3D Geomechanical Modelling of CO2 Storage with focus on Fault Stability

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INTRODUCTION

A digital twin of the subsurface is crucial for all performance and risks assessments of a CO_2 storage activities. The goal of the project is to develop an efficient fully-coupled geomechanical simulator for CO_2 storage capable to model fluid flow along cracks and faults and their associated opening and slip. To reach this goal, we extend the open-source finite element library Akantu [1] to simulate the time-dependent hydro-mechanical changes associated with CO_2 injection. Thanks to the high-performance computing capabilities of Akantu, the solver will allow to represent the complete three-dimensional geological structure of a site including the presence of natural fractures and faults whose reactivation potential is critical to assess.

GOVERNING EQUATIONS

Geological formations comprise porous and permeable rock matrix saturated with fluids and gases. Deformations of the solid phase are strongly coupled to the evolution of pressure. In the first stage, we model rock as an isotropic poroelastic material, faults having constant permeability, and approximate the CO_2 flow by single-phase transient flow equation. Deformations of the bulk porous medium and evolution of pressure are governed by following equations:

- Balance of momentum $\quad \nabla \cdot \boldsymbol{\sigma}(u,p) + \mathbf{f} = 0$
- Fluid mass conservation $\quad \dfrac{\partial \zeta(u,p)}{\partial t} + \nabla \cdot \mathbf{q}(u,p) = \gamma$
- Constitutive equations (w.r.t. the initial state)
  - Stress state $\quad \boldsymbol{\sigma} = \mathbb{C}\boldsymbol{\varepsilon}(u) - \alpha p \mathbb{I}$
  - Variation in fluid content $\quad \zeta = \alpha \boldsymbol{\varepsilon}(u) : \mathbb{I} + \dfrac{1}{M} p$
  - Darcy flow $\quad \boldsymbol{q} = -\boldsymbol{\kappa}(u,p)\nabla p$

Opening and slip of the faults and cracks as well as evolution of pressure along them are governed by the following set of equations:

- Continuity of tractions $\quad \boldsymbol{\sigma}'(u,p)\boldsymbol{n} = -\boldsymbol{t}$
- Lubrication flow $\quad \dfrac{\partial w}{\partial t} + w S_f \dfrac{\partial p_f}{\partial t} + \boldsymbol{\nabla}_{\parallel} \cdot (w \boldsymbol{q}_{\parallel}) = \gamma_f$
  - Fault traction $\quad \boldsymbol{t} = \begin{cases} 0 & \text{if } \delta_n > 0 \\ \mathcal{N}(\boldsymbol{\delta}) & \text{if } \delta_n \leq 0 \end{cases}$
  - Coulomb friction $\quad ||\boldsymbol{t_s}|| \leq f \sigma'_n$
  - Darcy flow in 2D $\quad \boldsymbol{q}_{\parallel} = -\boldsymbol{\kappa}_f(w,p)\nabla_{\parallel} p_f$

After implicit time integration, we obtain the following coupled system of equations:

$$\begin{bmatrix} \mathbb{K} & \mathbb{A}_{p\to u} \\ \mathbb{A}_{u\to p}/\Delta t & \mathbb{S}/\Delta t + \mathbb{C} \end{bmatrix} \begin{bmatrix} \partial u \\ \partial p \end{bmatrix} = \begin{bmatrix} f_{n+1} - \mathbb{K} u_n - \mathbb{A}_{p\to u} p_n \\ \gamma_{n+1} - \mathbb{C} p_n \end{bmatrix}$$

where **K** is the stiffness, **A** hydro-mechanical coupling, **S** storage, **C** conductivity matrix, **u** displacements, **p** pressures, **f** vector of external tractions and **γ** vector of imposed flux and fluid sources.

