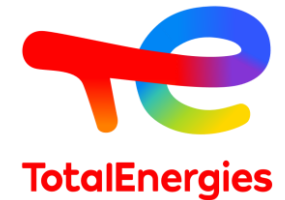


EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE FRACTURING MECHANISMS OF UNCONSOLIDATED SANDSTONES

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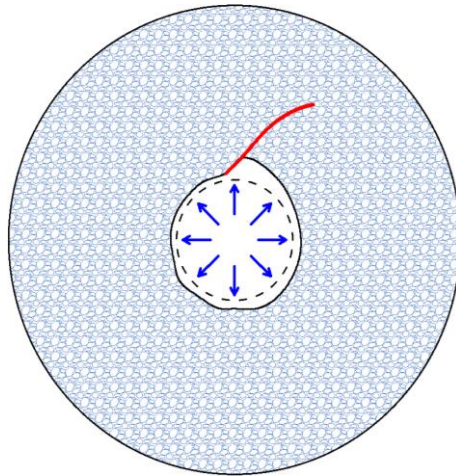
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² Total Energies

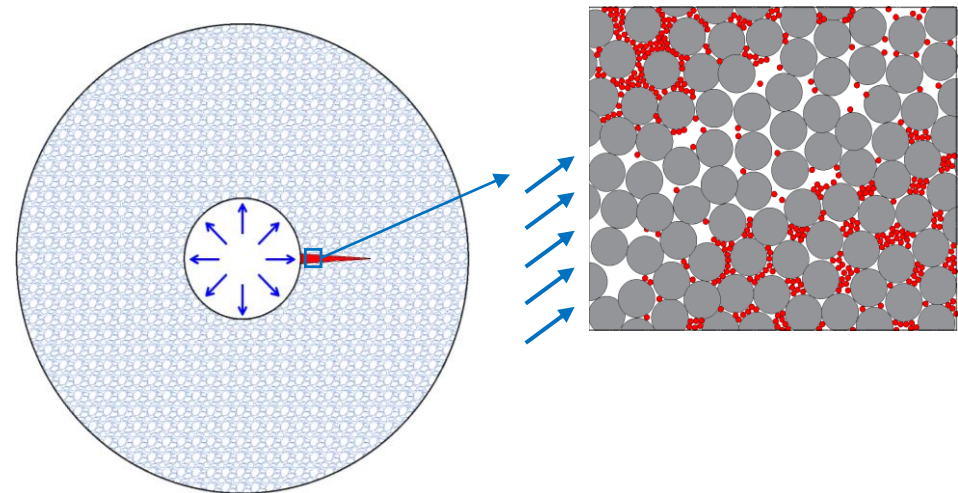


Context and motivation

- Unconsolidated (cohesionless) sandstone formations are important for secondary oil recovery and targets for the storage of CO₂ and hydrogen.
- Injection induced fractures can stimulate the reservoir but also pose concerns with loss of containment.
- The mechanisms of (**pseudo**) fracturing in unconsolidated sandstones is fundamentally different from those in cohesive formations, being a combination of:



Cavity expansion and shear banding

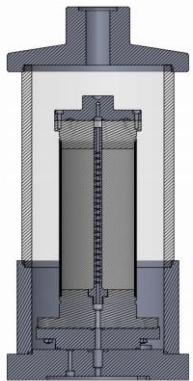


Internal erosion

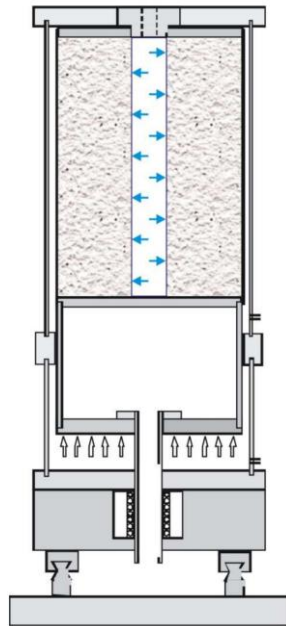
Experimental Campaign

T.T. Nguyen PhD Thesis (2021)

