Stochastic Modeling of Hydrodynamic Particle Bridging and Permeability Impairment in Porous Media: A Pore-Scale Approach

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Bridging Scales for Coupled Subsurface Processes through Numerical Models and Microfluidic Expertise

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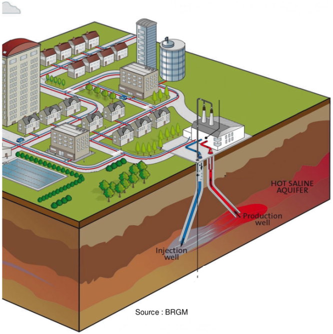
Challenges associated with fluid injectivity

The exploitation of underground resources presents numerous challenges, particularly regarding fluid injection into the subsurface, where **clogging** often occurs near wellbores.



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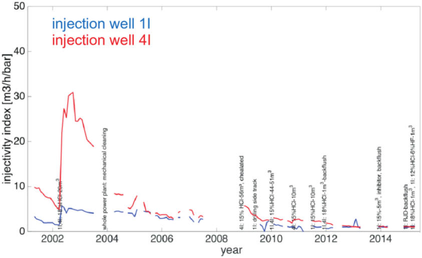
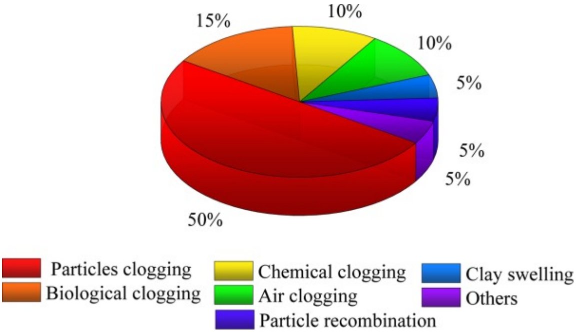


Brehme et al., 2017

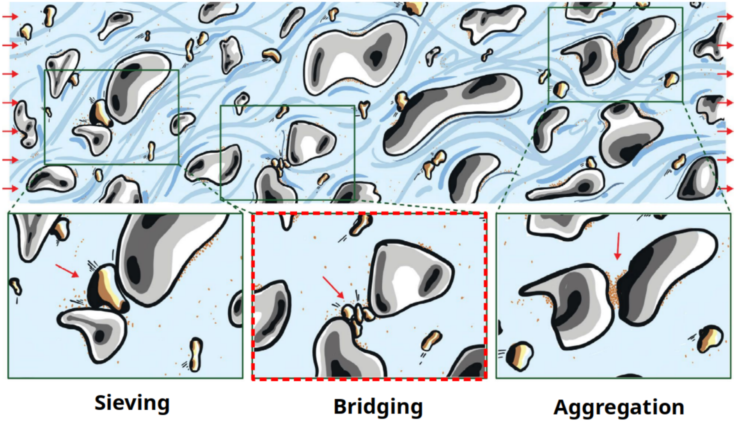
Causes of clogging

Half of the clogging incidents result from **particle retention** in the subsurface.



Song et al., 2020

Pore-clogging mechanisms due to particle transport



Modified from Dincau et al., 2023, Clogging: The self-sabotage of suspensions, Physics Today

Scientific question and objectives

How to capture the permeability impairment due to particle bridging mechanism in porous media?

Objectives: Predict the impact of the following key properties on the particle bridging in the pore network.

- Particle diameter
- Particle concentration
- Injection force
- Pore structure

Open challenges:

- Multi-scale physics
- Opacity of geological porous media

Computational Fluid Dynamics - Discrete Element Method (CFD-DEM)

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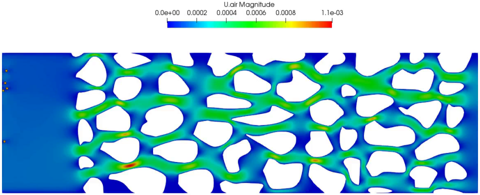


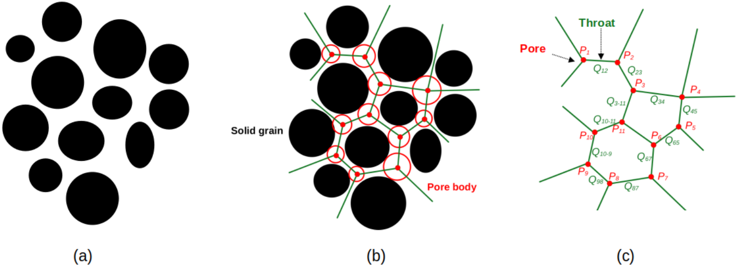
- + Direct use of real pore structure geometry.
- + Full resolution of physical interactions.
- − Computationally demanding.

