Offer #2025-08631

PhD Position F/M Numerical simulation of coupled Seismo-Hydro-Mechanical processes in seismicity induced by subsurface fluid injection

Contract type : Fixed-term contract

Level of qualifications required : Graduate degree or equivalent

Fonction : PhD Position

About the research centre or Inria department

The Inria centre at Université Côte d'Azur includes 42 research teams and 9 support services. The centre's staff (about 500 people) is made up of scientists of di?erent nationalities, engineers, technicians and administrative staff. The teams are mainly located on the university campuses of Sophia Antipolis and Nice as well as Montpellier, in close collaboration with research and higher education laboratories and establishments (Université Côte d'Azur, CNRS, INRAE, INSERM ...), but also with the regiona economic players.

With a presence in the fields of computational neuroscience and biology, data science and modeling, software engineering and certification, as well as collaborative robotics, the Inria Centre at Université Côte d'Azur is a major player in terms of scientific excellence through its results and collaborations at both European and international levels.

Context

The PhD thesis project is a collaboration between the departments of mathematics (LJAD) and geology (Géoazur) of University Côte d'Azur, Inria and IFPEN. It is part of the MathSout project within the PEPR Math-vives https://www.insmi.cnrs.fr/fr/maths-vives.

The PhD is co-supervised by Roland Masson (LJAD, Inria) and Jean-Paul Ampuero (Géoazur, IRD, Inria), and will be carried out in collaboration with other members of the Inria project team Galets as well as with IFPEN.

The PhD will take place at the J.A. Dieudonné Mathematics Laboratory (LJAD) at the University Côte d'Azur as part of the joint Galets project team, which involves Inria, LJAD, and Géoazur.

Assignment

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. 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.

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). The physical model couples Darcian fluid flow in the porous matrix and the fault network, the poro-elastic deformation of the rock in the matrix domain as well as the highly nonlinear frictional slip laws along the fault network. An essential feature is the dynamic nature of the friction law, commonly described by a Rate and State law [Pipping2016,Ampuero2011,Uphoff22] and for which the friction coefficient depends on the slip velocity (Rate) as well as on a State parameter accounting for the average contact age or the maturity of the fault asperities and allowing to model seismic cycles.

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.

* We will first focus on quasi-dynamic models [Ampuero24, Ampuero2011, Uphoff22], which are based on a quasi-static contact mechanics (without acceleration term) combined with a "radiation damping" stabilization term along the fault network. 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 [Droniou23] which combines a Virtual Element Method (VEM) nodal discretization of degree 1 for the displacement field, a facewise constant approximation of the traction vector 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 Geoazur.

References:
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

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.

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.

C. Uphoff, D.A. May and A.A. Gabriel. A discontinuous Galerkin method for sequences of earthquakes and aseismic slip on multiple faults using unstructured curvilinear grids, Geophysical Journal International, 233, 1, pp. 586-626, 2022.

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

Main activities

- Design efficient space-time discretisations to simulate induced seismicity models
- Implement these numerical methods on prototype codes and possibly in the open source parallel code ComPASS
- Validate these numerical methods on academic benchmarks
- Compare and calibrate the numerical simulations using lab and in situ experimental data from the Geoazur team
- Write reports and articles
- Present the results at workshops and conferences

Skills

Academic background in numerical methods for PDEs with applications to solid and fluid mechanics

Good experience in scientific programming for the numerical simulation of PDEs using languages like Fortran, Python, C++

First experience in writing scientific reports using Latex

Ability to present his work in english and to team working

Benefits package

- Subsidized meals
- Partial reimbursement of public transport costs
- Leave: 7 weeks of annual leave + 10 extra days off due to RTT (statutory reduction in working hours) + possibility of exceptional leave (sick children, moving home, etc.)
- Possibility of teleworking (after 6 months of employment) and flexible organization of working hours
- Professional equipment available (videoconferencing, loan of computer equipment, etc.)
- Social, cultural and sports events and activities
- Access to vocational training

- Social security coverage

Remuneration

Gross Salary:

1st year : 2200 € per month

2nd and 3rd year : 2300 €per month

General Information

- **Town/city :** Nice
- **Inria Center :** Centre Inria d'Université Côte d'Azur
- **Starting date :** 2025-09-01
- **Duration of contract :** 3 years
- **Deadline to apply :** 2025-04-17

Contacts

- **Inria Team :** AT-SOP AE
- **PhD Supervisor :**
  Masson Roland / Roland.Masson@inria.fr

About Inria

Inria is the French national research institute dedicated to digital science and technology. It employs 2,600 people. Its 200 agile project teams, generally run jointly with academic partners, include more than 3,500 scientists and engineers working to meet the challenges of digital technology, often at the interface with other disciplines. The Institute also employs numerous talents in over forty different professions. 900 research support staff contribute to the preparation and development of scientific and entrepreneurial projects that have a worldwide impact.

The keys to success

Master's degree (M2) or engineering school in the fields of numerical methods for PDEs and scientific computing.

Interest in applications in geosciences

Good communication skills (oral and written)

Ability to teamwork.

Warning : you must enter your e-mail address in order to save your application to Inria. Applications must be submitted online on the Inria website. Processing of applications sent from other channels is not guaranteed.

Instruction to apply

Defence Security :
This position is likely to be situated in a restricted area (ZRR), as defined in Decree No. 2011-1425 relating to the protection of national scientific and technical potential (PPST).Authorisation to enter an area is granted by the director of the unit, following a favourable Ministerial decision, as defined in the decree of 3 July 2012 relating to the PPST. An unfavourable Ministerial decision in respect of a position situated in a ZRR would result in the cancellation of the appointment.

Recruitment Policy :
As part of its diversity policy, all Inria positions are accessible to people with disabilities.