Liquid redistribution behind a drainage front in porous media imaged by neutron radiography

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Introduction

- Drainage processes are **highly dynamic** where front velocity and pore geometries shape the front region and entrapped phases behind, affecting unsaturated transport properties
- **Different drainage mechanisms** occur from front to dryest region at the surface resulting from the dominance of either forces of inertia, gravity, capillarity and viscosity (Fig. 1)
- At the **frontal region** pores are rapidly invaded in piston-like manner due to pinning/depinning mechanisms of the interface at pore throats with significant inertial forces
- Behind the irregular frontal region a transition to **smooth liquid flow** limited by viscous forces is established at distance L_v (Fig. 1)
- To predict **transition** from fractal front displacement to steady capillary flow, the governing forces in 3 regions must be quantified

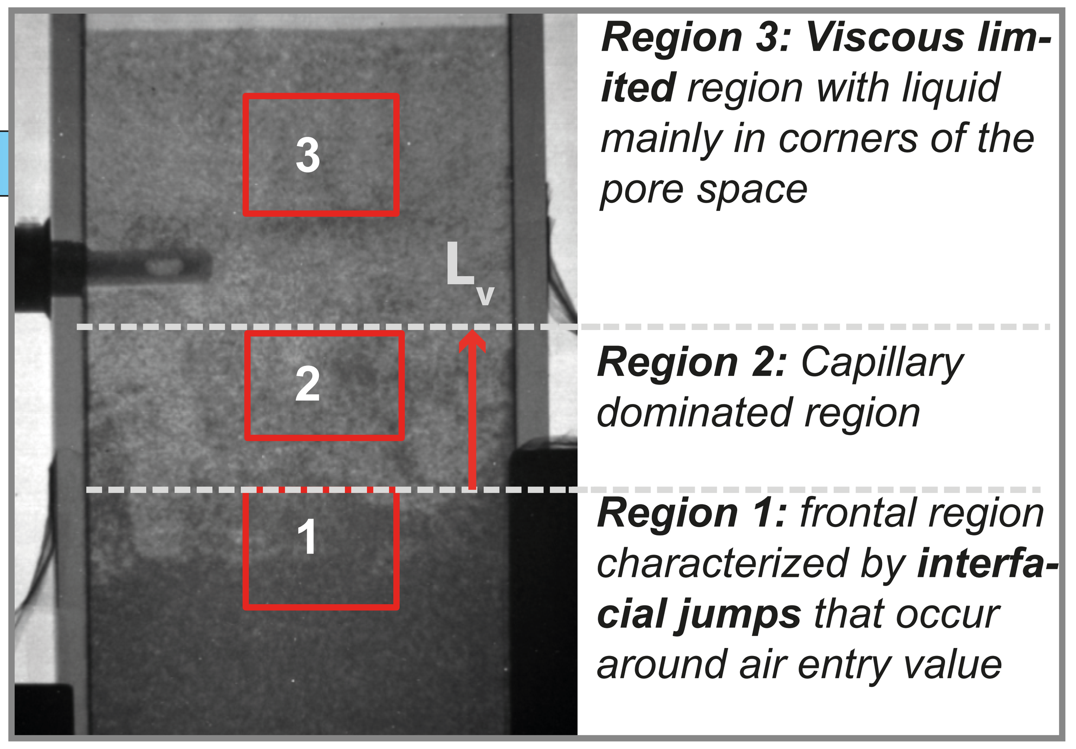

Fig. 1: Neutron image of drainage from sand filled Hele Shaw cell and conceptual diagram of three regions with different flow regimes and dominant forces.

Objectives

- To experimentally **characterize displacement regimes** – piston to corner flow
- To define boundary conditions and media properties affecting morphology and transitions among these flow regimes
- Outlook: to determine characteristic lengths and times for transitions based on soil water characteristics and dimensionless numbers

Experimental Setup

Pore scale experiments of drainage (Fig. 2)

Method: Fast X-ray 3-D imaging of drainage from saturated coarse sand (0.3-0.9 mm) at fixed suction

