Flow Transition during Buoyancy-Driven Gas Migration: Experiments and Theory

Helmut Geistlinger, Detlef Lazik and Shirin Samani

Department of Soil Physics, UFZ

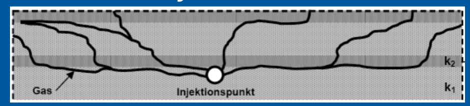
Geometry and Stability of Channelized Gas Flow at different Scales

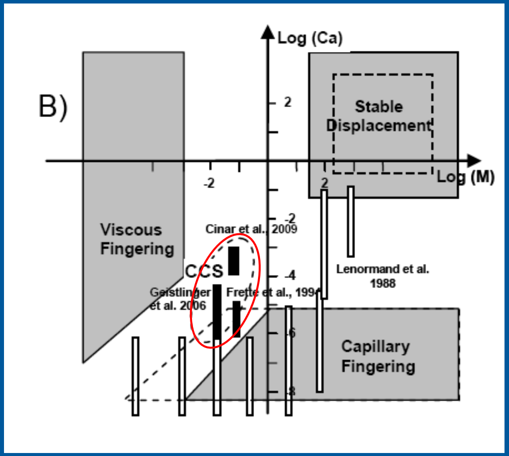
HELMHOLTZ
CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Department of Soil Physics

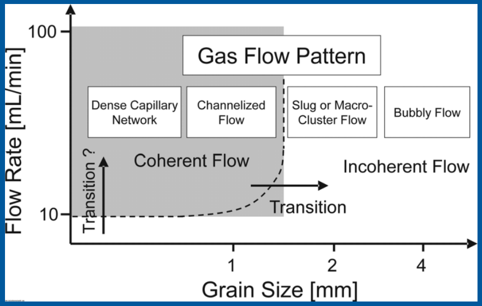
Motivation “Transition between coherent and incoherent flow”

- Remediation: air sparging, SWI (CO_2-H_2O)
- CCS-technology (CO_2-H_2O)
- Bubble dynamics within the capillary fringe (DYCAP)

Reality on field scale:



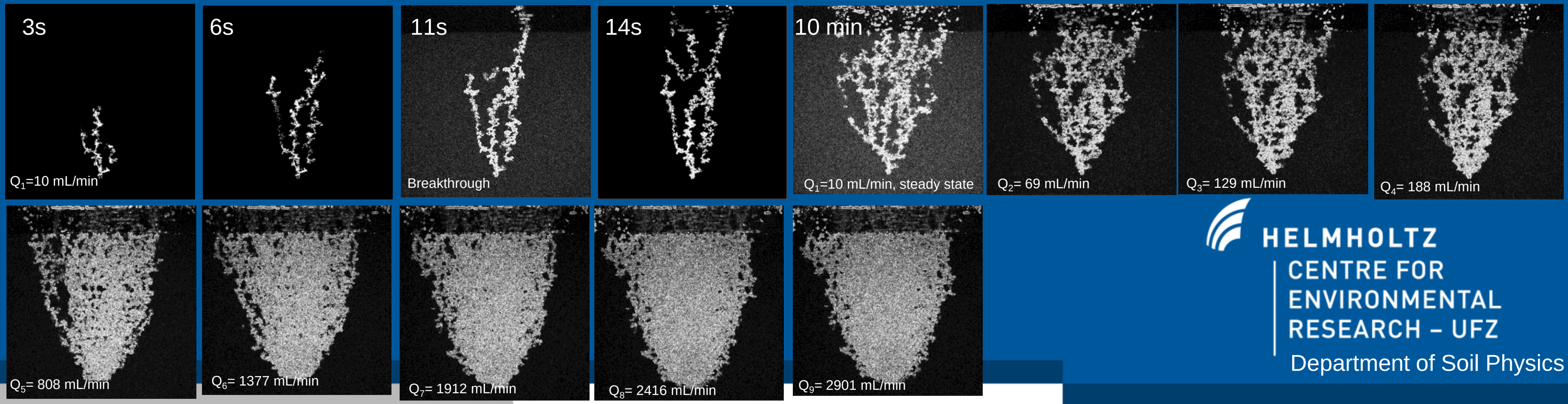




Outline

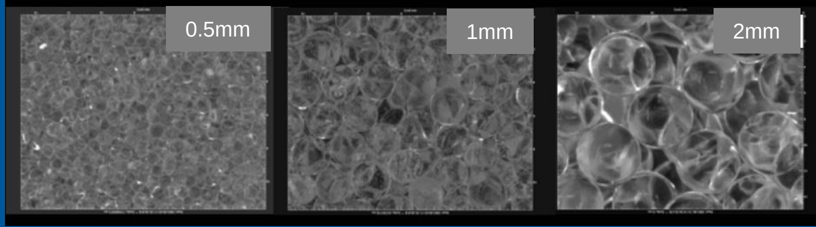
1. Transition from coherent to incohernt flow
2. Geometry and stability of gas channels/fingers
3. Can continnum models describe the channelized flow?