1. Radial injection tests

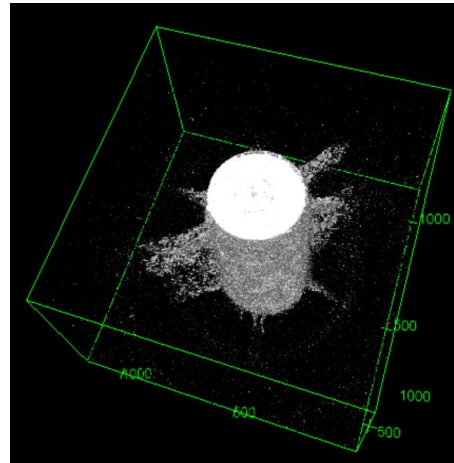


Injection cell
($h = 20$ cm, $D = 10$ cm, $D_i = 1$ cm)

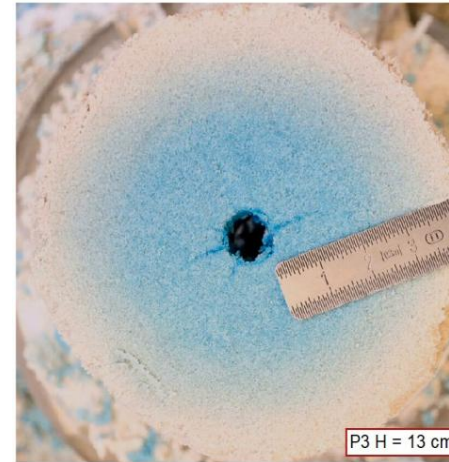


Injection chamber
($h = 40$ cm, $D = 52$ cm, $D_i = 7$ cm)

