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► **To cite this version:**

Pierre Sochala, Vivien Desveaux, Darius Seyedi, Jeremy Rohmer. A coupled large-scale model for hydromechanical simulation of CO₂ geological storage. SIAM Geosciences 2011, Mar 2011, Long Beach, United States. hal-00606982

HAL Id: hal-00606982

<https://brgm.hal.science/hal-00606982v1>

Submitted on 7 Jul 2011

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A coupled large-scale model for hydromechanical simulation of CO_2 geological storage

P. Sochala*, V. Desveaux*, J. Rohmer*, and D. Seyedi*

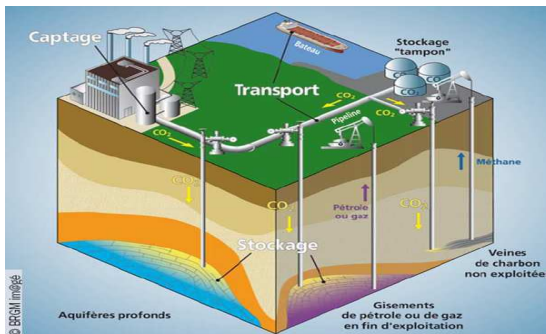
* BRGM (French Geological Survey)
Natural Risks and Safety of CO_2 storage
Orléans

SIAM Geosciences 2011
March 21 - 24, Long Beach



General introduction

Greenhouse gas emissions \Rightarrow Global warming



CO₂ injection \Rightarrow reservoir overpressure \Rightarrow caprock damage or fault reactivation ?

General introduction

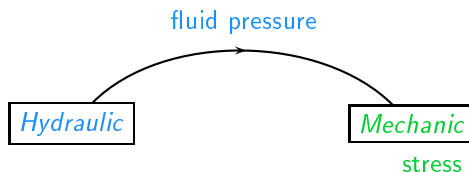
Hydraulic

Mechanic

Hydromechanical modeling of CO_2 sequestration

- ▶ Tough2 - FLAC^{3D} → *Rutqvist et al.*
- ▶ ToughReact - FLAC^{3D} → *Taron et al.*
- ▶ Modified CODE_BRIGTH → *Vilarrasa et al.*
- ▶ ATH2VIS → *Mainguy et al.*

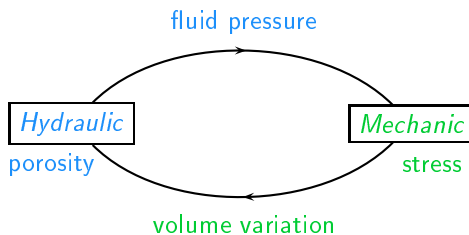
General introduction



Hydromechanical modeling of CO_2 sequestration

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General introduction



Hydromechanical modeling of CO_2 sequestration

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Geohydrological system

- ▶ Two-phase γ (liquid, gaz) and two-component χ (water, CO_2) flow
- ▶ **Mass conservation** of χ with a source term S_χ

$$\partial_t \left(\varphi \sum_{\gamma} \rho_{\gamma} s_{\gamma} \omega_{\chi, \gamma} \right) + \nabla \cdot \left(\sum_{\gamma} \omega_{\chi, \gamma} \mathbf{F}_{\gamma} \right) = S_{\chi}$$

φ porosity, ρ_{γ} density, s_{γ} saturation, $\omega_{\chi, \gamma}$ mass fraction of χ in γ

- ▶ **Darcy's law**

$$\mathbf{F}_{\gamma} = -\rho_{\gamma} \frac{k_i k_{r, \gamma}}{\mu_{\gamma}} (\nabla p_{\gamma} - \rho_{\gamma} g \mathbf{e}_z)$$

k_i porous media intrinsic permeability, $k_{r, \gamma}$ relative permeability
 μ_{γ} dynamic viscosity, p_{γ} pressure

