PhD proposal in scientific computing

Numerical simulation of coupled Seismo-Hydro-Mechanical processes in seismicity induced by subsurface fluid injection

MathSout project of PEPR Math-Vives

as part of a collaboration between
the departments of mathematics (LJAD) and geology (Géoazur)
of University Côte d'Azur, Inria and IFPEN

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Subsurface resources such as deep geothermal energy, underground hydrogen storage, and geological CO2 sequestration have become crucial pillars of the energy transition and sustainable development. However, injecting or extracting fluids into or from the subsurface modify the pressure and stress state of the surrounding rocks, often extending far beyond the injection point. These changes can potentially trigger fault reactivation (see Figure 1). Such phenomena pose seismic risks that must be better understood and mitigated to ensure operational safety, reduce risks to nearby populations, and enhance the social acceptance of these projects.

If it remains sufficiently low, this induced seismicity (then referred to as microseismicity) raises no issue and can even contribute to site monitoring. However, the ability to predict and mitigate the risks of induced seismicity is key for sustainable exploitation of the subsurface. In recent years, anthropogenic activities in storage reservoirs have triggered earthquakes with magnitudes up to 6, high enough to cause damage, in regions where natural seismic activity was otherwise low. A recent example is a magnitude 3.9 earthquake in Vendenheim, Alsace, which led to the closure of this deep geothermal site in 2021.

In this context, numerical simulation stands out as a key tool for better understanding, predicting, and managing these phenomena. It allows to account for coupled multiphysical processes underlying induced seismicity, evaluating the potential impacts of human activities on the subsurface, and designing strategies to minimize associated risks.

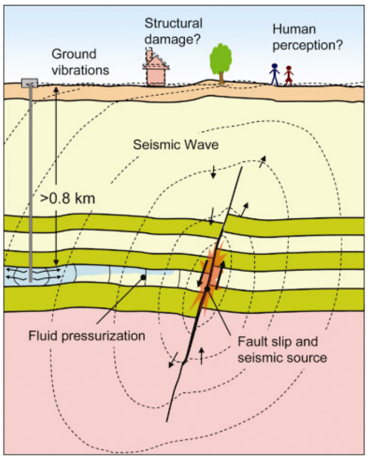

Figure 1: Illustration of fault reactivation and induced seismicity caused by CO2 injection in a saline aquifer [J. Rutqvist, F. Cappa et al 2014]

At sufficiently large spatial scales, the models are based on a represention of the faults as interfaces equipped with mechanical properties (normal stiffness, friction laws, etc.) and hydraulic properties (aperture and hydraulic conductivity). Figure 2 illustrates the model concept of contact at the asperity level and the transition to the interface representation coupled with the surrounding matrix. The physical model couples Darcian fluid flow in the porous matrix $\Omega\backslash\Gamma$ and the fault network Γ, the poro-elastic deformation of the rock in the matrix domain $\Omega\backslash\Gamma$, as well as the highly nonlinear frictional slip laws along the fault network Γ. An essential feature is the dynamic nature of the friction law, commonly described by a Rate and State law [5, 3, 4] and for which the friction coefficient depends on the slip velocity

$$\mathbf{V} = \partial_t [\![\mathbf{u}]\!]_\tau,$$

where $[\![\mathbf{u}]\!]_\tau = \Big(\mathbb{I} - \mathbf{n}^+ \otimes \mathbf{n}^+\Big)(\mathbf{u}^+ - \mathbf{u}^-)$ stands for the tangential displacement jump along the fault network Γ, as well as on a so called state parameter ψ accounting for the average contact age or the maturity of the fault asperities and allow to model seismic cycles. Given functions F and G of Rate and State type, the frictional slip law is given as follows:

$$\mathbf{T}_\tau = F(|\mathbf{V}|, \psi)\ T_n\ \frac{\mathbf{V}}{|\mathbf{V}|},$$
$$\frac{d\psi}{dt} = G\Big(|\mathbf{V}|, \psi\Big).$$

The normal traction $T_n = \Big(\sigma(\mathbf{u}, p_m)\mathbf{n}^+ + p_f\mathbf{n}^+\Big) \cdot \mathbf{n}^+ \leq 0$ is assumed compressive with $\sigma(\mathbf{u}, p_m)$ standing for the total stress poro-elastic tensor. The tangential traction $\mathbf{T}_\tau = \sigma(\mathbf{u}, p_m)\mathbf{n}^+ - T_n\mathbf{n}^+$ is proportional to both the dynamic friction coefficient $F(|\mathbf{V}|, \psi)$ and to the normal traction T_n. The decrease of $|T_n|$ with the fault pressure p_f is the source of the potential fault reactivation which can further accelerates and induce seismicity when the friction coefficient and consequently the resistance to slip decreases with the slip velocity.

The goal of the PhD thesis is to develop numerical methods to efficiently simulate these strongly coupled Seismo-Hydro-Mechanical processes, taking into account 3D fault networks and dynamic rate and state friction laws.