Gas flow pattern within 1mm-glass beads

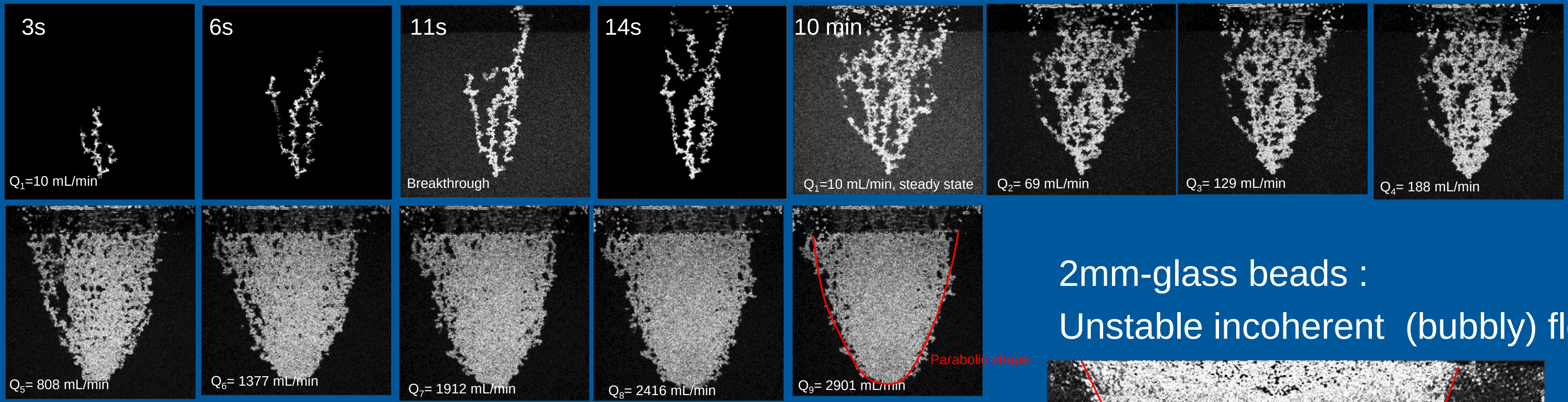


HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Department of Soil Physics

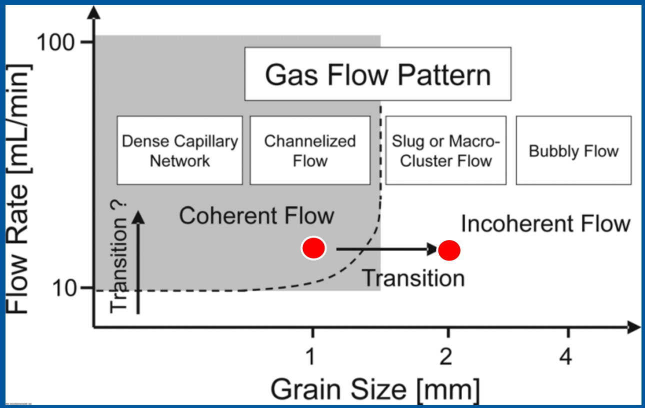
Transition between two different flow regimes

