Numerical modelling of salt caverns

Literature assessment, brainstorming

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Poromec - a 3D poroelastic solver with explicit fractures

- Poroelastic solver (non linear to cope with fracture flow)
- Validated with Terzaghi and mandel solution
- Validating now fracture mechanics (working good so far...)
- Non-structured. gmsh generates the mesh
- Integrated to cmake and parallel computing in LNCC (sdumont)

I am using the solver to a final project in geomechanics course.
The idea is to exercise homogeneization of mechanical and poroelastic parameters in a fractured media.

Mechanical equilibrium:

$$\sigma_{ij,j} = 0$$

$$\sigma_{ij} = \sigma'_{ij} - \alpha_{ij}\ p \qquad e_{kl} = \frac{1}{2}(u_{k,l} + u_{l,k})$$

$$\sigma'_{ij} = C_{ijkl}\ e_{kl} \qquad \sigma'_{ij} = C_{ijkl}\ u_{k,l}$$

Finite element formulation:

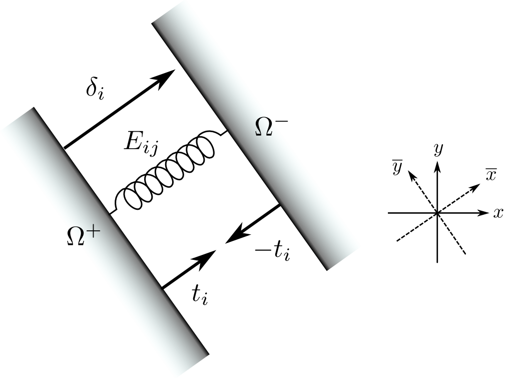
$$u_k^\gamma \int_\Omega C_{ijkl}\ \phi_{,l}^\gamma\ \psi_{,j}^\beta\ d\Omega + p^\gamma \int_\Omega \alpha\ \delta_{ij}\ \phi_{,j}\ \psi^\beta\ d\Omega = \int_\Gamma \sigma'_{ij}\ n_j\ \psi^\beta\ d\Gamma$$

Tensor rotation

$$T_{ij} = R_{ki}\ R_{lj}\ \overline{T}_{kl}$$

$$\overline{E}_{kl} = \overline{E}_{kl}(d, \overline{\delta}_l) = \begin{bmatrix} \overline{E_n} & - & - \\ - & \overline{E_s} & - \\ - & - & \overline{E_t} \end{bmatrix}$$

$$t_i = R_{ki}\ R_{lj}\ \overline{E}_{kl}\ (u_j^+ - u_j^-)$$



$$\int_\Gamma t_i\ \psi^\beta\ d\Gamma = \int_\Gamma E_{ij}\ u_j^{+\gamma} \phi^{+\gamma}\ \psi^\beta\ d\Gamma - \int_\Gamma E_{ij}\ u_j^{-\gamma} \phi^{-\gamma}\ \psi^\beta\ d\Gamma$$

Hydraulic continuity:

$$\dot{\zeta} + q_{k,k} = Q_{src}$$

$$\alpha \ \dot{\epsilon_{kk}} + S_\epsilon \ \dot{p} - \frac{\kappa}{\mu} p_{,kk} = Q_{src}$$

Finite element formulation:

$$S_\epsilon \ \dot{p}^\gamma \int_\Omega \phi^\gamma \ \psi^\beta d\Omega + \frac{\kappa}{\mu} \ p^\gamma \int_\Omega \phi^\gamma_{,k} \ \psi^\beta_{,k} \ d\Omega + \dot{u_k}^\gamma \ \alpha \int_\Omega \phi^\gamma_{,k} \ \psi^\beta \ d\Omega = \int_\Gamma q_n \ \psi^\beta \ d\Gamma$$

