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Advanced multiphysics modelling of geomaterials: multiscale approaches and heterogeneities

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°847593

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Advanced multiphysics modelling of geomaterials: numerical modelling of discrete gas pathways and cracking

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Delft University of Technology – Faculty of Civil Engineering and Geosciences

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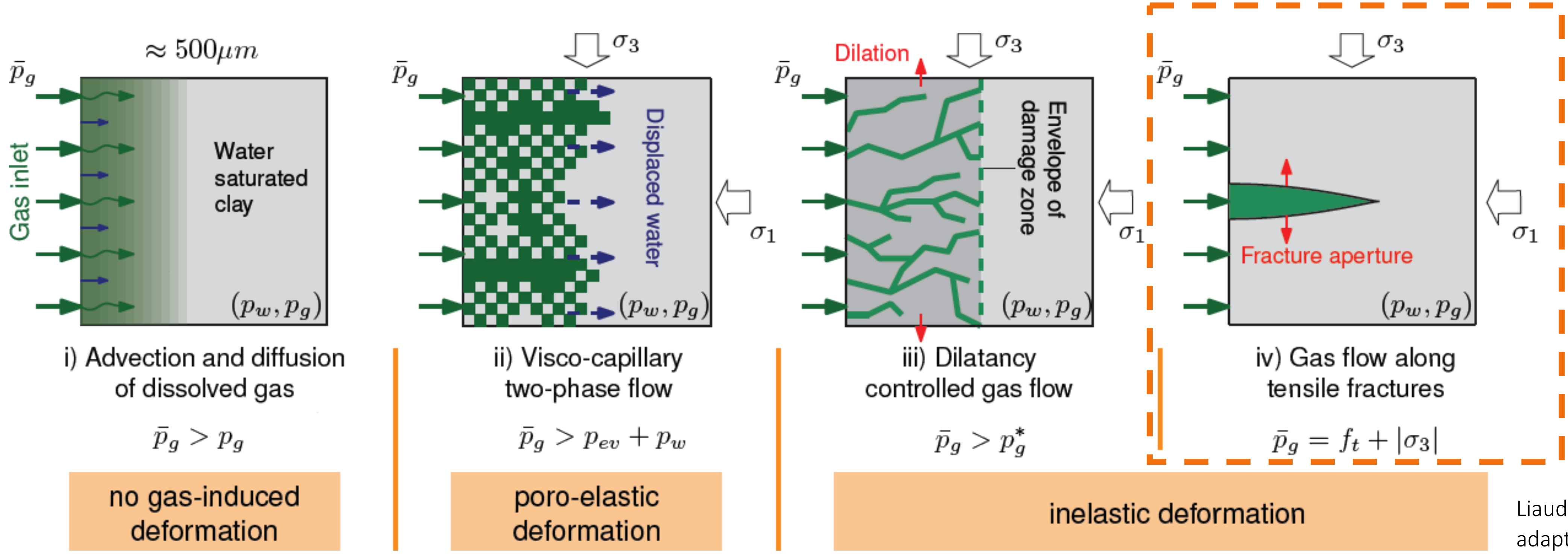
GAS MIGRATION MECHANISMS IN CLAYS



i) Advection and diffusion of dissolved gas

$\bar{p}_g > p_g$

no gas-induced deformation

ii) Visco-capillary two-phase flow

$\bar{p}_g > p_{ev} + p_w$

poro-elastic deformation

iii) Dilatancy controlled gas flow

$\bar{p}_g > p_g^*$

iv) Gas flow along tensile fractures

$\bar{p}_g = f_t + |\sigma_3|$

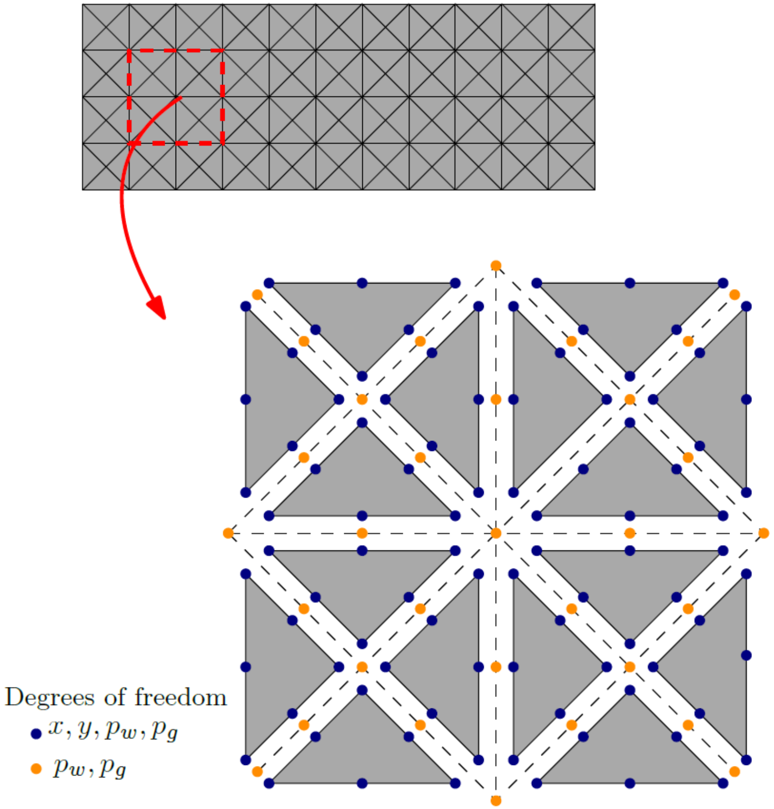
inelastic deformation

Liaudat *et al.* (2023), adapted from Marschall et al. (2005)

p_w, p_g : water and gas pressures in the REV
$\bar{p}_g$: gas injection pressure
p_{ev} : clay gas entry value
f_t : tensile strength
σ_1, σ_3 : principal stresses

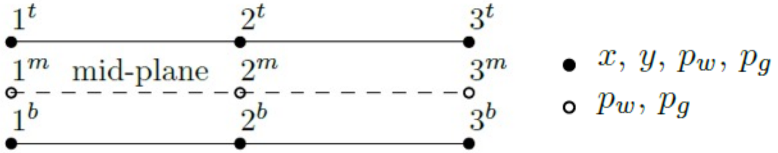
FEM+Z MODELLING APPROACH (LIAUDAT *ET AL.*, 2023)

1. **Continuum elements** with classical two-phase flow in porous media formulation
2. Explicit representation of gas cracking via **zero-thickness interface elements (“+Z”)** equipped with a cohesive fracture constitutive model
    - Interface elements are introduced a priori in between continuum elements as potential cracking paths
    - Closed interface elements do not influence the overall response of modelled material



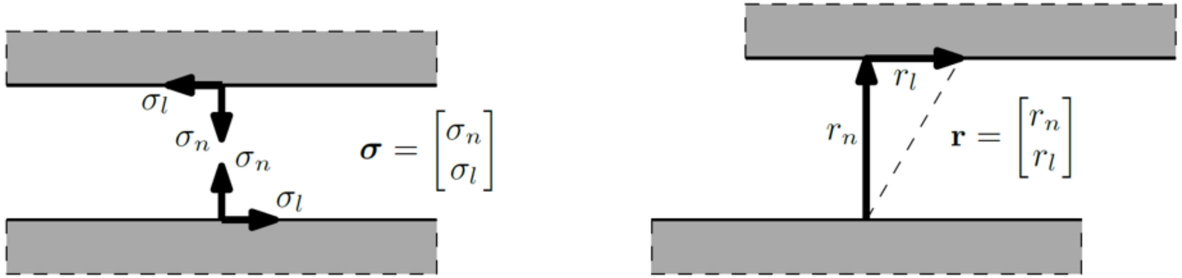
PNEUMO-HYDRO-MECHANICAL INTERFACE (PHMI) ELEMENT (LIAUDAT *ET AL.*, 2023)

3-node zero-thickness interface element



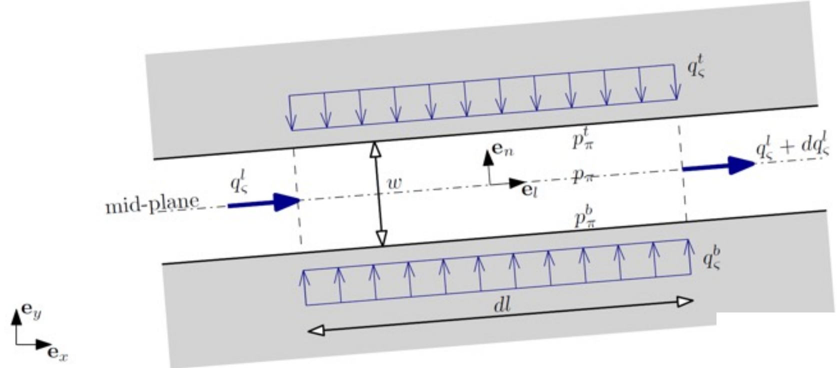
Mechanical Governing equations

- Basic variables:
  - normal and tangential stress components on mid-plane
  - conjugate relative displacements



