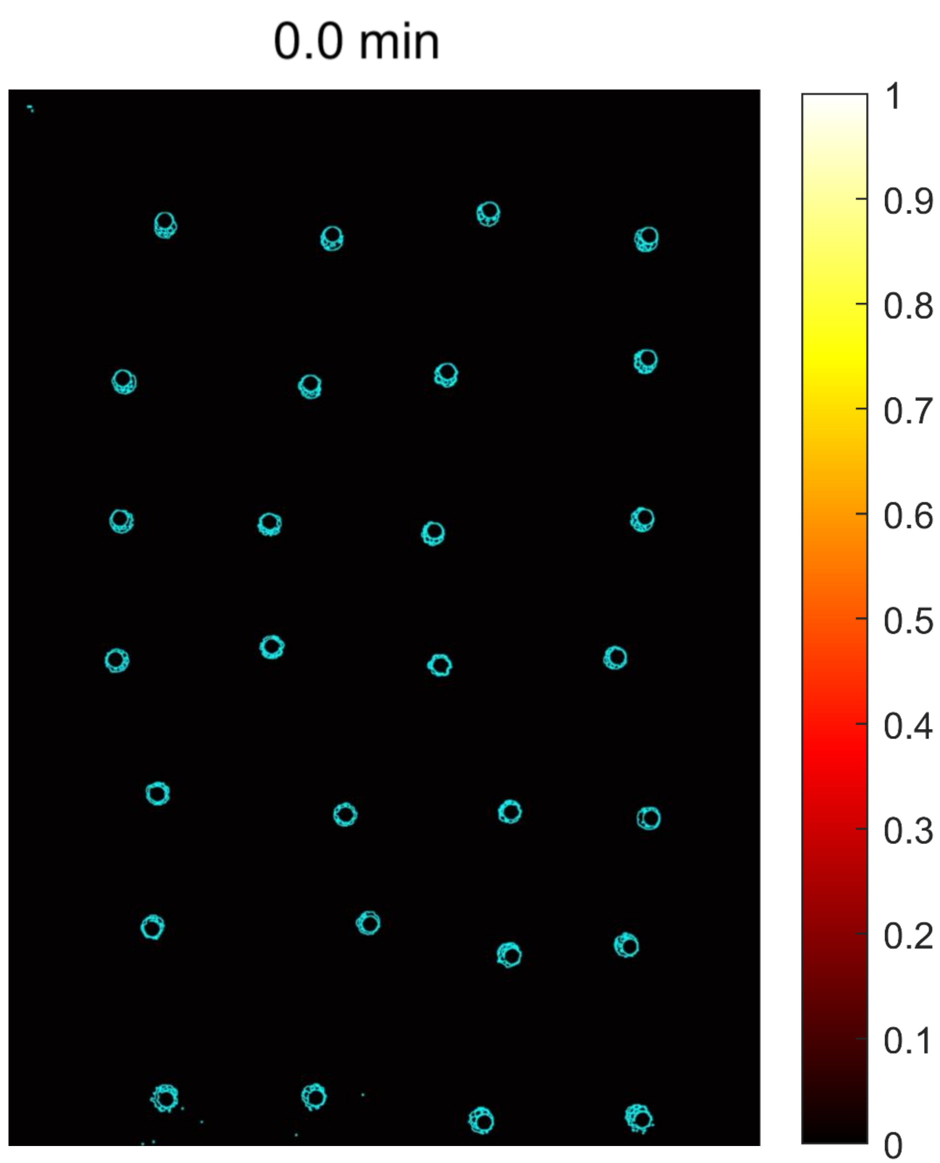
$$S_{i,j} = \frac{V_\mathrm{w}}{(ds)^2 \cdot d} \cdot \frac{1}{\phi}$$

where:

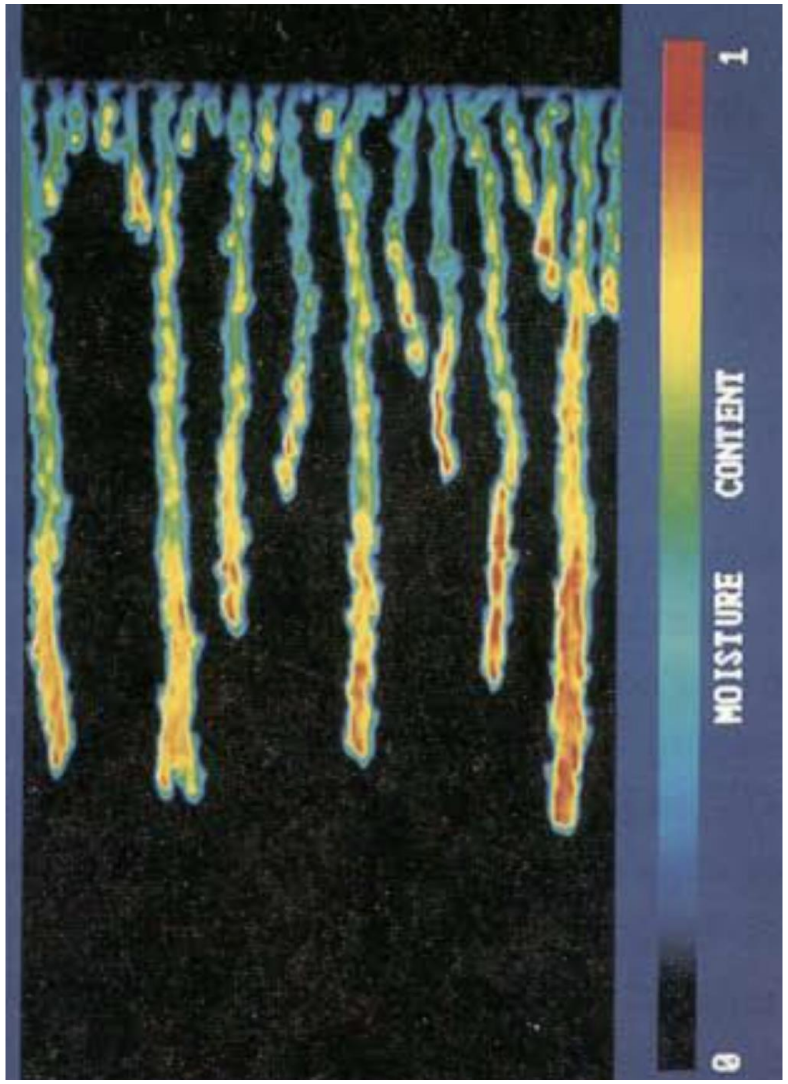
d: Thickness of the gap [mm]
ϕ: Porosity [-]

A downscaling exercise (2D)

- We downscale the saturation distribution from the microfluidic experiments to a coarser resolution.
- Downscaling in 2D shows that our experiments match previous macroscopic observations of gravity fingering in bead packs.



