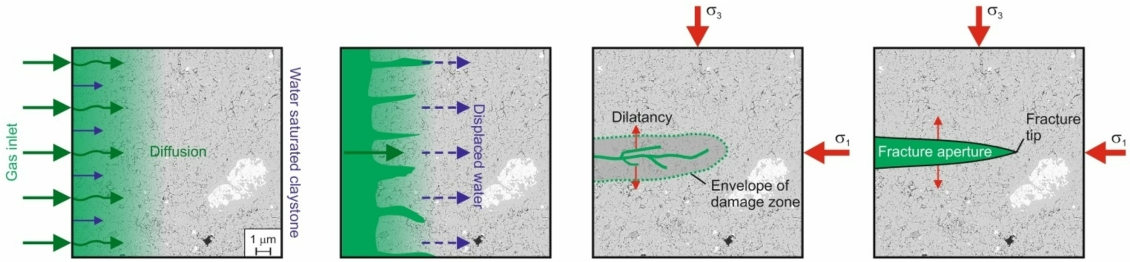
SAND2022-4930C

Sandia National Laboratories

DECOVALEX 2023 TASK B - MAGIC: How to move fluids through deformable low-permeability media

DECOVALEX2023 WORKSHOP, APRIL 2022



Advection and diffusion of dissolved gas

Visco-capillary flow of gas and water phase ("two-phase flow")

Dilatancy controlled gas flow ("pathway dilation")

Gas transport in tensile fractures ("hydro-/gasfrac")

PRESENTED BY

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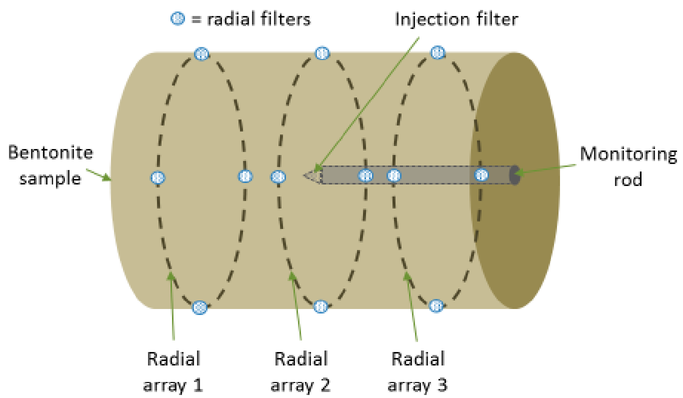
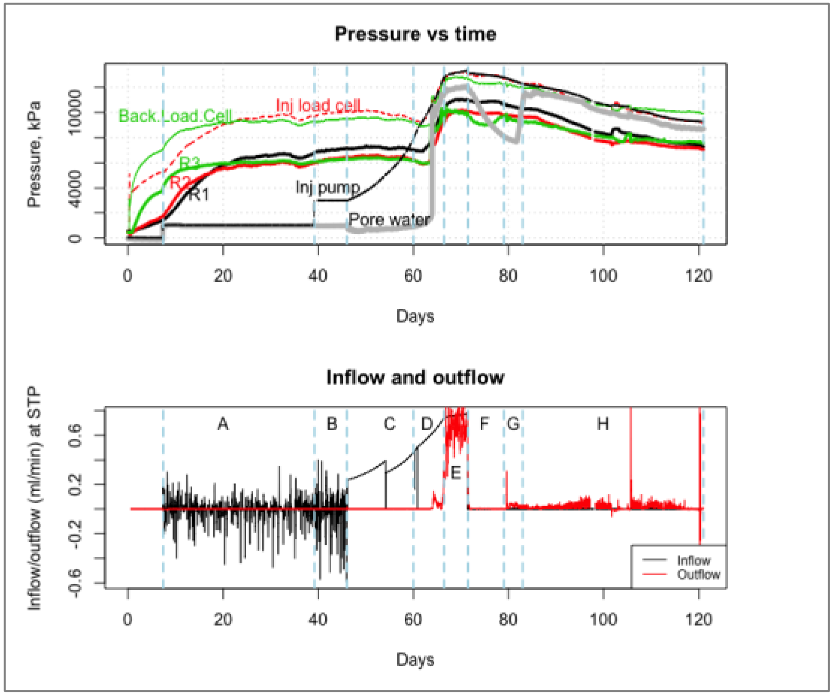
U.S. DEPARTMENT OF ENERGY NNSA

Time series analyses

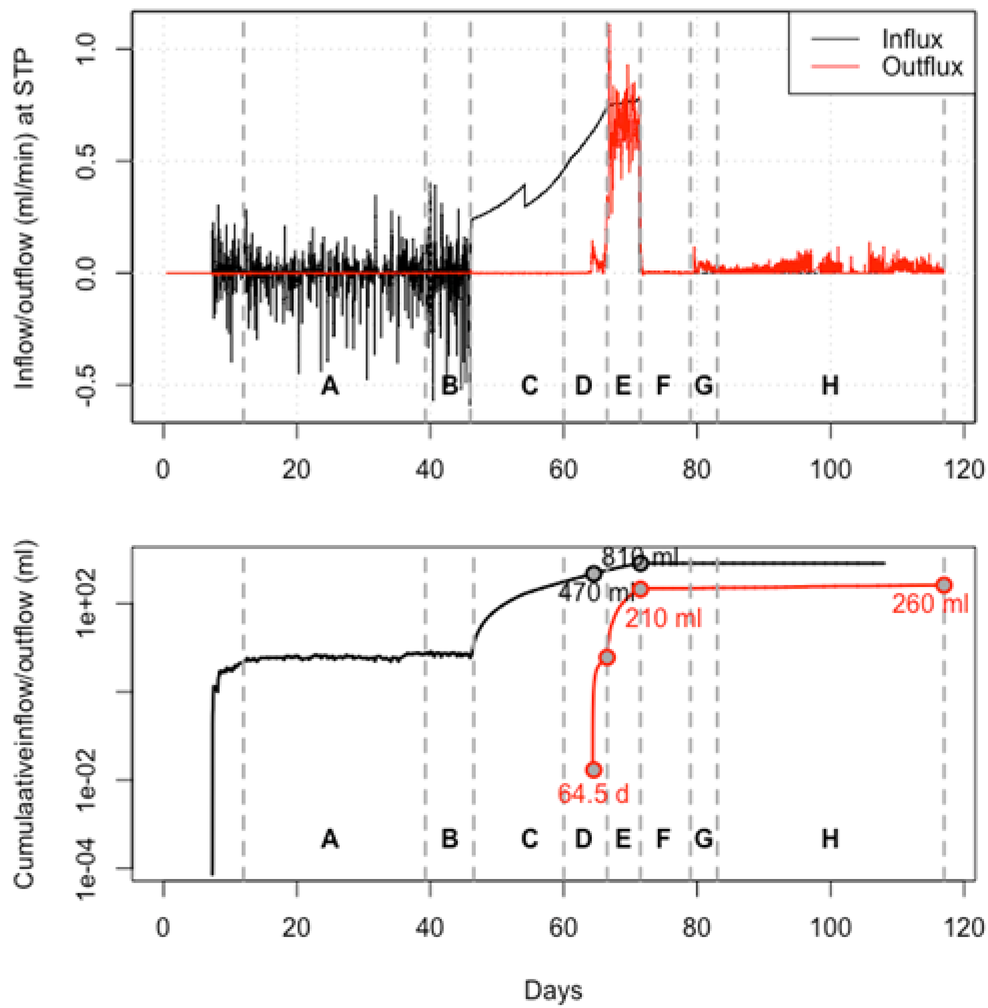
Segmentation of inflow and outflow time series based on time variation of the injection pressure





