28th ALERT Workshop Program

Aussois, 4th October 2017

Eulerian-Lagrangian scheme for hydro-mechanical simulations on CT-scans

Never Stand Still

Unconventional Geomechanics Group

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Lesueur M., et al., Modelling fluid-microstructure interaction on elasto-visco-plastic digital rocks, Geomechanics for Energy and the Environment (2017), http://dx.doi.org/10.1016/j.gete.2017.08.001.

THMC modelling at macro-scale

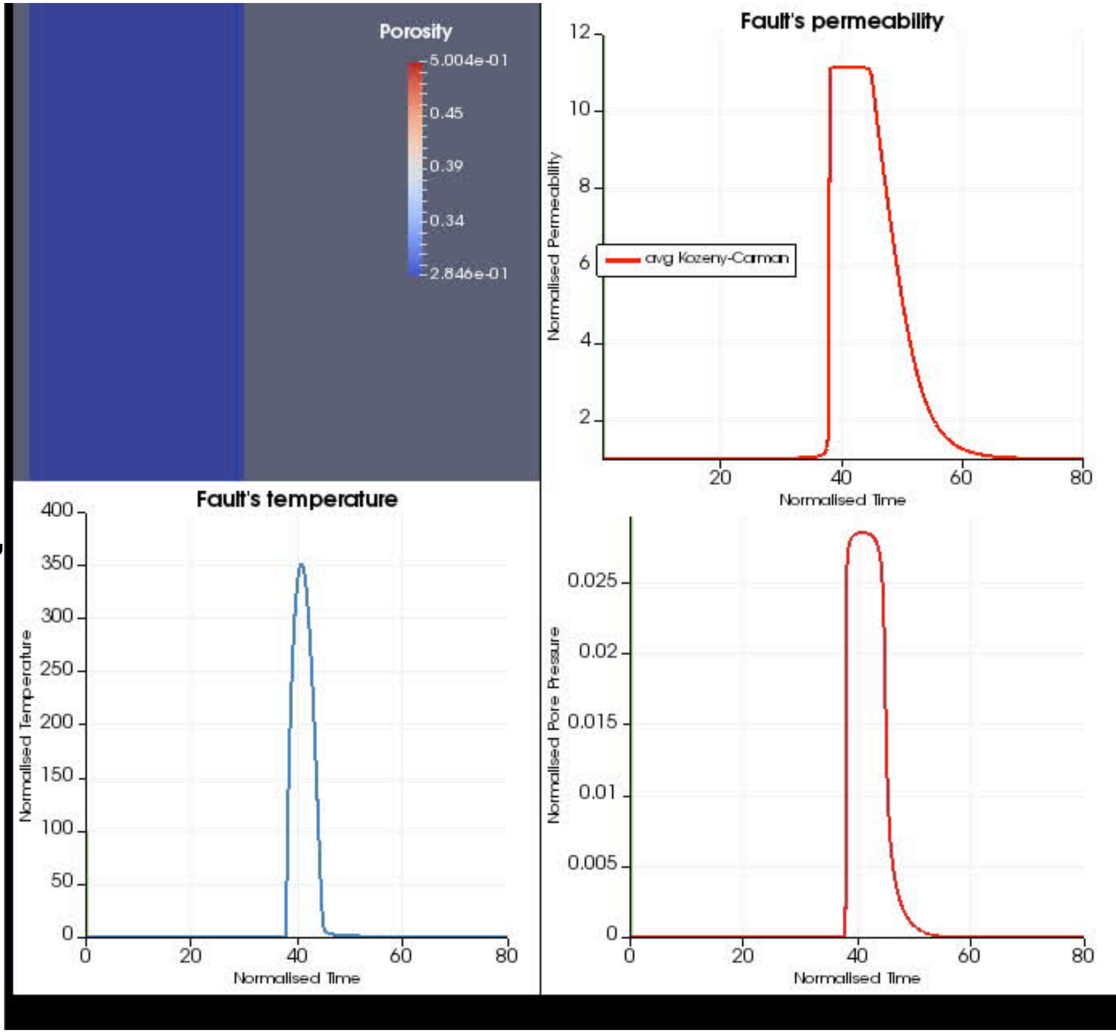
<u>Chemical fault reactivation:</u>

- Shear heating
- Chemical pressurization
- Mechanical deformation

→ THMC

Macro-scale is insufficient to describe completely the phenomena, missing crucial information from the micro-scale.

THMC modelling should be done across scales



Mesh reconstructed from CT-scans

Finite Element simulator REDBACK(1)
→ need for a mesh

Stack of segmented 2D CT-scan images
→ **3D meshes of digital rock**

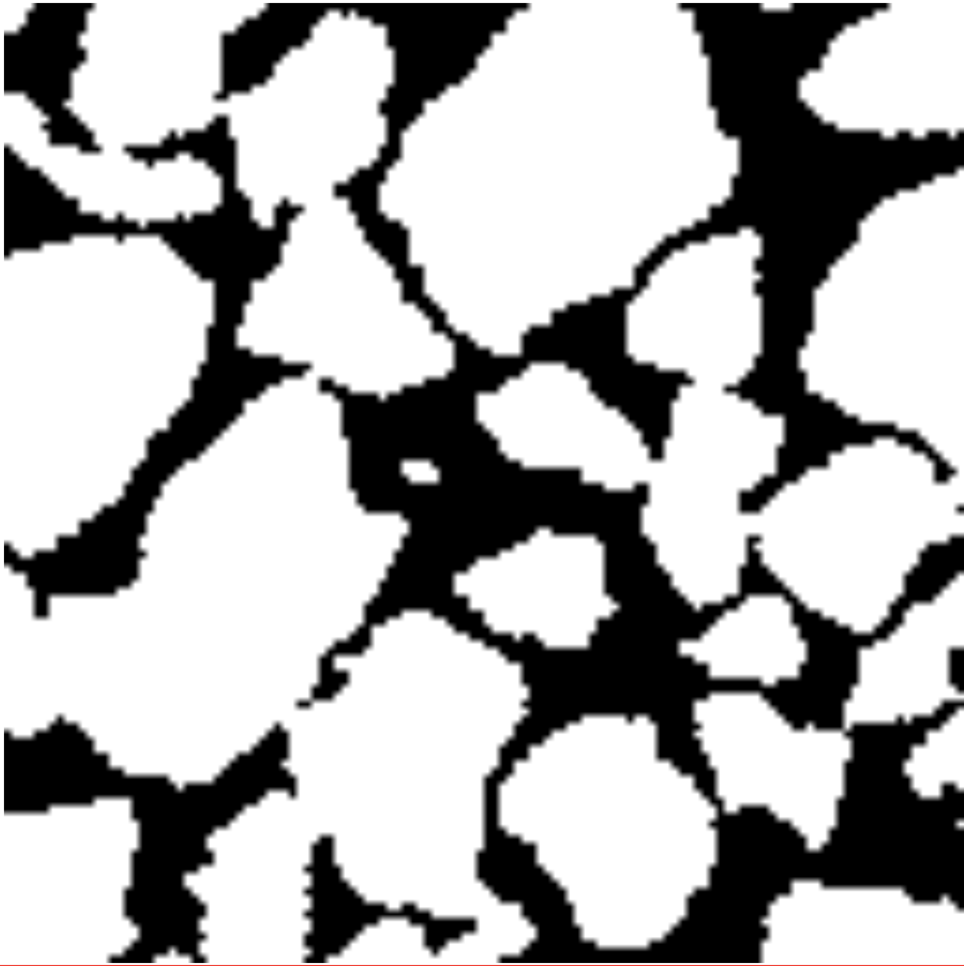
Meshing flexibility:

- Structured or unstructured
- Multiple element types
- Independent final resolution

+ Iterative coarsening away from interface following an octree method

3D mesh of CT-scan images with optimal refinement

Segmented 128x128 LV60A(2) CT-scan image



1. T. Poulet and M. Veveakis. A viscoplastic approach for pore collapse in saturated soft rocks using redback: an open-source parallel simulator for rock mechanics with dissipative feedbacks. Computers and Geotechnics.
2. I. C. C. on Pore-scale Modelling. LV60A sandpack. 10 2014.

