

Analysis of hydro-mechanical response under deep geological conditions

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Background

- The underground storage of gases plays a key role in energy transition strategies (cf Fig 1.a,b for different applications). To avoid fracturations or micro-seisms, every project must define the maximum injection and reservoir pressures according to local geo-mechanical constraints.

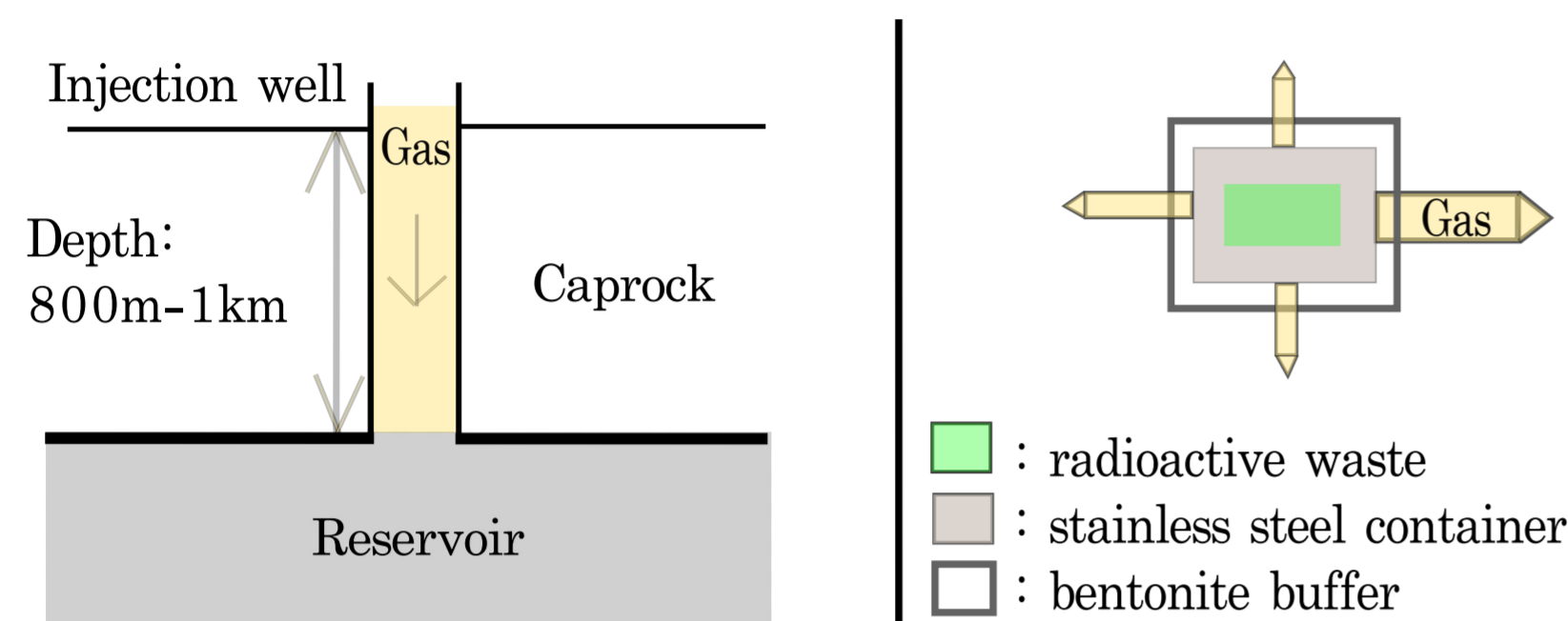


Figure 1.a: CO₂ or H₂ storage: gas injection

Figure 1.b: Nuclear waste disposal application: gas release by corrosion of metallic containers

- Most countries require operating pressures that remain below fracturing values and within safety margins.

Motivation

- The objective of this project is to determine three key coefficients that allow engineers to predict changes in water saturation (A), stress in the rock (B), and water pore pressure (C), knowing the variation of the gas pore pressure.