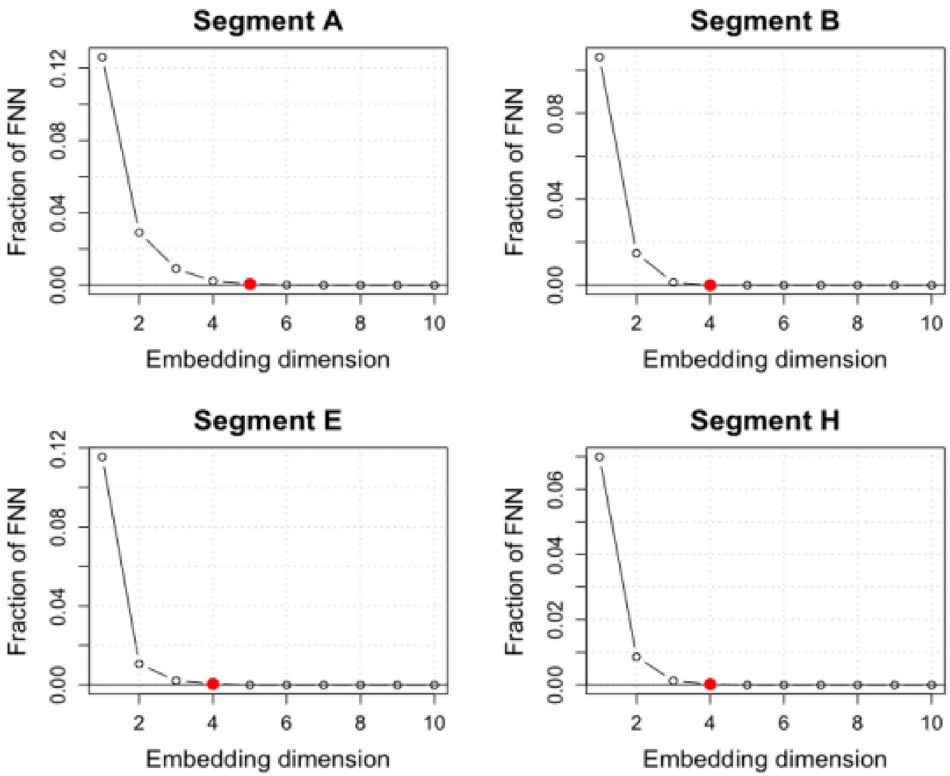
Segments A and B for the inflow, and Segments E and H for outflow were selected for further time series analysis

Limited gas saturation degree



Global embedding dimension

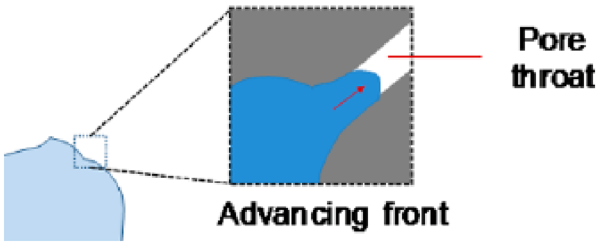
Evaluation of the Global Embedding Dimension (GED=4-5) indicates phenomena of low-dimensional chaos with both deterministic and small stochastic components



Global Embedding Dimension was calculated using the False Nearest Neighbors Method (Faybishenko et al., 2022).