Sample size: 100 mm height, 5.4 mm diameter

Resolution: 5.5 µm in space, 3-D tomography of 4 mm section obtained in 0.6 s

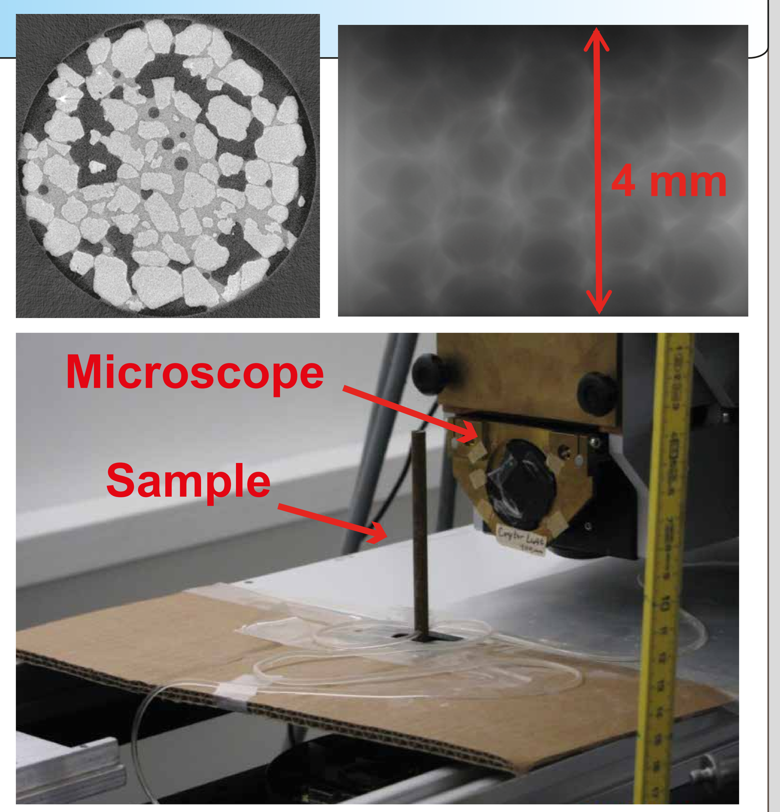

Fig. 2 (Right): Experimental Setup of fast X-ray imaging a) sample cross section showing different phases of air, liquid and solids. b) Original transmission image. c) Photo of the relative positions of sample and microscope. Attached tubes lead to outlet suction.

Column scale experiments of drainage (Fig. 3/4)

Method: Neutron radiography of drainage from saturated sands at fixed flow rate

Sample size: Hele-Shaw cell (260x76x10 mm^3)

Resolutions: Spatial resolution of 0.1 mm and images taken every 3 seconds

Pressure data: Pressures were measured at top and bottom of the column (Fig. 3)

Fig. 3: Experimental Setup during neutron imaging.

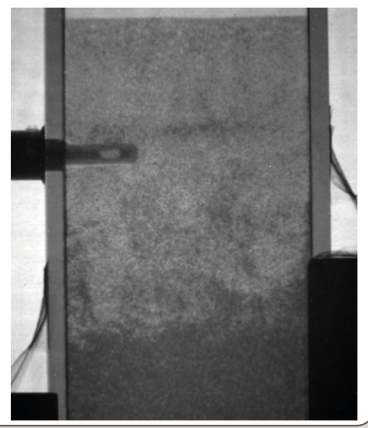

Fig. 4: Neutron image with wet region in dark and partially dry region in bright gray.

Results

1. Pore scale drainage observations of initial front invasion:

- X-ray images show configuration of liquid, air and solid grains at different scanning times (Fig. 5)
- Initially saturation drops rapidly with **invasion of largest pores** around the front ("pistons") (Fig. 6)