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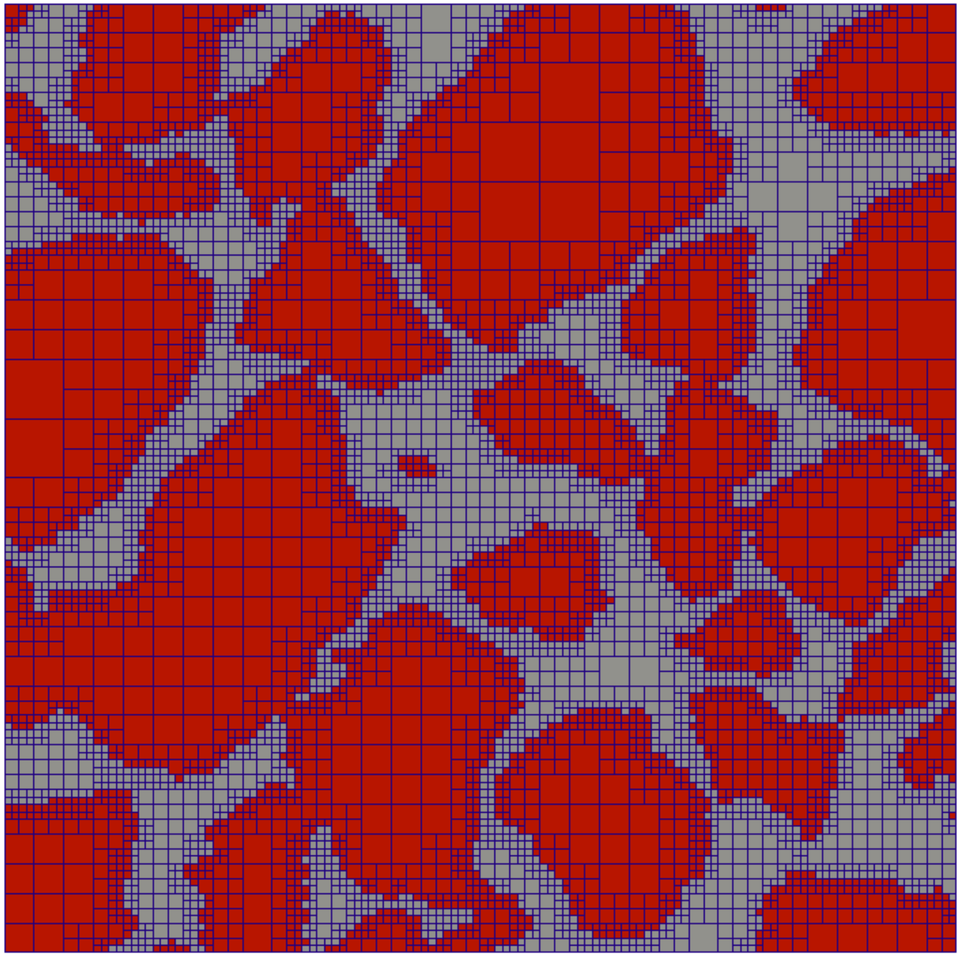
3D mesh of CT-scan images with optimal refinement

Final optimised mesh with 7,597 quadrangle elements



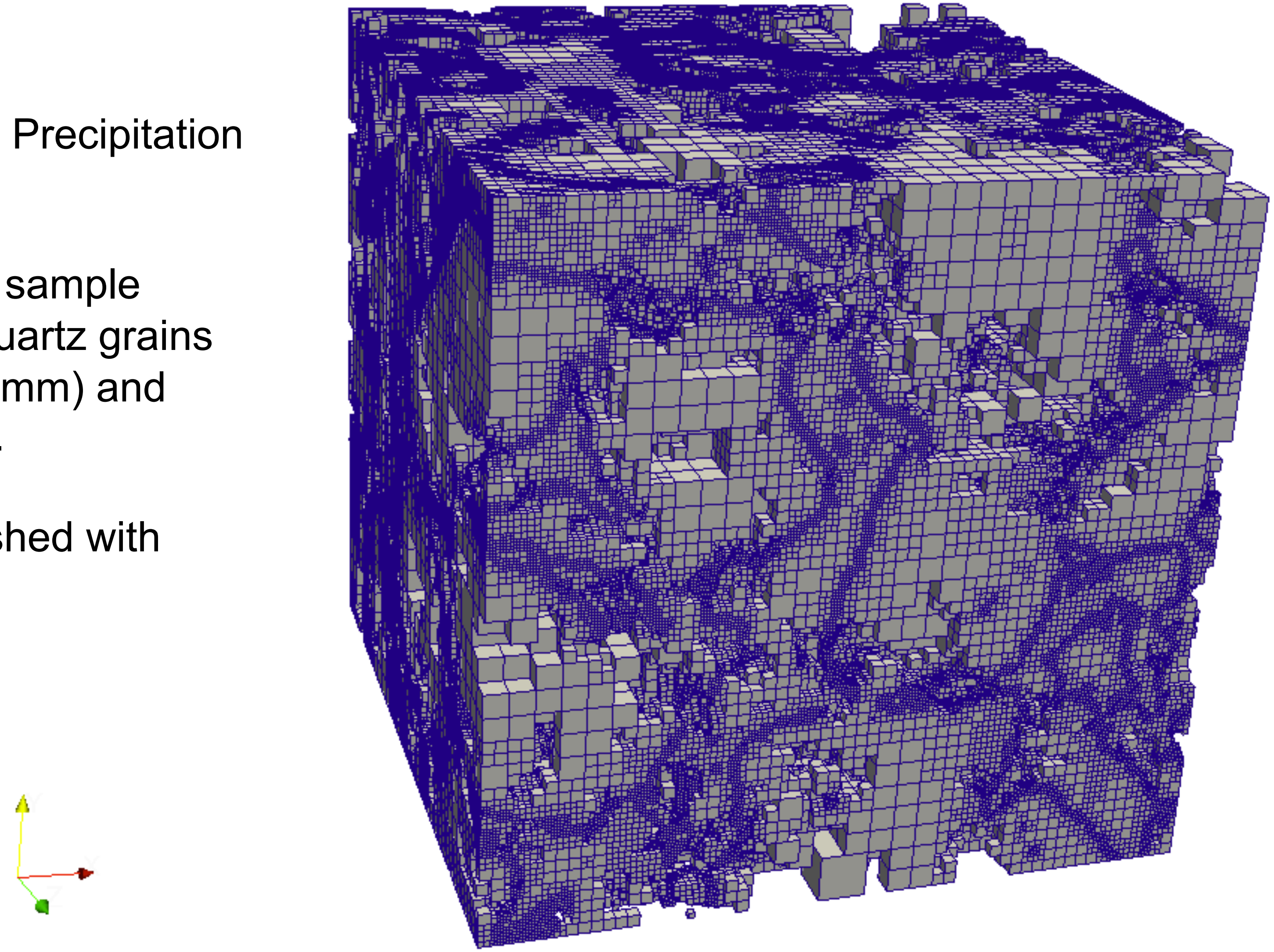
1. T. Poulet and M. Veveakis. A viscoplastic approach for pore collapse in saturated soft rocks using redback: an open-source parallel simulator for rock mechanics with dissipative feedbacks. Computers and Geotechnics.