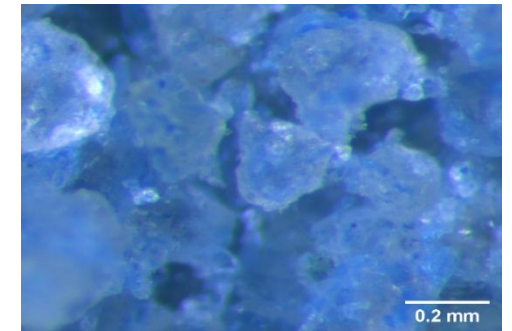
2. Post-mortem imaging



X-ray μ CT



Pictures during disassembly



Optical microscopy

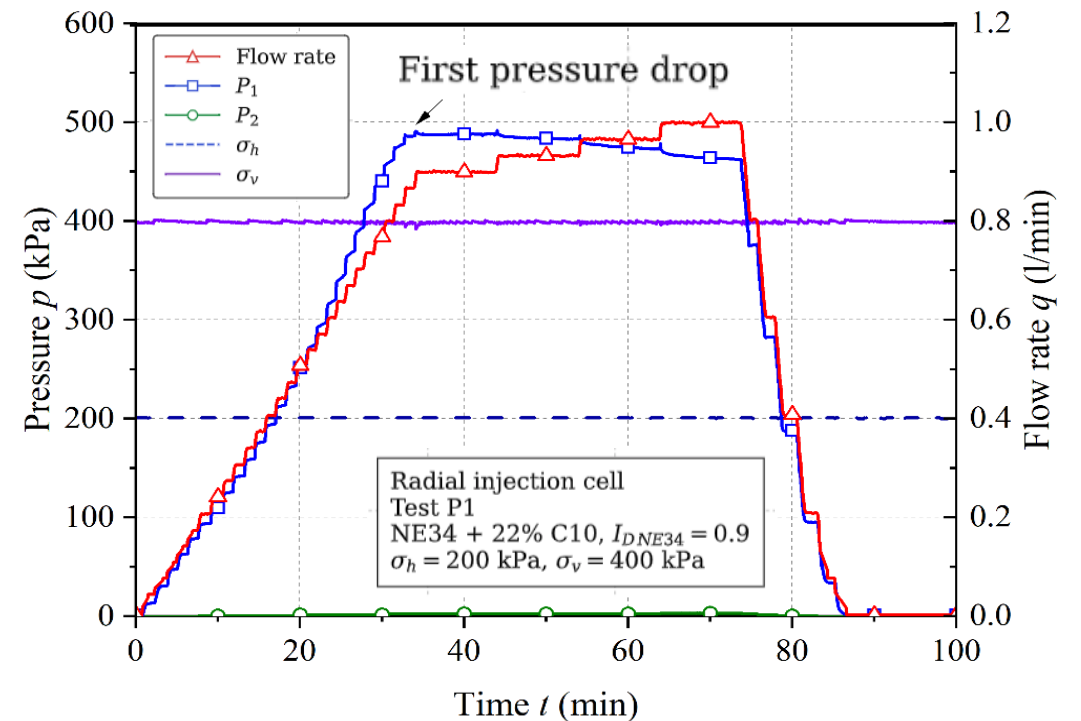
Experimental Campaign

Material

- Mixture of Fontainebleau sand ($D_{50} = 210 \mu\text{m}$) + 22% C10 silica particles ($D_{50} = 20 \mu\text{m}$) at dense state
- Gap-graded material, susceptible to internal erosion

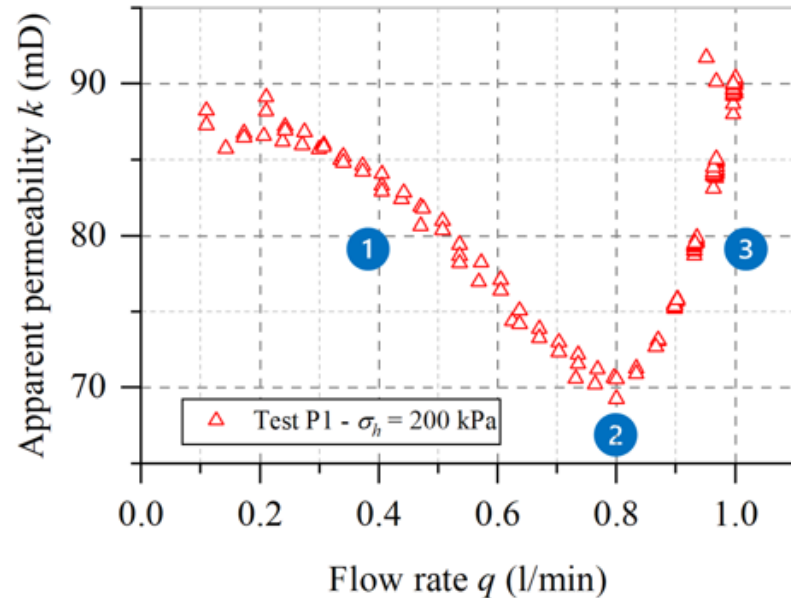
Injection protocol

- Saturation and loading to triaxial stress state
- Water injection at controlled flow rate, increased in steps (step rate test)
- Inlet and outlet pressures are measured
- Injection is made until observing a pressure drop (onset of fracturing mode)
- A few longer injection steps are made in frac regime before unloading and shut-down
- Dyed colloidal-silica gel is injected and cured to freeze the fractures