Flow governing equations

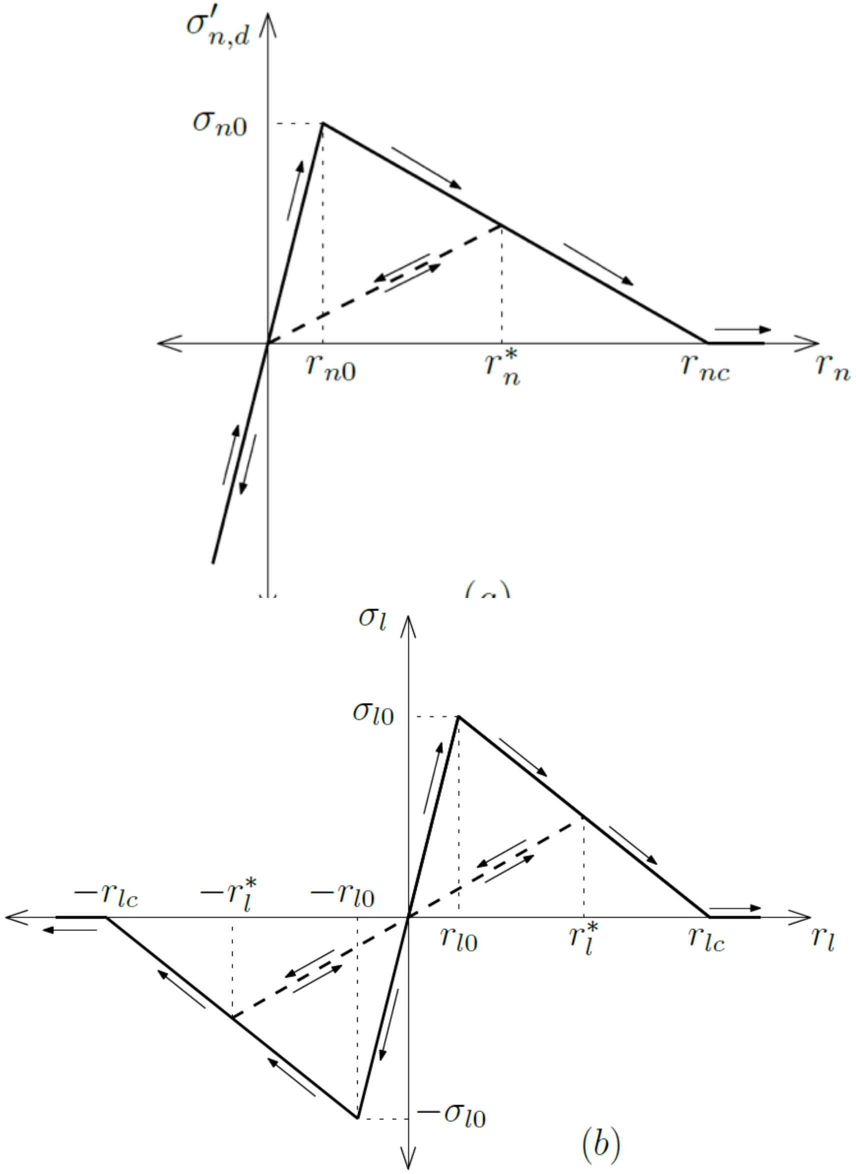
- Two-phase flow
- Diffusion-advection of dissolved gas
- Longitudinal and transversal flows
- Longitudinal transmissivity and diffusivity dependent on normal aperture



MECHANICAL CONSTITUTIVE FORMULATION

Crisfield's cohesive zone model

- Bilinear damage model
- Unique damage variable for shear and tension (coupled damage)
- No damage is produced by compression (negative) normal displacements.
- Normal stiffness in compression is affected by a penalty term to prevent significant overlapping in compression.
- Frictional effects are not accounted for (strictly valid only for a purely cohesive material)



RETENTION CURVES

- For solid elements:

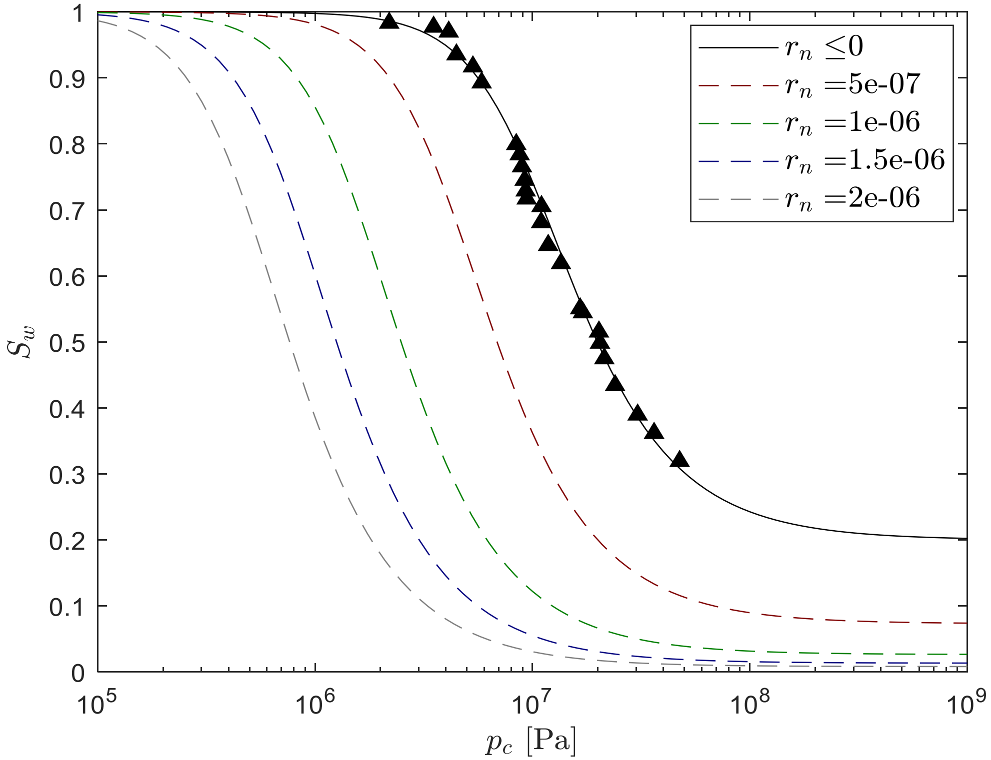
$$S_w = (1 - S_{wr})\left[1 + \left(\frac{p_c}{p_b}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} + S_{wr}$$

- For interface elements:

$$\bar{S}_w = (1 - \bar{S}_{wr})\left[1 + \left(\frac{p_c}{\bar{p}_b}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} + \bar{S}_{wr}$$

with $\bar{p}_b(r_n) = \dfrac{d}{d + 2\langle r_n\rangle} p_b$ and $\bar{S}_{wr}(r_n) = \dfrac{nd}{nd + \langle r_n\rangle} S_{wr}$

where n and d [m] are the porosity and the characteristic
pore size of the continuum porous medium.



Solid line: retention curve for continuum medium and closed fractures

Dashed lines: retention curves for increasing fracture aperture

Markers: Experimental data (Boom Clay) from Gonzalez-Blanco et al. (2016)

RELATIVE PERMEABILITY CURVES

- The same power laws are adopted for solid and interface elements:

$$k_{w,r} = S_e^{n_w}\ ; \quad k_{g,r} = (1 - S_e)^{n_g}$$

  where n_w and n_g are shape parameters, and S_e is the effective saturation degree.