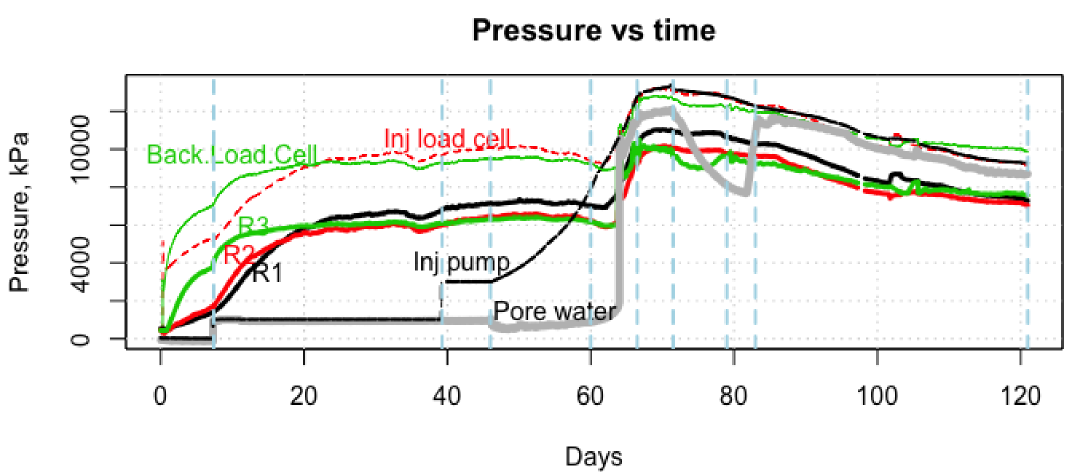
Capillary pressure

$$P_c = \frac{2\sigma\cos(\theta)}{r}$$

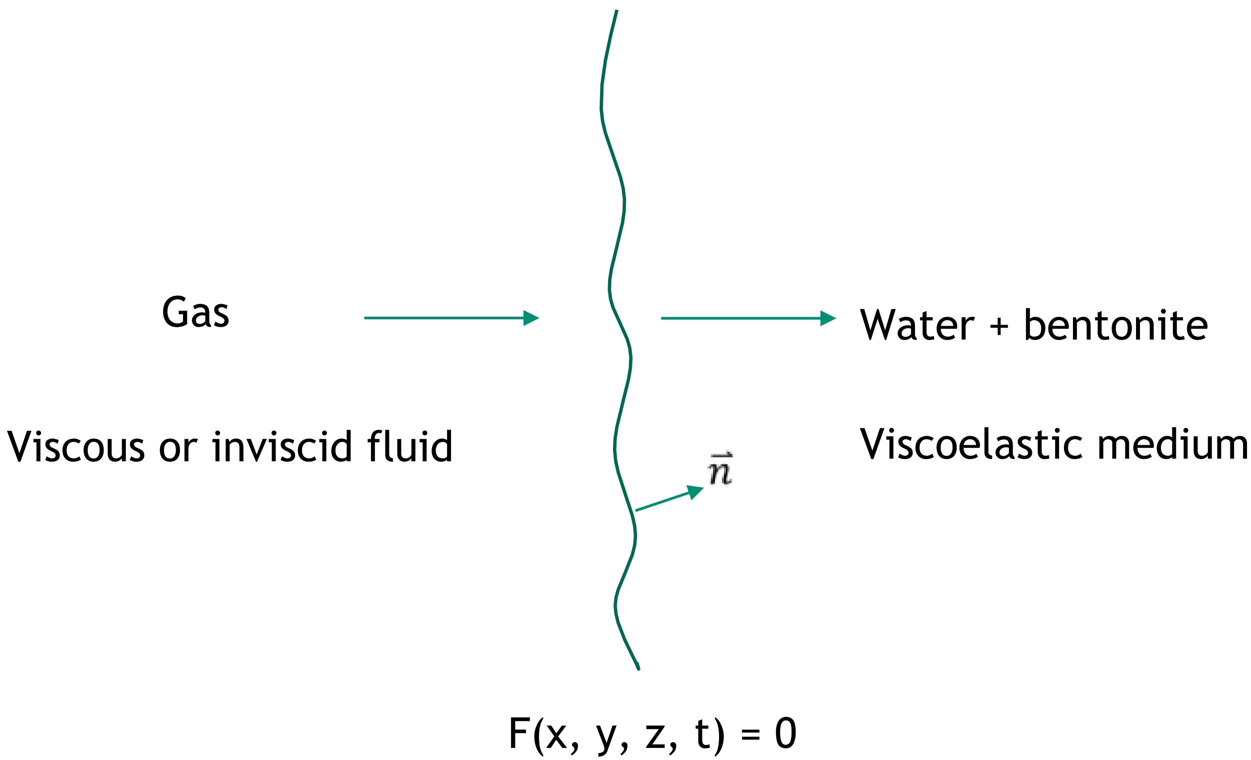


Given the typical values:
σ = ~70 mN/m
θ = ~40°
r = 1 - 10 nm (radius of pore necks)

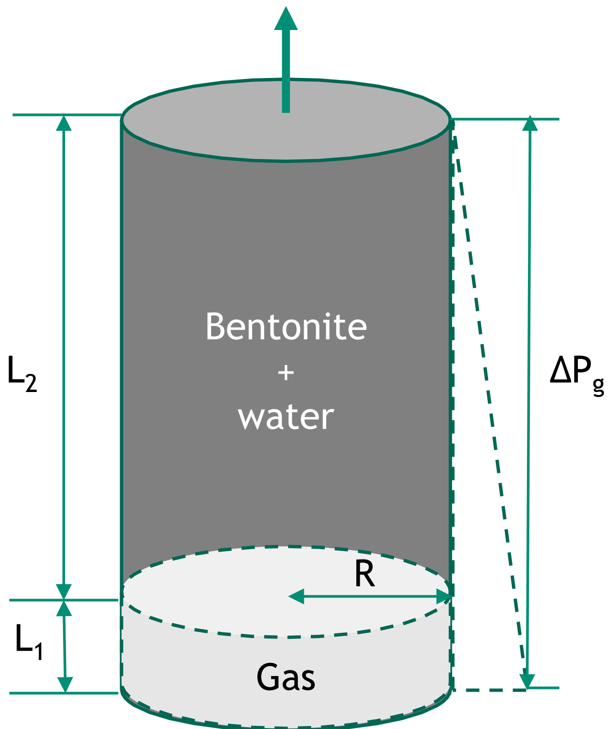
P_c is estimated to ~10 - 100 MPa, which is significantly higher than a gas pressure generally used in an experiment.