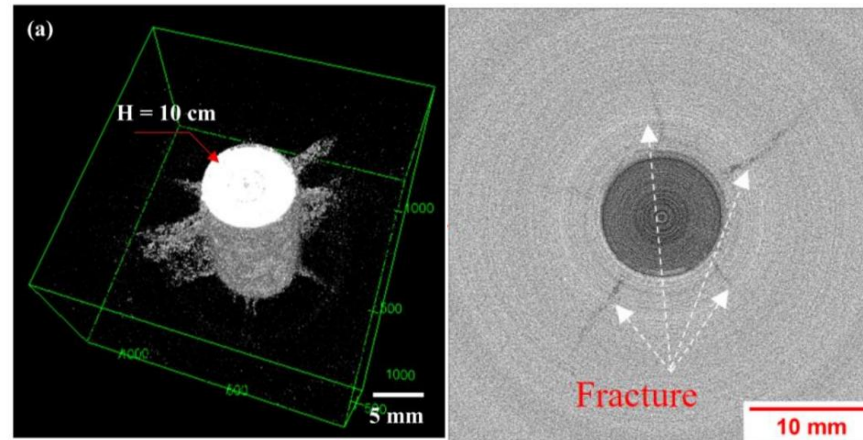
Experimental results

Evolution of permeability



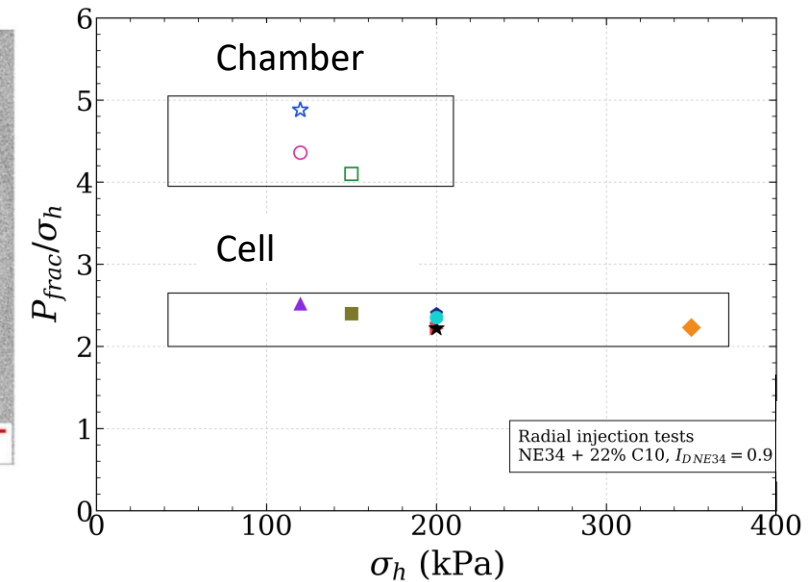
1. Loss of injectivity due to suffusion
2. Onset of frac regime
3. Fracture propagation

Pseudo-fracture geometry



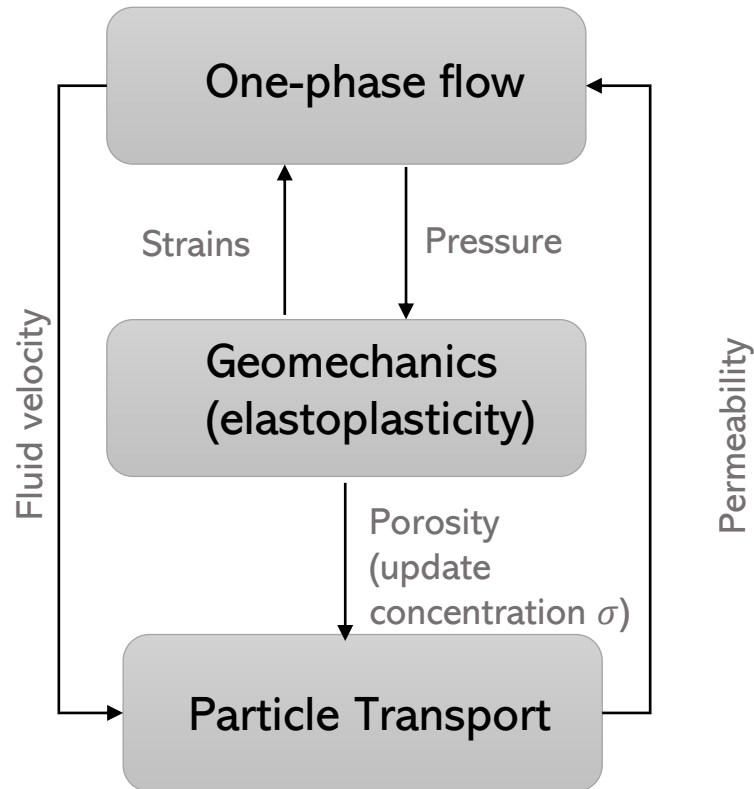
- Radial pseudo-fractures/erosion channels
- They present fewer C10 particles and higher porosity