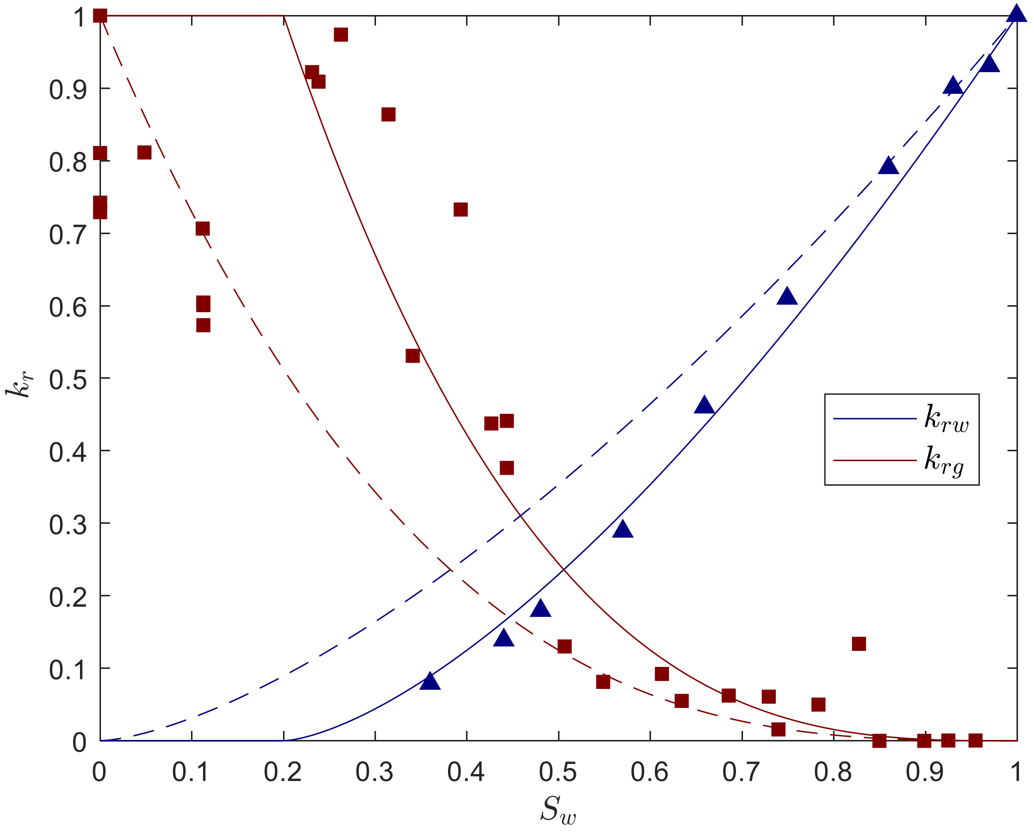
- For solid elements,

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr}}$$

- For interface elements,

$$S_e = \frac{S_w - \bar{S}_{wr}}{1 - \bar{S}_{wr}}$$

with $\bar{S}_{wr}(r_n) = \dfrac{nd}{nd + \langle r_n \rangle} S_{wr}$



<u>Solid line</u>: continuum medium and closed fractures
<u>Dashed lines</u>: fracture with large aperture
<u>Markers</u>: Experimental data (Boom Clay) from Volkaert et al. (1995)

MODELLING RESULTS

1D gas injection under isochoric conditions

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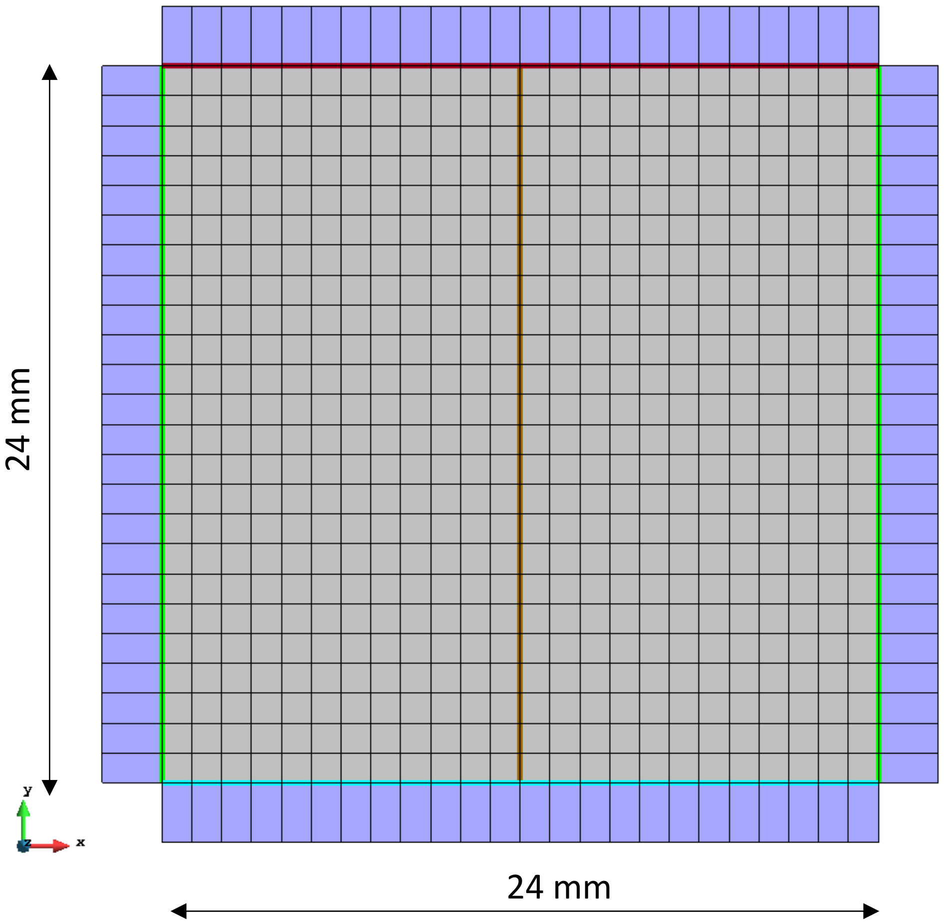
MODEL GEOMETRY AND FE MESH

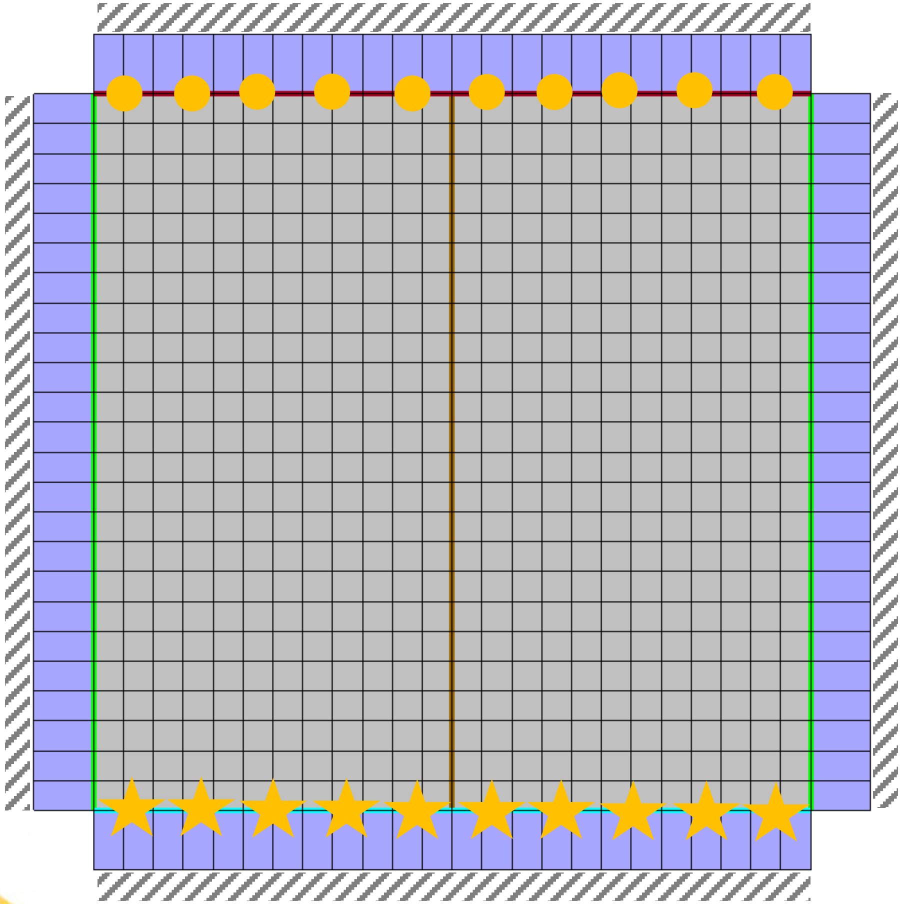


🟪 Very stiff, impervious loading plates

⬜ Boom clay sample (linear elastic)

▬ Bottom contact
▬ Lateral contact
▬ Top contact
▬ Potential fracture path

INITIAL AND BOUNDARY CONDITIONS



Initial conditions

Isotropic initial stress state: $\sigma_x = \sigma_y = 4.5$ MPa

Initial pore pressure $p_g = p_w = 2.2$ MPa ($S_w = 1$)