Poromec - formulation

Fracture hydraulics

$$q_{k,k} + \dot{\delta} = 0$$

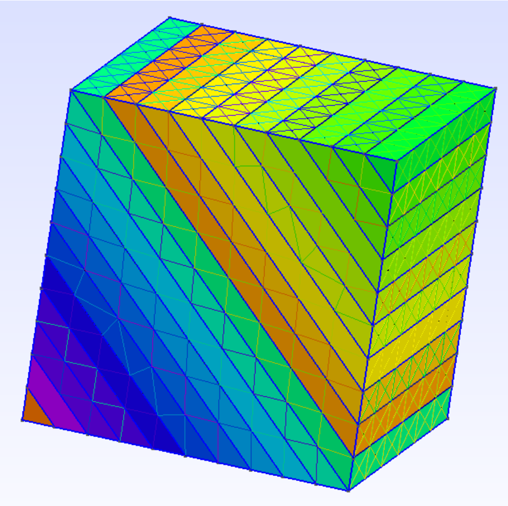
$$\overline{q_\xi} = -\frac{\delta^2}{12\mu} p_{,\xi} \quad \rightarrow \quad \int_0^\delta q_\xi \; d\eta = \frac{-\delta^3}{12\mu} p_{,\xi}$$

$$-\int_\Gamma q_k \; n_k \; \psi \; d\Gamma = \frac{1}{12\mu} \int_\xi \delta^3 \; p_{,\xi} \; \psi_{,\xi} \; d\xi + \int_\Gamma \dot{\delta} \; \psi \; d\Gamma$$

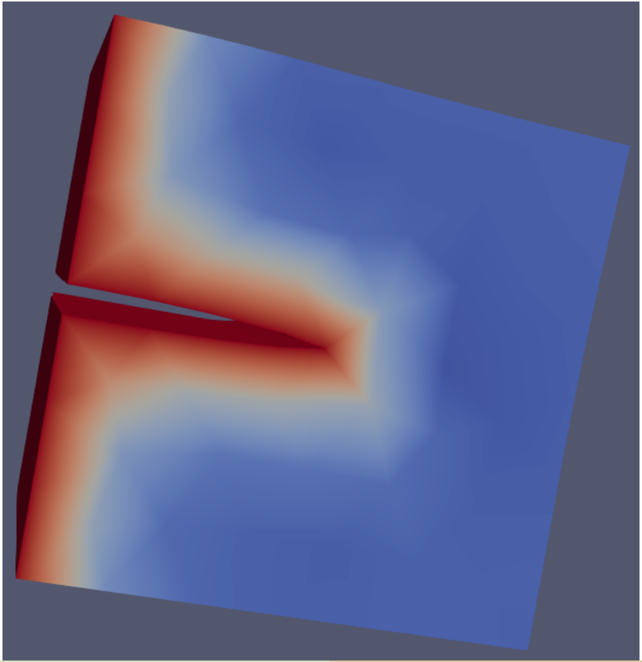
$$-\int_\Gamma q_k \; n_k \; \psi \; d\Gamma = \frac{1}{12\mu} \int_\xi \kappa \; p_{,\xi} \; \psi_{,\xi} \; d\xi + \int_\Gamma \dot{\delta} \; \psi \; d\Gamma$$

Results - mechanics

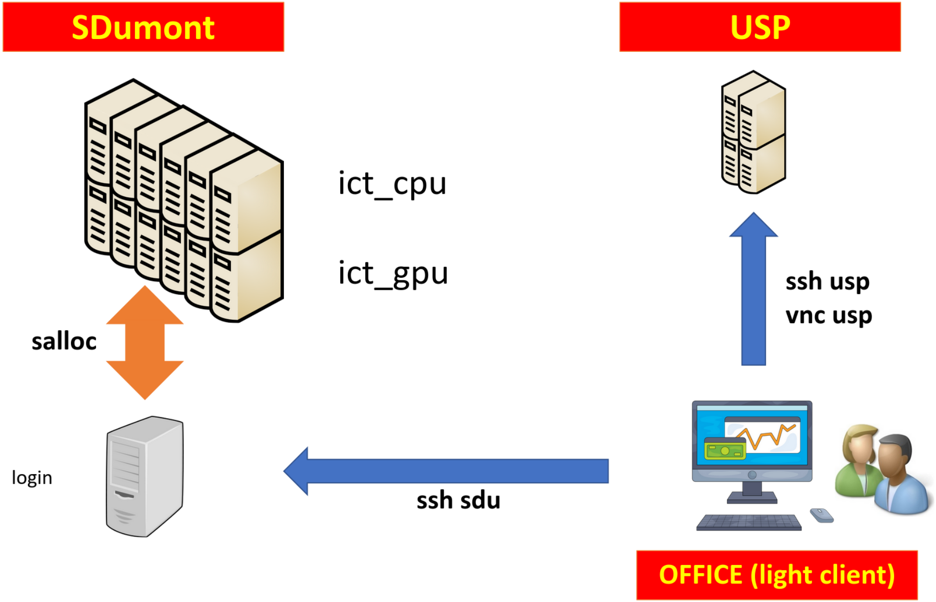
K(input):9.44e+09
K(output):2.34e+09
$\rightarrow$ 75% reduction