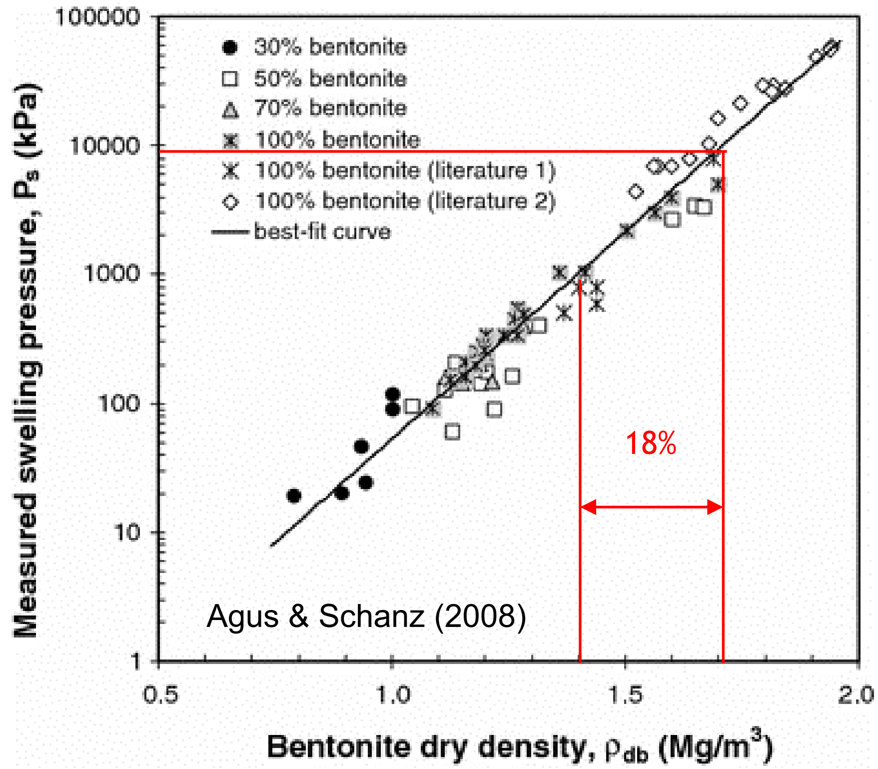


Immiscible fluid displacement



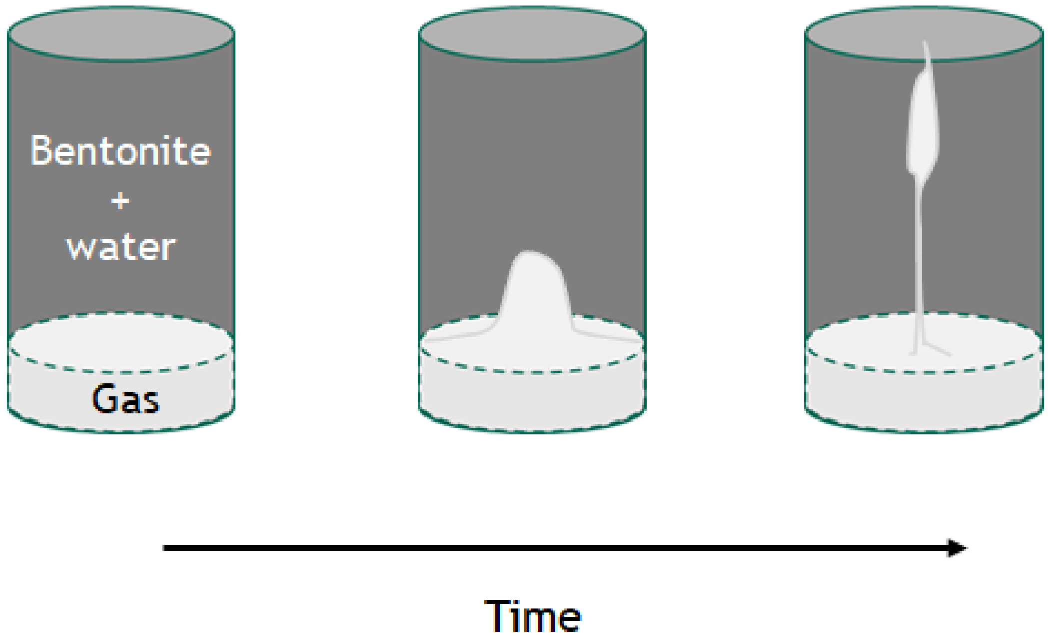
Limited gas saturation degree

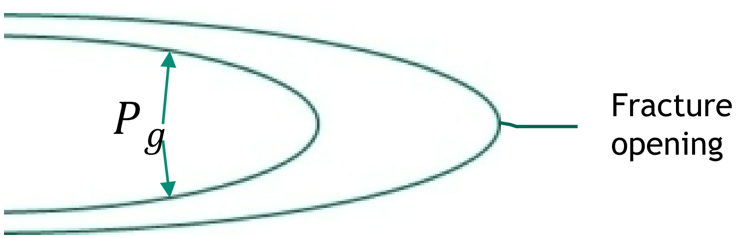




If gas migrates through channeling, the gas saturation degree would be about $L_1/(L_1+L_2)$, which is relatively small and determined by the swelling pressure curve.

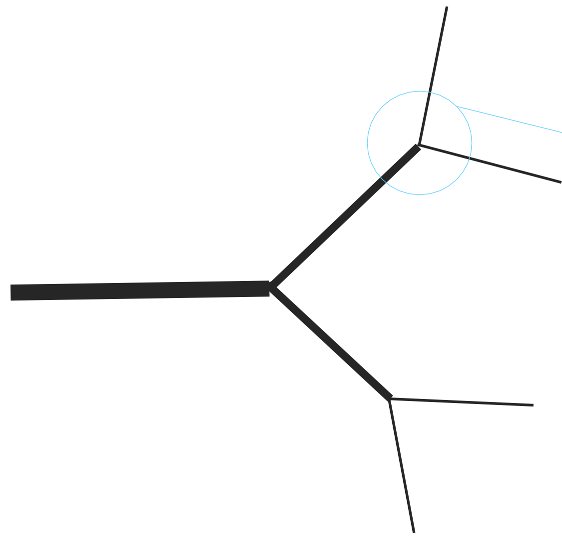
Channeling, fracturing and interface instability

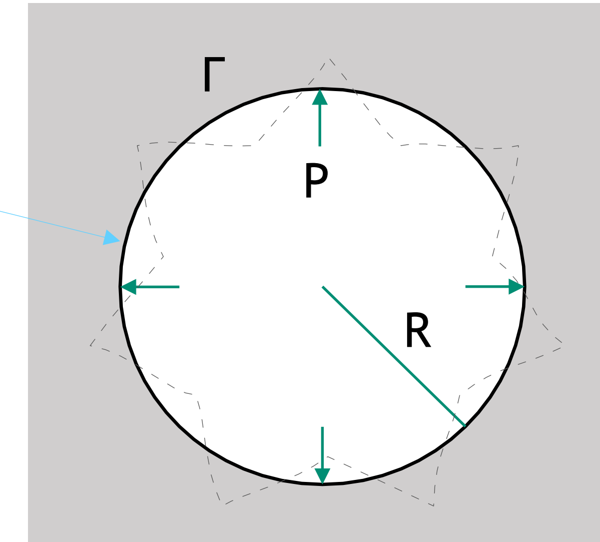




Buoyancy flow??