- ▶ Hydraulic relations \rightarrow *Van-Genuchten80, Mualem76*
 Thermodynamic equilibrium \rightarrow *Spycher&Pruess05*

Mechanical equations

► Conservation of momentum

$$\nabla \cdot \sigma + \rho g e_z = 0$$

σ total stress tensor, ρ average density

► Effective stress concept

$$\sigma = \sigma' - bpl$$

σ' effective stress tensor, b Biot's coefficient, p pore pressure

► Linear elasticity

$$\sigma' = \frac{E}{1+\nu} \left(\nabla u + {}^t\nabla u + \frac{\nu}{1-2\nu} (\nabla \cdot u) I \right)$$

E Young's modulus, ν Poisson's ratio, u displacement

Coupling conditions

- ▶ **pore pressure** equal to the mean-value of the two-phase system

$$p = \sum_{\gamma} s_{\gamma} p_{\gamma}$$

- ▶ **permeability-porosity relation** \rightarrow *David05*

$$k_i = k_i^0 \left(\frac{\varphi}{\varphi^0} \right)^m$$

m empirical parameter

- ▶ **Biot's law** \rightarrow *Biot41*

$$d\varphi = b d(\operatorname{div}(u)) + \frac{1}{M} dp$$

M Biot's modulus

Tough2 and Code_Aster discretization

Tough2 → Lawrence Berkeley National Laboratory

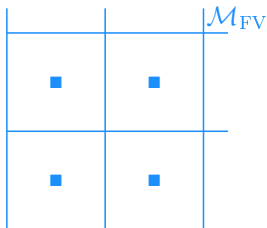
- ▶ Multi-phase fluid and heat flow in porous and fractured media
- ▶ **Finite volume** with finite difference evaluation of the flux term
Integrated Finite Difference Method → *Narasimham76*
- ▶ Euler implicit scheme
- ▶ Newton Raphson Algorithm

Code_Aster → EDF (French Electricity Compagny)

- ▶ Non-linear models of mechanical phenomena
- ▶ **Finite element**

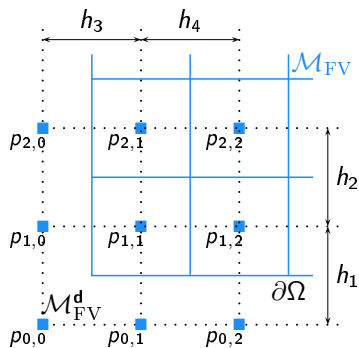
Transfer operator $\mathcal{T}_{FV \rightarrow FE}$ for pressure field

step 1 - construction of a dual mesh



Transfer operator $\mathcal{T}_{FV \rightarrow FE}$ for pressure field

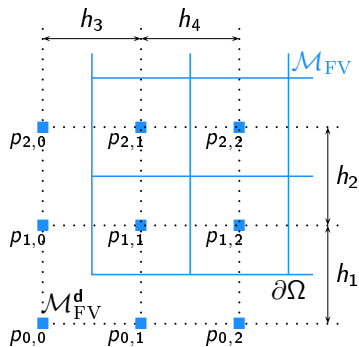
step 1 - construction of a dual mesh



$$\rho_{0,i} = p_{1,i} + \frac{h_1}{h_2}(p_{1,i} - p_{2,i})$$

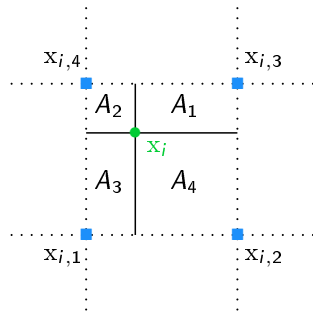
Transfer operator $\mathcal{T}_{\text{FV} \rightarrow \text{FE}}$ for pressure field