Mesh reconstructed from CT-scans

CIPS (Calcite In-situ Precipitation System)

synthetic sandstone sample composed of pure quartz grains (diameter 0.15-0.35 mm) and cemented by calcite.

0.5mm^3 sample meshed with 2.4M elements



Yang, Sam; Liu, Keyu; Mayo, Sherry; Tulloh, Andrew (2012): CIPS sandstone microstructure. v2. CSIRO. Data Collection. http://doi.org/10.4225/08/5476787A1A50F

Solid Mechanics Simulator

Stress equilibrium + Constitutive law
(Any constitutive law can be used)

$$\nabla \cdot \boldsymbol{\sigma}_s = \vec{0}$$

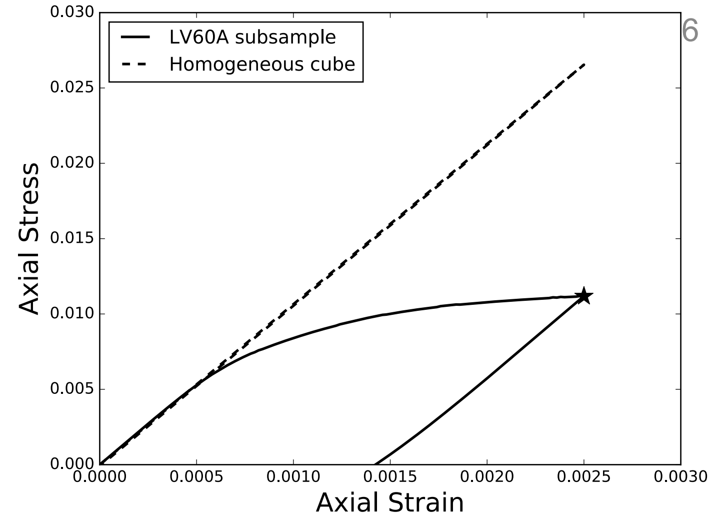
Decomposition of the strain rate of the solid into an elastic and a plastic part

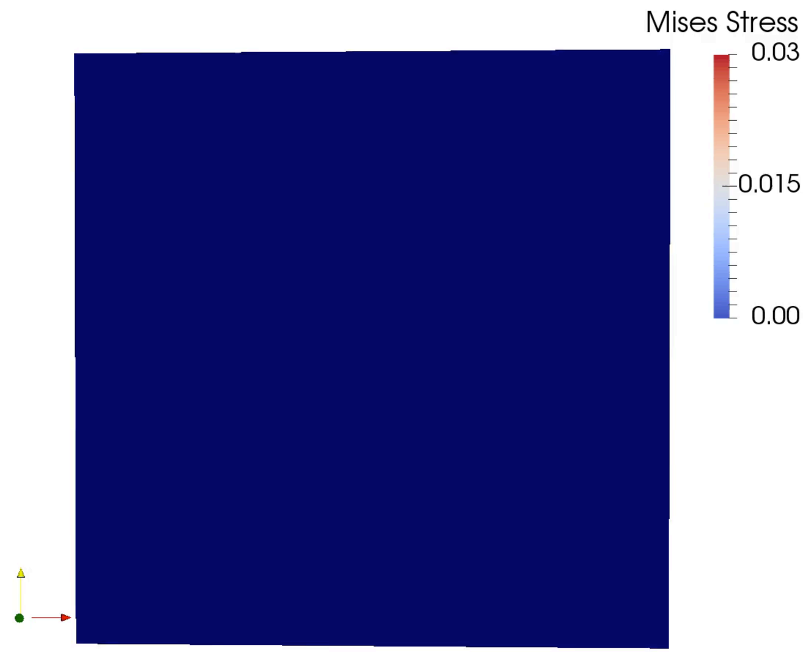
$$\dot{\boldsymbol{\varepsilon}}_s = \dot{\boldsymbol{\varepsilon}}_s^e + \dot{\boldsymbol{\varepsilon}}_s^p$$

For the elastic part we assume linear elasticity

$$\boldsymbol{\sigma}_s = \mathbb{C}\,\boldsymbol{\varepsilon}_s^e$$

For the plastic component, we use an overstress (visco)plastic formulation with associative von-Mises plasticity(1)
→ REDBACK





Uniaxial compression for 0.6mm³ LV60A sample

(1) T. Poulet and M. Veveakis. A viscoplastic approach for pore collapse in saturated soft rocks using redback: an open-source parallel simulator for rock mechanics with dissipative feedbacks. Computers and Geotechnics, 74:211–221, 2016.

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Fluid Flow Simulator

- single phase incompressible fluid
- low-velocity flow → laminar
- steady-state flow in compliance with quasi-static assumption for mechanics

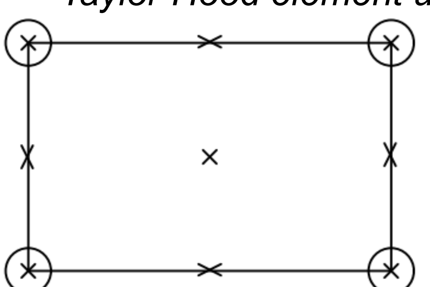
→ Stokes flow:

$$-\nabla^2 \vec{v_f} + \rho_f \nabla p_f = 0,$$
$$-\nabla \cdot \vec{v_f} = 0$$

Velocity intensity

Visualisation of pore space, flow intensity and streamlines on a 1.5mm³ subsample of LV60A meshed with 1,237,177 elements

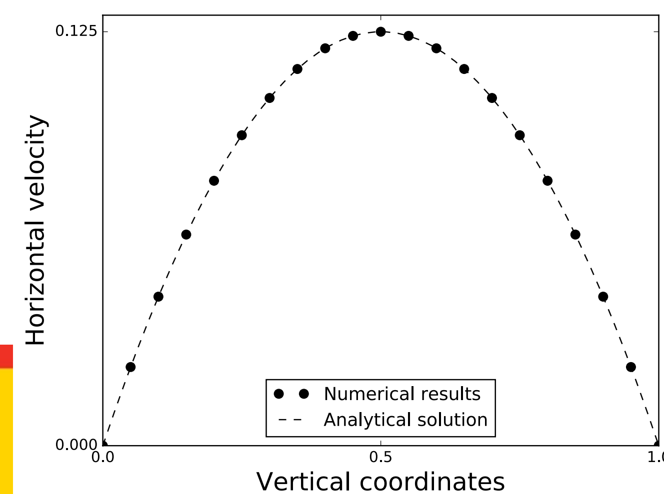
Taylor-Hood element used for simulation



Velocity: bi-quadratic (9 nodal points: x)
Pressure: bi-linear (4 nodal points: 0)

Accuracy velocity: $O(h^3)$
Accuracy pressure: $O(h^2)$

Validation for Poiseuille flow



Research School for Fluid Mechanics. Finite element methods for the incompressible Navier-Stokes equations. Ir. A. Segal. 2017. Delft University of Technology.