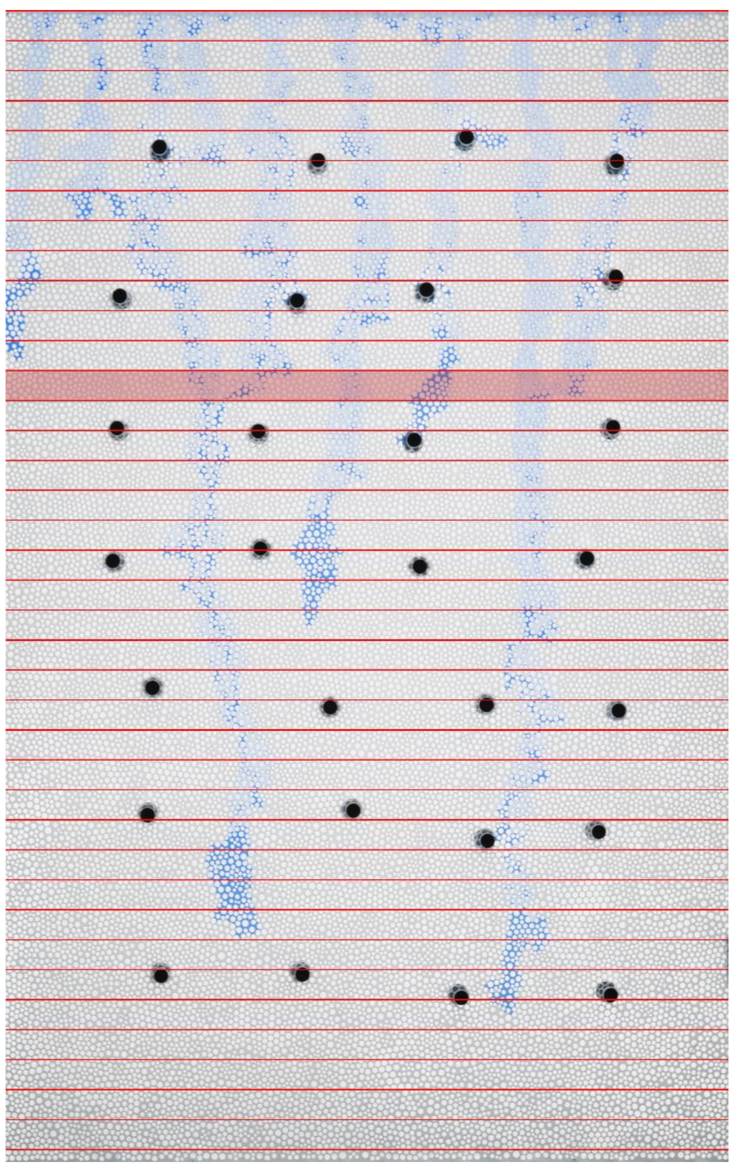
$R_s = 0.002$

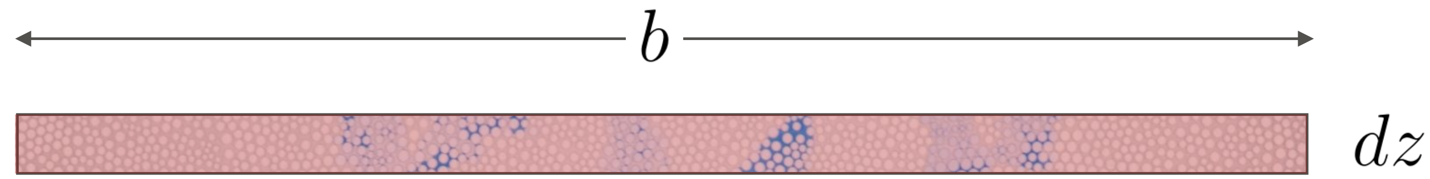


Glass et al., Soil Sci.,1989

A downscaling exercise (1D)

- We further downscale the saturation distribution to obtain the average saturation evolution as a function of depth as infiltration progresses.