Fracture opening as a moving boundary problem





$$\boldsymbol{\nabla} \cdot \boldsymbol{\nabla u} + (1 - 2\mathrm{v}) + \boldsymbol{\nabla}^2 \boldsymbol{u} = 0$$

$$\frac{d\Gamma}{dt} = k(\sigma_t - \sigma_c)$$

Cohesion

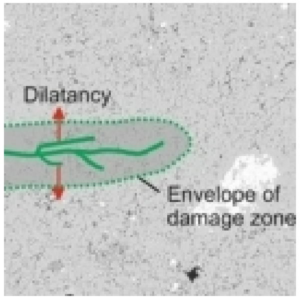
$$\sigma_n = -P$$

(Herrmann et al., 1993)

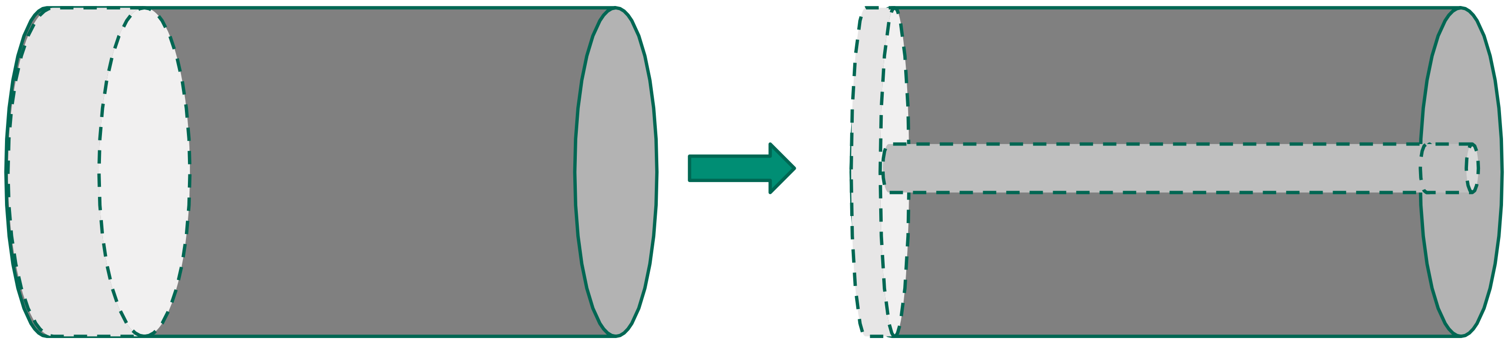
Dispersion equation

$$\zeta(\omega) = \frac{4k}{R}(\omega - 1)$$

Unstable WRT almost all perturbation modes → fractal pattern → scale invariant→ upscaling

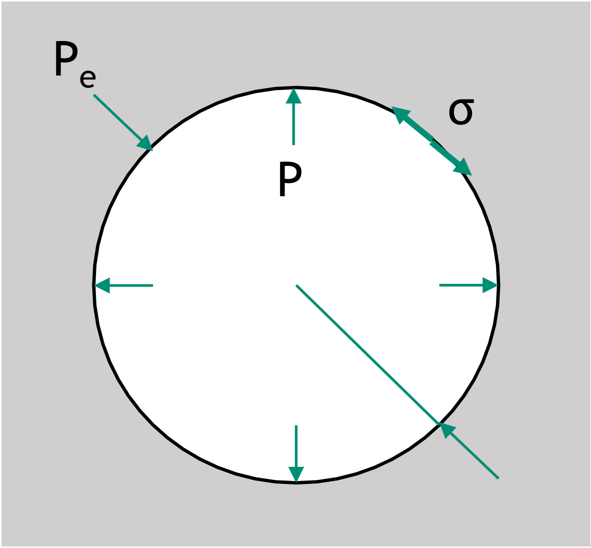


Gas breakthrough

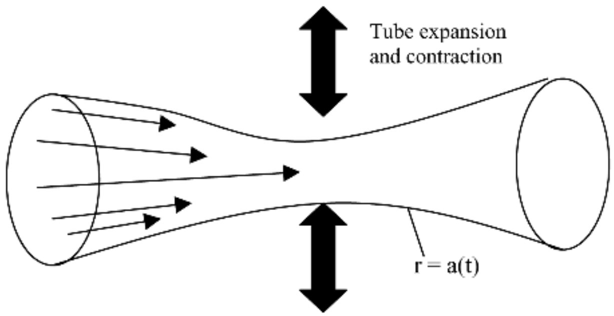


- Make enough room for gas phase to percolate through (one percolating channel).
- Internal pressure is high enough to sustain the compression by the confining stress and the surface tension.

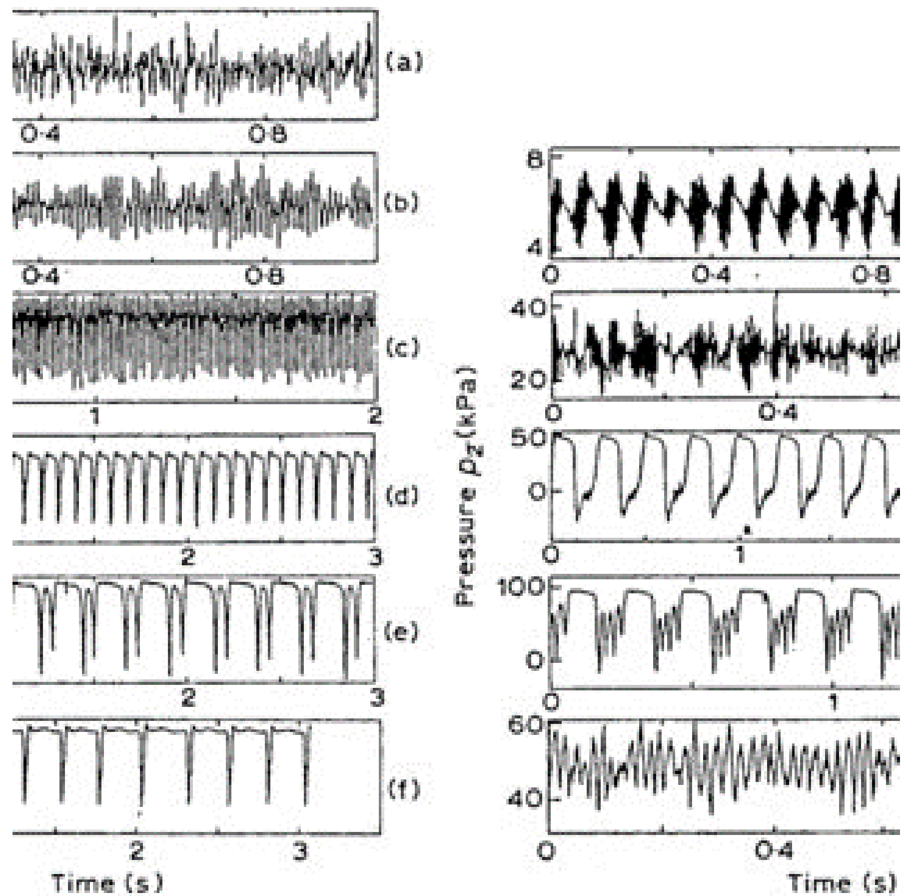
$$P = P_e + \frac{2\sigma}{D}\sqrt{\frac{L_1}{L}}$$