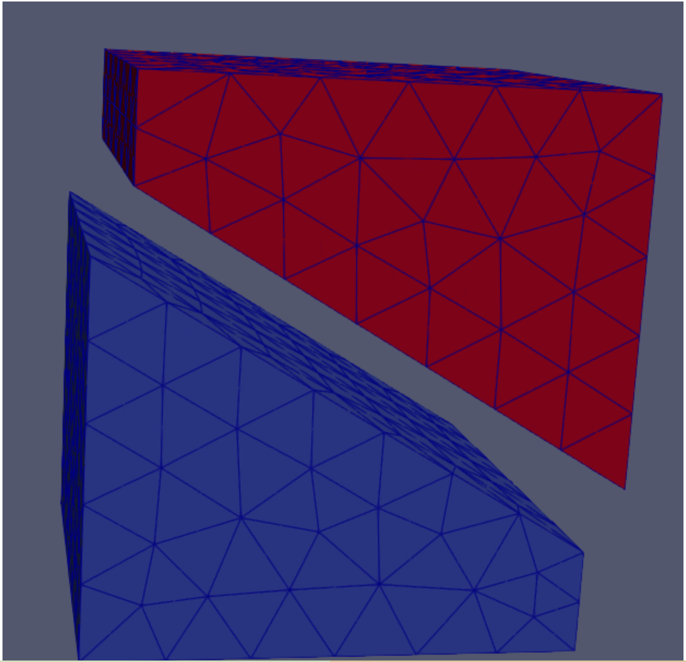
Results - hydraulics



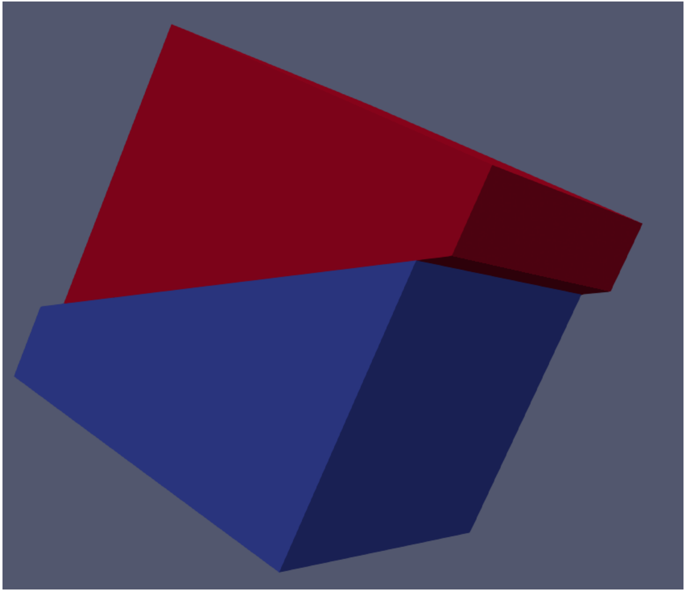
IT Setup


SDumont
USP
ict_cpu
ict_gpu
ssh usp
vnc usp
salloc
login
ssh sdu
OFFICE (light client)