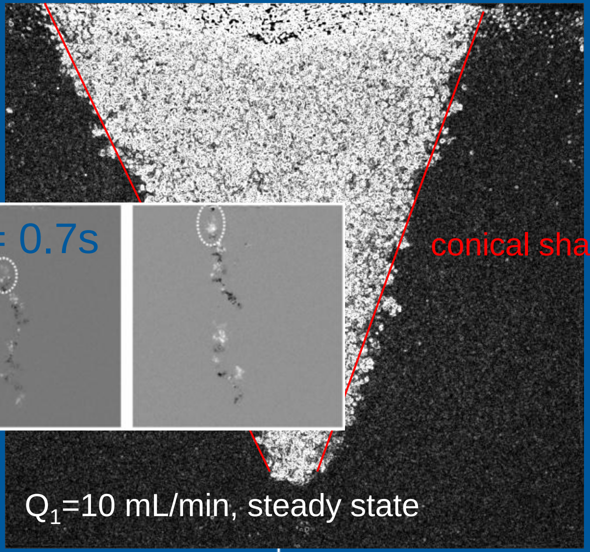


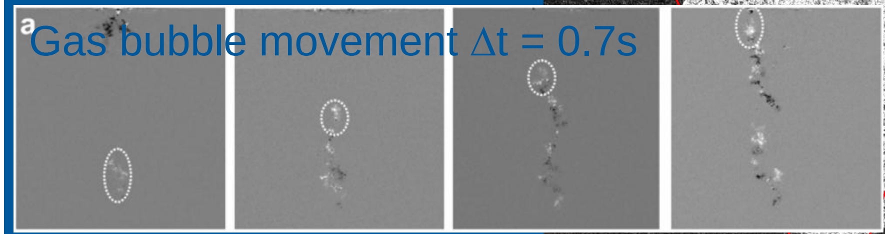
1mm-glass beads : Stable coherent (channelized) flow



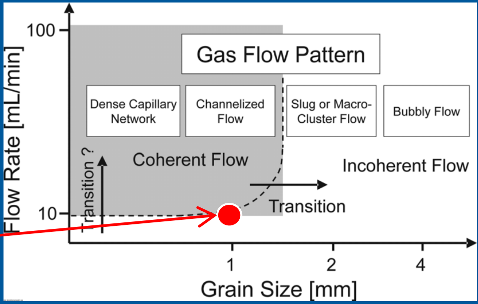
2mm-glass beads : Unstable incoherent (bubbly) flow

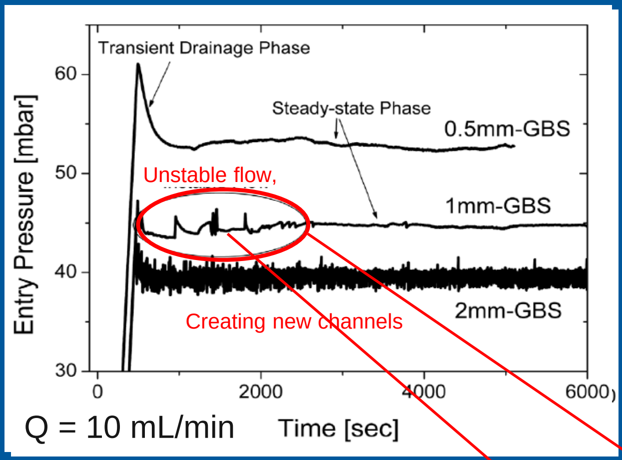






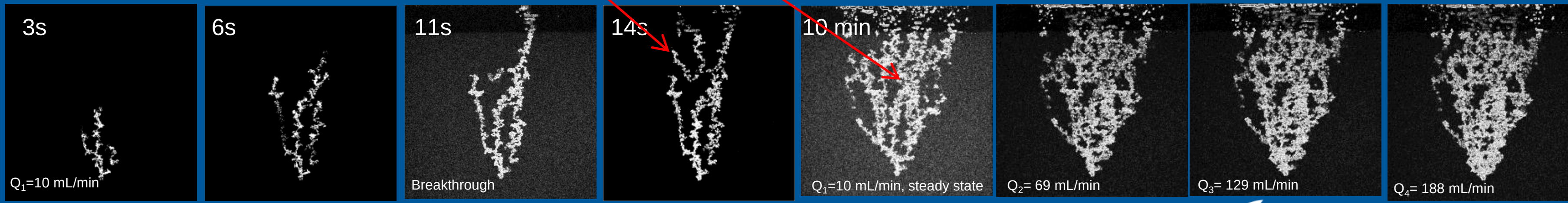
- 0.5mm-GBS: stable coherent flow
- 2mm-GBS: unstable incoherent flow
- Interesting case: 1mm-GBS at neutral curve

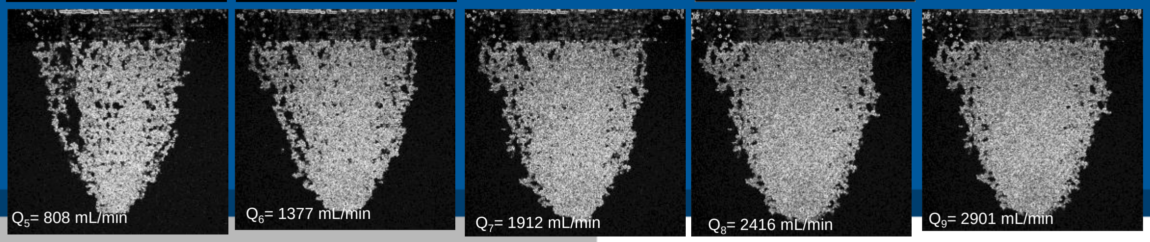




Is there any explantation at pore scale?