Instability of a single deformable channel



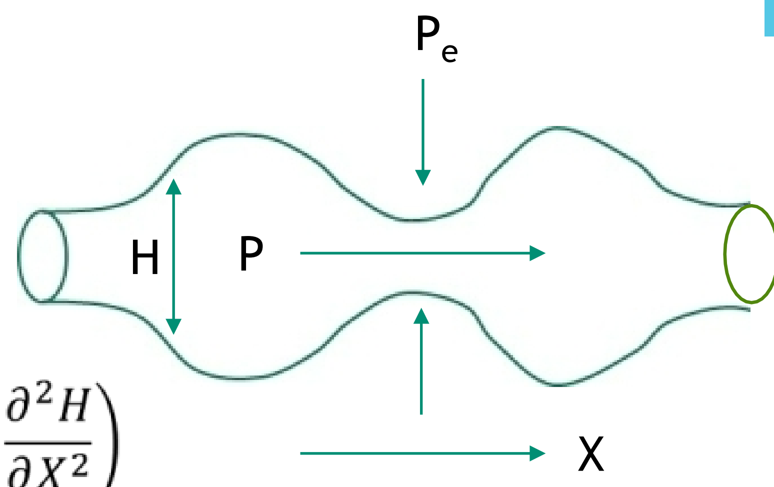
Makinde (2005)



Pedley and Luo (1998)

Gas flow in a deformable channel

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial X}\left(kH^3\frac{\partial P}{\partial X}\right)$$



$$\frac{\partial H}{\partial t} = \lambda\left(\alpha H^2 + (P - P_e) - (H - H_0)E + \beta\frac{\partial^2 H}{\partial X^2}\right)$$

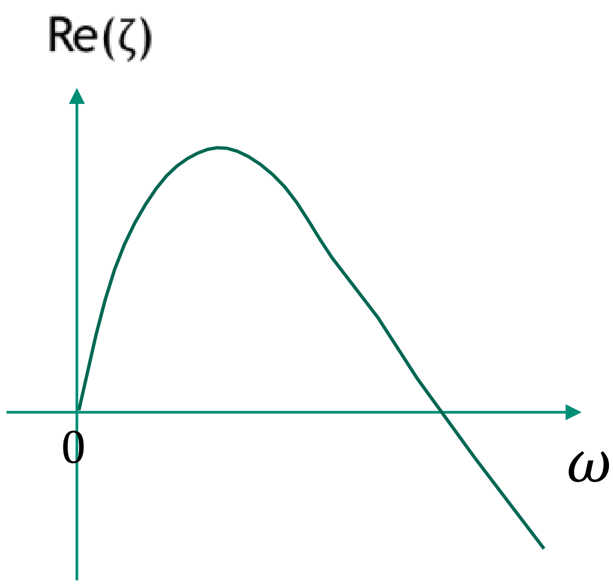
Bernoulli-like effect

Surface tension

$$\zeta(\omega) = \frac{\lambda k\bar{H}^3\omega^2(2\alpha\bar{H} - E - \beta\omega^2) - 3\lambda kq\bar{H}^2\omega i}{\lambda + k\bar{H}^3\omega^2}$$