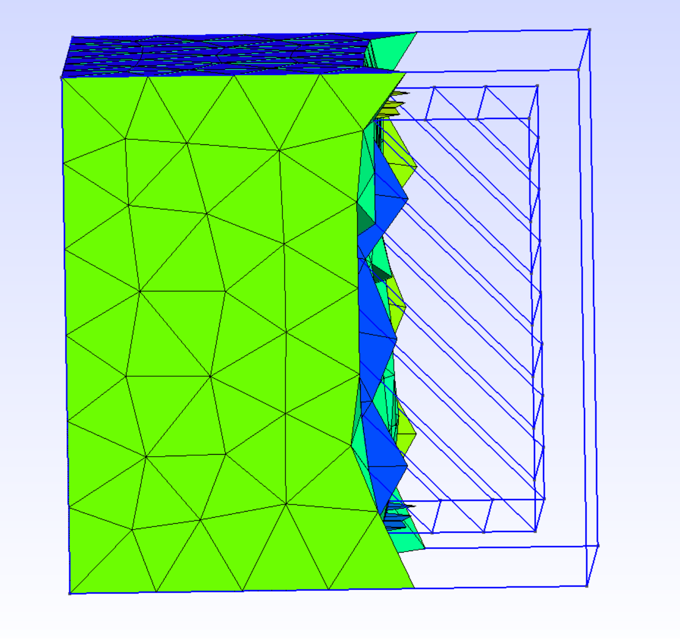
Pure normal opening



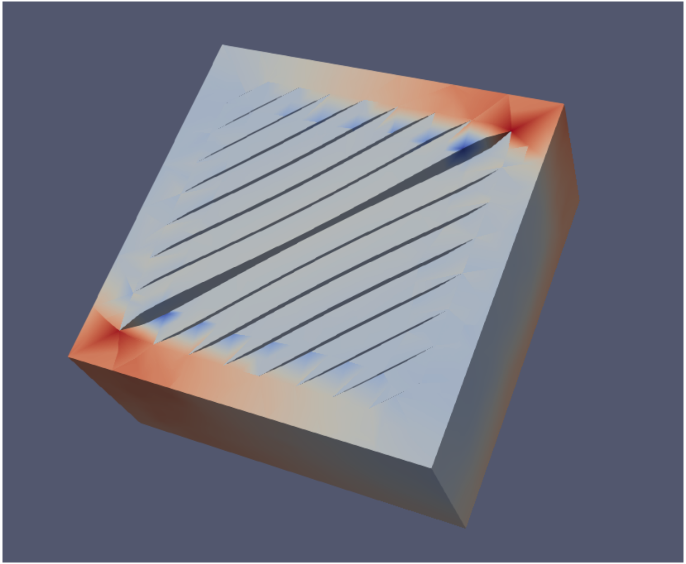
Pure shear opening



Mesh design - GMSH



Dilated fractures



Preliminary results

```
E(input):1.70e+10
K(input):9.44e+09
K(output):5.59e+09
eps:5.17e-07
sxx:2.82e+03
syy:2.84e+03
szz:3.01e+03
sxy:-8.04e+00
syz:-5.70e-01
sxz:1.49e+00
sm:2.89e+03
tri_dx:1.03e-05
tri_dy:1.03e-05
tri_dz:5.29e-06
```

Ideation - overall goals and start narrowing

- Cavern creation
  - Chemical reaction
  - Circulate fluid and model the size/shape of the cavern
- Volumetrics, cavern design
  - Given a shape, what is the capacity
  - Analytical approach or simple numerics will solve most cases (ref:[Maraggi and Moscardelli, 2023])
- Risks, legislation
  - Geomechanics
  - Well as a critical feature for leakage - modelling of cement, chemical reactivity, abandonment etc
- Numerics
  - Complex models for salt creep
  - Need to include plasticity
  - Need data do calibrate (mechanical data for salt is not abundant - afaik)
  - Large displacements need to be considered for long term creep
  - Advanced computer architecture (GPUs, ...)

Workflow (still to fill...)

- Understand the problem
  - Overall picture
  - Where it is applied
  - Main challenges
  - Accidents?
  - Risks, regulations
- Prototype
  - Proof of concepts - currently using PoroMec (own simulator)
  - Standalone software
- Case study
  -
- Optimize

Talk to Hassan Abadi

- A sponsor: RESPEC website
- Impact of the cycles in stability
- Low energy density of the caverns (H_2)
- Overview of projects worldwide? It seems that Canada has a well-set market on storage in caverns
- Adcore - utility company in Canada?
- The key of the research is risk and regulation (form companies and governments)
- Percolation of H2 in water saturated rock.
- Flow in caverns is in open space and mainly gravitational
- Well is a critical point. Cement-rock interface, how to ensure seal? Wellbore is a critical point of leakage

Lorena (UT @ Austin)

[Maraggi and Moscardelli, 2023] Modeling hydrogen storage capacities, injection and withdrawal cycles in salt caverns: Introducing the GeoH2 salt storage and cycling app

Modeling hydrogen storage capacities, injection and withdrawal cycles in salt caverns: Introducing the GeoH$_2$ salt storage and cycling app

Leopoldo M. Ruiz Maraggi[*], *Lorena G. Moscardelli*

Bureau of Economic Geology, The University of Texas at Austin

- Presents the online tool GeoH$_2$ to calculate overall aspects of a salt cavern (volumetrics, pressure, flow rate etc).
- Considers simple geometries (spherical, cylindrical)
- Mainly analytical work
- Discusses the physics involved
- Does not assess risks and geomechanics
- Conclusions could be more clear "there are *many* (...) technical challenges that still need ..." sounds too generic (which challenges?)