DISCRETISATION & SOLUTION SCHEME

Interdependent behaviour of the fluid and the rock mass is solved in a fully-coupled manner by an iterative partitioned conjugate gradient procedure [2]. Both subsystems share the same numerical mesh and are discretised with finite elements (FEs) of the 1st order. Faults and cracks are discretised with cohesive elements - zero-thickness interface elements embedded between solid elements [3]. The same element type is used to resolve the 2D fluid flow along faults, for which a 2-node interace flow formulation is adopted [4].

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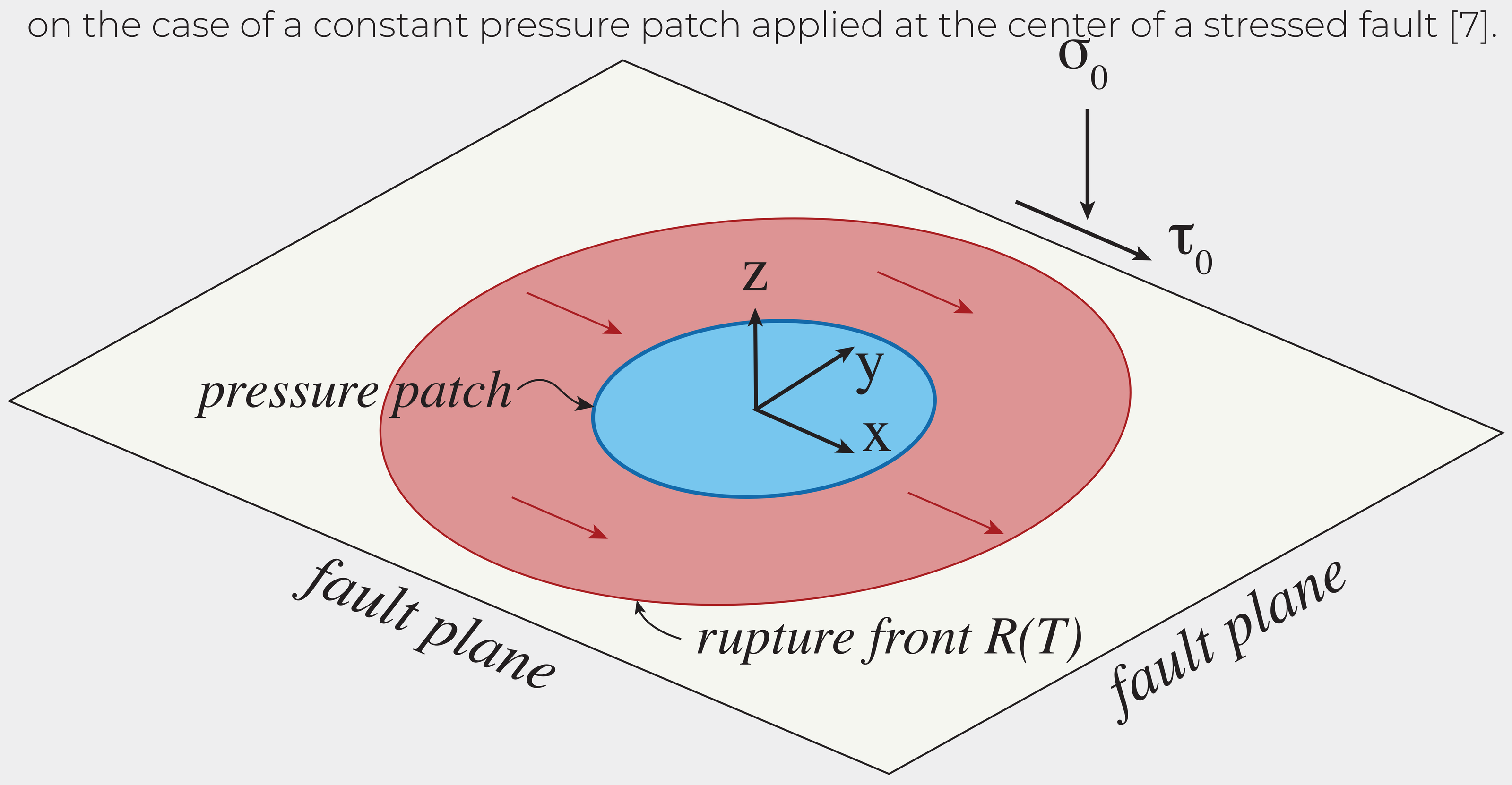
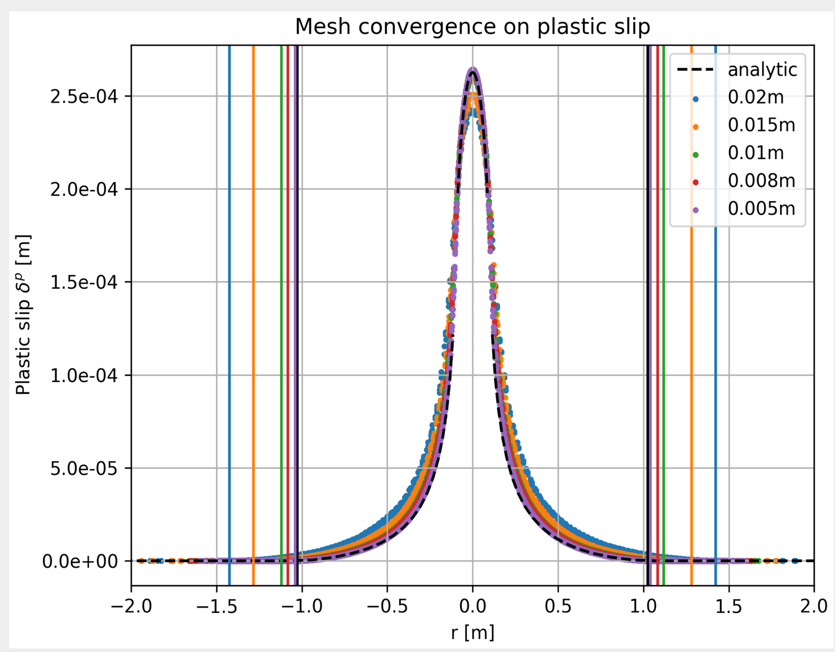
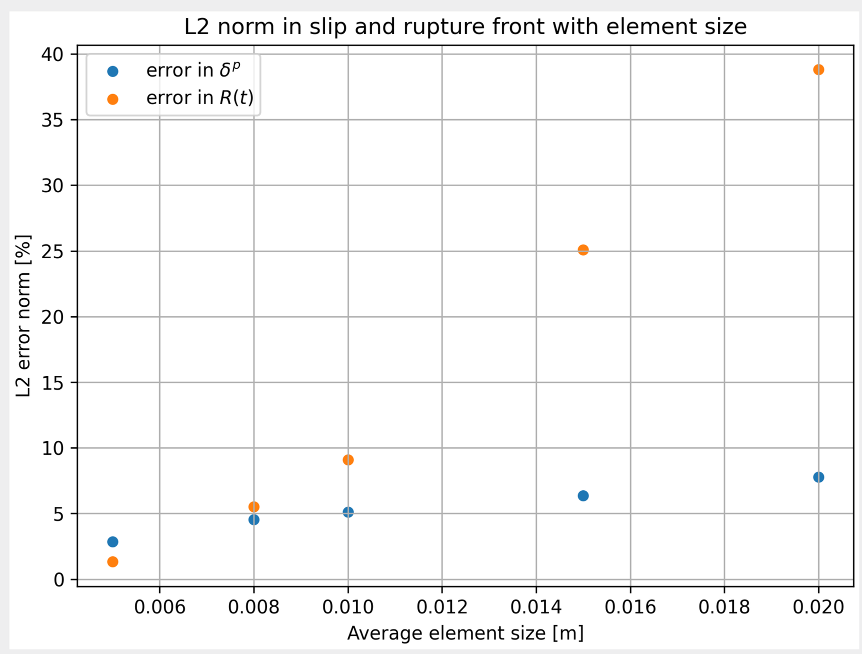
BENCHMARKING

Proposed geomechanical simulator was successfully benchmarked on analytical solutions for several solid mechanics, fluid flow and hydro-mechanical problems [5,6]. Here, we focus on the case of a constant pressure patch applied at the center of a stressed fault [7].