Gas flow pattern within 1mm-glass beads



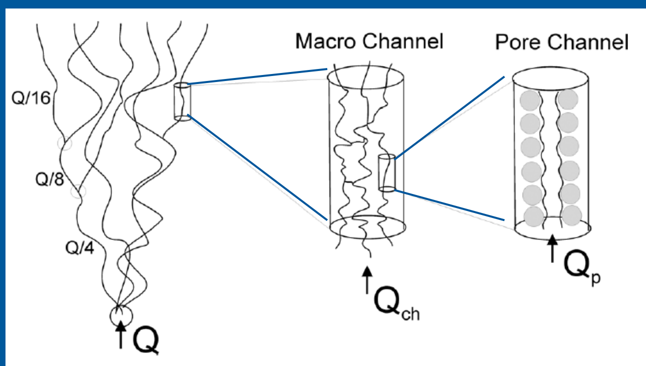


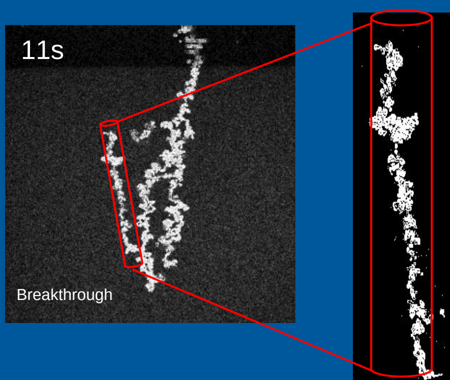
HELMHOLTZ
CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Department of Soil Physics

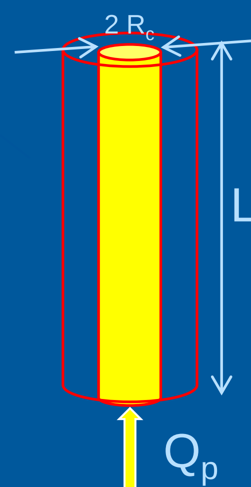
Competition between Capillary and Viscous Forces at Pore scale

Conceptual model (1): Cylindrical flat gas-water interface with radius R_c

Bench scale → Pore scale







Free energy =
excess surface free energy + internal viscous energy

$$F = \sigma \cdot (2\pi R_c L) + 8\mu_g Q_p L^2 / R_c^2$$

$$F \rightarrow Min: \ \delta F = 0$$

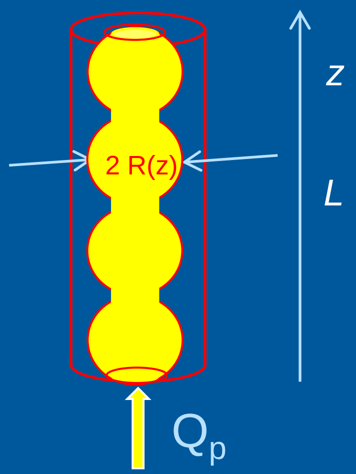
$$R_c = 2 \cdot \sqrt[3]{\frac{Q_p \cdot L \cdot \mu_g}{\pi \cdot \sigma}}$$

Note scale dependence: $R_c \sim L^{1/3}$

HELMHOLTZ
CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Department of Soil Physics

Competition between Capillary and Viscous Forces at Pore scale

Conceptual model (2): Undulating gas-water interface *R(z)*



Free energy functional:

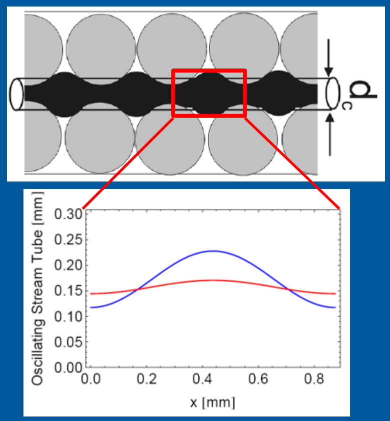
$$F(\beta) = \int_0^{L_z} dz \left(2\pi\sigma R(z,\beta) + \frac{8\mu_g Q z}{(R(z,\beta))^2} \right)$$