RCGI - Brazil

[Goulart et al., 2020] Technology readiness assessment of ultra-deep salt caverns for carbon capture and storage in Brazil

- Funded by FAPESP RCGI (Research center for gas innovation - link). Founder sponsors: Shell and Fapesp.
- One of the authors is Alvaro Maia, a ex-Senior Consultant in Petrobras (well drilling, geomechanics).
- They study caverns of up to 150x450m, created by dissolution, with geomechanical simulations.
- Well is the critical element of an underground storage system, special attention to the cement.
- May store 4 billion Sm^3
- Used simulator COVES, developped by Alvaro Maia in the 1980s (See [Costa, 1984])

See also: [Abreu et al., 2023]

PUCRIO - Investigation of well abandonment relying on salt creep

[Firme et al., 2023] - Geomechanics of salt towards natural barriers for the abandonment of pre-salt wells in Brazil

- Geomechanical study – risk assessment.
- Proof of concept: can we abandon a well without cementing, just relying on natural closure after salt creep?
- 2D modelling of a well closure considering salt creep
- It seems to me that they used linear elastic, small strains FEM - which might not be good enough in this case
- Deviatoric stress up to 15MPa – seems high to me, after creep
- Conclusion: creep takes too much time! (I think the study must be refined)
- EDMT - Enhanced Double Mechanism Creep Model (Pedro develloped during Phd - there's a thesis for that)

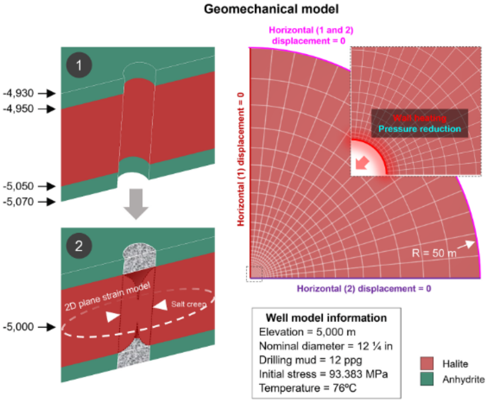


Fig. 6. 2D plane strain model of the Pre-salt well. Elevations in meters.

[Caglayan et al., 2020]Technical potential of salt caverns for hydrogen storage in Europe

[Li et al., 2021] Investigation of thermal-mechanical effects on salt cavern during cycling loading

Thermo-dependent salt creep. Thermo mechanical simulation. Pressure cycles, collapse and tensile fractures.

[Coarita-Tintaya et al., 2023] Hydromechanical modelling of salt caverns subjected to cyclic hydrogen injection and withdrawal

2D models, to consder cyclic loading, with fundamental creep and plasticity. Storage depths varying from 350 to 1350m. They claim the deeper is more mechanically unstable. They find the caverns are feasible.

Regarding formation of hydrogen plume (I could not completely understand the physics yet):

> *In addition to the hydromechanical modeqlling, an analysis of the hydrogen extent within the rock mass is carried out. Since water and hydrogen are immiscible, we assume hereafter that the threshold capillary pressure of rock salt is much higher than hydrogen pressure within the cavern due to the nanometric size of pore throats and hence no free gas phase will be flowing. Assuming hydrogen is a non-reactive solute (no chemical reaction or sorption with salt), we use the following mass transport equation to delineate the extent and mass of dissolved hydrogen plume. Transport of dissolved H2 is only driven by advection (Darcy's law) and by diffusion, since mechanical dispersion is negligible due to the low permeability of the porous medium.*

[Zhao et al., 2022] Feasibility analysis of salt cavern gas storage in extremely deep formation: A case study in China

I see concern with geomechanical behavior, targeted to creep, collapse and tensile fracturing. The cyclic behavior of the pressure is a significant difference compared to oil drainage and waterflooding.

- Geomechanics: creep, thermal, tensile fracture, shear fractures
- Chemical: dissolution
- Cyclic operations
- Temperature dependent creep
- Plume extension (H_2 dissolved in water - percolation of H_2 in water saturated rock (?))
- Heat transfer, especially considering cyclic operations
- Well integrity

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