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PhD POSITION IN GEOMECHANICS

Water–Gas–Rock Interactions in the EDZ of Underground Storage Facilities: A Numerical Approach for the Cigéo Project

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Scientific context

The safe management of nuclear waste in deep geological storage relies largely on the stability and tightness of underground structures excavated in clay formations (Europe), such as the Callovo-Oxfordian (COx), the host rock of Andra's Cigéo project, one of the most thoroughly documented geological containment systems in the world (Armand et al., 2013; 2017a; Conil et al., 2020).

During the excavation of galleries, an Excavation Damaged Zone (EDZ) develops around these structures (Fig. 1), characterized by induced fracturing that evolves under the influence of water, gas, and thermal and mechanical stresses. Despite the abundant literature on the multiphysical characteristics of the COx, some key mechanisms remain poorly understood or insufficiently implemented into models at the scale of the structure.

Coupled thermo-hydro-mechanical (THM) models, predominantly continuous, reproduce certain field observations (Manica et al., 2022; Alonso et al., 2024; Souley et al., 2024), but encounter challenges in precisely characterizing fracturing, its geometry, its dynamics, and its effects in the near field, which are nonetheless essential for assessing the stability of storage structures during operation and after closure. Indeed, the COx is globally continuous, but its behavior becomes locally discontinuous within the EDZ. Discontinuous approaches (DEM, FDEM) as well as hybrid continuous–discontinuous methods now represent a relevant alternative to conventional continuous models. They make it possible to better capture the initiation and propagation of fractures, as well as to characterize the EDZ and its evolution under THM loading. They are thus more appropriate for representing and incorporating the EDZ in the design and evaluation of Cigéo structures and specific experimental setups, although major scientific challenges still persist.

In this context, it is necessary to develop a multiscale and multiphysical approach to better understand and predict the evolution of fracturing within the EDZ, and to ensure the long-term performance and integrity of underground storage structures such as the Cigéo radioactive waste repository.

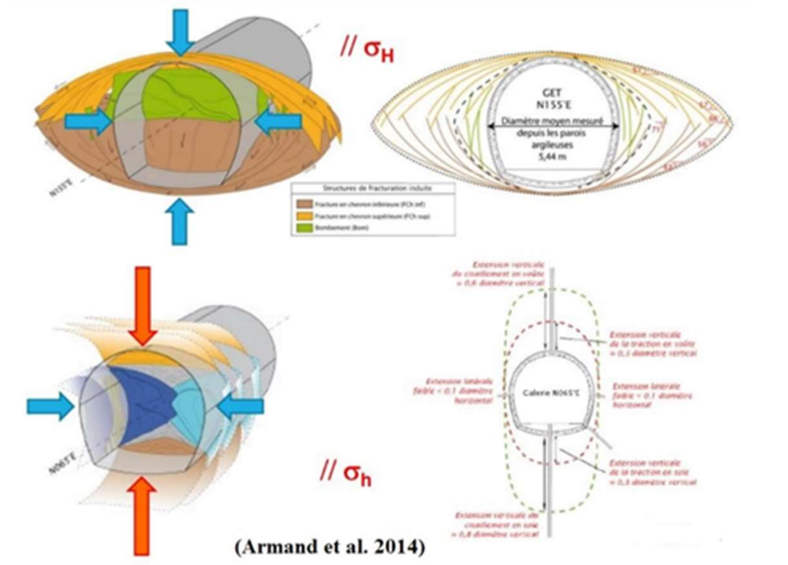

Fig. 1 – Geometry of the induced fracturing around the M-HM URL structures: Left = fracturation observed in situ; Right = conceptual model proposed by Armand et al. (2014); Top = galleries parallel to the major horizontal stress; Bottom = galleries parallel to the minor horizontal stress.