Maya Fogouang et al. "Particulate Transport in Porous Media at Pore-Scale. Part 1: Unresolved-Resolved Four-Way Coupling CFD-DEM" (2025) Journal of Computational Physics.

Maya Fogouang et al. "Particulate Transport in Porous Media at Pore-Scale. Part 2: CFD-DEM and colloidal forces" (2024) Journal of Computational Physics.

Multiscale strategy

Implement a pore-network modeling approach

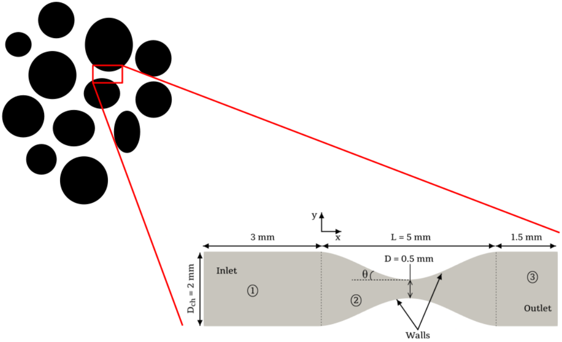


Step 1: Pore-network modelling

- $+$ Preserve the network topology.
- $+$ Can deal with large volume, up to the REV size.
- – Approximate the pore and throat geometry.
- – Require input law for clogging.

Multiscale strategy

Implement a pore-network modeling approach **incorporating a probabilistic law to describe particle bridging within individual pores.**



Step 2: Clogging law in a single pore.

- Particle concentration ϕ.
- Particle-to-constriction size ratio D/d_p.
- Constriction angle θ.
- The injection force.

Probabilistic law for particle bridging in a single pore

Clogging is characterized by the **average number of particles** that pass through the constriction before a clog forms.

$$\langle s \rangle = \frac{1 - P_{clog}(n)}{P_{clog}(n)} \text{ where } n = \left\lfloor \frac{D}{d_p} \right\rfloor + 1, \quad P_{clog} = f(D/d_p, \phi, \theta)$$

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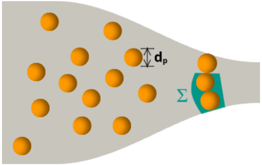
A clog of n particles is formed under 03 conditions:

- The arch composed of n particles must fully span the constriction.
- Upon the arrival of a particle at the constriction, $n-1$ other particles must be located within its vicinity Σ.
- The resulting arch must remain mechanically stable.



$$P_{\text{clog}}(n) = P_{\text{arch}}(n) \times P_{\text{stable}}(n)$$

More than 700 simulations were used to calibrate the stochastic law by varying ϕ, D/d_p, θ, and Re_p.

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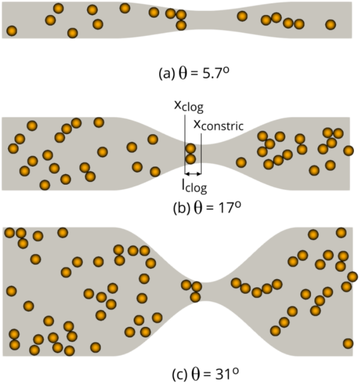
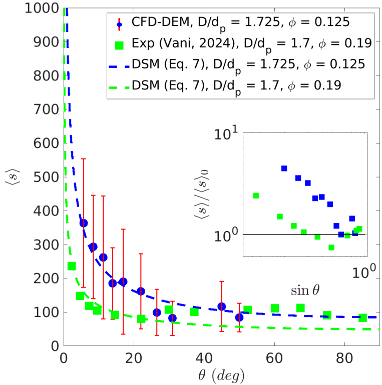
Single pore-bridging: impact of the constriction angle θ

The number of particles, **s**, escaping the constriction decreases as the constriction angle, θ, increases up to a threshold beyond which it remains nearly constant.