Hydro-Mechanical Simulator

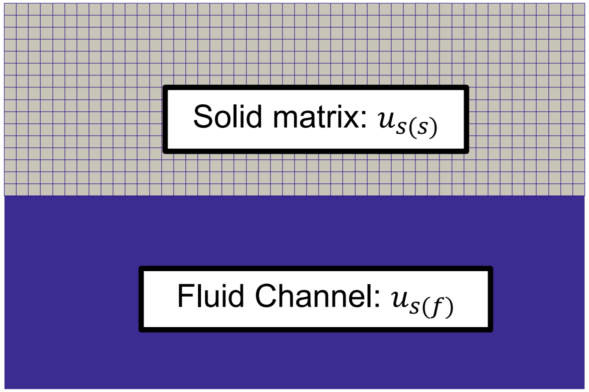
Coupling: Euler-Lagrange scheme

Effect of mechanical deformation on the flow:
Geometrical changes of the pore space due to the displacement of the pore-grain interface.

+ flow path variation imposed by grain movements

→ Moving pore-grain boundary

⚠ Eulerian Flow vs Lagrangian Mechanics



Scheme: **mesh diffusion** $\vartheta \Delta \vec{u}_{s(f)}^{\,*} = 0$

adapt the mesh smoothly in the pore space without any interaction with the mechanical problem

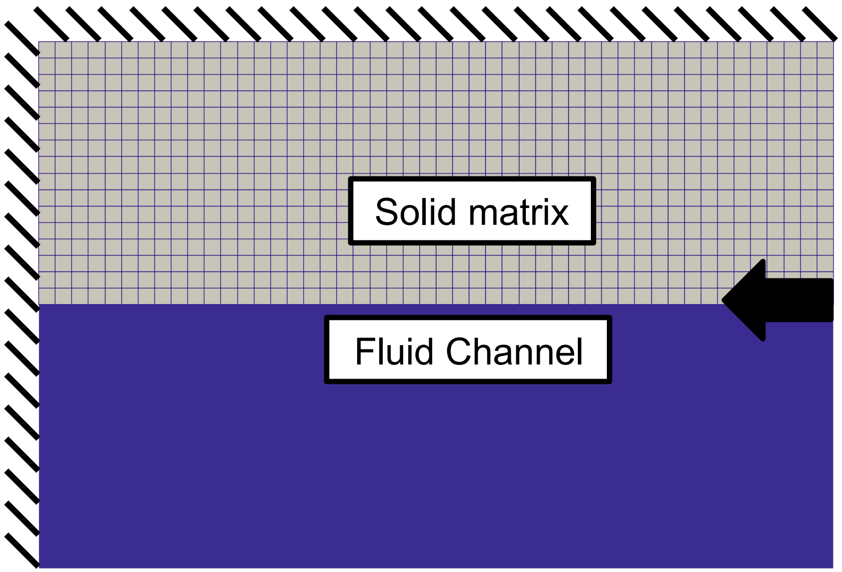
Hydro-Mechanical Simulator

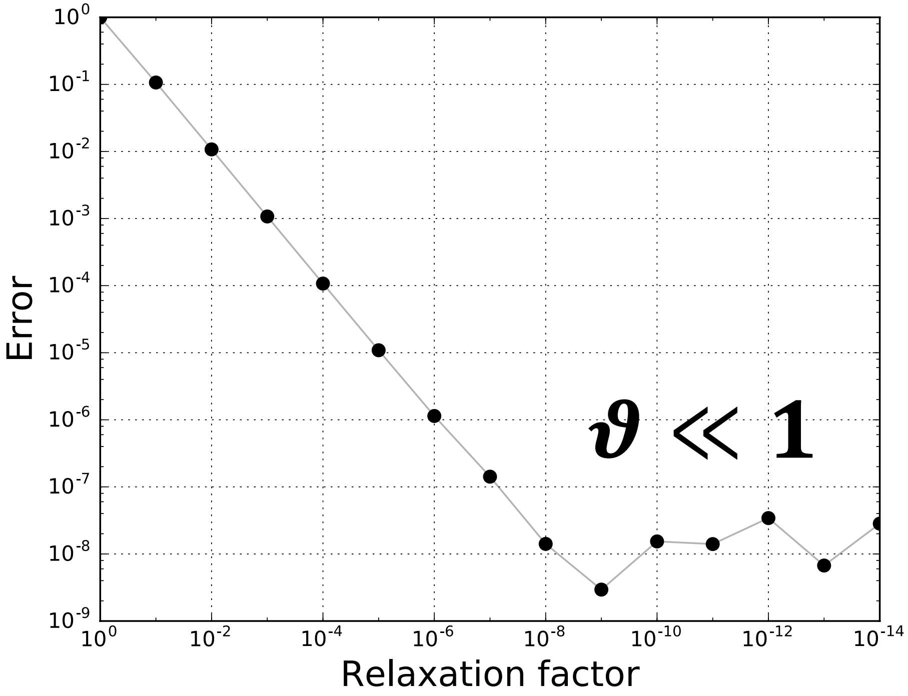
Coupling: Euler-Lagrange scheme

$$\vartheta \Delta \vec{u_{s(f)}}^{*} = 0$$

adapt the mesh smoothly in the pore space without any interaction with the mechanical problem

Unwanted coupled BC at interface → numerical resistance $\sigma_{BC} = \vartheta \nabla \vec{u_{s(f)}}^{*}$





Hydro-Mechanical Simulator

Coupling: Fluid pressure force on the grains

<u>Effect of the fluid pressure on the solid stress</u>

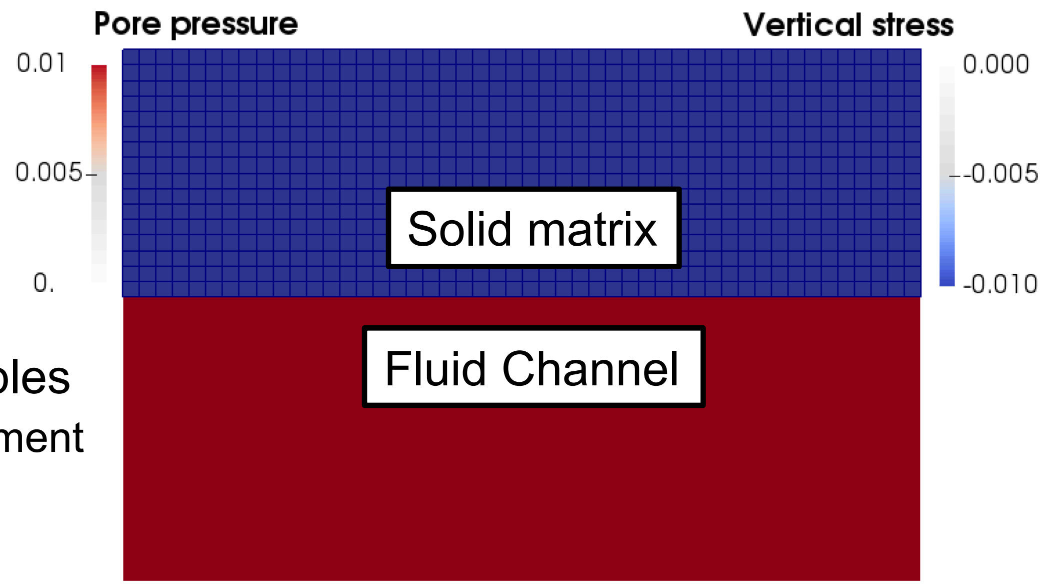
Terzaghi's concept of effective stress at the macro-scale