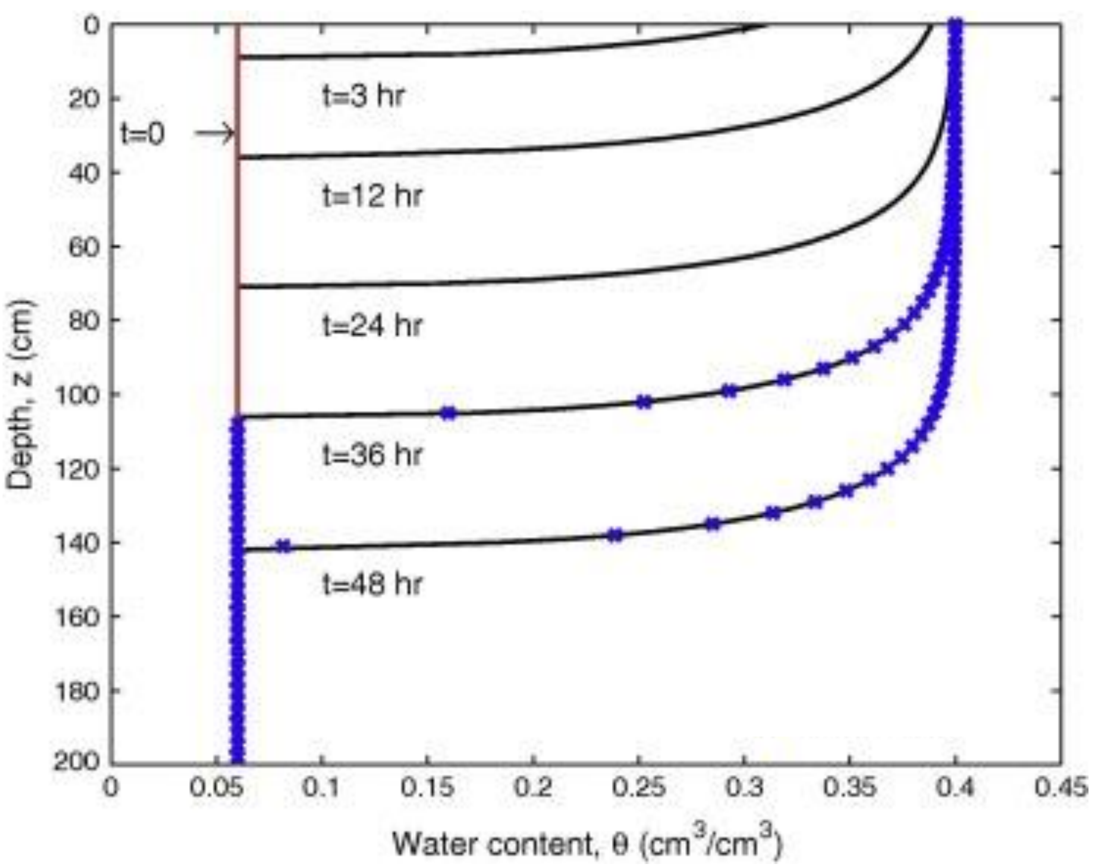
$$S_i = \frac{V_{\mathrm{W}}}{dz \cdot b \cdot d} \cdot \frac{1}{\phi}$$

where:

b: Width of the cell [mm]
d: Thickness of the gap [mm]
ϕ: Porosity [-]

Richards equation

- The Richards equation (1931) is the most widely-used mathematical description of infiltration.
- However, the Richards equation cannot predict the emergence of gravity fingering.



Numerical solution of the Richards equation in 1D describing infiltration into an initially dry soil

❖ Richards equation

$$\frac{\partial \theta_w}{\partial t} + \frac{\partial}{\partial z}\left[K_r(\theta_w)\frac{\mathrm{d}(\psi_w(\theta_w))}{\mathrm{d}z} + K_r(\theta_w)\right] = 0$$