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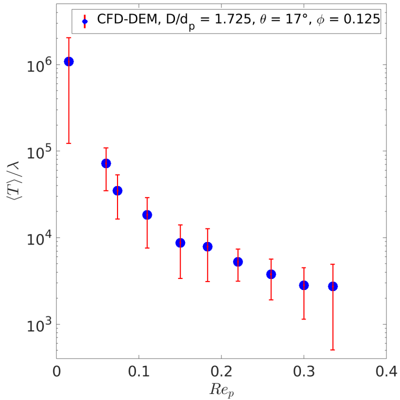
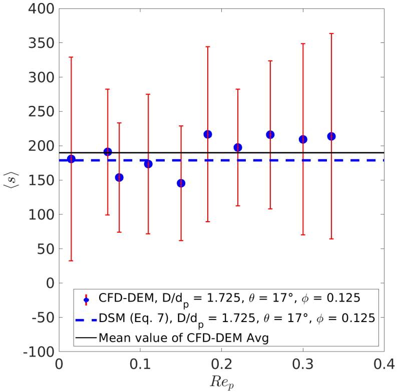
Single pore-bridging: impact of the injection force

Increasing the injection force shortens the clogging time of the pore but has little effect on the number of escapes.





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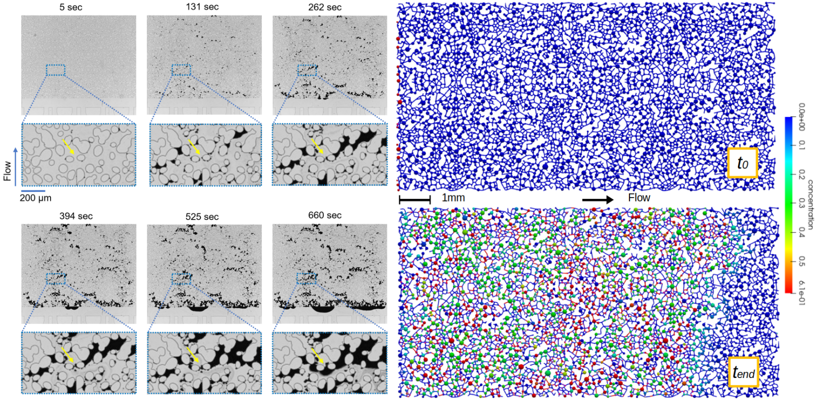
Particle-induced permeability impairment using probabilistic pore network model versus microfluidics

Injected **0.3**% of **6**μ**m** particles, density-matched with water, under $\Delta p = \mathbf{150mbar}$.



(a) Microfluidics

(b) PNMs

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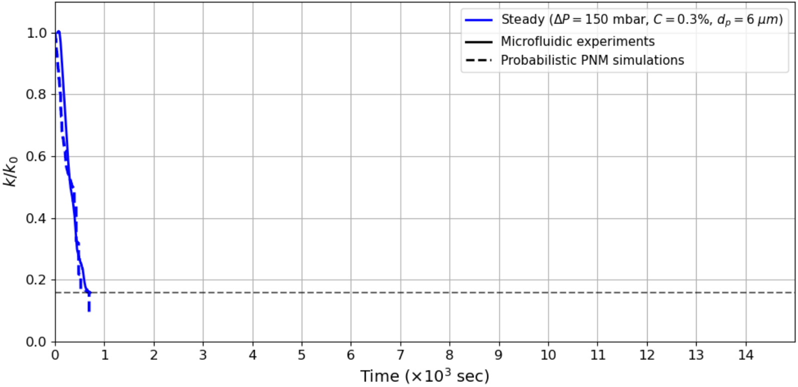
Particle-induced permeability impairment using probabilistic pore network model versus microfluidics