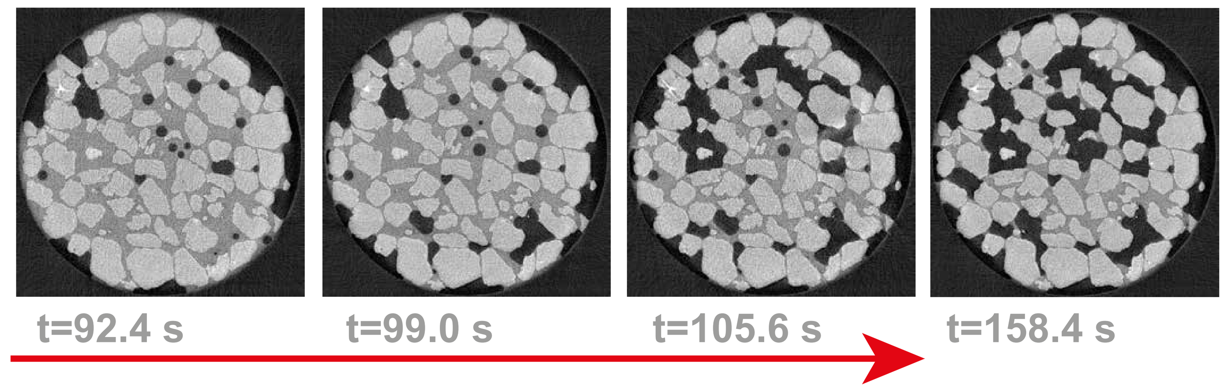

Fig. 5: Sample cross sections showing evolution of liquid (intermediate gray) and air (dark gray) phase as drainage proceeds.

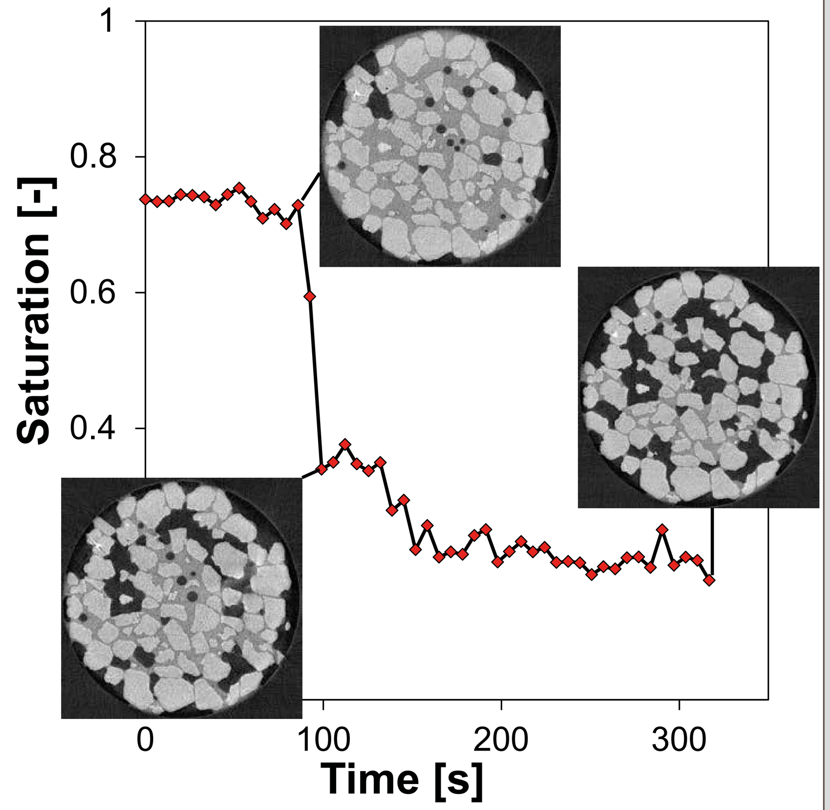

Fig. 6: Saturation versus time for sample cross section of X-ray tomographic scans. Insets show cross section with air (dark gray), liquid (intermediate gray) and solid (light gray). Rapid invasion of the frontal region as a sequence of piston-like pore invasions leads to a fast drop in saturation.

2. Column scale observations of liquid redistribution behind the front:

- With neutron imaging water content profile dynamics could be quantified (Fig. 7)
- Drainage from different media ranging from fine to coarse sand and different applied flow rates
- For coarse sand (0.3-0.9 mm) and fixed high outflow rate (13.2 mm/min) a **redistribution of liquid** from top to front occurred after drainage (Fig. 7/8)
- Pressure signals show viscous drop followed by **pressure relaxation** (in saturated zone) and convergence to hydrostatic equilibrium (Fig. 9)