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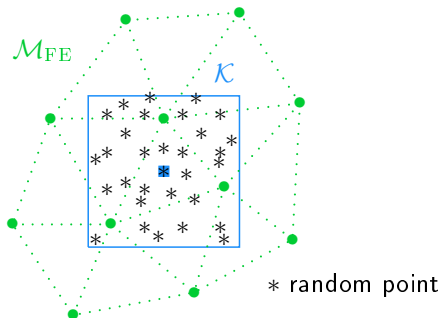
step 2 - linear interpolation



$$p_{\text{FE}}(x_i) = \sum_{k=1}^4 \frac{A_k}{A} p_{\text{FV}}(x_{i,k})$$

Transfer operator $\mathcal{T}_{\text{FE} \rightarrow \text{FV}}$ for porosity field

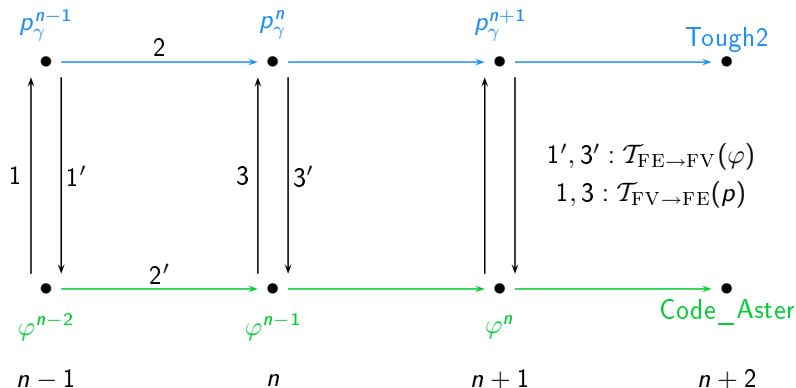
Mean-value of φ on \mathcal{K} estimated by MC



$$\varphi_{\text{FV}}|_{\mathcal{K}} = \frac{1}{N} \sum_{j=1}^N \varphi_{\text{FE}}(x_j)$$

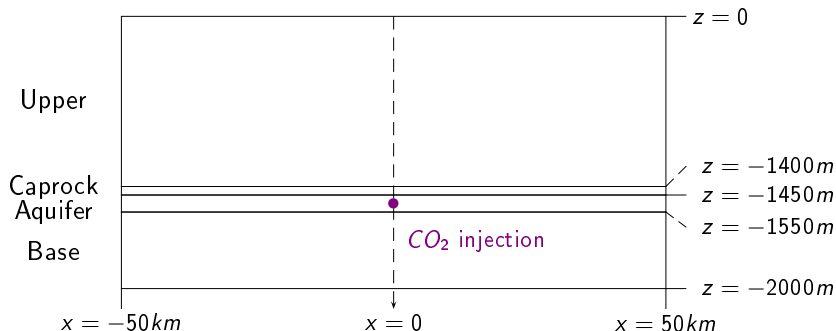
Time coupling

Conventional Parallel Staggered algorithm \rightarrow *Piperno et al 95*



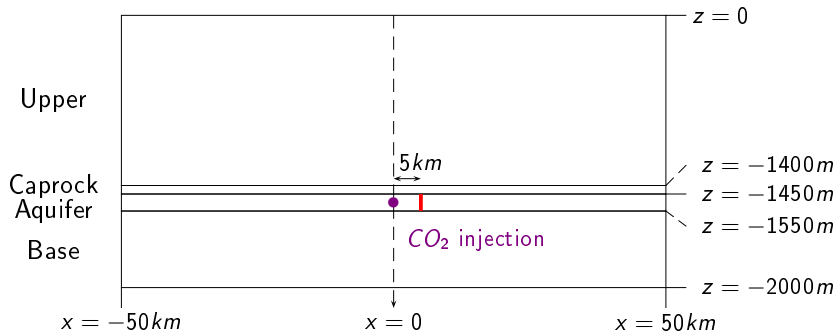
Test case presentation

- ▶ CO_2 injection by horizontal well in deep aquifer
- ▶ 2D geometry $\Omega = [-50km, 50km] \times [0, -2km]$ and $T = 5years$
- ▶ $S_{CO_2} = 500t/m/year$
- ▶