$$K_r(\theta_w) = K k_{rw}(\theta_w)$$

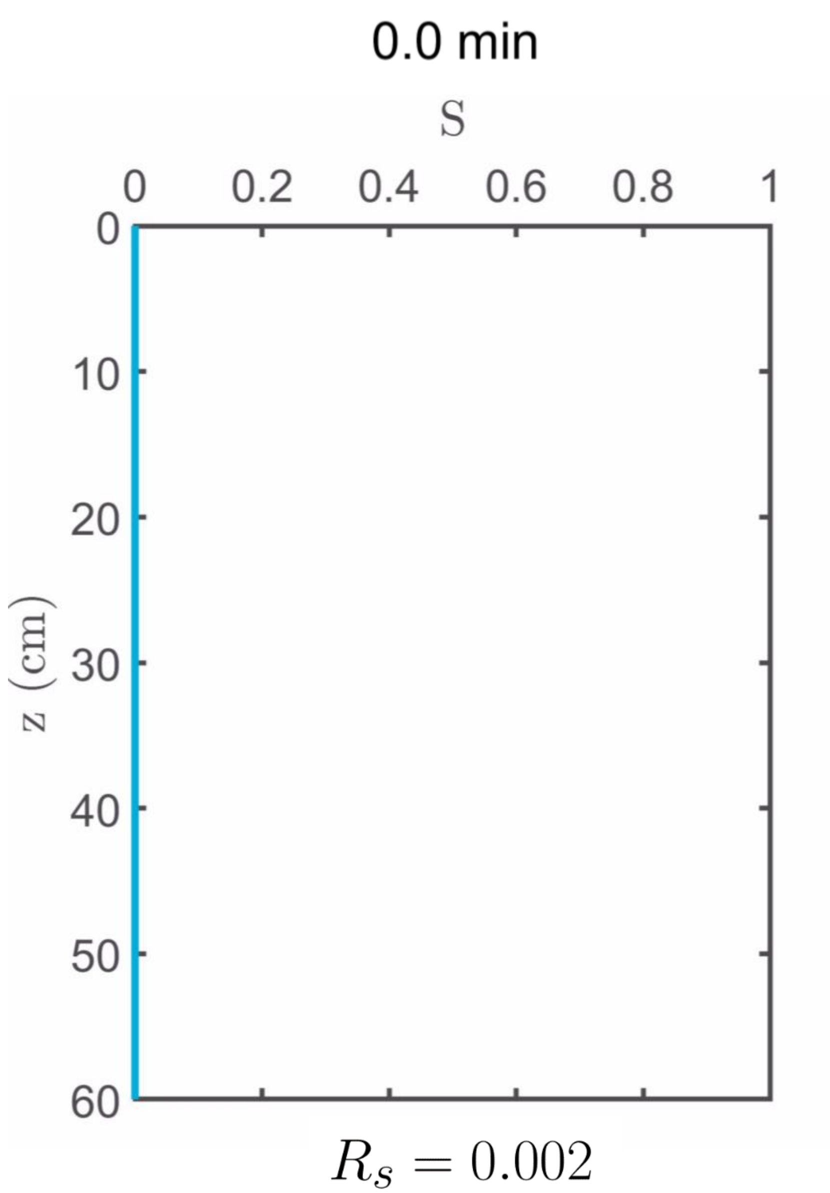
θ_w : soil moisture [-]