$$\boldsymbol{\sigma}'_s = \boldsymbol{\sigma}_s - p_f \boldsymbol{I}$$

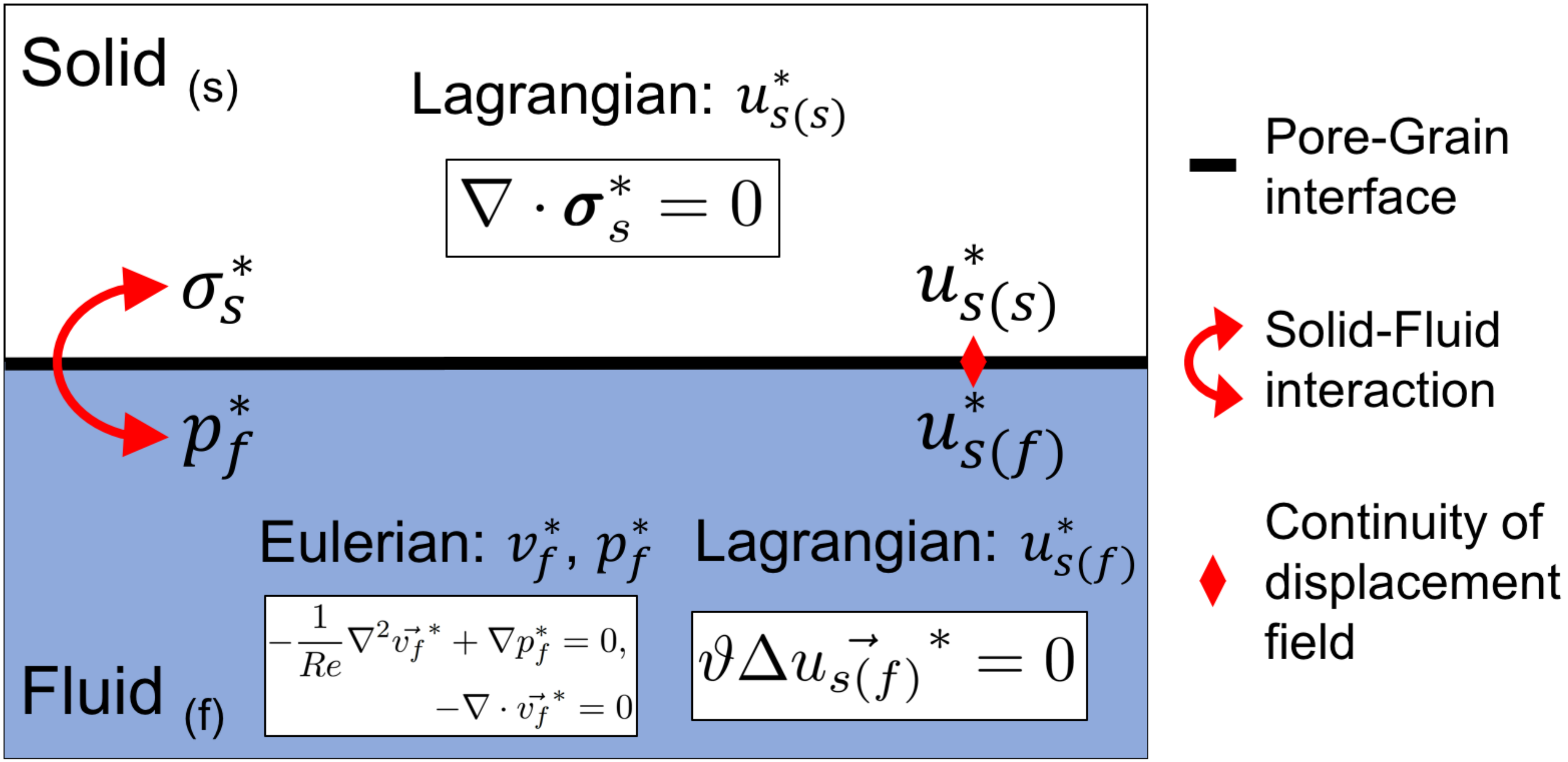
The fluid pressure act as
a stress boundary for the rock.

System solved with displacement variables
Fluid pressure = Neumann BC of displacement

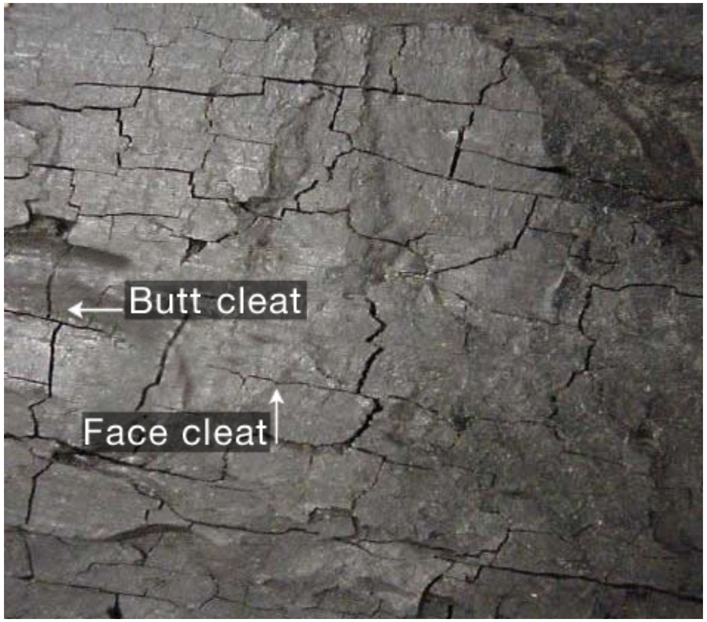
Force direction ensured with boundary's
normal vector

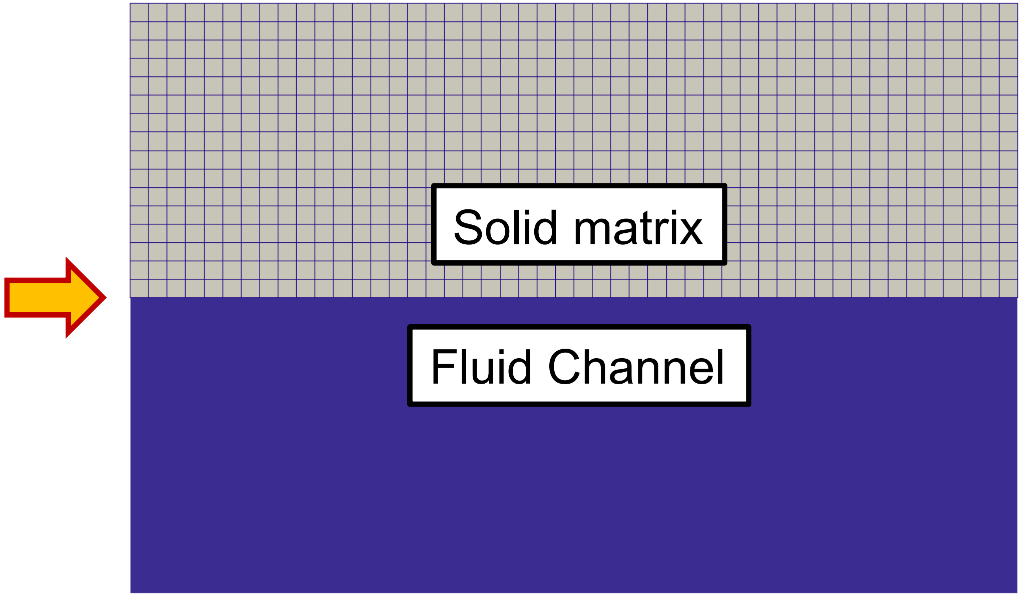


Summary


Solid (s)
Lagrangian: $u^*_{s(s)}$
$\nabla \cdot \boldsymbol{\sigma}^*_s = 0$
σ^*_s
$u^*_{s(s)}$
p^*_f
$u^*_{s(f)}$
Eulerian: v^*_f, p^*_f
Lagrangian: $u^*_{s(f)}$
$-\frac{1}{Re}\nabla^2 \vec{v_f}^* + \nabla p^*_f = 0,$
$-\nabla \cdot \vec{v_f}^* = 0$
$\vartheta \Delta \vec{u_{s(f)}}^* = 0$
Fluid (f)
Pore-Grain interface
Solid-Fluid interaction
Continuity of displacement field