Analytical formulation

- Coefficients to determine:

$$A = \frac{\Delta S_r}{\Delta u_g}, B = \frac{\Delta \sigma}{\Delta u_g}, C = \frac{\Delta u_w}{\Delta u_g}$$

$u_{g/w}$: Pore gas/ water pressure (Pa)

S_r : Degree of saturation of water (dimensionless)

σ : Total stress of the rock (Pa)

- Key boundary conditions are imposed:

1) Pore water cannot leave the control volume (undrained condition).

2) Pore gas can enter or leave the control volume (drained condition).

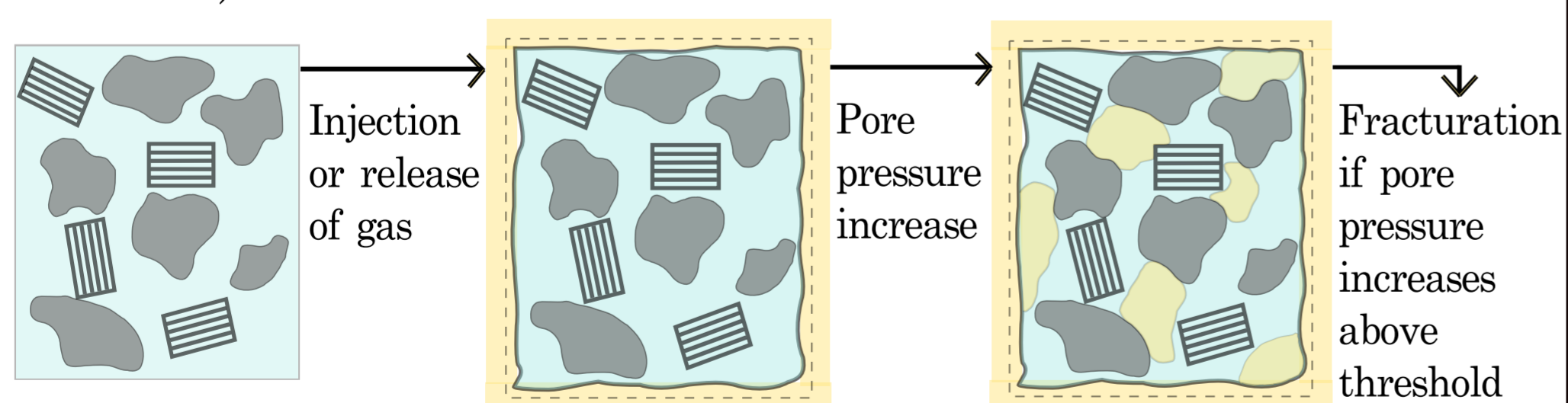


Figure 2.a: Saturated rock ($S_r=1$) before injection or release of gas

Figure 2.b: Saturated rock with pore water and grains but with pore gas at the boundary

Figure 2.c: Rock with pore water, grains and pore gas inside

: clay particle
 : pore gas
 : grains
 : undrained boundary for the water
 : drained boundary for the gas

- Assumptions:

- 1) Medium is linear, elastic, homogeneous, and isotropic
- 2) Gas injection or release occurs sufficiently fast so that the process is undrained with respect to pore water
- 3) Isothermal conditions are assumed throughout the process

- Data input:

K : Bulk modulus of the rock (Pa)

α : Biot coefficient (dimensionless)

C_g : Coefficient of compressibility of gas (Pa^{-1})

C_w : Coefficient of compressibility of water (Pa^{-1})

$\zeta = \Delta S_r / (\Delta u_w - \Delta u_g)$: (Pa^{-1})

n : Initial porosity of the soil (dimensionless)

- System of coupled equations solved with Python:

$$\begin{cases} B - (\alpha S_r + n S_r C_w K) C + \alpha (u_g - u_w) A = -n(1 - S_r) C_g K - \alpha (S_r - 1) \\ A = \zeta (C - 1) \\ A = -S_r C_w C - \frac{S_r}{nK} [B - \alpha S_r C + \alpha (u_g - u_w) A + \alpha (S_r - 1)] \end{cases}$$

Results and Discussion

- Baseline simulation: $C_g = 5.10^{-7} \text{ Pa}^{-1}$, $T = 313 \text{ K}$

$A = 1,246.10^{-7} \text{ Pa}^{-1}$, $B = 0,875$, $C = 1,000$

- Δu_g is equal to Δu_w .