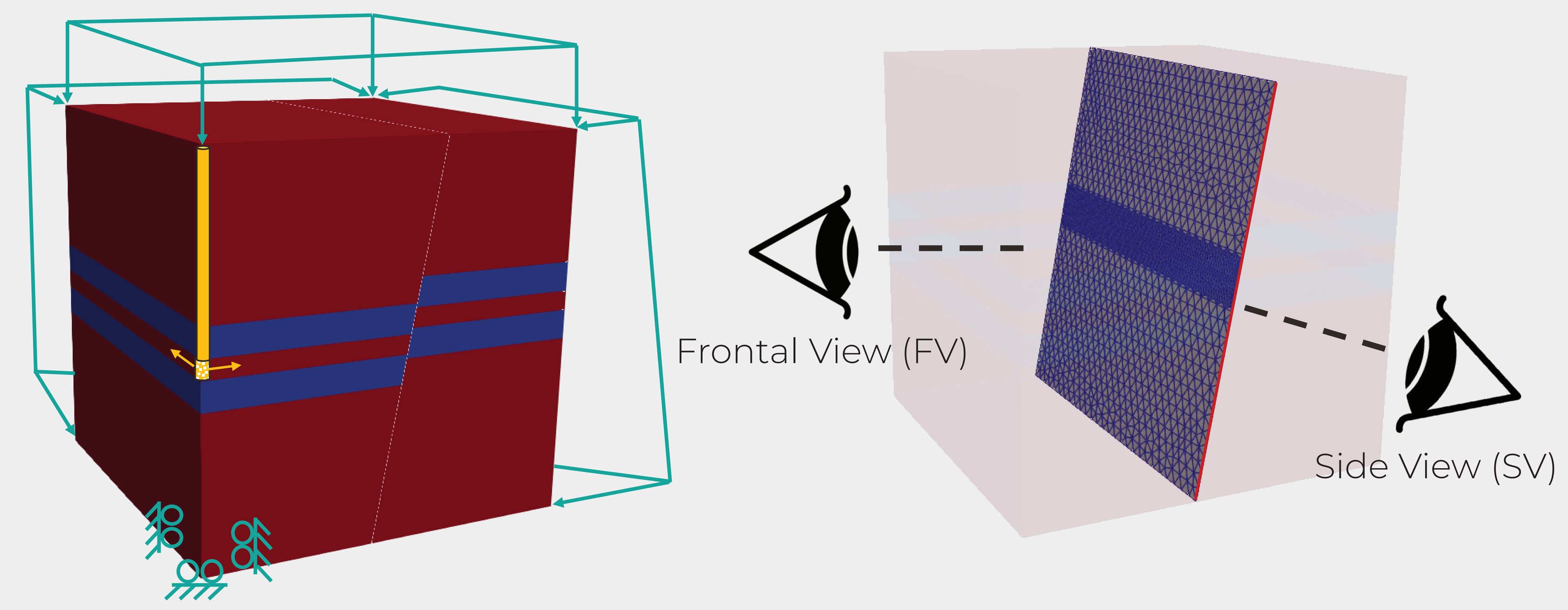
In response to the pressure increase, the fault slips starting from the center of pressure patch. Both rupture front radius and slip profile are analytically derived and compared with the numerical predictions.