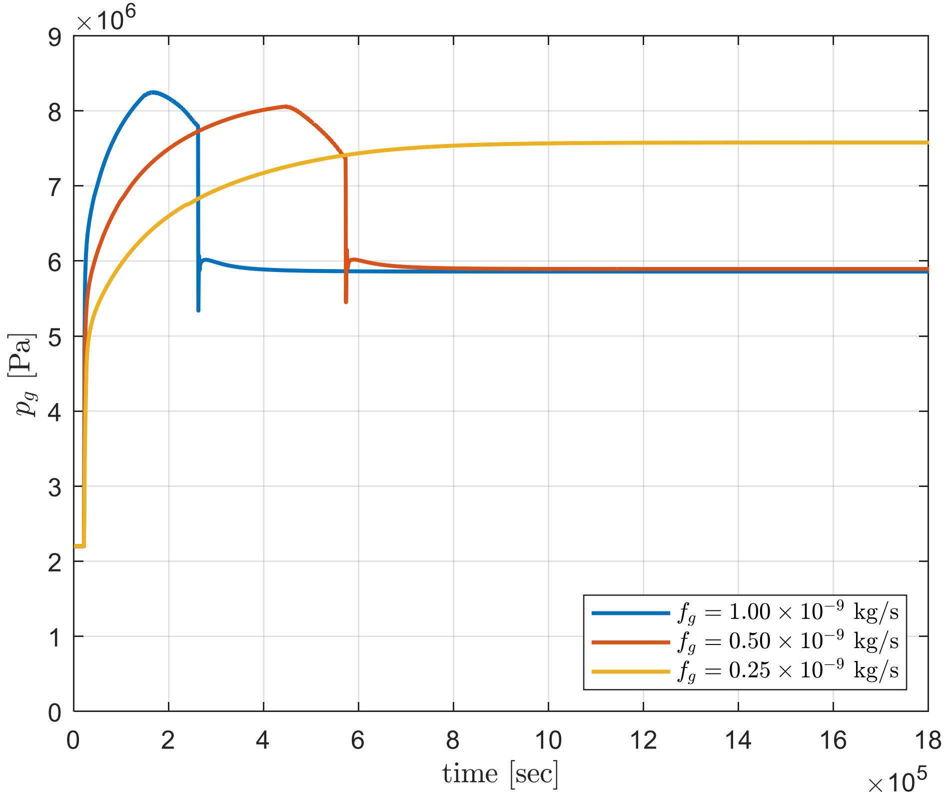
Boundary conditions

Isochoric conditions

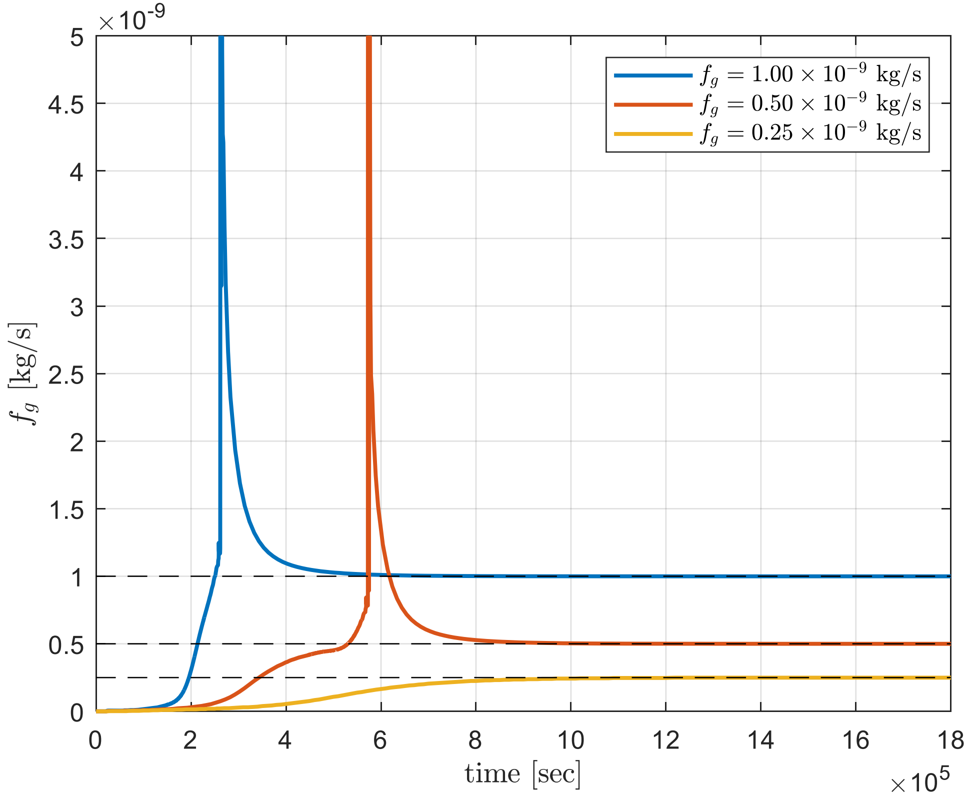
- ● Gas and water pressure fixed at the top contact
- ★ Gas injection at the bottom contact ($f_g = 1.0\times10^{-9}$ kg/s)

EFFECT OF THE GAS INJECTION RATE: Time evolution curves

Gas injection pressure

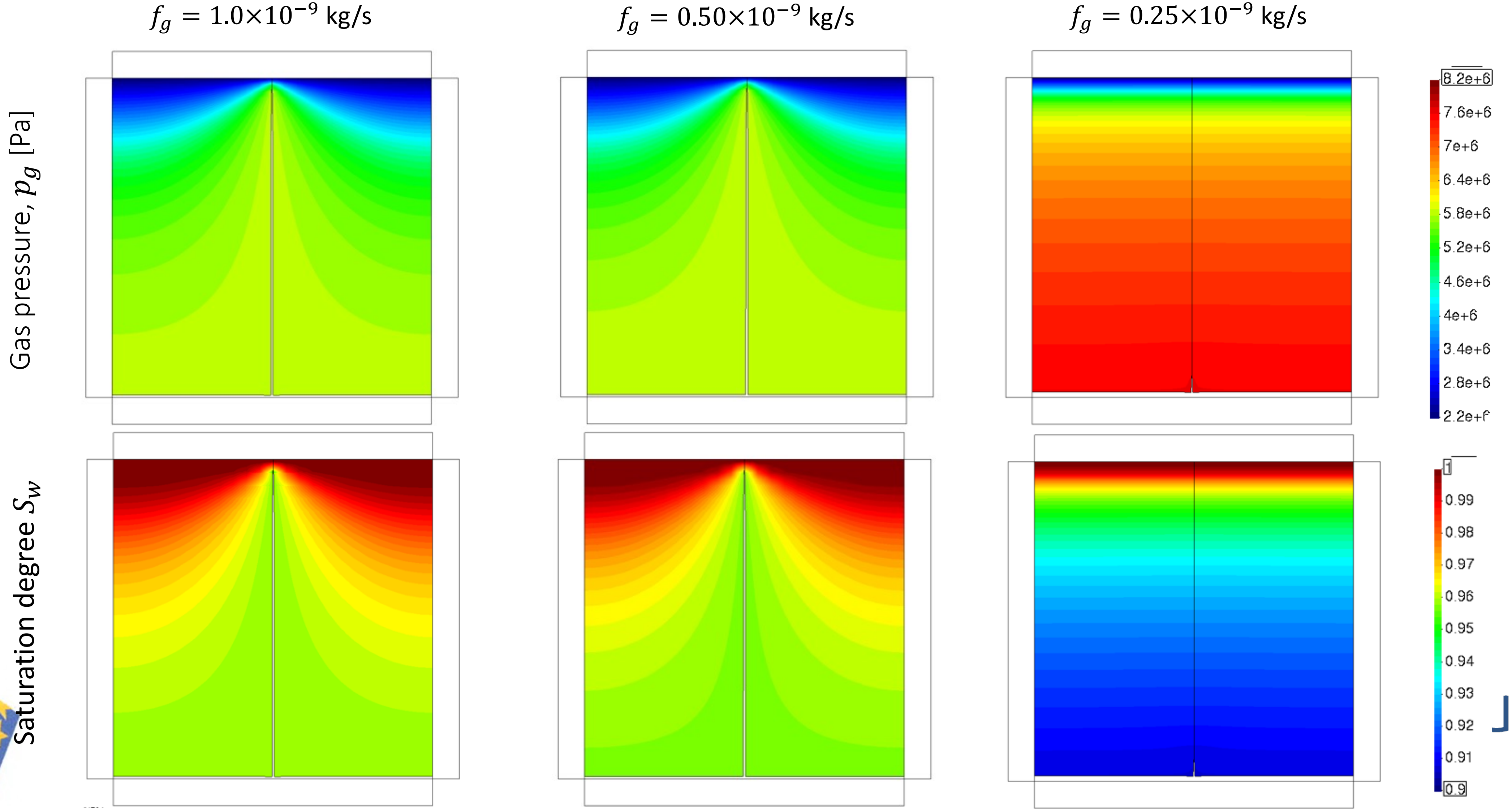


Gas outflow



Initial stress and pore pressure for all cases: $\sigma = 4.50$ MPa, $p_w = p_g = 2.2$ MPa