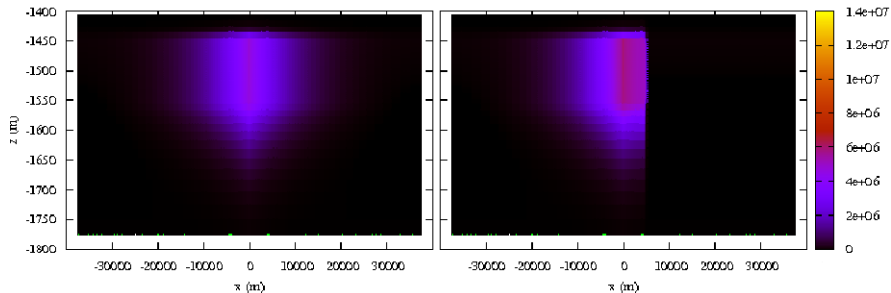
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- ▶ $S_{CO_2} = 500t/m/year$
- ▶ impact of a sealing fault near the injection zone



Overpressure (Pa)

t=1 year

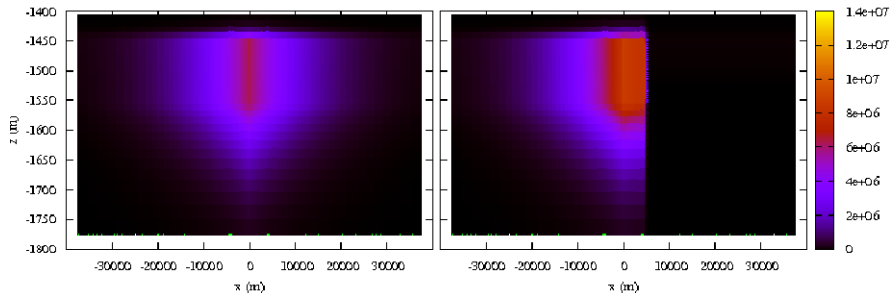


Initial case

Perturbated case

Overpressure (Pa)

t=2 years

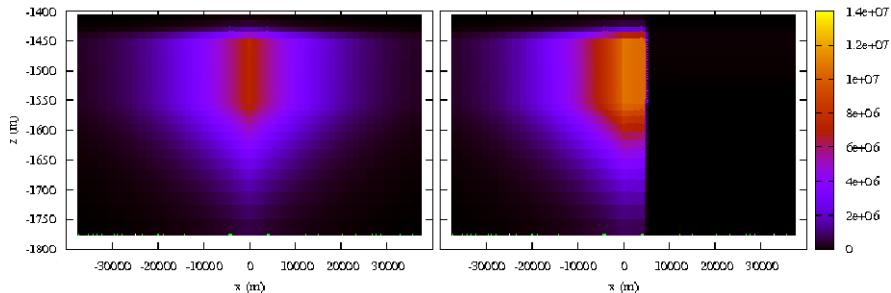


Initial case

Perturbated case

Overpressure (Pa)

t=3 years

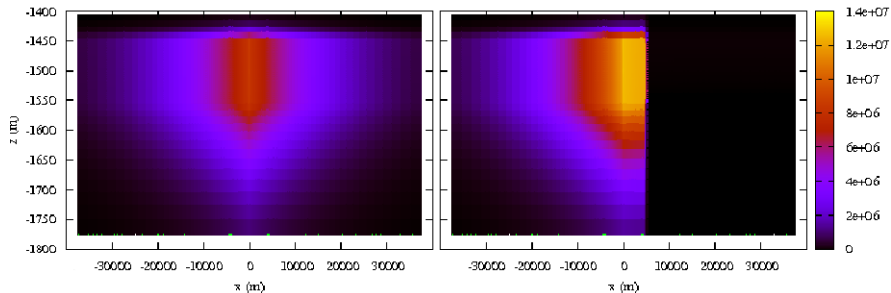


Initial case

Perturbated case

Overpressure (Pa)