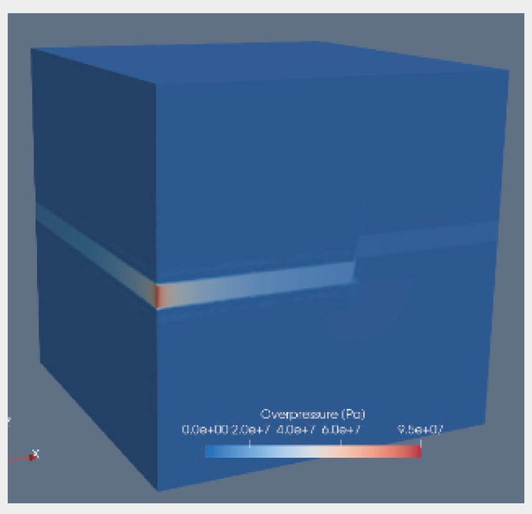




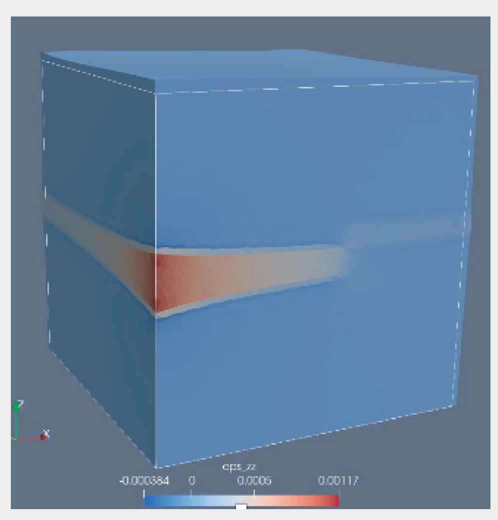
DEMONSTRATION CASE

To demonstrate capacities of the geomechanical simulator, we model fluid injection into a faulted aquifer. The aquifer is situated between two cap rocks and intersected by a normal fault which is permeable both in longitudinal and transversal direction. Only quarter of the domain is modelled. As injection continues, pressure builds up in the inner part of the aquifer and transfers to the outer part through the fault. This leads to the expansion of the aquifer and drop in the effective traction along the fault which triggers the slip.

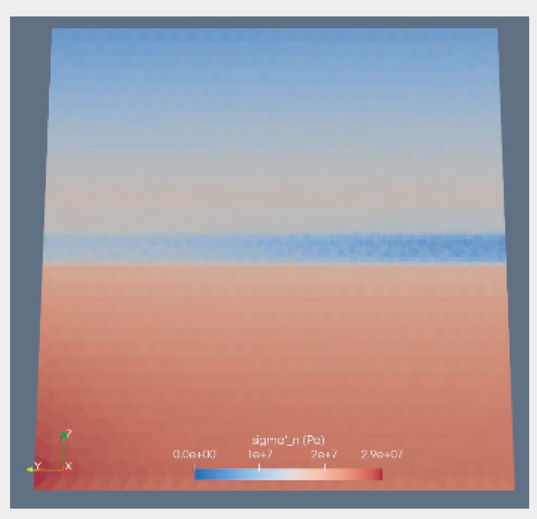




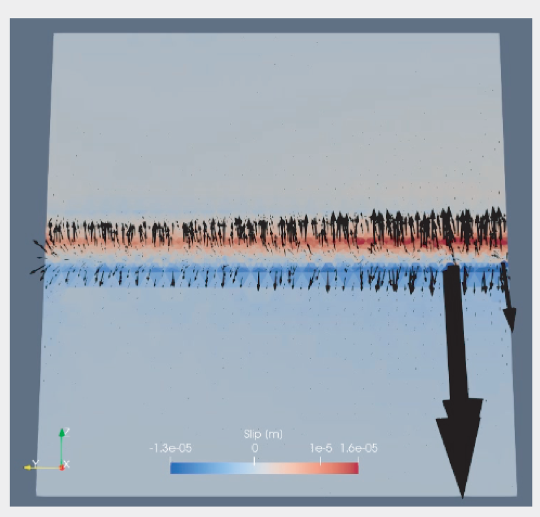
Pressure build-up



Magnified expansion



Effective traction (FV)



Total fault slip (FV)