Influence of stress state



- Consistent ratio between fracturing pressure and σ_h
- Much higher pressures in the chamber. Why ?

Numerical model



$$\frac{d(\varphi \rho_w)}{dt} + \nabla \cdot (\mathbf{u} \rho_w) = 0$$

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = 0$$

$$\frac{d(\varphi C + \sigma)}{dt} + \nabla \cdot (\mathbf{u} C - \varphi D_L \nabla C) = 0$$

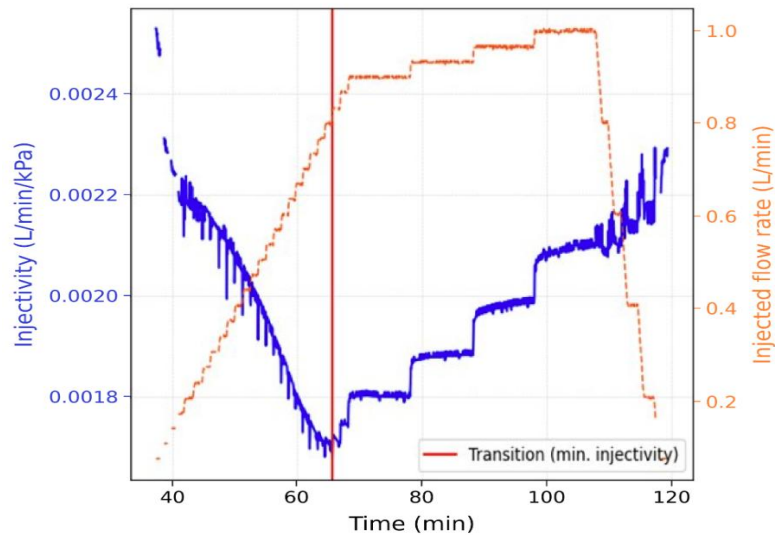
Computational tool:
Elfen Advance - Rockfield



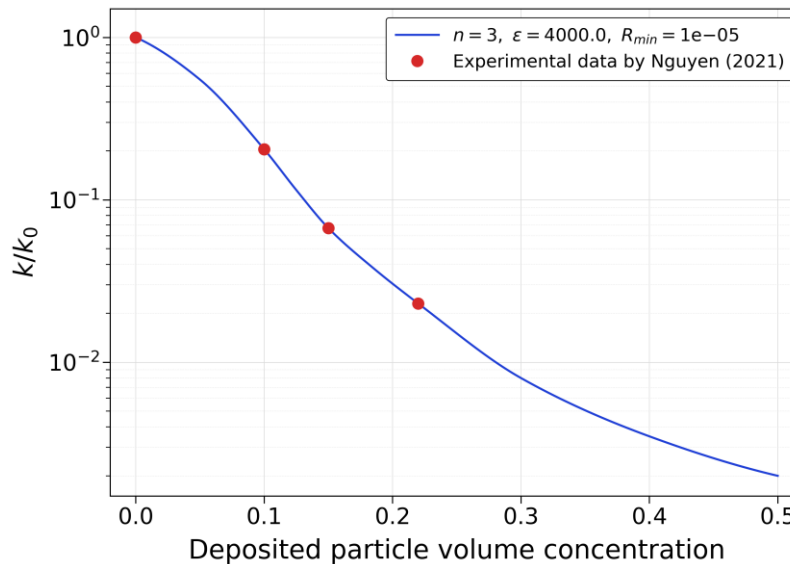
Numerical model

Important ingredients:

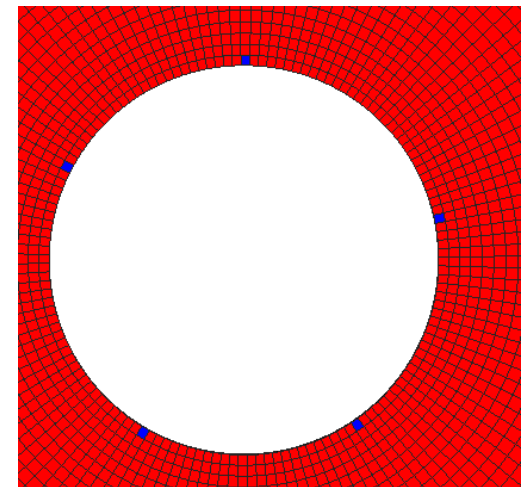
1. Deposition mobilization law, with one **OR** the other depending on fluid velocity being above or below a **critical velocity** (calibrated from shift in injectivity)



2. Permeability law: function of particle concentration (indirectly, of porosity)



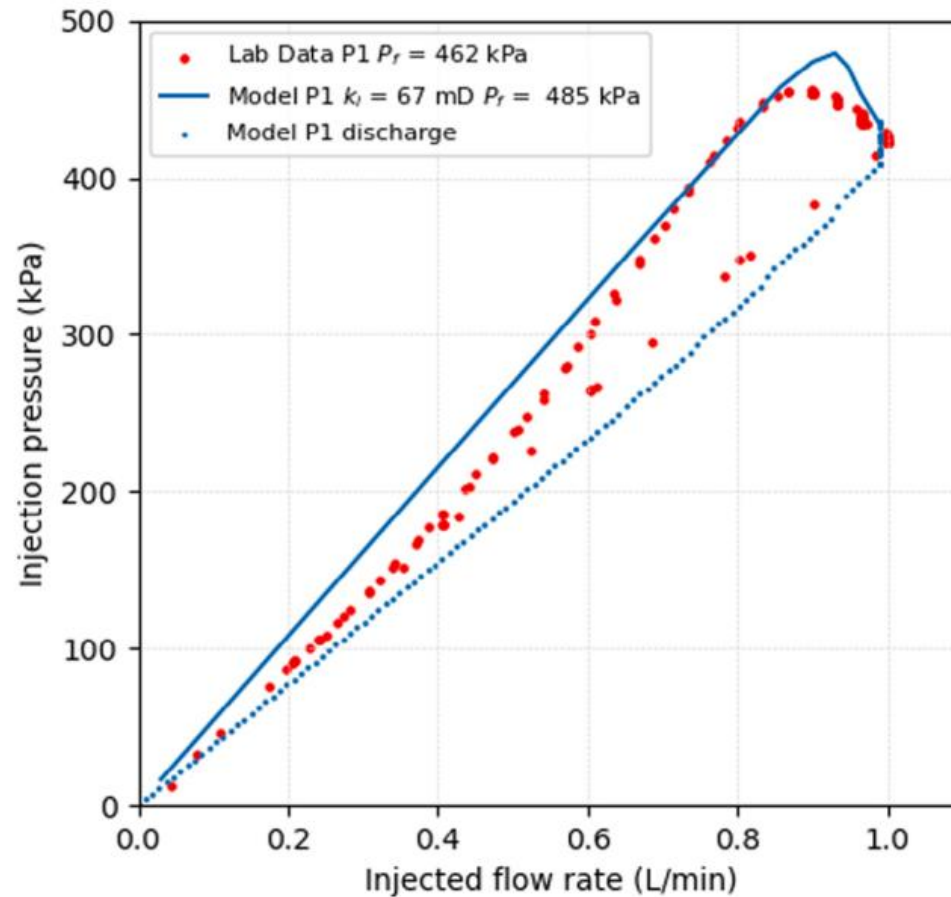
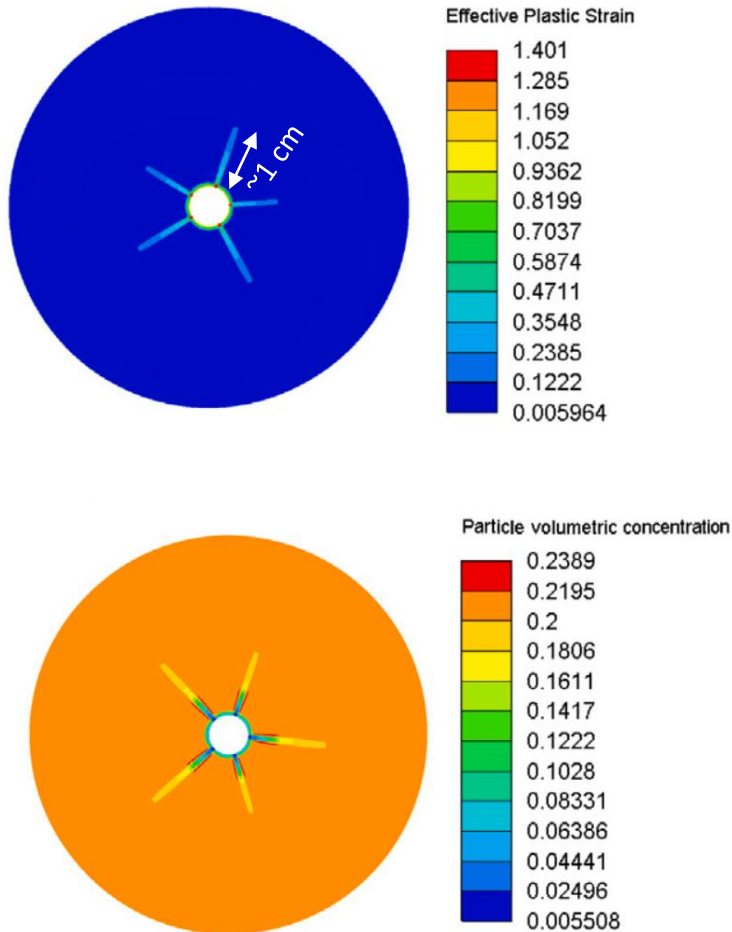
3. Strain-softening Mohr Coulomb (parameters from triaxial tests) + **weak elements** for fracture seeds