Variational treatment: $F \rightarrow Min: \delta F = 0$

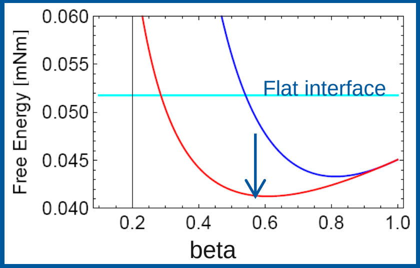
Two different variational functions for the gas-water interface:

Pore-Neck-function: $$R_1(z,\beta) = \beta \frac{d_k}{4} \left\{ (\xi_{\max} + \xi_{\min}) - (\xi_{\max} - \xi_{\min}) \cos\left(\frac{2\pi z}{\lambda}\right) \right\}$$

Pore-function: $$R_2(z,\beta) = \frac{d_k}{4} \left\{ (\beta\xi_{\max} + \xi_{\min}) - (\beta\xi_{\max} - \xi_{\min}) \cos\left(\frac{2\pi z}{\lambda}\right) \right\}$$



Finding the *Free energy* minimum
→ geometric shape of the gas-water interface
at different *length scales L* and
for different *flow rates Q*

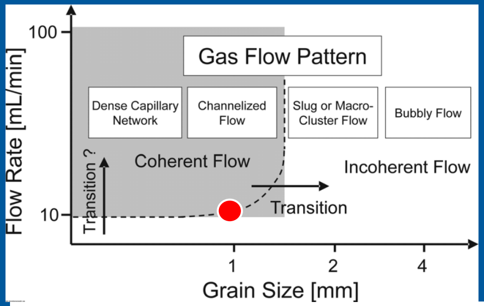


HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ
Department of Soil Physics

Destabilizing gravitational forces versus *stabilizing* viscous forces

Buoyancy forces are taken into account by the stability or coherence condition: For a stable vertical (pore) gas channel the gas pressure gradient is given by the hydrostatic gradient $\rho_w g$.

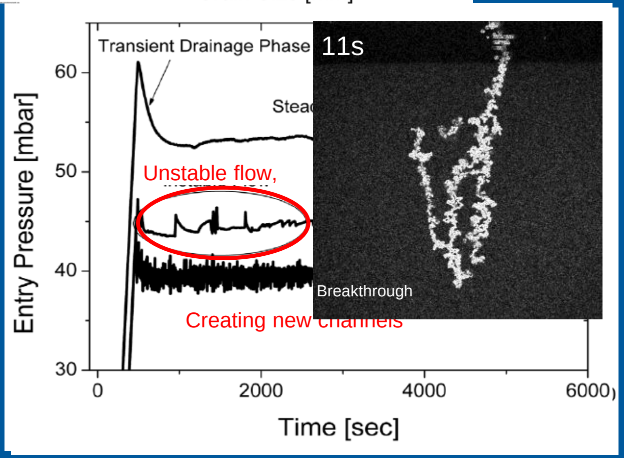
$$Q_{crit} = \frac{\pi \rho_w g}{8 \mu_g} R_c^4$$



Is there any explanation at pore scale?

(1) Thermodynamical treatment → geometrical shape of the undulating pore channel taking into account capillary and viscous forces

(2) Calculating the critical flow rate for the neck region (snap-off) yields for the *1mm-GBS* the 5 mL/min
→ i.e. after splitting the flow channel into two flow channels the flow becomes unstable!



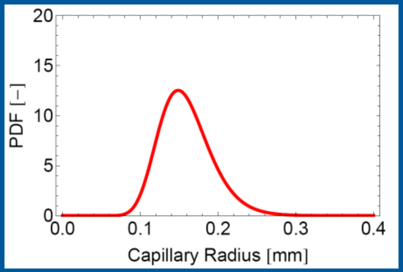
Note there is a *length scale-dependent transition* of the flow regime:

$$Q_{crit} \sim L^{4/3}$$

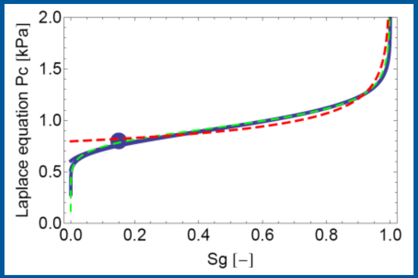
HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