- A being close to zero means that the variation of the degree of saturation is negligible compared to Δu_g so only a small volume of water is displaced by gas.

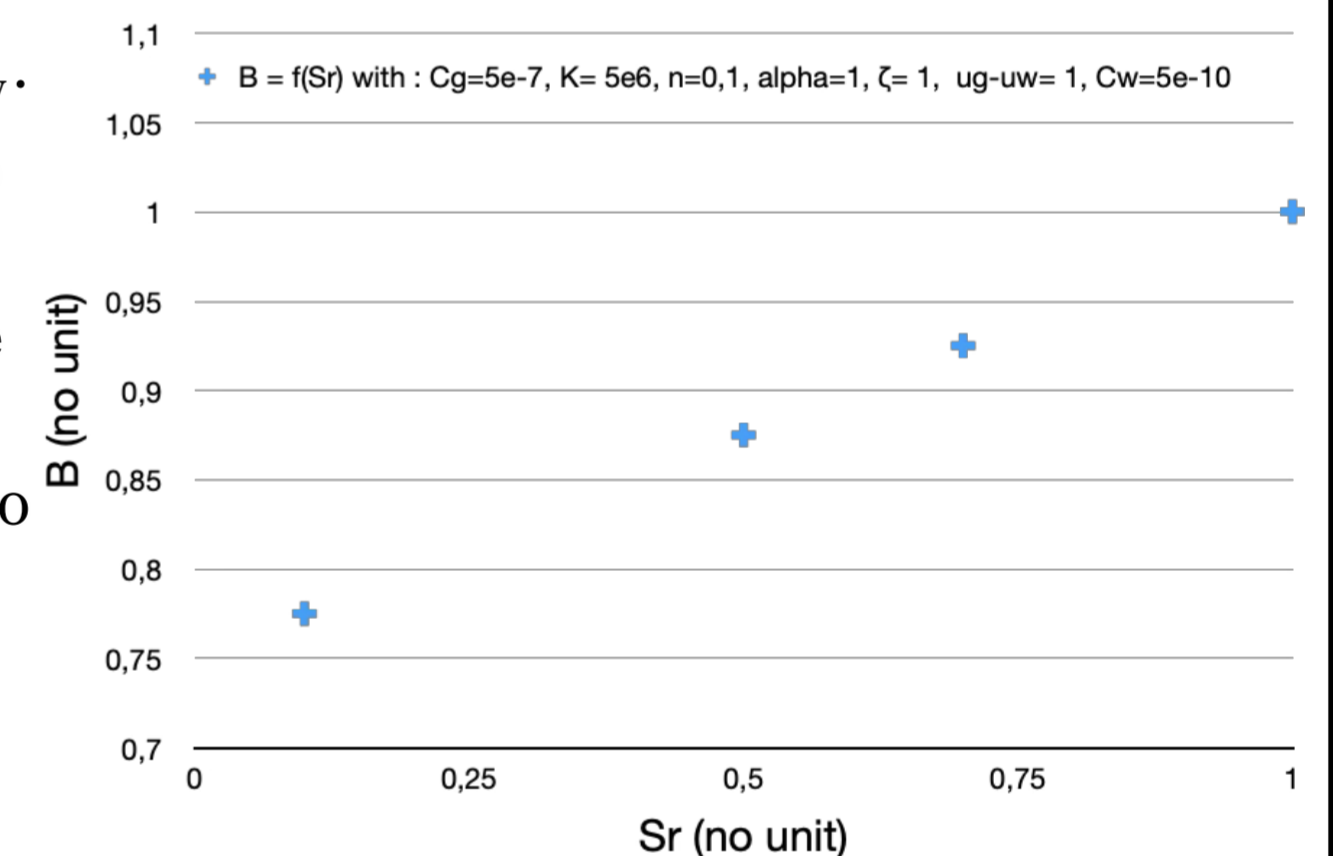


Figure 3: B as a function of S_r

- When S_r increases, less pore gas is present initially, as gas is more compressible than water, the stress applied to the rock is higher (B increases) (Fig. 3). For the same reason, when C_g increases, B decreases (Fig. 4).