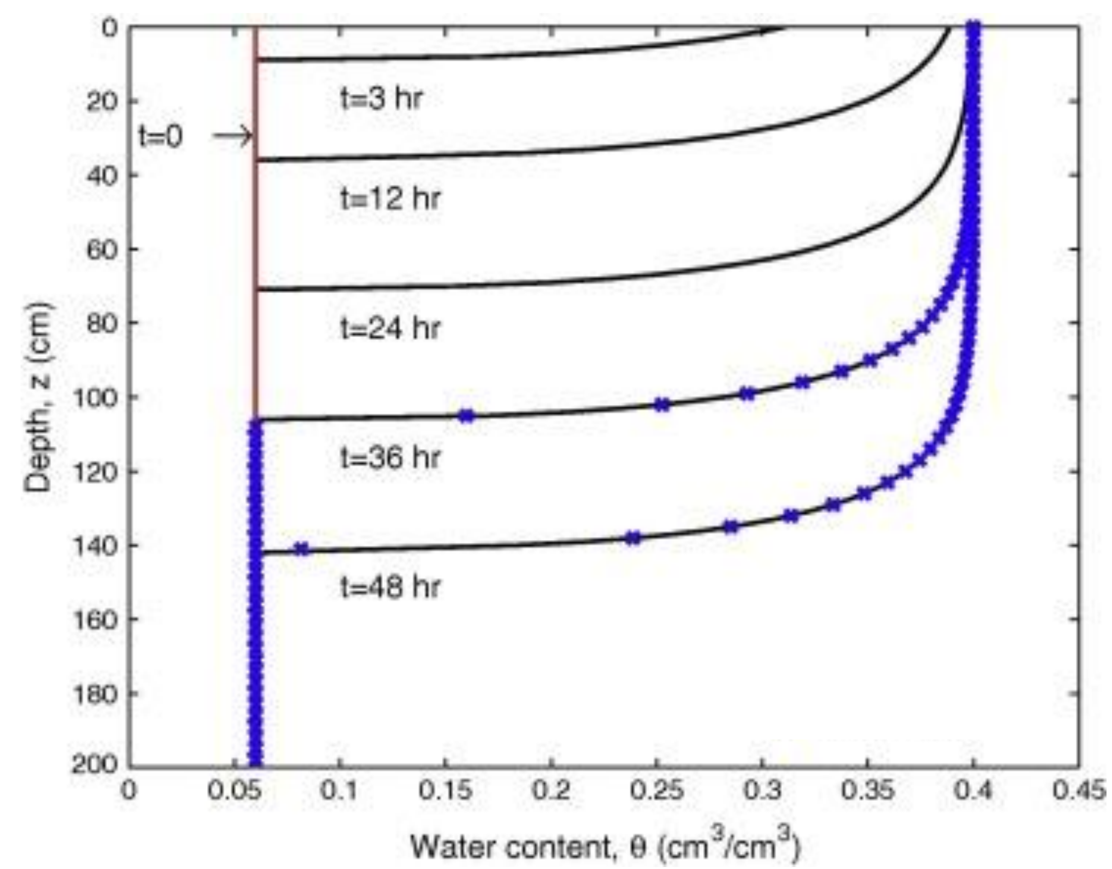
K_r : multiphase hydraulic conductivity [L/T]

k_{rw} : relative permeability [-]

A downscaling exercise (1D)

- We further downscale the saturation distribution to obtain the average saturation evolution as a function of depth as infiltration progresses.
- In contrast to predictions of the Richards equation, saturation at a given depth does not monotonically increase in time – there is clear desaturation behind the infiltration front.