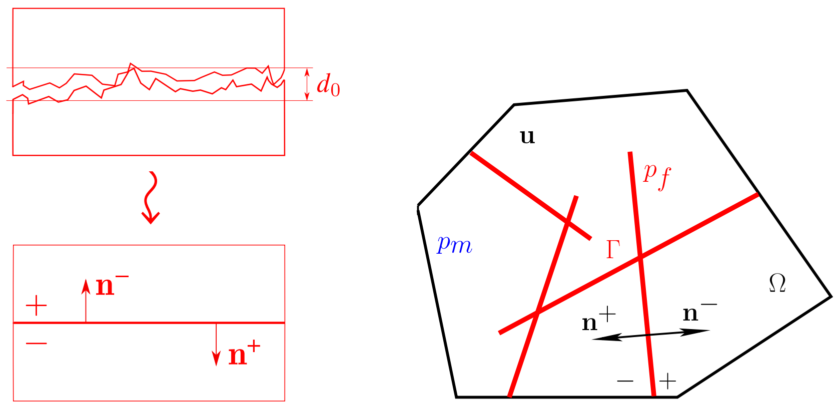

Figure 2: Zoom on a fault zone with contact at the asperity level and transition to the interface model (on the left). Model representing the fault network as interfaces (right) with the main variables of the model, namely the displacement field $\mathbf{u}$, the pressures in the matrix p_m, and in the fault network p_f.

- We will first focus on quasi-dynamic models [2, 3, 4], which are based on a quasi-static contact mechanics (without acceleration term)

$$-\mathbf{div}(\sigma(\mathbf{u}, p_m)) = \rho \mathbf{g},$$

  combined with a "radiation damping" stabilization term along the fault network leading to the following modified slip law:

$$\mathbf{T}_\tau = F(|\mathbf{V}|, \psi)\; T_n \,\frac{\mathbf{V}}{|\mathbf{V}|} - \eta \mathbf{V}.$$

  We will then consider the extension to elastodynamic models capable of modeling the propagation of seismic waves in the rock.

- The spatial discretization will be polytopal to cope with the complexity of geological meshes. It will build upon our previous work in contact mechanics [1] which combines a Virtual Element Method (VEM) nodal discretization of degree 1 for the displacement field $\mathbf{u}$, a facewise constant approximation of the traction vector $\mathbf{T}$ stabilized by a face bubble enrichment of the displacement space. This method has the advantage of leading to a diagonal coupling operator for contact, which facilitates its extension to account for dynamic friction. Higher order VEM spatial discretisations will also be investigated to achieve sufficient spatial resolution, particularly in 3D.

- We will then focus on developing adaptive time integration and coupling algorithms between the hydrodynamic model (in the matrix and the fault network) and the frictional contact mechanichal model. This adaptive nature is crucial in order to capture the very large time scale contrasts (up to 6 orders of magnitude) between the different phases of induced seismicity, ranging from pressure buildup to slip onset, from aseismic slip to seismic slip, and finally to slip arrest.

- The numerical models developed in the PhD thesis will be evaluated through benchmarks and also compared, after calibration, with experimental data from laboratory and in situ studies conducted by Géoazur.

Profile: Master's degree (M2) or engineering school in the fields of numerical methods for PDEs and scientific computing, proficiency in programming for scientific computing (Fortran, Python, C++), and an interest in applications in geosciences and teamwork.

Location and supervision: the PhD thesis is part of the MathSout project within the PEPR Math-vives `https://www.insmi.cnrs.fr/fr/maths-vives`. It will take place at the J.A. Dieudonné Mathematics Laboratory (LJAD) at the University of Côte d'Azur as part of the joint Galets project team, which involves Inria, LJAD, and the Géoazur laboratory. The thesis will be co-supervised by Roland Masson (LJAD, Galets team) and Jean-Paul Ampuero (Géoazur, Galets team), and will be carried out in collaboration with other members of the Galets team: Frédéric Cappa (Géoazur), Konstantin Brenner (LJAD), Louis de Barros (Géoazur), François Passelegue (Géoazur), as well as with Isabelle Faille and Guillaume Enchery from IFPEN.

Duration and starting date: the funding for the PhD thesis is for 3 years, with the starting date typically set for September 2025, but it can be flexible.

Application: send CV and references and accademic results to roland.masson@univ-cotedazur.fr, ampuero@geoazur.unice.fr

References

[1] J. Droniou, G. Enchery, A. Haidar, I. Faille , R. Masson, A bubble VEM-fully discrete polytopal scheme for mixed-dimensional poromechanics with frictional contact at matrix fracture interfaces, CMAME 2024, `https://hal.archives-ouvertes.fr/hal-04343287`.

[2] P. Romanet, M. M. Scuderi, J.P. Ampuero, S. Chaillat and F. Cappa. Coupled Boundary Element and Finite Volume Methods for Modeling Fluid-Induced Seismicity in Fault Networks within Low-Permeability Rocks, preprint `https://arxiv.org/abs/2412.03194`, 2024.

[3] Kaneko, Y., Ampuero, J.-P. and Lapusta, N., Spectral-element simulations of long-term fault slip: Effect of low-rigidity layers on earthquake-cycle dynamics, Journal of Geophysical Research: Solid Earth, 116, 2011.

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[5] E. Pipping, Dynamic problems of rate-and-state friction in viscoelasticity, PhD, 2015. `https://refubium.fu-berlin.de/handle/fub188/3568`