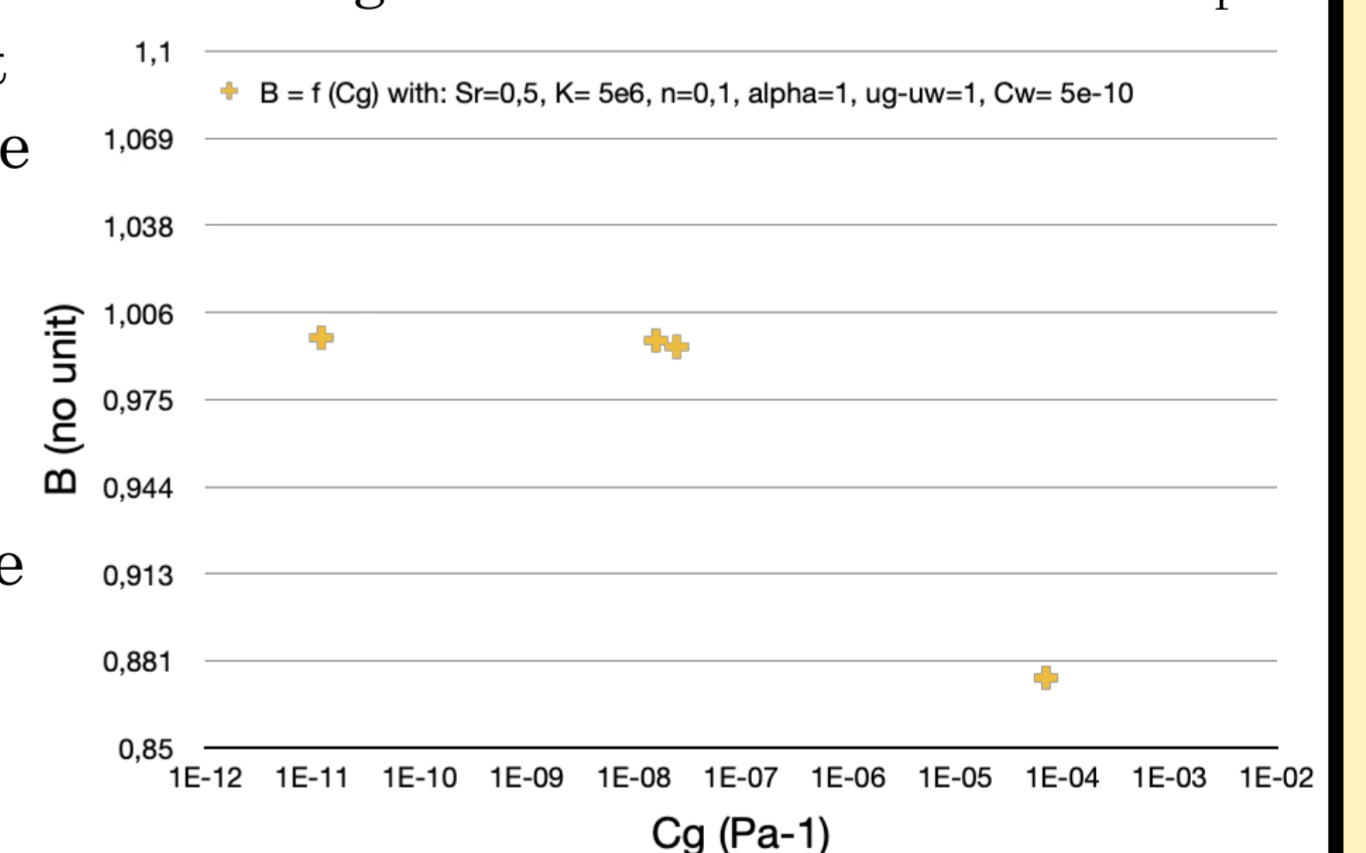


Figure 4: B as a function of C_g

Conclusion and Next steps

- The model provides a first-order tool to anticipate hydro-mechanical responses under deep geological conditions (high stresses, high pore pressures and various degree of saturation).

- Validate the analytical formulation against numerical simulations and experimental data.

- Extend the model to account for non-linear water retention curves.

- Apply the methodology to case studies in CO₂ storage, H₂ storage, and nuclear waste disposal.