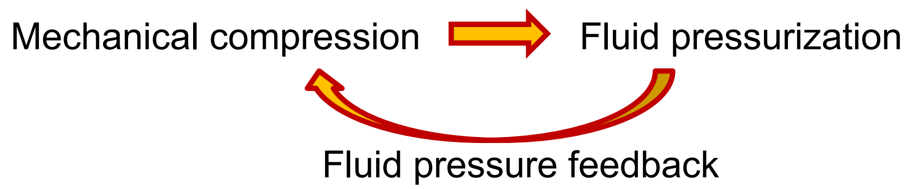
Justification of tight coupling for synthetic coal



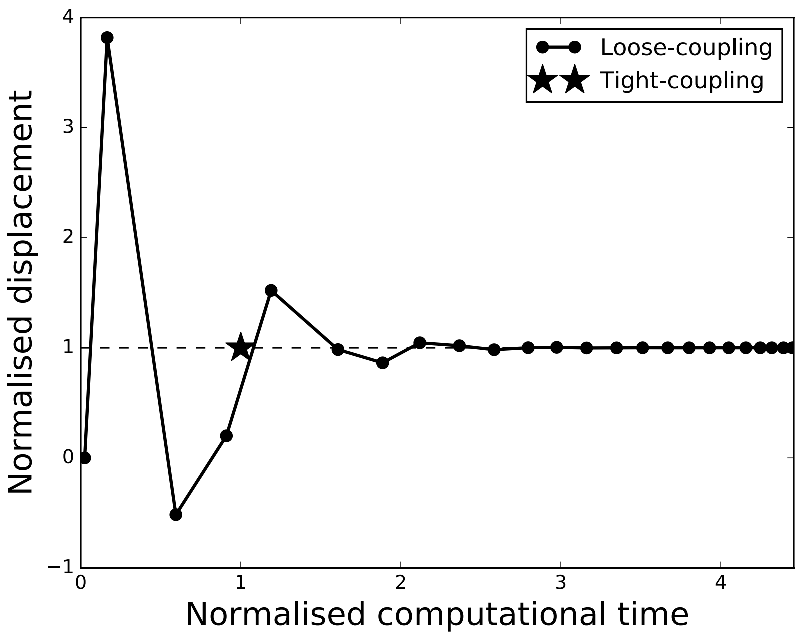


Justification of tight coupling for synthetic coal

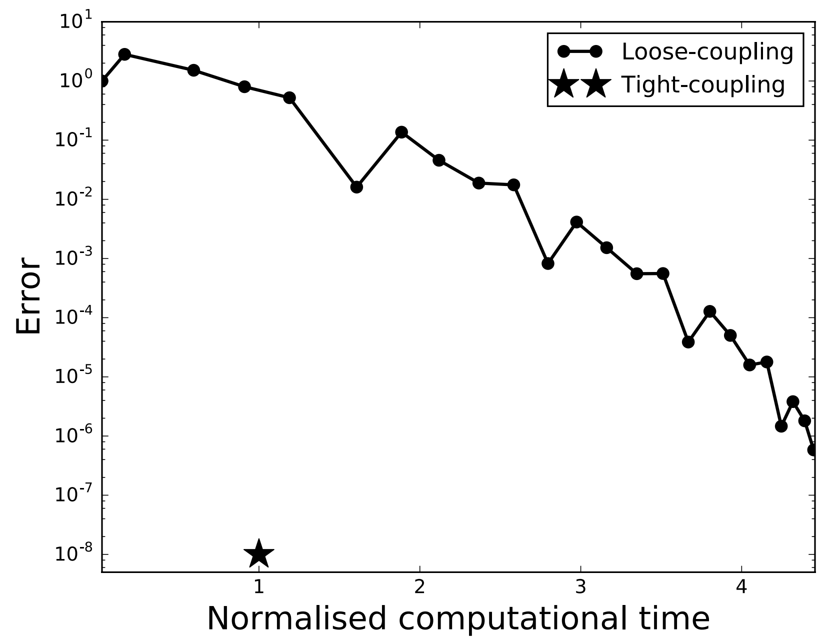
Comparison with loose coupling:



Oscillatory *response due to the lagging application of the FSI*



slow *convergence of loose coupling*



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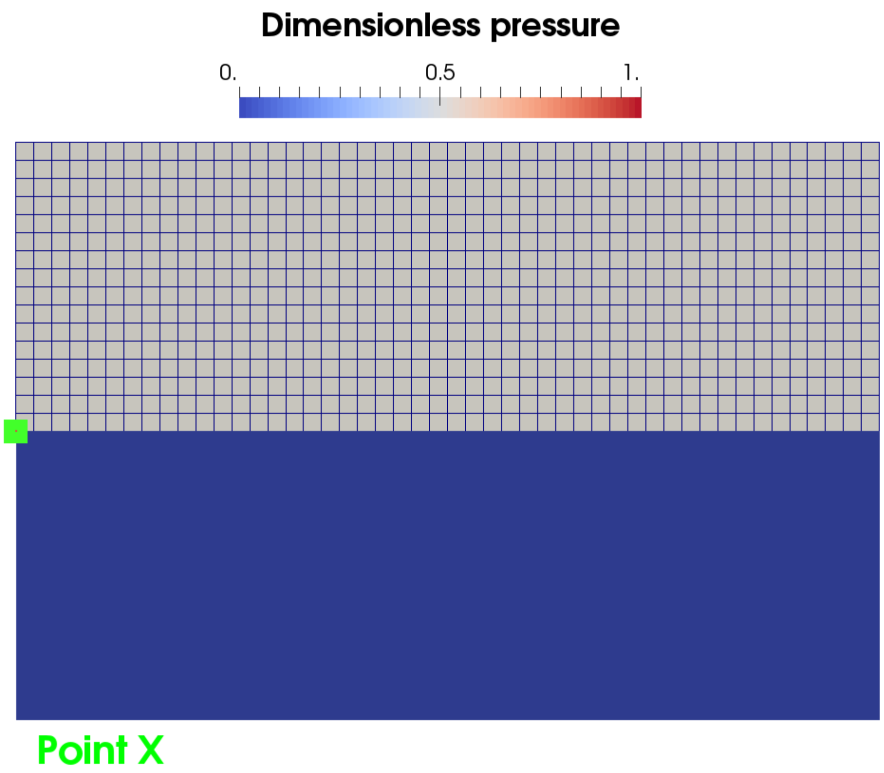
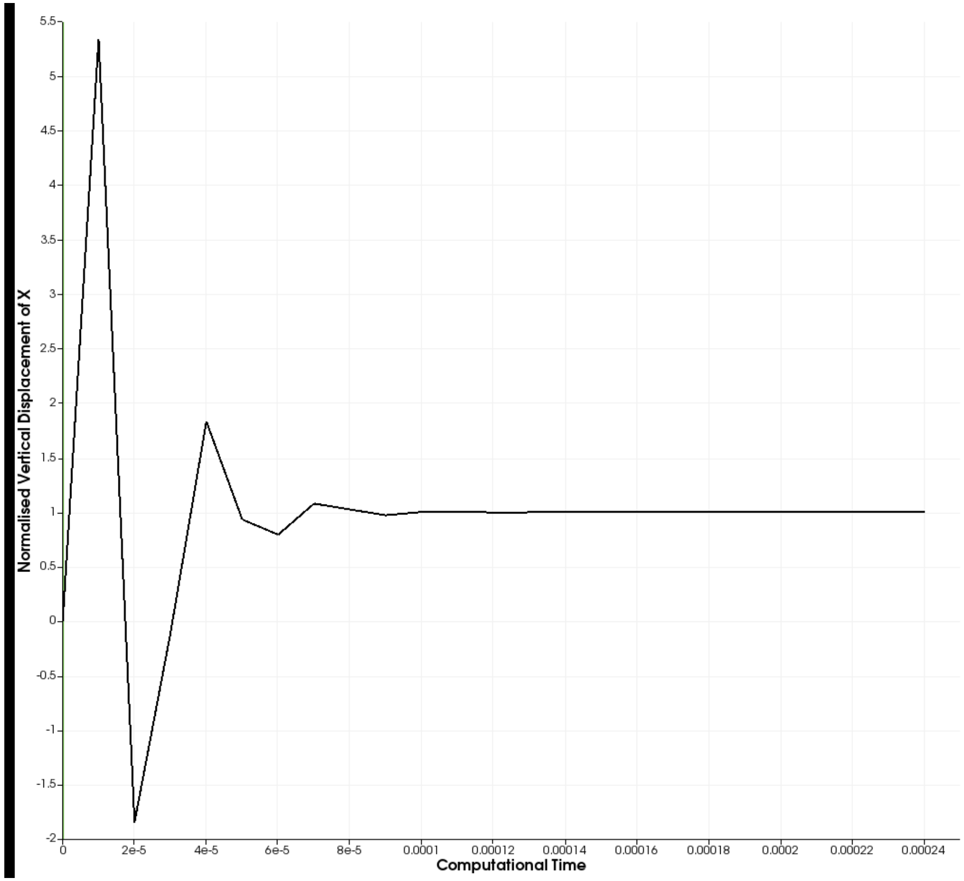