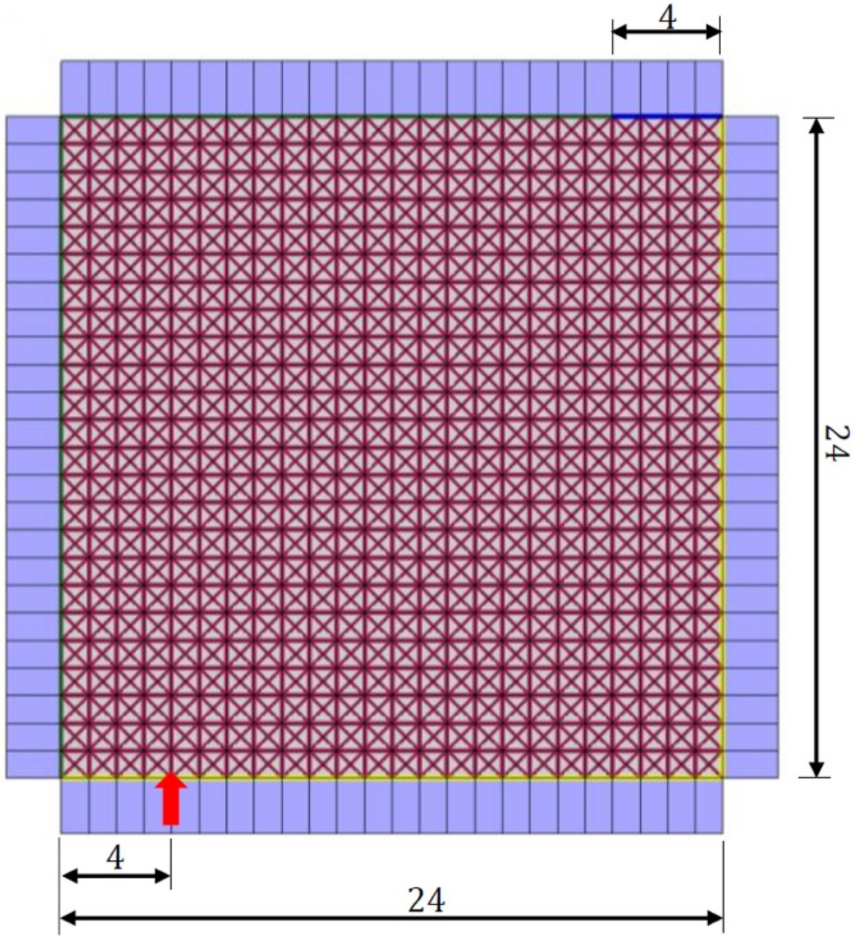
EFFECT OF THE GAS INJECTION RATE: p_g and S_r at the end of the simulation (steady state)


$f_g = 1.0\times10^{-9}$ kg/s

$f_g = 0.50\times10^{-9}$ kg/s

$f_g = 0.25\times10^{-9}$ kg/s

FREE CRACKING PATH



Dimensions in mm

🟦 Very stiff, impervious loading plates

⬜ Boom clay sample (linear elastic)

━ Clay-cell interface (impervious bottom side)
━ Clay-cell interface (impervious top side)
━ Back-pressure filter
━ Potential cracking paths

Initial conditions

Isotropic initial stress state: $\sigma_x = \sigma_y = 4.5$ MPa

Initial pore pressure $p_g = p_w = 2.2$ MPa ($S_w = 1$)

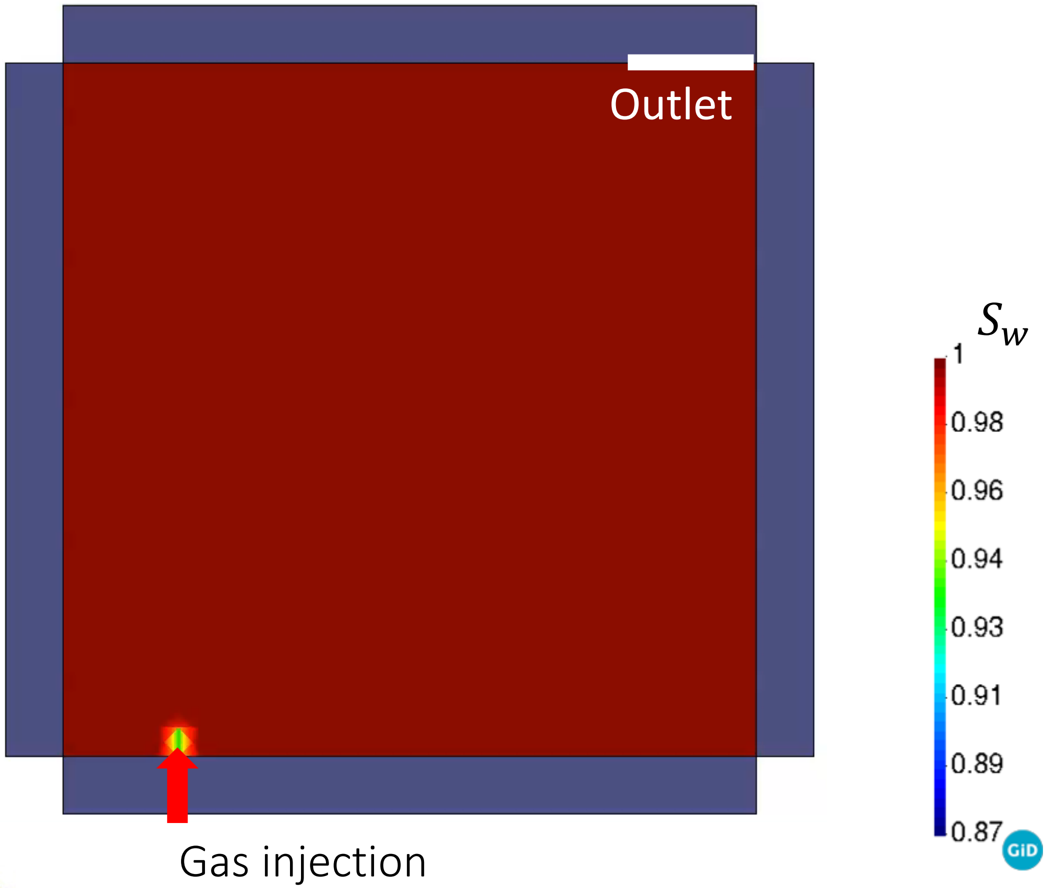
Boundary conditions

Isochoric conditions

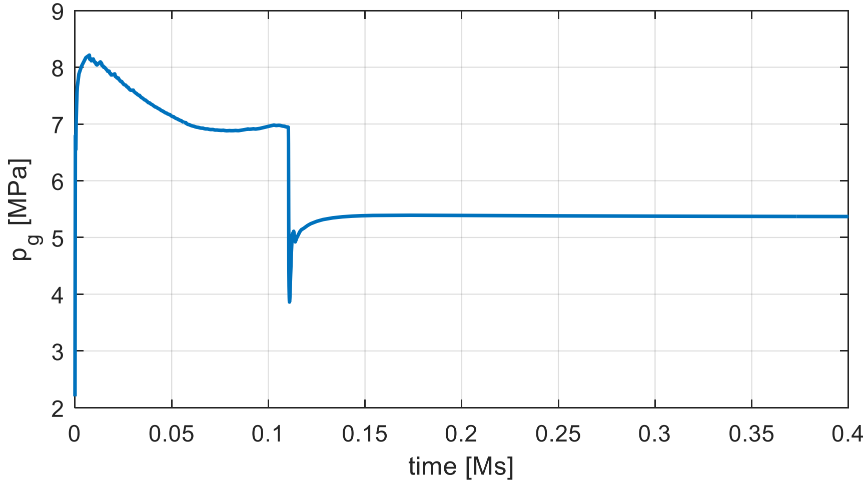
Gas and water pressure fixed at the sink