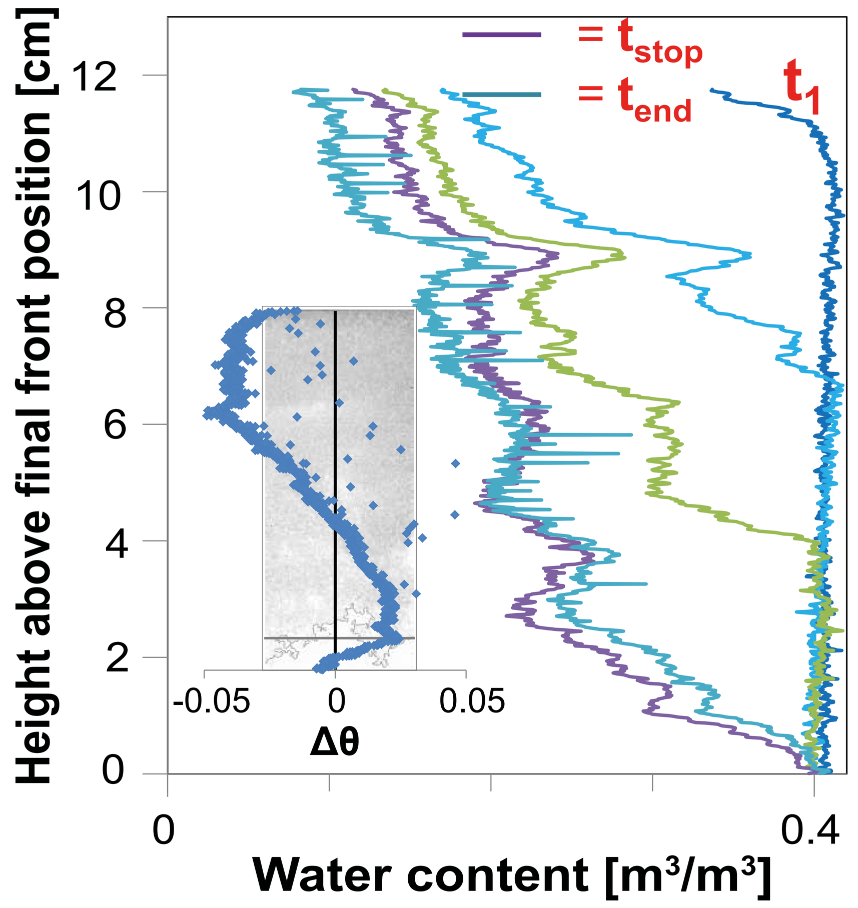

Fig. 7: Water content profiles at different times during fast drainage from coarse sand. At t_{stop} drainage stopped with front remaining at 11.3 cm depth. 10 minutes later at t_{end} the profile has changed revealing a redistribution of liquid from top to frontal region. The magnitude of water redistribution is shown in the inset.