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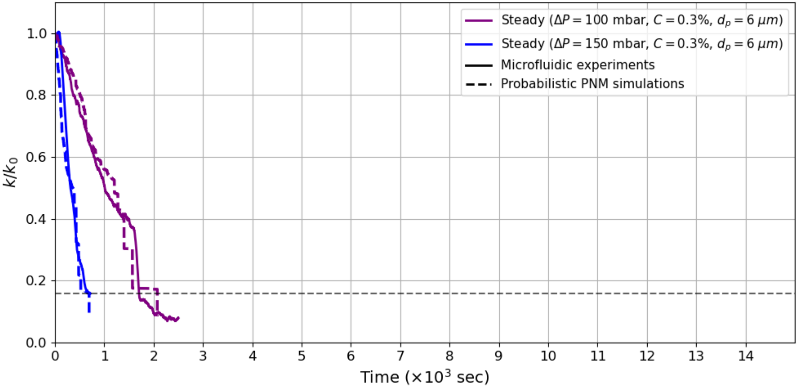

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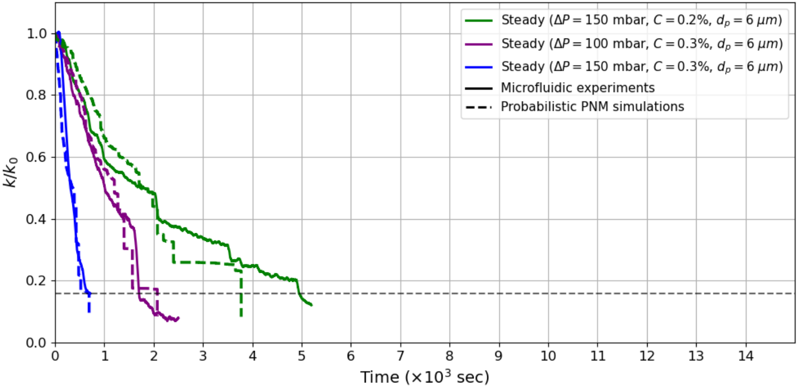

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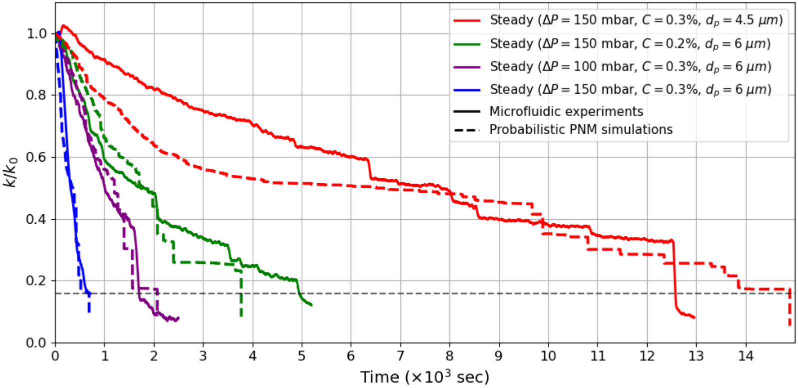

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Conclusions and Perspectives

- Modeling the transport and bridging of fine particles is challenging due to a large parameter space (e.g., particle size and concentration, flow rate, and pore structure).
- The probability law offers an effective approach to quantify bridging by considering the number of particles, s, escaping the constriction.
- High-fidelity CFD–DEM simulations are used to calibrate the probabilistic law.
- The probabilistic pore-network model reproduces the trends observed in microfluidic experiments, demonstrating its ability to capture the bridging phenomenon in heterogeneous two-dimensional porous media.
- Apply the probabilistic pore-network modeling framework to clogging in three-dimensional porous media.

#Open to Postdoc positions!

Acknowledgments

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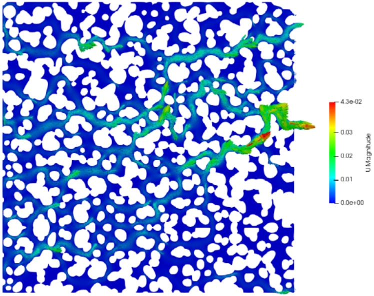

Thank you for your attention!

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SCAN ME

Backup slides

Discrete stochastic model for bridging in a single pore

Clogging is characterized by the **average number of particles escaping the constriction**, denoted as s.