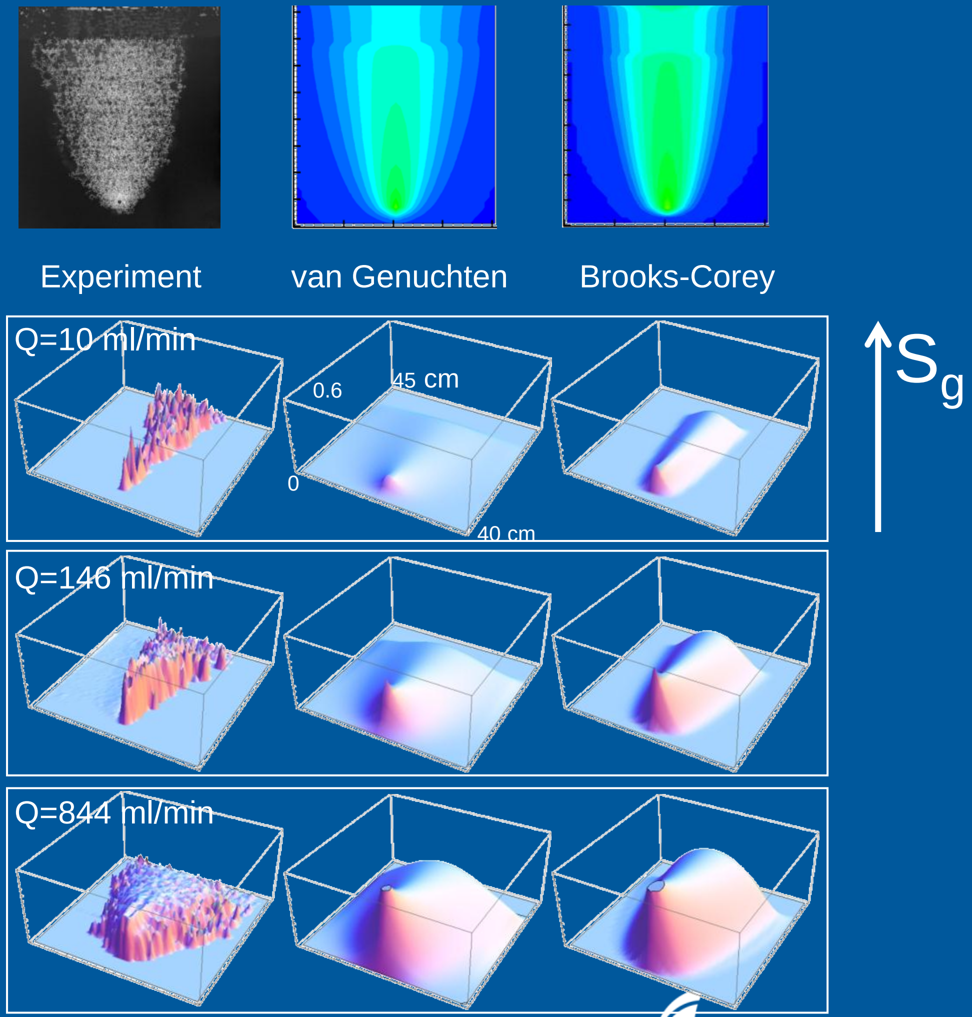
Modeling of channelized flow at REV-scale (1)

Pore size distribution



Capillary pressure



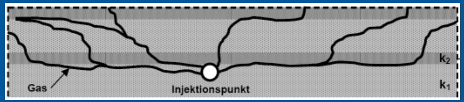


HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ
Department of Soil Physics

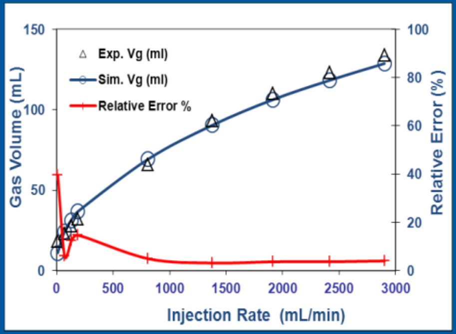
Modeling of channelized flow at REV-scale (2)

→ Excellent agreement for flow rates, where a dense capillary network is established
→ No fitting of additional parameters!