Weak elements in blue

Results of the numerical model

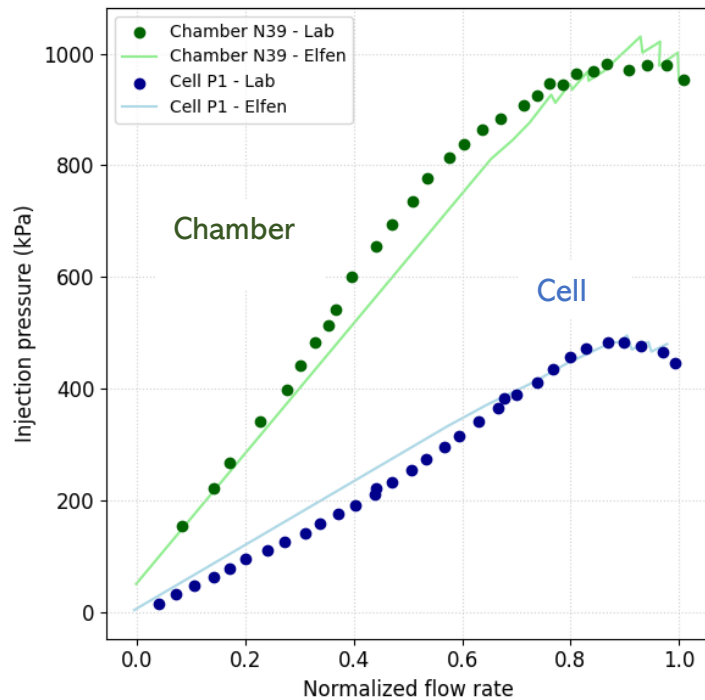
Test P1 ($\sigma_h = 200$ kPa, $\sigma_v = 400$ kPa)