The average number of escapes:

$$\langle s \rangle = (1 - P_{clog})/P_{clog} \tag{1}$$

The probability of clogging a pore with an n-arch particle:

$$P_{clog}(n) = P_{arch}(n) \times P_{stable}(n) \quad \text{with} \quad n = \lfloor D/d_p \rfloor + 1 \tag{2}$$

The probability of forming an n-arch particle:

$$P_{stable}(n) = k(\sin\theta)^{\alpha} \exp\left[\left(\frac{\phi}{\phi_m}\right)^{n^3}\right]\left(\frac{d_p}{D}\right)^{n} \tag{3}$$

More than 700 simulations were performed by varying ϕ, D/d_p, θ and Re_p resulting in $k = \mathbf{0.3}$ and $\alpha = \mathbf{0.6}$

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Stochastic pore-network model

The volumetric flow rate, Q_{ij}, through the throat connecting pore i to pore j,

$$Q_{ij} = \frac{\alpha_{ij}\left(D_{ij}, h\right)}{\mu L_{ij}}\left(P_i - P_j\right), \tag{4}$$

The geometric hydraulic conductance factor

$$\alpha_{ij} = \frac{a^3 b}{12},\ \text{a} = \min(D_{ij},\text{h}),\ \text{b} = \max(D_{ij},\text{h}) \text{ and } \alpha_{ij} = D_{ij} h \frac{d_p^2\left(1 - C_{jam}\right)^3}{180 C_{jam}^2} \text{ if clogged}$$

The suspension viscosity is defined by (Zarraga et al., 2000),

$$\mu\left(C\right) = \mu_f \frac{\exp\left(-2.34 C\right)}{\left(1 - C/C_m\right)^3} \tag{5}$$

The Taylor-Aris dispersion in the throat ij reads,

$$\mathcal{D}_{ij} = \mathcal{D}_m + \frac{min(h, D_{ij})^2}{4\mathcal{D}_m} U_{ij}^2 \left(\frac{2}{105} - \sum_{n=1}^{\infty} \frac{18}{(n\pi)^6} \exp\left(-4\left(\frac{n\pi}{min(h, D_{ij})}\right)^2 \mathcal{D}_m t\right)\right) \tag{6}$$

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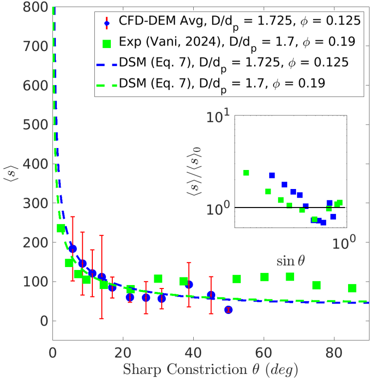
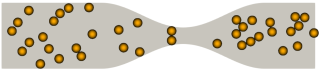
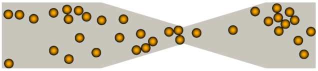
Pore-bridging: impact of the constriction shape

Sharp constriction promotes more stable and frequent clogs than a round one.





(a) Round constricition



(b) Sharp constriction

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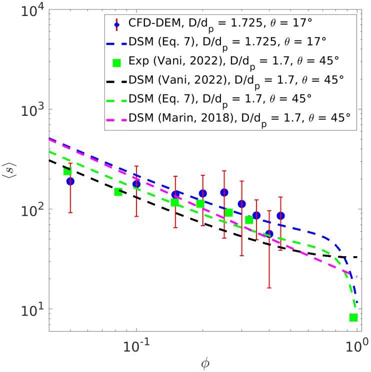
Pore-bridging: impact of the particle concentration ϕ

The number of escapees decreases with increasing particle concentration, with the decline becoming more pronounced in the dense suspension regime.



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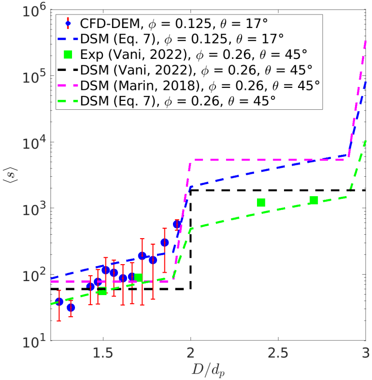
Pore-bridging: impact of the particle-to-constriction size ratio D/d_p

The number of escapes, **s**, increases with the particle-to-constriction size ratio, following a stepwise trend with oblique transitions between successive steps.



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