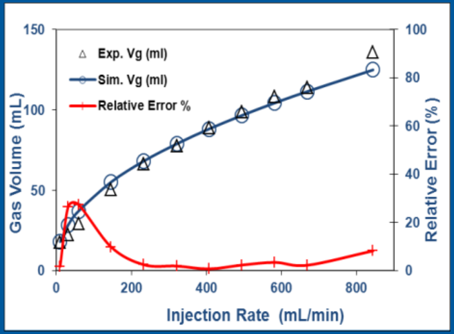
Reality on field scale:



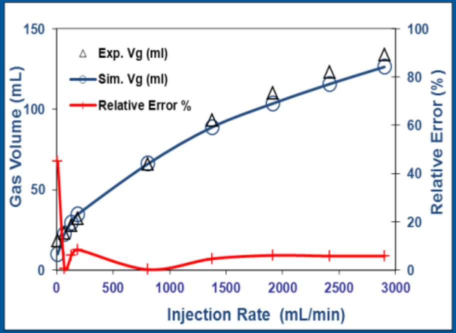
1mm-GBS-van Genuchten



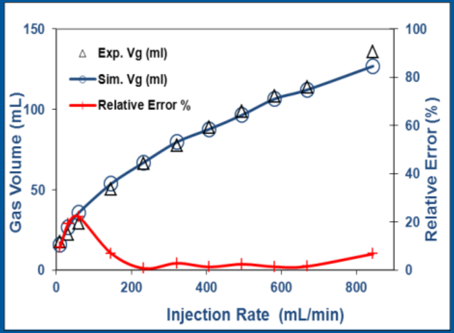
0.5mm-GBS-van Genuchten



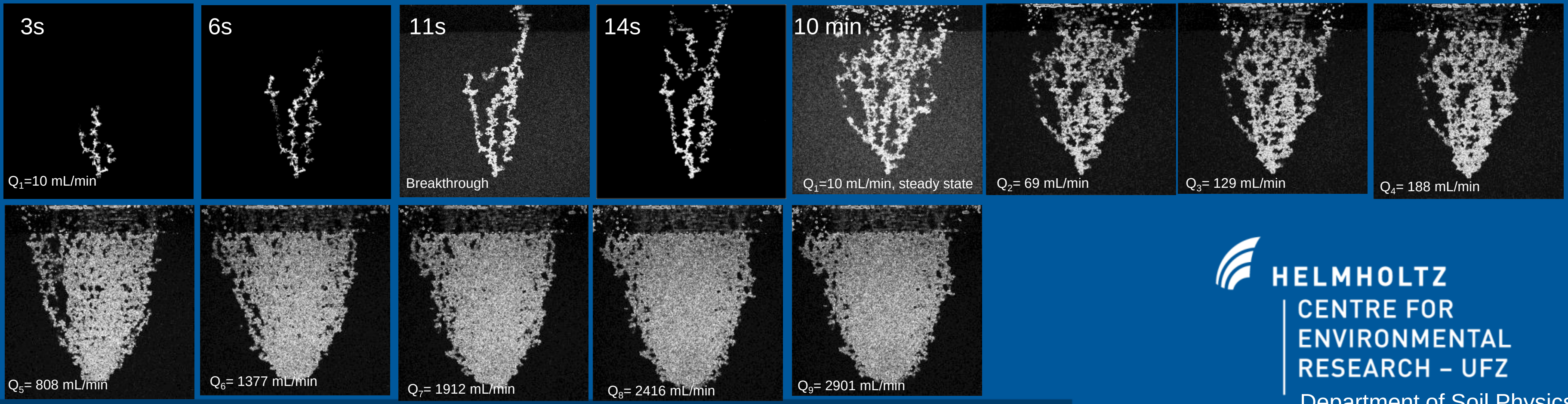
1mm-GBS-Brooks Corey



0.5mm-GBS-Brooks Corey



Gas flow pattern within 1mm-glass beads

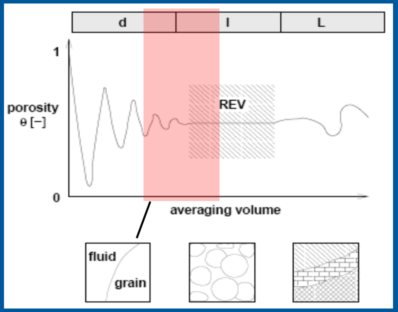


HELMHOLTZ
CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Department of Soil Physics