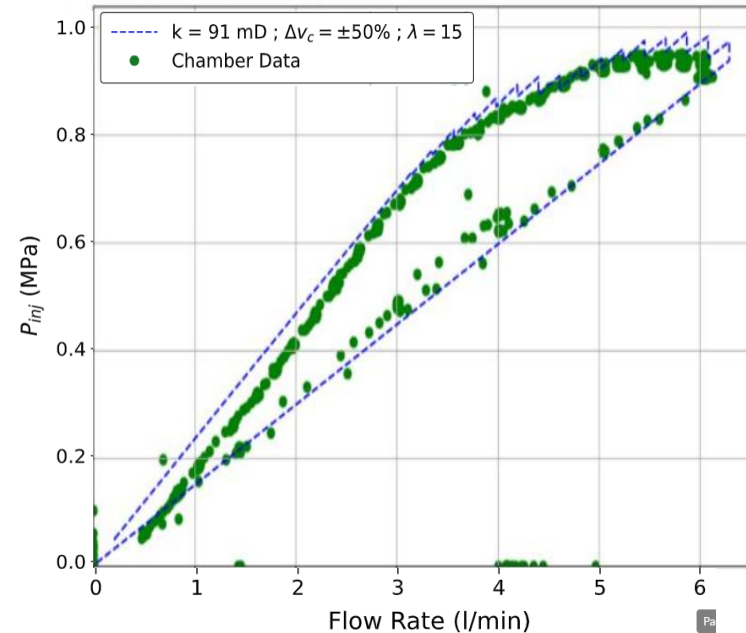
- Tests with other initial stress states can also well reproduce the dependency of the fracturing pressure on σ_h , and show longer fractures as the σ_h decreases
- Recently, the weak element approach has been replaced by random fields of porosity, which yields similar results

About the size effect

- From a flow and transport perspective, the critical velocity is reached at a higher injection pressure in the chamber than in the cell, due to the larger internal diameter of the injection tube in the chamber.
- This suggests that it is fundamental to characterize a critical velocity above which mobilization-dominated transport and significant internal erosion occur.



Flow-and-transport-only models, $v_c = 160$ m/day, $\lambda = 50$ /m, $\mu = 0.2$ /m



Recent hydromechanical model for chamber test N39

MERCI

- [1] T. T. Nguyen, Experimental study of fracturing mechanisms in unconsolidated sand reservoirs under fluid injection, PhD thesis, École des Ponts ParisTech, 2021.
- [2] T. T. Nguyen, J. Sulem, R. D. Muhammed, J.-C. Dupla, J. Canou, J.-G. Boero-Rollo, J. Ochi, An experimental setup with radial injection cell for investigation of fracturing in unconsolidated sand reservoirs under fluid injection, *Journal of Petroleum Science and Engineering* 213 (2022) 110362. <https://doi.org/10.1016/j.petrol.2022.110362>
- [3] T. T. Nguyen, J. Sulem, R. D. Muhammed, J.-C. Dupla, J. Canou, J.-G. Boero-Rollo, J. Ochi, Experimental investigation of plugging and fracturing mechanisms in unconsolidated sand reservoirs under injection of water containing suspended fine particles, *Geoenergy Science and Engineering* 221 (2023) 211346. <https://doi.org/10.1016/j.geoen.2022.211346>
- [4] A. Loyola, J. Sulem, J.-C. Dupla, J. Ochi, Numerical modeling of the fracturing mechanisms of unconsolidated sand reservoirs under water injection, *Geomechanics for Energy and the Environment* 38 (2024) 100550. <https://doi.org/10.1016/j.gete.2024.100550>