Numerical solution of the Richards equation

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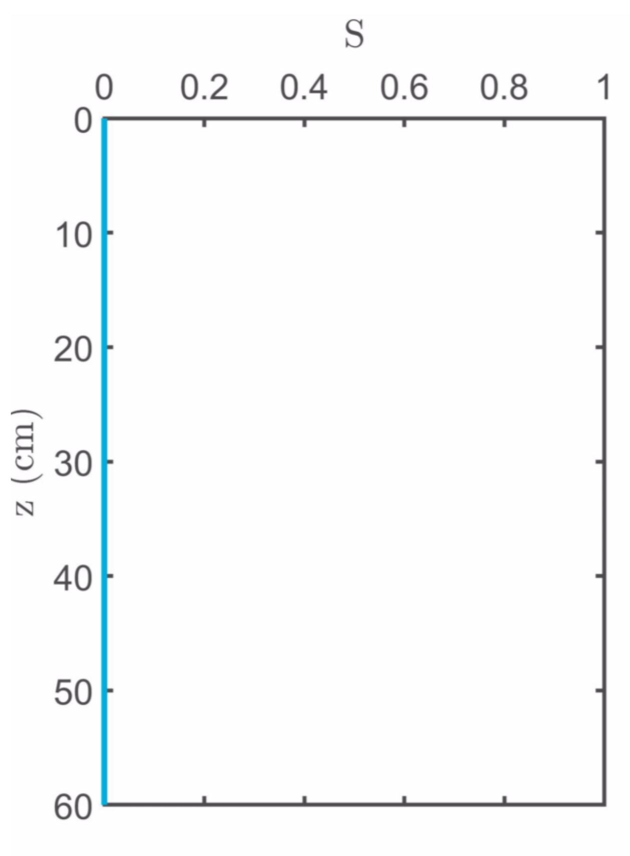
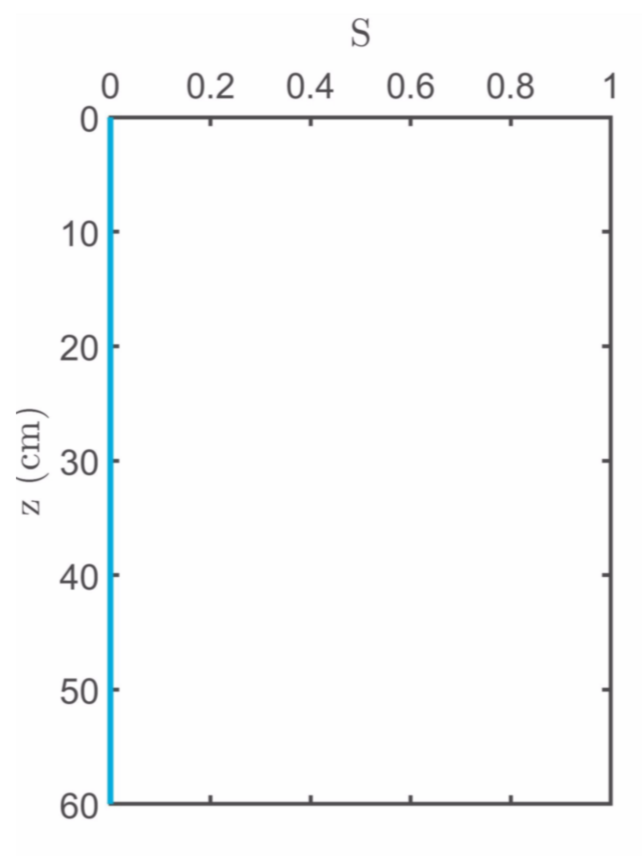
0.0 min