⬆ Gas injection $f_g = 1.0\times10^{-9}$ kg/s

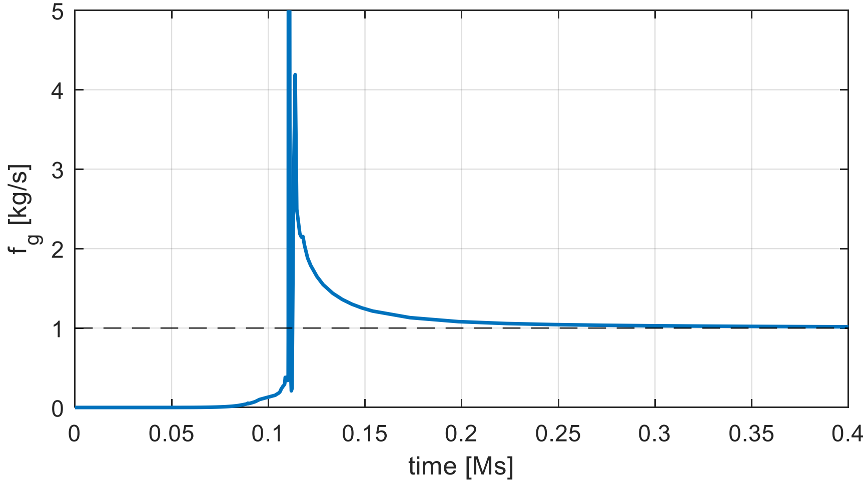
FREE CRACKING PATH



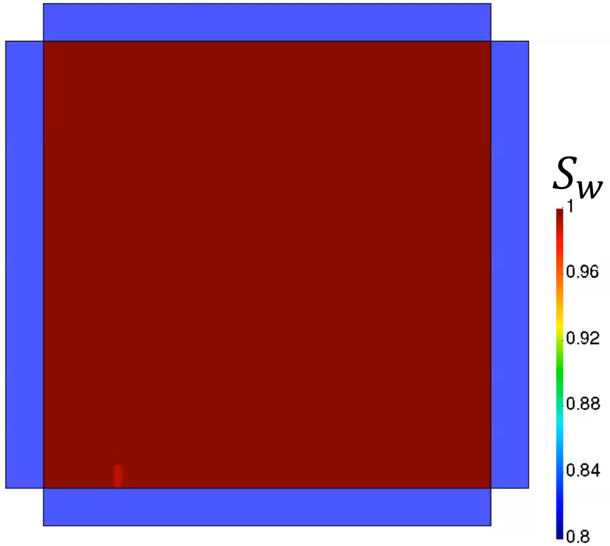
Gas injection pressure



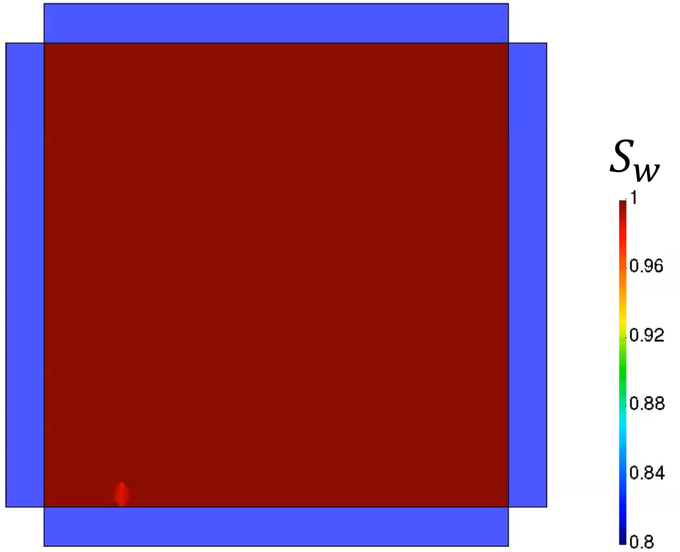
Gas outflow



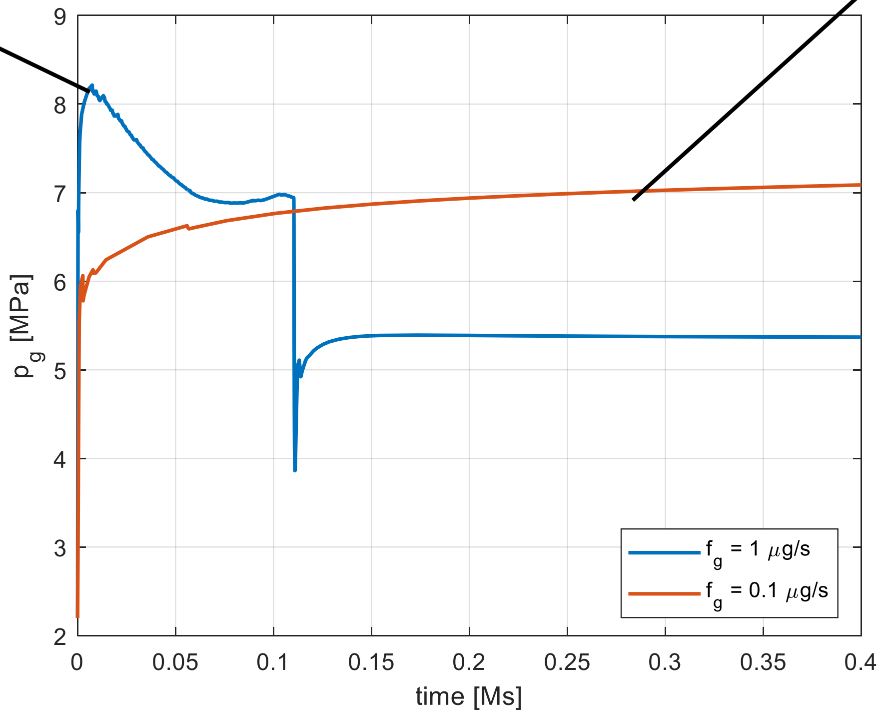
FREE CRACKING PATH



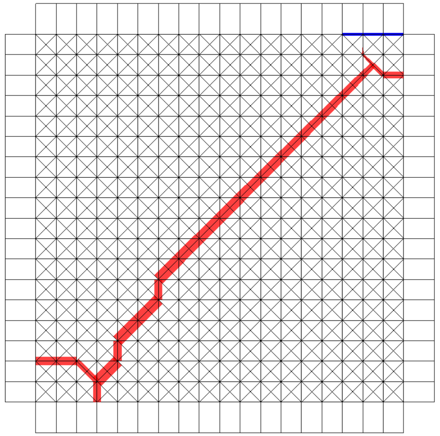
$f_g = 1\ \mu\text{g/s}$



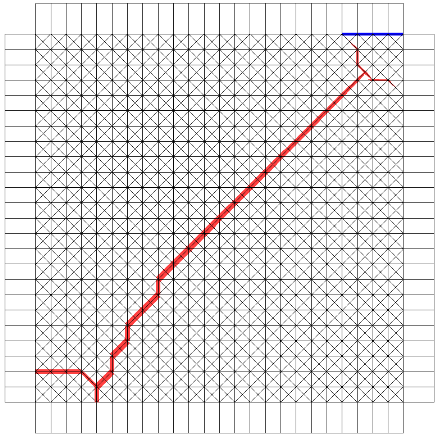
$f_g = 0.1\ \mu\text{g/s}$



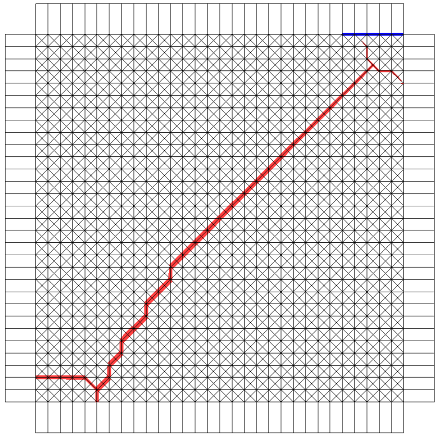