t=4 years

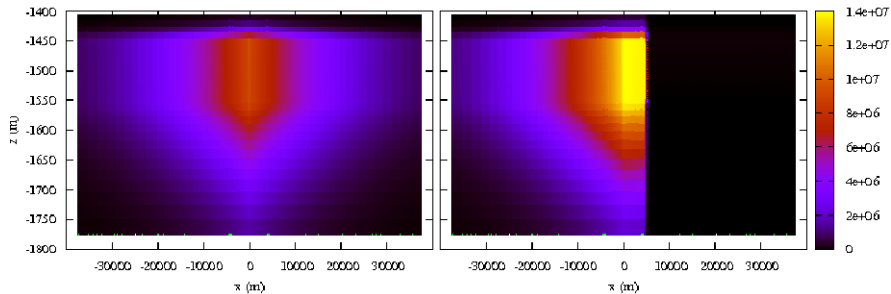


Initial case

Perturbated case

Overpressure (Pa)

t=5 years

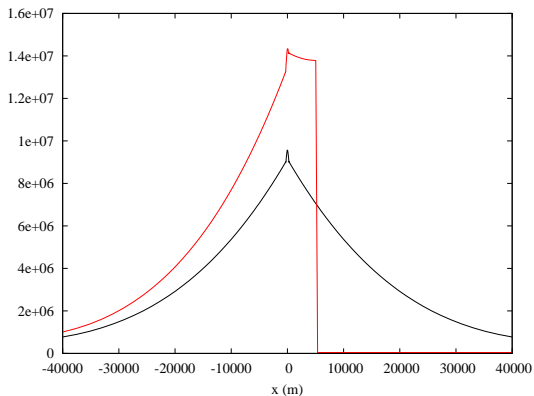


Initial case

Perturbated case

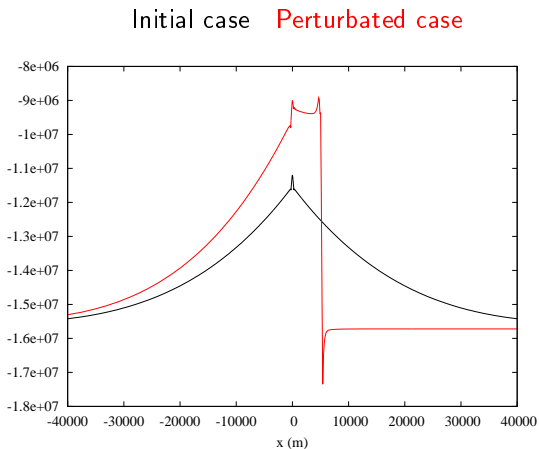
Overpressure in the aquifer (Pa)

Initial case Perturbated case



Increase of 40% of the overpressure at 5 years

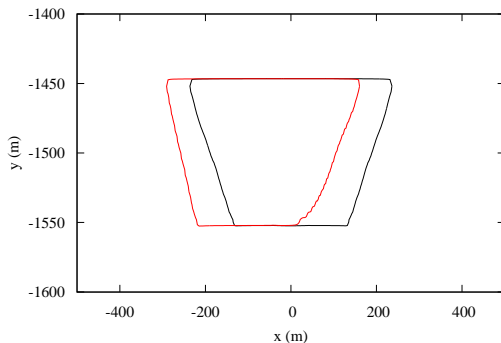
Horizontal effective stress change due to injection (Pa)



More change in effective stress

CO₂ plume

Initial case Perturbated case



Displacement at the opposite side of the fault

Conclusion

- ▶ robust method to transfer fields between different meshes
- ▶ efficient parallel time coupling algorithm
- ▶ significant increase of the overpressure due to the impermeable fault

Further work

- ▶ tensile and shear stress failure criteria → sustainable pressure
- ▶ non-linear constitutive law of the geological formation
- ▶ more realistic geometry