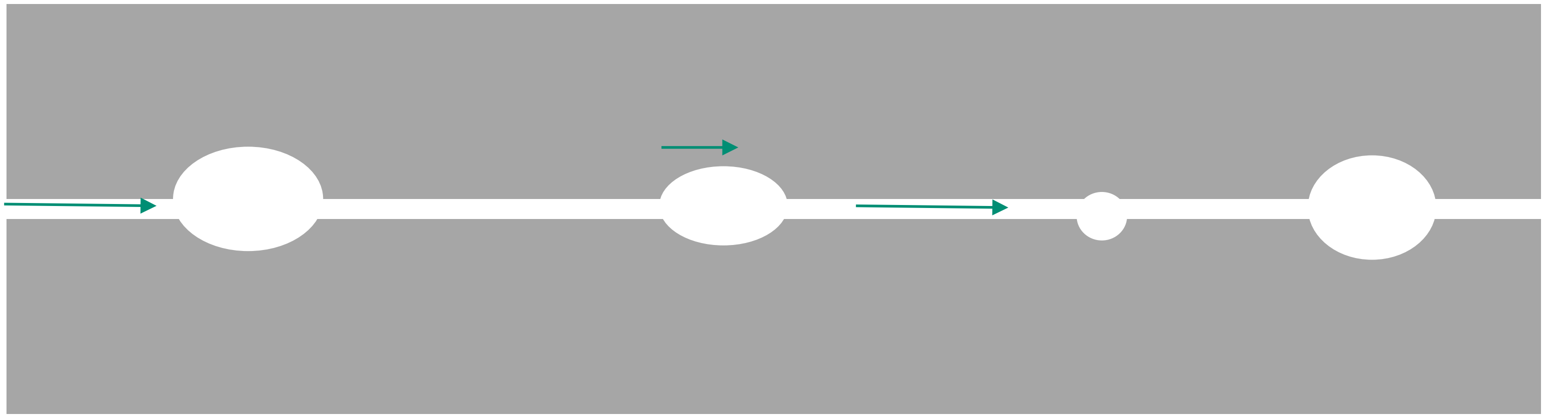
Perturbation growth rate

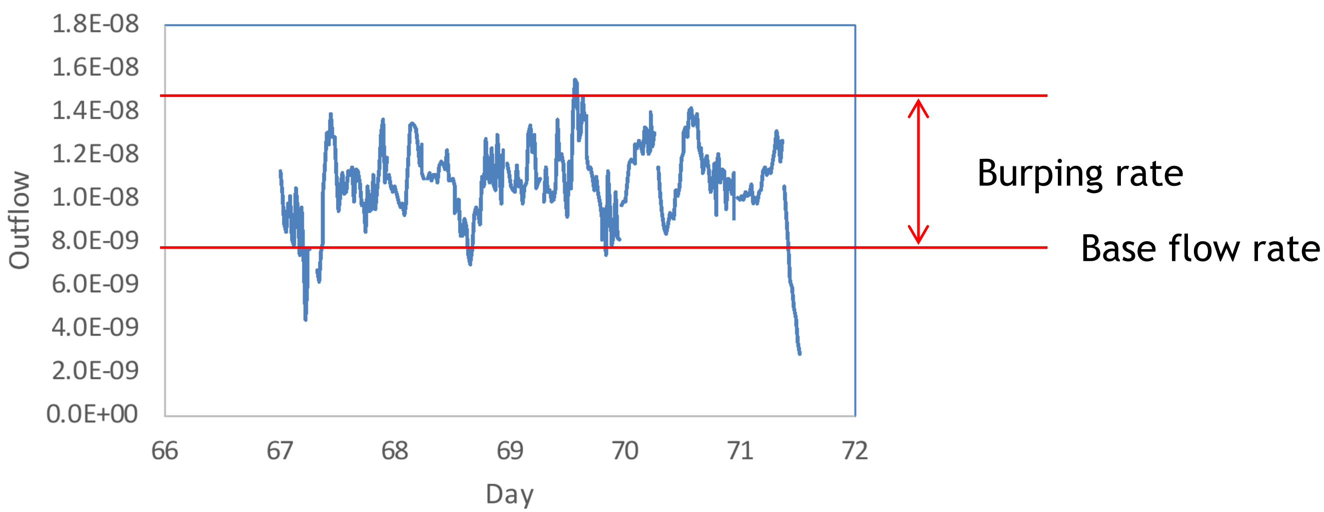
Re(ζ)



Instability → a chain of bubbles percolating through a deformable channel

Instability of a deformable channel

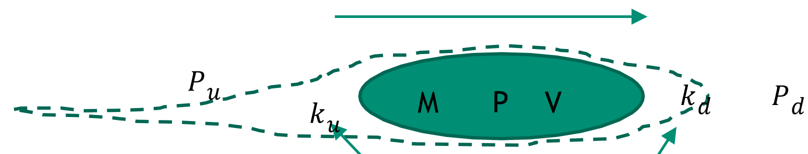




- Critically stressed medium
- Individual gas bubbles
- High frequency variations → material properties

Gas bubble movement: Deterministic chaos

- As a gas bulb or channel nucleates and migrates in a water saturated compacted bentonite, complex nonlinear dynamics of gas flow would emerge due to the dynamic coupling between fluid flow and matrix deformation.
- The complex behaviours of the system arise from constantly unstable gas percolation fronts.



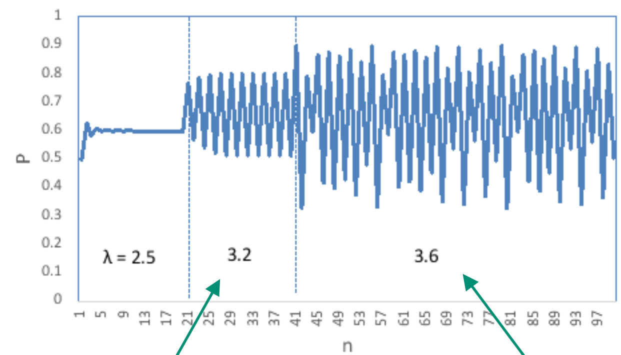
$$\frac{dP}{dt} = \lambda_1 p\left(1 - \frac{P}{K}\right)$$

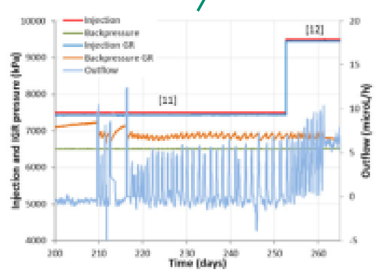
$$P_{n+1} = P_n + \lambda_1 P_n\left(1 - \frac{P}{K}\right)\Delta t$$

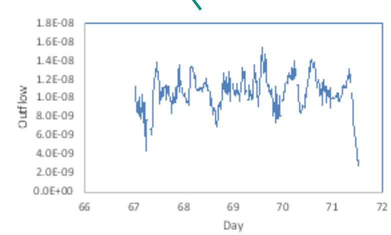
$$\lambda = 1 + \lambda_1 \Delta t$$

$$p_{n+1} = \lambda p_n(1 - p_n)$$

Assume stepwise movement of a bubble to overcome the threshold for bubble opening at its advancing front.