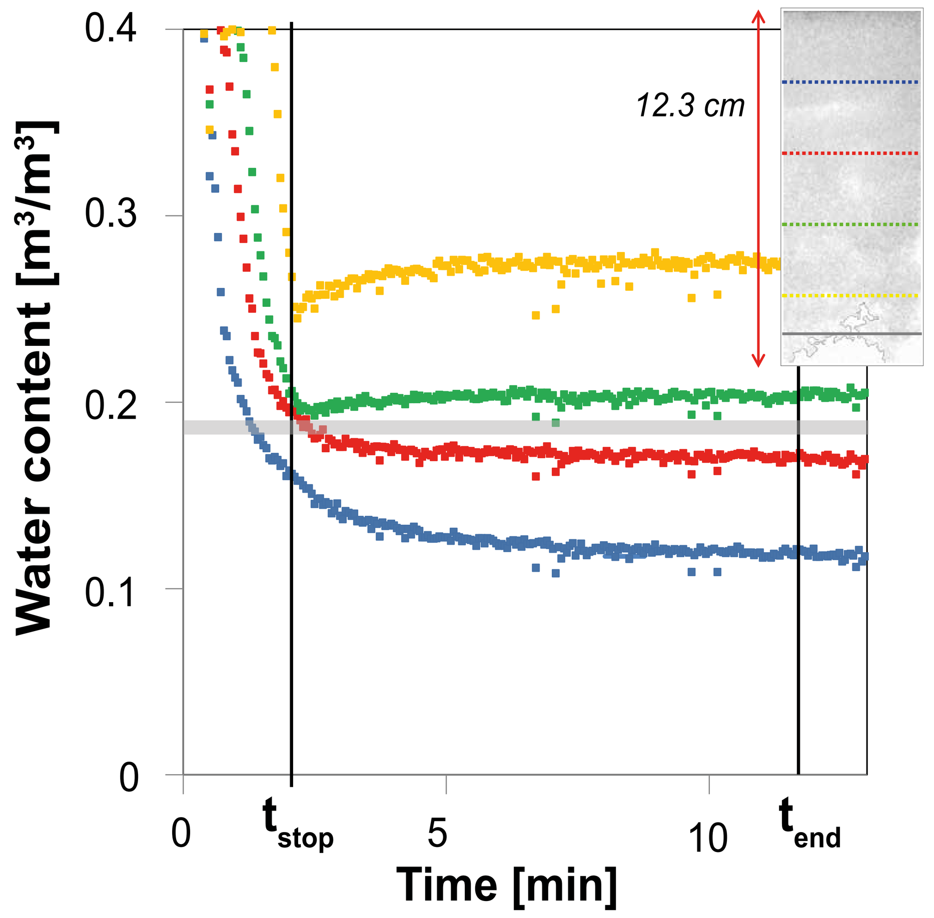

Fig. 8: Water content versus time at four depths (indicated by inset). Between t_{stop} and t_{end} water content increases close to the front (yellow and green) and decreases close to column surface (red and blue). A transition towards viscous limited region 3 is thus assumed to occur between the green and red position at water content value indicated by gray area.

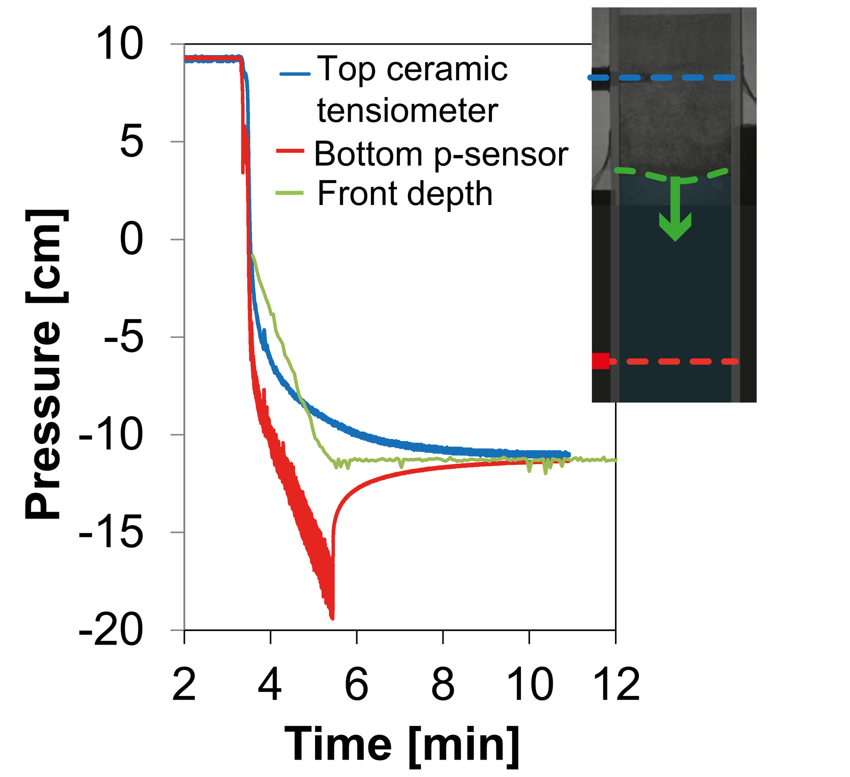

Fig. 9 : Pressure signal in partially dry (blue) and saturated (red) region during fast drainage from coarse sand (inset shows relative positions in 26 cm high column). Pressure signals are shifted to match air entry value of 9 cm. Front position is indicated by the green line. As soon as drainage is stopped the pressures relax back to hydrostatic value.

Conclusions and further outline

- Experimental data from X-ray tomography show rapid **piston-like pore invasions around front**
- Column scale drainage experiments show emergence of different regions and **delayed redistribution** (corner flow) towards the main drainage front
- The separation of rapid piston displacement and formation of a redistribution zone marks the **influence of viscous limited corner flow** and separation of time scales for the drainage process
- Boundary conditions affect displacement regimes reflecting competition between rapid piston displacement to meet withdrawal rates (at non equilibrium) and subsequent corner flow towards equilibrium
- Characteristic times and lengths of transition between regions will be determined in future based on soil water characteristics (first tests promising) and dimensionless numbers (Bo, Ca)

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