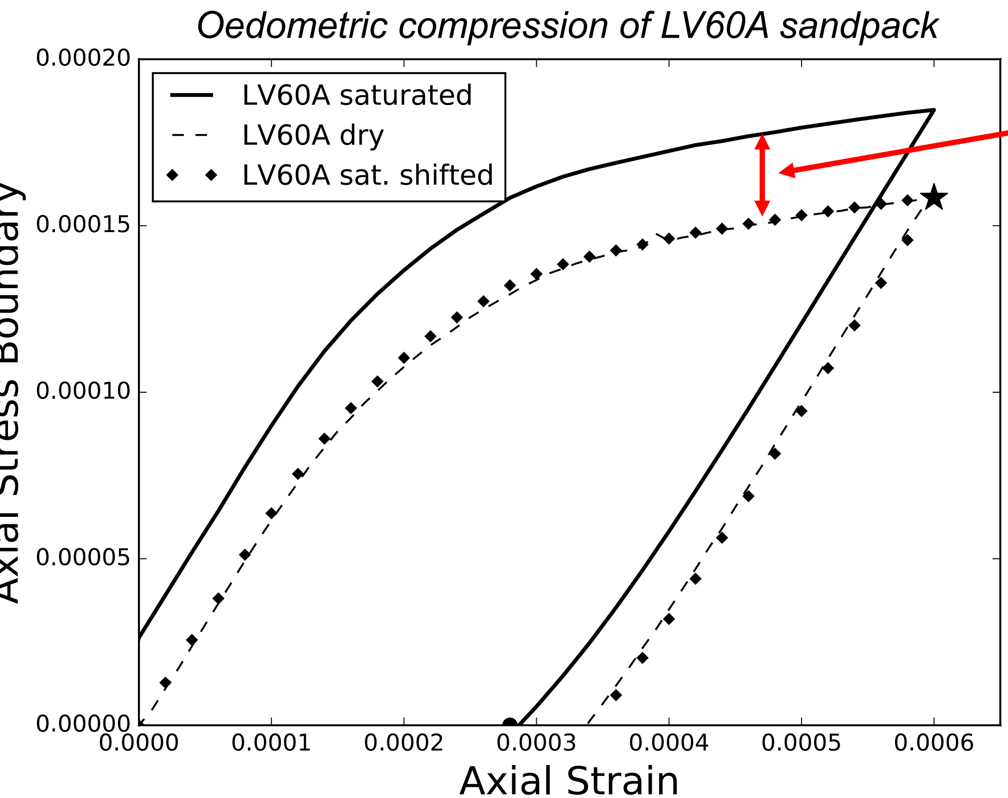
Loose coupling simulation of FSI in synthetic pore channel

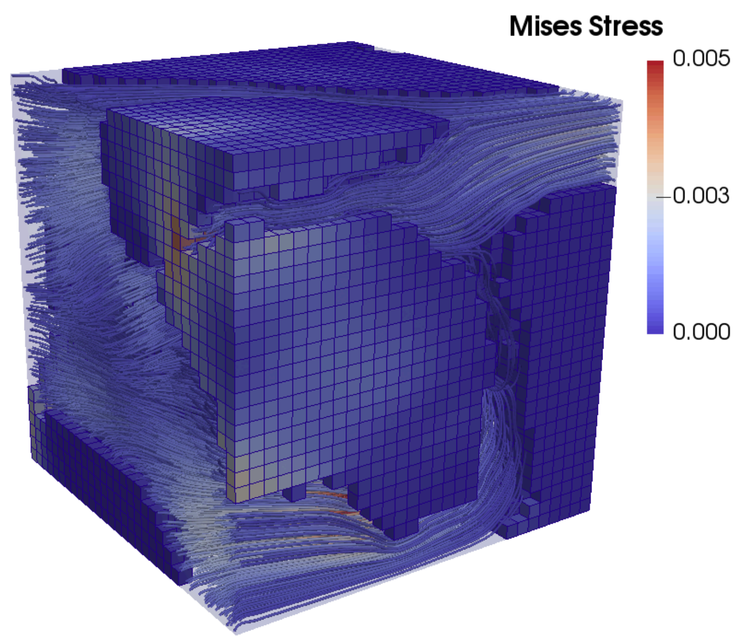
Retrieving Terzaghi's principle at micro-scale