FREE CRACKING PATH: MESH SENSITIVITY



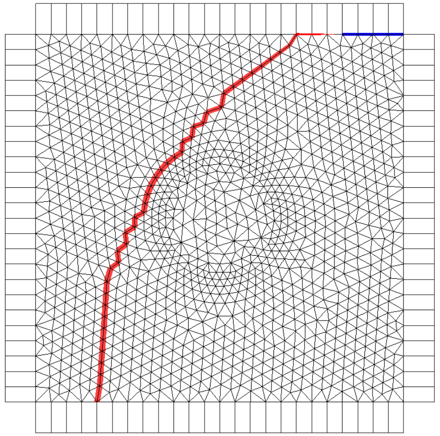
Mesh 18s



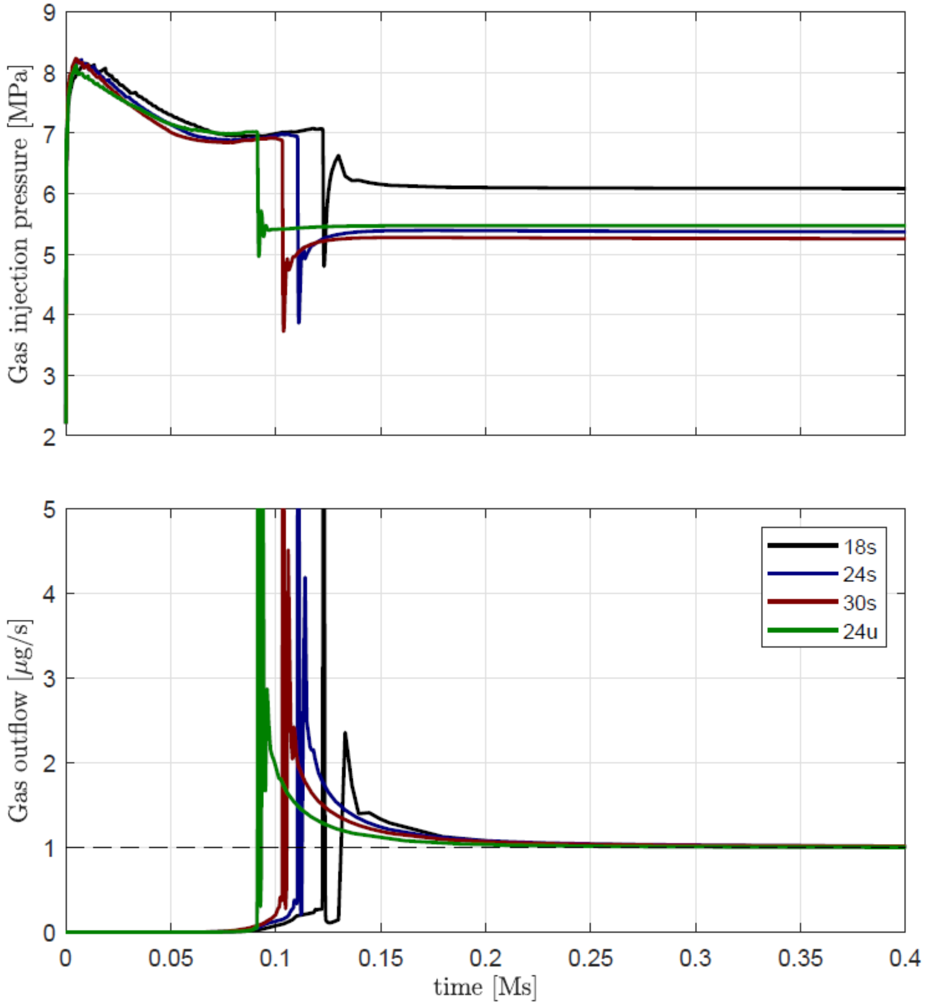
Mesh 24s



Mesh 30s



Mesh 24u



MODELLING RESULTS

“2D” Gas fracturing tests (BGS)

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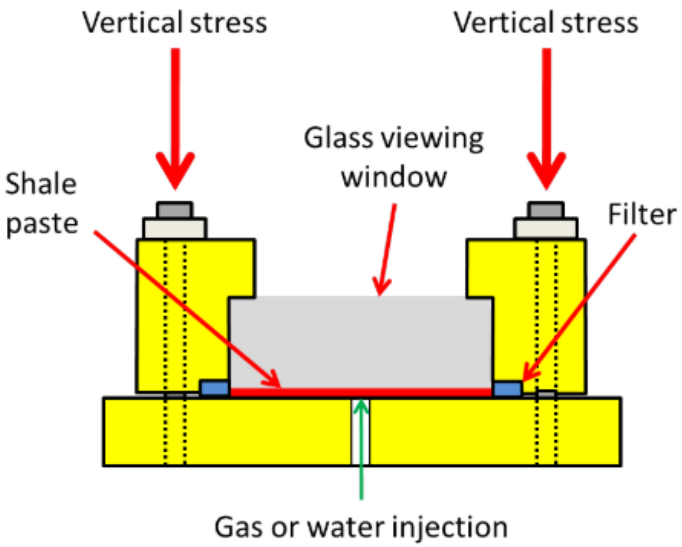
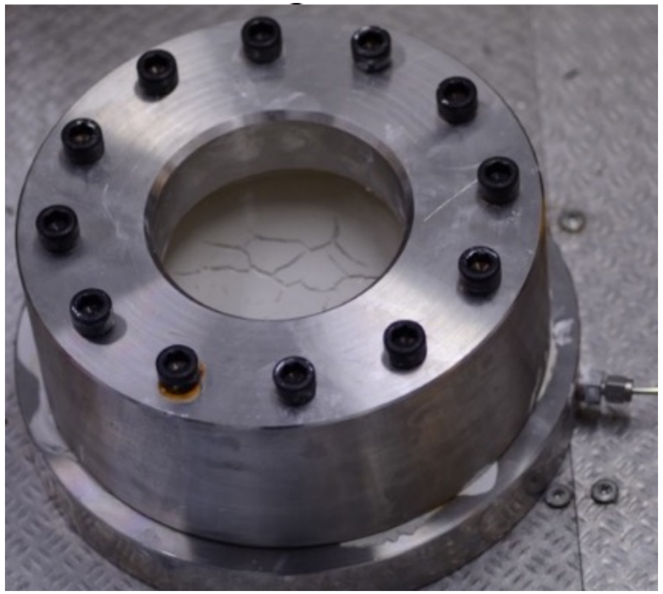
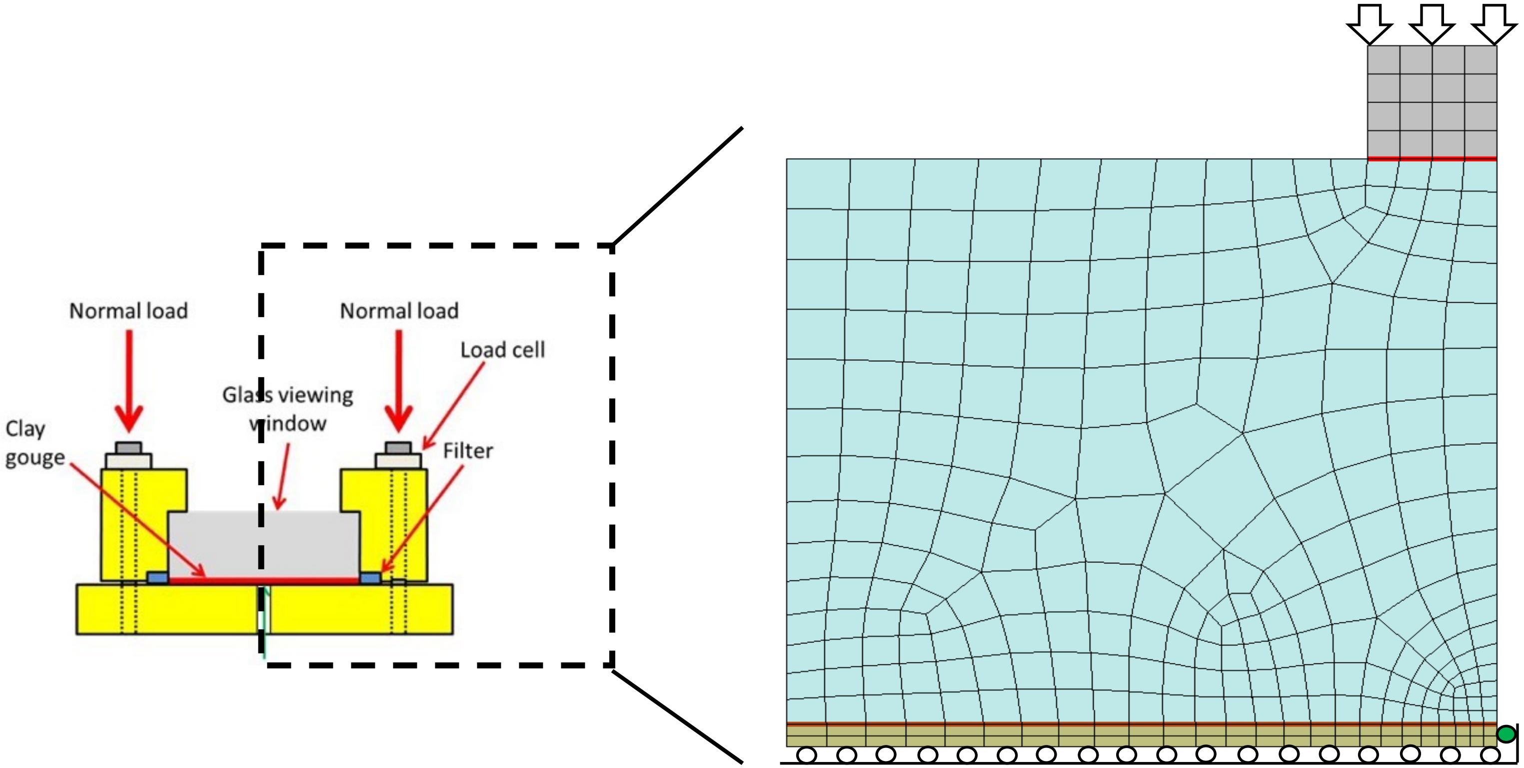
BGS FRACTURE VISUALIZATION RIG Wiseall, Cuss, Graham & Harrington (2015)