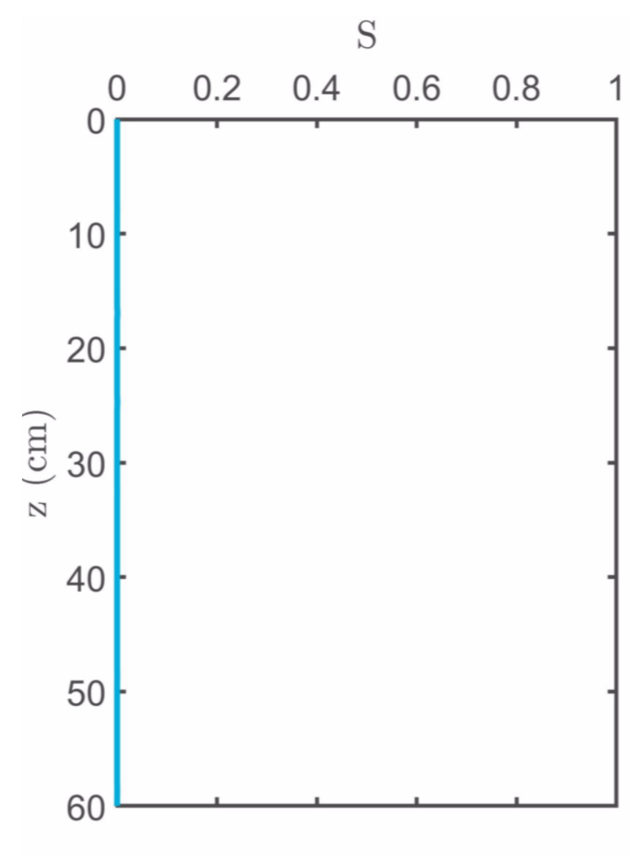
$R_s = 0.002$

0 s



$R_s = 0.046$

0.0 s



$R_s = 0.294$

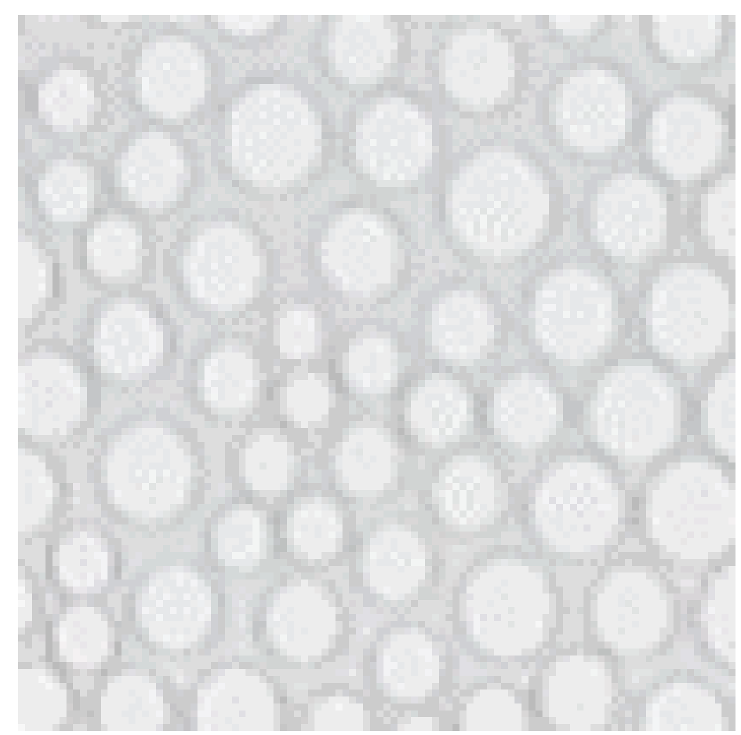
Pore-scale observations

- At **low infiltration rates**, de-wetting behind the infiltration front at the pore-scale contribute to saturation overshoot at the fingertip.
- A thin film is left coating the surface after de-wetting, which remain persistent.
- Subsequent water transport through the de-wetted region occur via packets of disconnected ganglia.
- At **high infiltration rates**, de-wetting is suppressed due to sufficiently high water flux.

0.0 min

$R_s = 0.002$

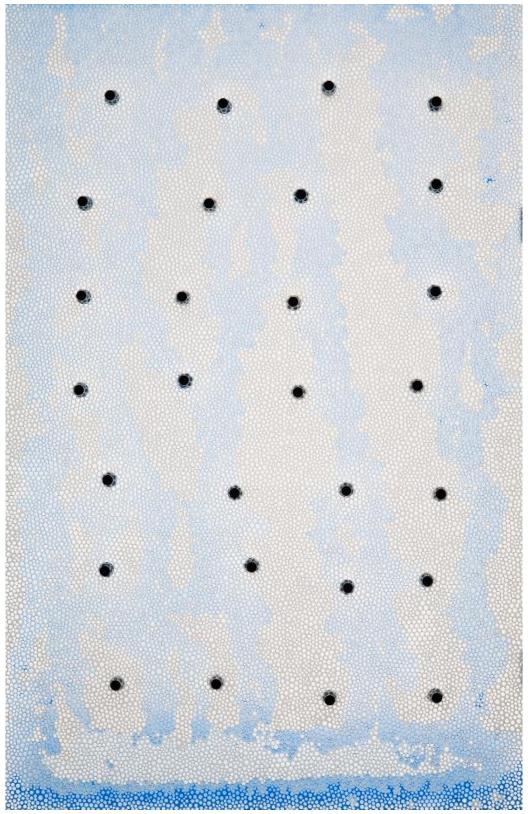
0.0 s



$R_s = 0.294$

Future work

- Perform further image analysis to extract pore-scale interfacial curvature, local capillary pressure, ganglia dynamics, etc. to obtain a better understanding of the pore-scale physics of gravity fingering.
- Investigate how our pore-scale analysis can inform macroscopic modeling of gravity fingering.
- Study evaporation and re-infiltration processes (experiments already performed).



Evaporation Test

Re-infiltration Test