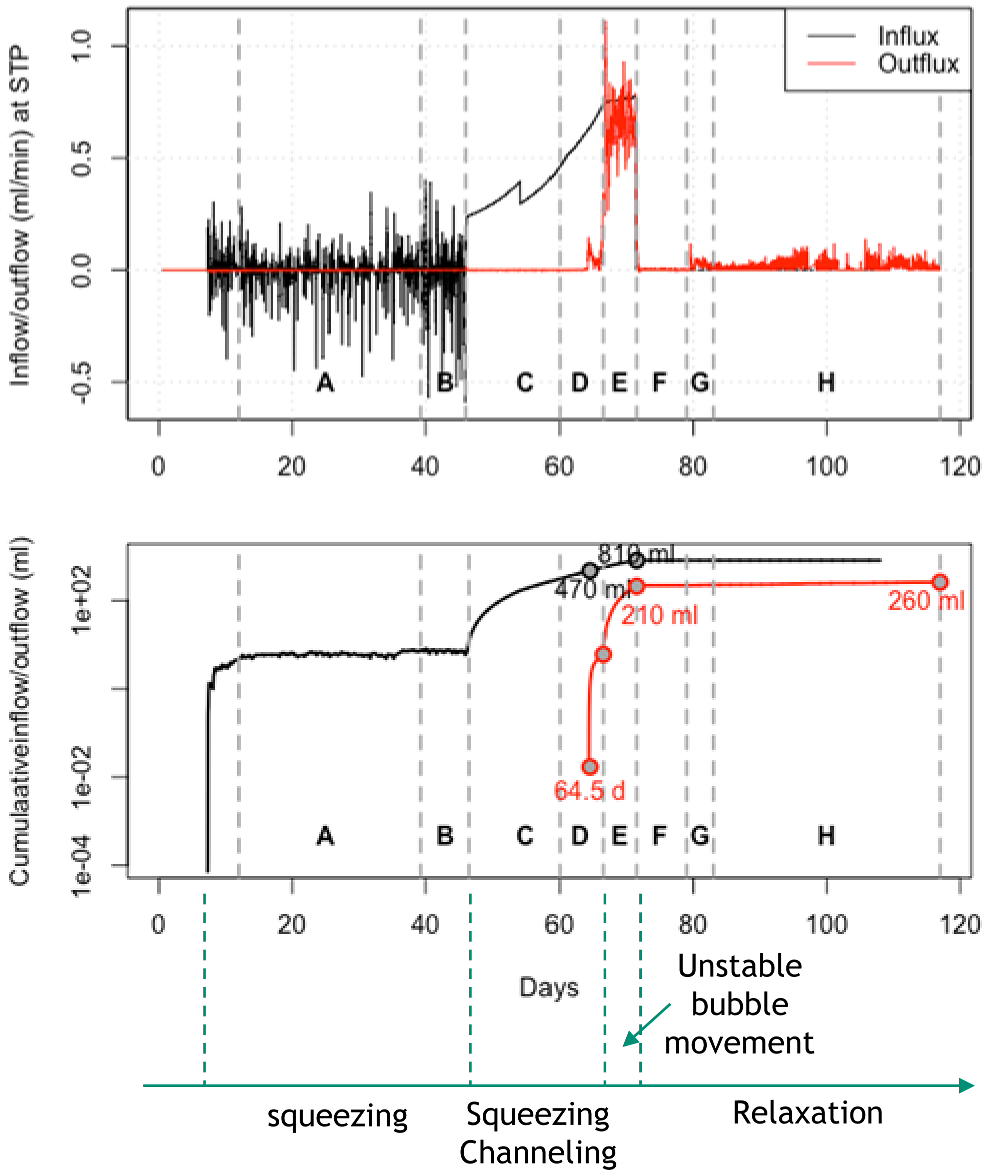




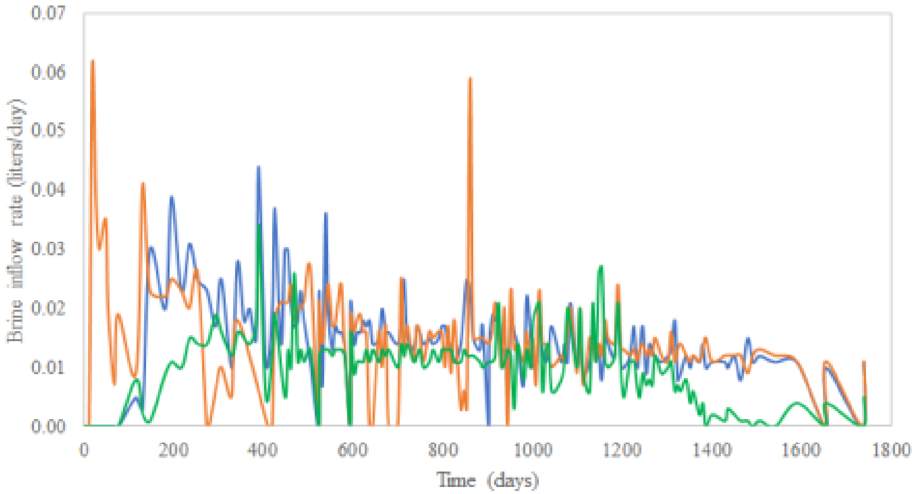


FORGE Report D4.17 (Harrington, 2013)

Put everything together …



Beyond bentonite and clays …
Porosity waves

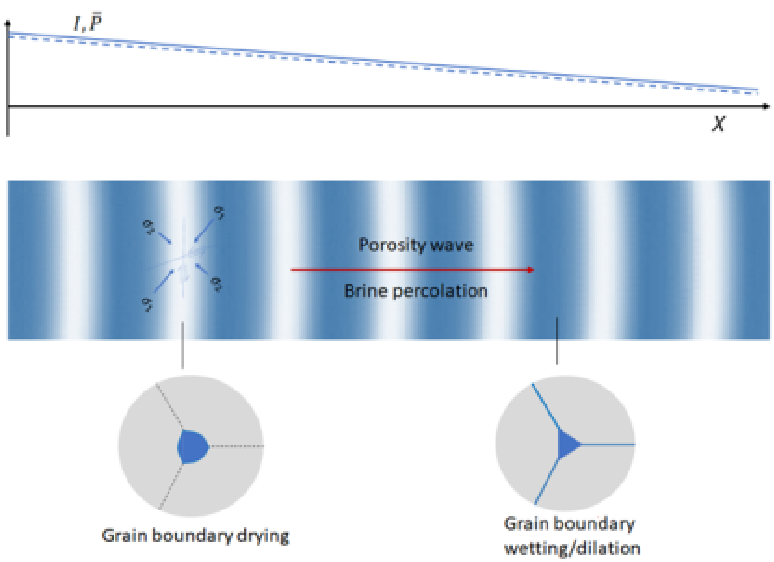


$$\frac{[illegible]}{[illegible]} = \frac{[illegible]}{[illegible]} \, [illegible]^2 \, \frac{[illegible]}{[illegible]}$$

$$\frac{[illegible]}{[illegible]} = [illegible]\left[[illegible]^2 + [illegible]([illegible] - [illegible]) - [illegible]([illegible] - [illegible]_0)\right]$$

$$(1 + [illegible]^{[illegible]})\,[illegible] = [illegible]^{[illegible]}$$

$$[illegible] \; 1 - [illegible] + [illegible]\frac{[illegible]^2 \, [illegible]}{[illegible]^2} \; (1 - [illegible]) = 1$$



Shear-induced porosity waves creating geofluid localization and episodic releases in salt formations

Yifeng Wang, Hua Shao, Kristopher L. Kuhlman, Carlos F. Jove-Colon, Olaf Kolditz

Perspective

- Completed conceptual model
- Nest steps
  - Formulate a dynamic model for channeling (partially completed)
  - Formulate a dynamic model for gas permeation in a viscoelastic channel. (Completed)
  - Perform linear stability analyses for the dynamic models.
    - Simple geometry: infinite domain
    - Experimental systems
  - Perform numerical simulations.
  - Refine the model for individual bubble movement (3-4 variables).
  - Manuscripts (one on dynamic model, one on time series analysis for large-scale tests)
- Data requirements
  - High resolution sampling interval
  - Data from large-scale tests