Dry and saturated curves are identical, shifted by a constant

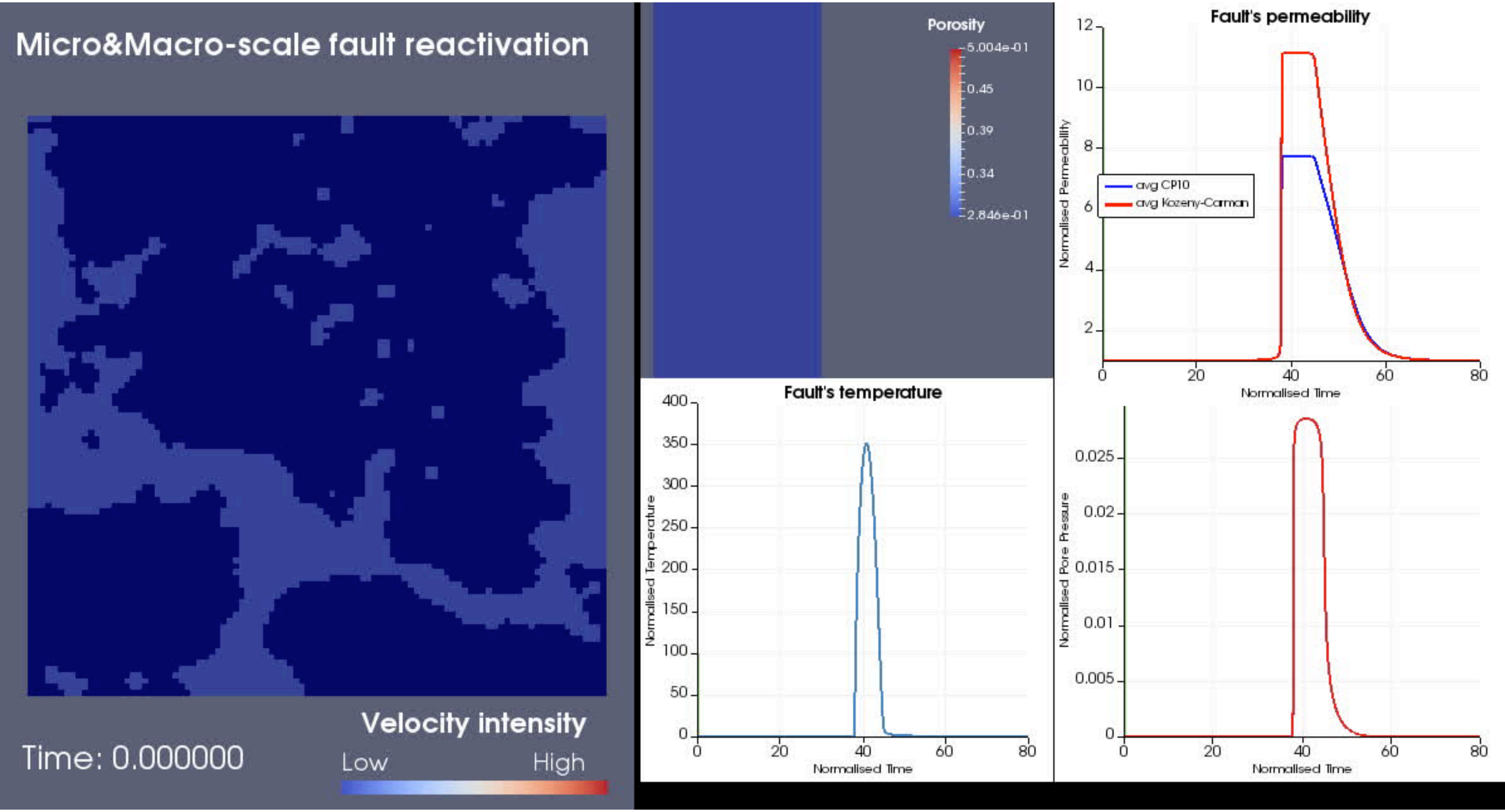
→ Terzaghi's principle is retrieved with a macroscopic value of the pore pressure

$$\boldsymbol{\sigma}'_s = \boldsymbol{\sigma}_s - p_f \boldsymbol{I}$$





Permeability computation during fault reactivation

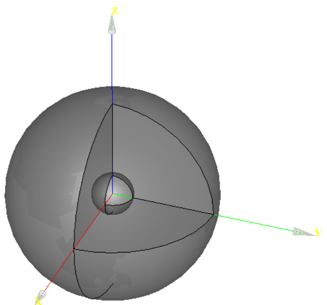


Pressure sensitive yield surface

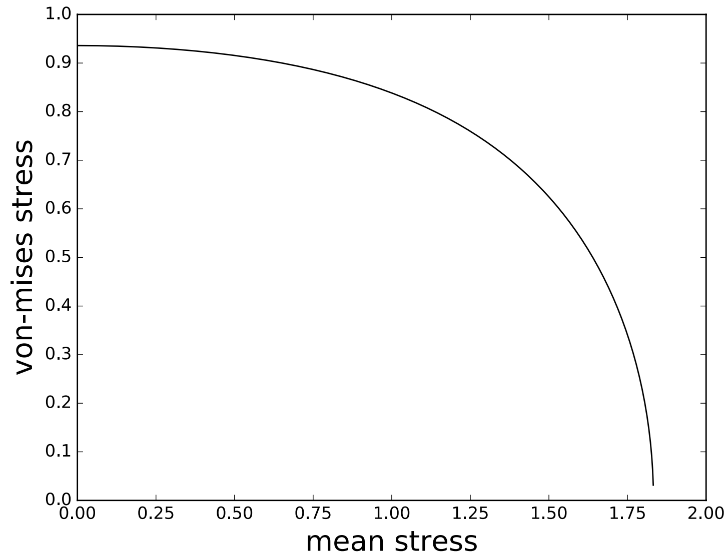
Metals → Non-porous → Pressure-insensitive
Rocks → Porous → Pressure-sensitive

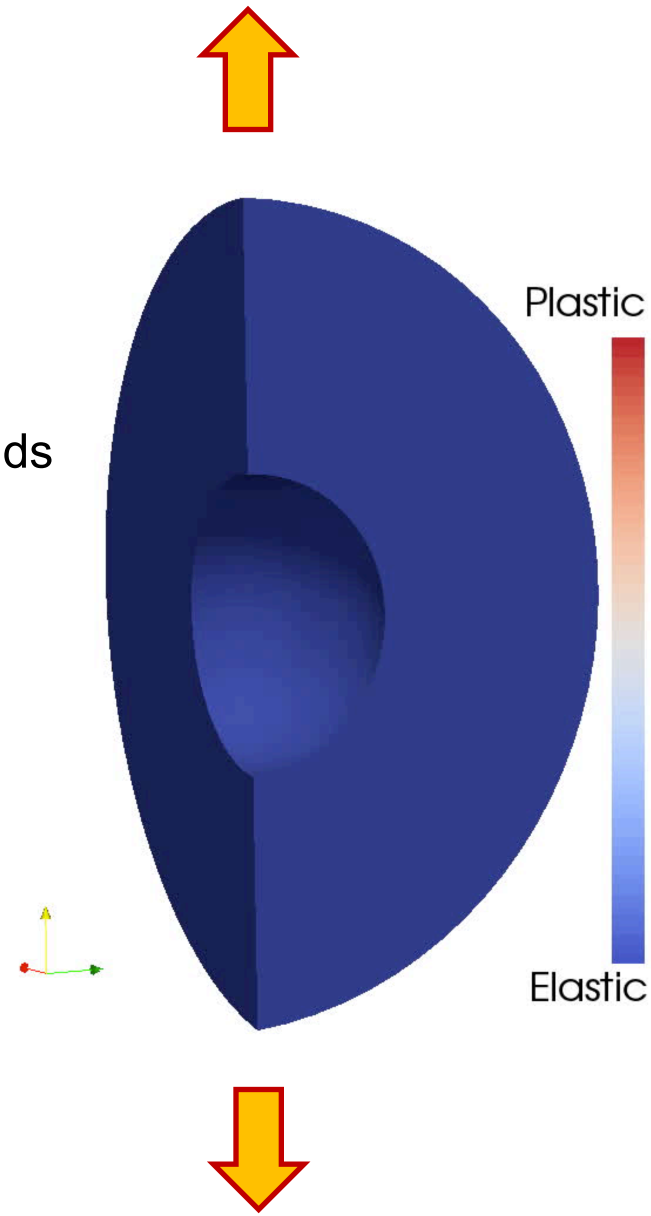
Porous J2 material → Pressure-sensitive

This framework can determine yield surfaces that depends on the micro-structure of the rock and its evolution with deformation.



Gurson's[1] yield surface of a hollow sphere





1. Gurson, A. L. (1977). Continuum theory of ductile rupture by void nucleation and growth: Part I—Yield criteria and flow rules for porous ductile media. *Journal of engineering materials and technology*, *99*(1), 2-15.