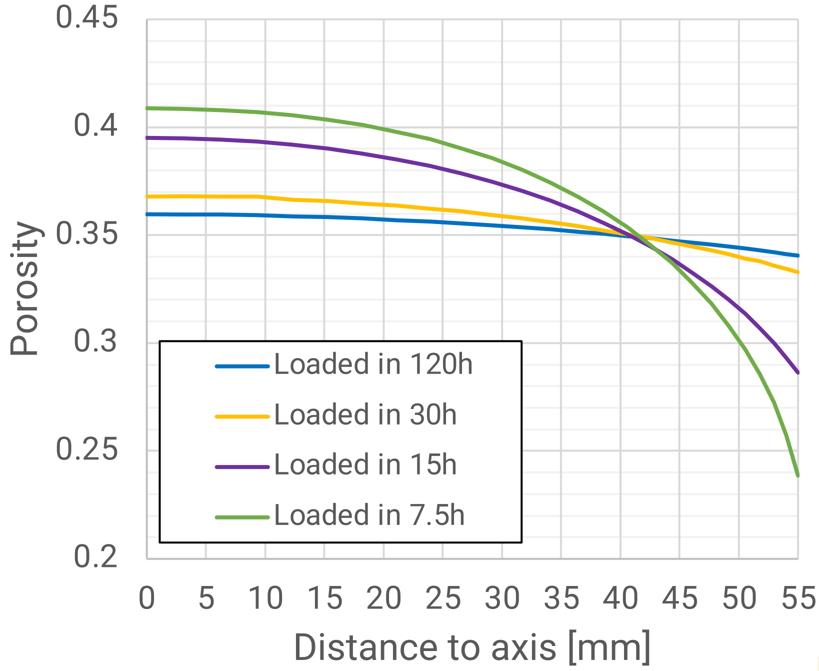


- Gas fractures developed under approx. plane strain conditions
- Crack propagation can be observed as gas is injected

MODEL GEOMETRY, FE MESH AND INITIAL CONDITIONS

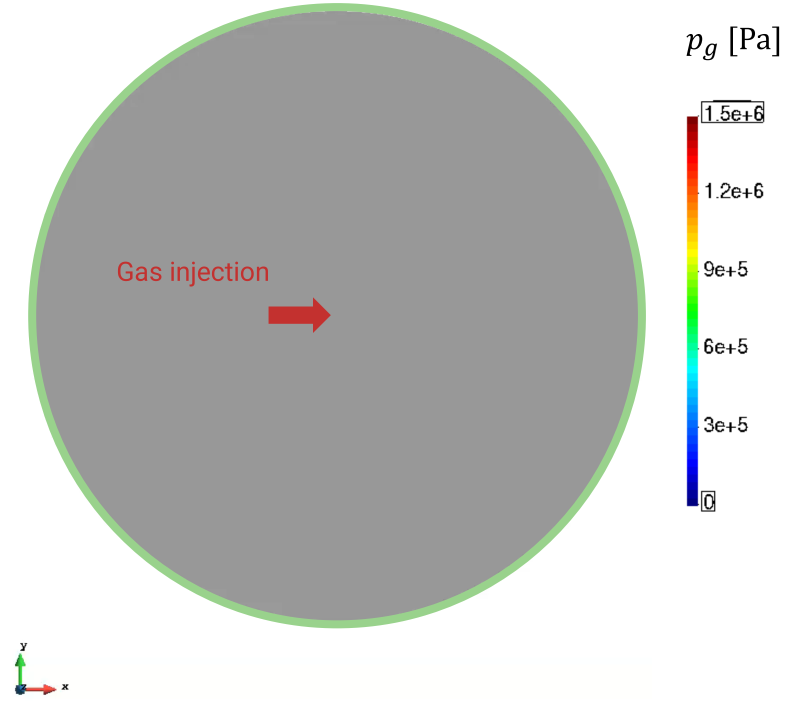


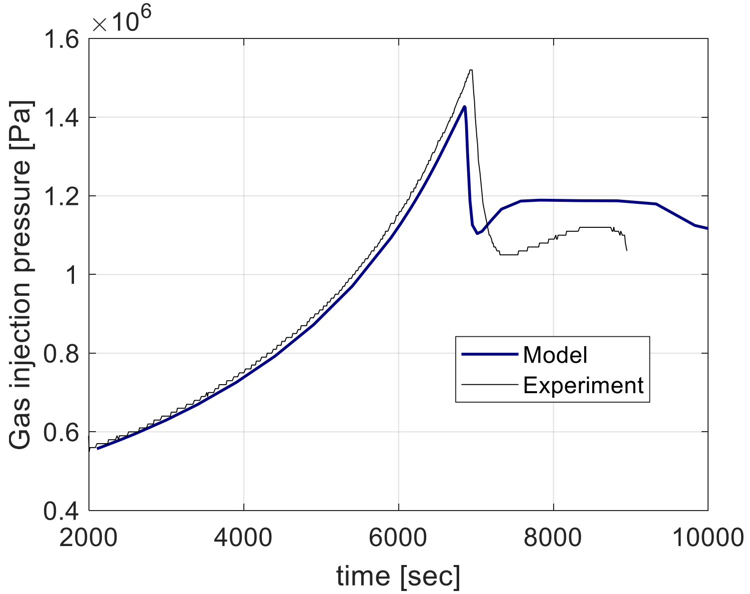
Vertical loading simulation

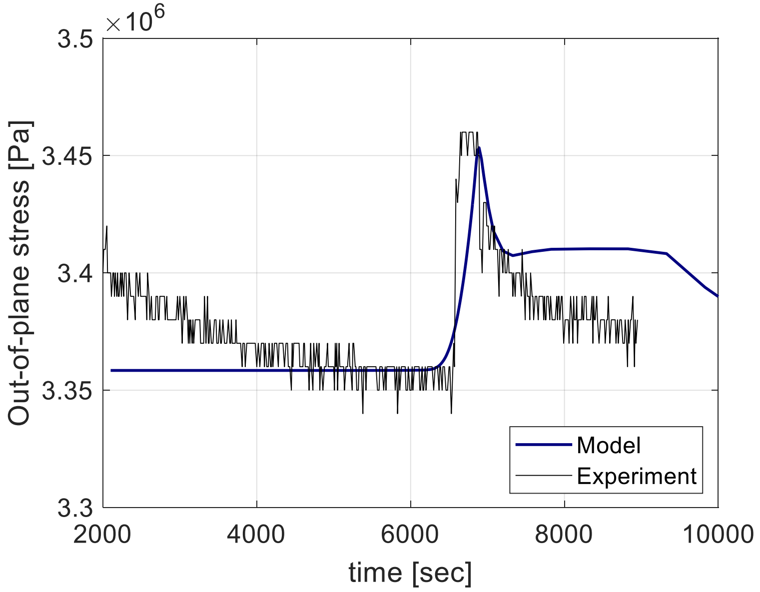


GAS FRACTURING SIMULATIONS

Back-pressure







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CONCLUSIONS

- The proposed FEM+z approach can simultaneously simulate
  - Diffusion/advection of dissolved gas and two-phase flow both in the continuous porous medium

  and

  - Gas flow along/across macroscopic cracks induced and propagated by the gas pressure.
- Self-sealing is achieved automatically when the induced cracks close as the gas pressure is reduced.
- Experimental observations are qualitatively reproduced by the model.
- The explicit representation of discontinuities (e.g., fractures, joints, faults, material interfaces, etc.) allows a more detailed study of the effect of these features in the overall pneumo-hydro-mechanical behaviour of the clay barriers.

REMARK

Dialogue between experimentalists and modellers is crucial to better understand the observed behaviour and the impact of testing equipment and protocols… especially when dealing with gas!

- Realistic representation of clay-experimental device interfaces and boundary conditions is important as these may have a significant influence on the results.
- In addition to the gas injection, simulation of the initial conditioning of the sample, as well as the dismantling process may be necessary to explain experimental observations.

REFERENCES

- Liaudat J., Dieudonné A.C. and Vardon P.J. (2023) Modelling gas fracturing in saturated clay samples using triple-node zero-thickness interface elements. Computers and Geotechnics 154, 105128.