Modeling of channelized flow at Sub-scale

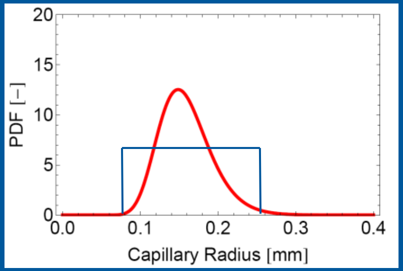
Stauffer, F., Xiang-Zhao Kong, and W. Kinzelbach (2009) Advances in Water Resources 32 (2009) 1180–1186

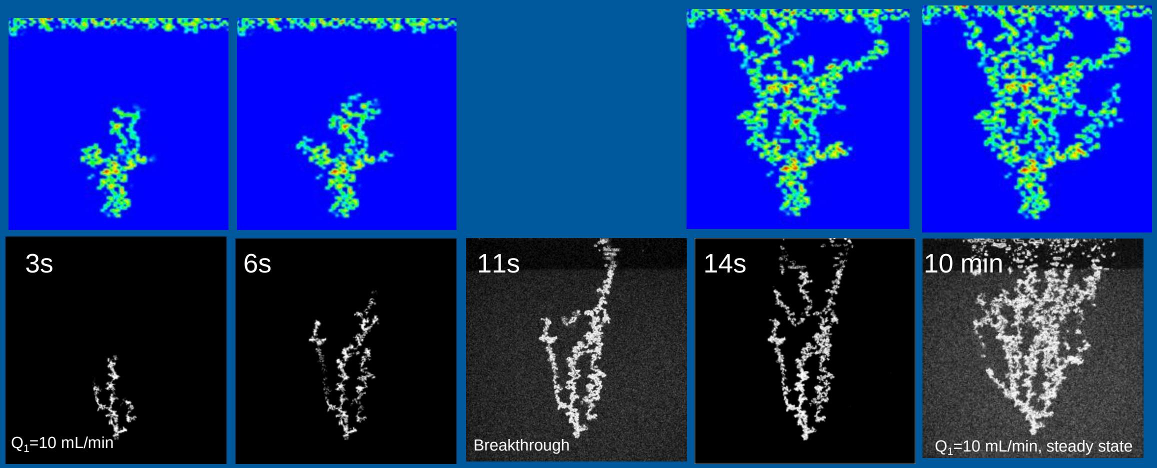
- TOUGH2-program
- uniform distribution
- Leverett-scaling
- Cell size = 5 mm



Pore scale REV-scale Field scale

Pore size distribution



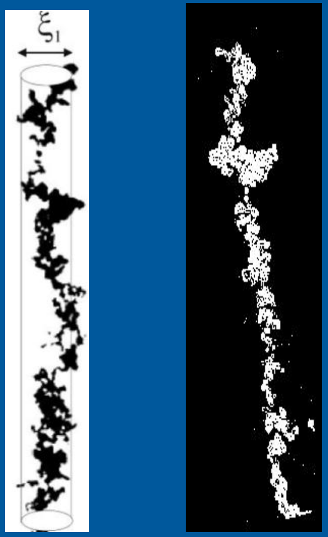


Gas flow pattern within 1mm-glass beads

HELMHOLTZ
CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Department of Soil Physics

Conclusions

$\xi_{Bo} \sim (Bo)^{-0.47}$

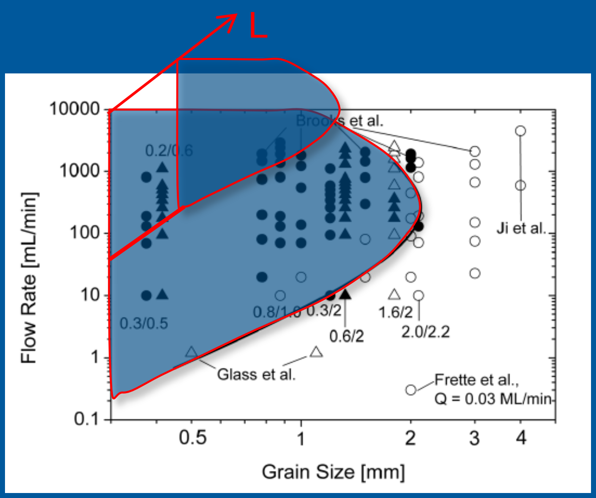


→ Be cautious with geometric similarity, since *Invasion percolation* neglects viscous forces

→ Apply continuum models (generalized Darcy equation), if *stability* and *coherence condition* is satisfied !

→ Upscaling can lead to a *scale-dependent transition* of the flow regime, i.e. to a transition from stable coherent to unstable incoherent flow !

→ The experimental flow chart needs a third dimension: The Length scale L



HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ
Department of Soil Physics