Dissertation topic

The state of the art on the COx highlights the complexity of the THM behavior of claystone (Souley et al., 2026; Vu et al., 2026), characterized by strongly coupled interactions that are scale-dependent (Armand et al., 2013; 2017b). Their understanding and modeling require a multiscale approach that consistently integrates experimental data, in situ observations, and both continuous and discontinuous models. This PhD thesis is positioned within this framework, in connection with our scientific partnership with Andra.

Exploratory work by Camusso et al. (2022) and Thoraval et al. (2026) has enabled 2D/3D models that reproduce induced fracture networks and their response to hydromechanical loading. However, these models, based on a DEM approach using the 3DEC software, remain computationally expensive when multiphysical couplings are considered. This PhD thesis aims to propose an alternative based on a multiscale (structure → district → repository) and multitemporal (design, operation, closure) modeling methodology, relying on a hybrid (continuous–discontinuous) approach that incorporates coupled multiphysical processes, both within the clay matrix (COx) and in the induced fractures and their evolution kinetics. This methodology will enable:

- To elucidate the mechanisms governing fracture initiation, evolution, and impact around underground storage structures.
- To analyze the effects of coupled hydraulic, gaseous, and mechanical loading on fracture activation and propagation.
- To evaluate the resulting effects of fracturation on the overall assessment and performance of Cigéo's closure structures and underground storage systems.

Beyond the specific context of Cigéo, this research will contribute to fundamental advances in the understanding of fractured porous media behavior, multiphase transport, and the mechanical response of porous materials under coupled loading. It thereby opens perspectives for applications to other underground storage across a variety of host rocks and geological environments.

What you will do in practice

- **Field data analysis**: You will work with a unique database compiled from more than two decades of in-situ monitoring (pressure, deformation, fracturing, etc.) and laboratory tests to characterise the formation and evolution of the EDZ around the Cigéo facilities.
- **2D/3D numerical modelling (Distinct Elements, Finite Elements)**: You will develop and apply innovative discontinuous or hybrid geomechanical models initiated in the exploratory work of Thoraval et al. (2026) to simulate fracture development, its long-term evolution, and the effects of hydraulic, gaseous, and mechanical loads, including the resulting water–gas–rock interactions.
- **An approach built on gradually increasing the complexity of the matrix and fracture behavior**: linear → nonlinear, anisotropy, time-dependent effects, hydromechanical coupling in saturated single-phase conditions (water, gas).
- **Validation based on comparison with field measurements and with the numerous predictions of continuous COx models described in the literature**: You will compare your numerical results with field observations, propose additional interpretations of the measurements when needed, and contribute to refining numerical models based on recent scientific advances and the interpretation of underlying physical mechanisms.
- **Safety assessment of structures**: You will analyze the consequences of the fracturing evolution on the short-, medium-, and long-term stability and performance of Cigéo's closure structures and related underground storage components.
- **Collaboration and communication**: You will collaborate with recognized specialists (Ineris, University of Lorraine, Andra), present your findings in meetings, seminars, and conferences, and take an active role in the scientific life of a dynamic international research team.

Why is this topic so exciting?

- **A real-world challenge:** Your work will contribute directly to environmental safety and responsible management of the highest-hazardous radioactive waste.
- **A unique Rock Mechanics URL**: You will have access to a world-class underground research laboratory with exceptional data and rare experimental conditions.
- **A scientific and human adventure:** You will join a dynamic, multidisciplinary and international team where collaboration, curiosity and innovation drive everyday progress.
- **A wide range of rewarding skills:** Your work will enable you to further develop skills in modeling, data analysis, interpretation of experiments, scientific communication — you will develop expertise that is in high demand across a wide range of industries.
- **A wide range of career opportunities:** At the end of your PhD, you will be able to pursue a career in industry, public research, or higher education, both in France and internationally.

For whom?

- Master's degree (M2) or engineering diploma in geosciences, civil engineering, mechanics, physics, or related fields.
- Curious and motivated by major environmental and industrial challenges.
- A desire to understand, model, challenge results, and see the real-world impact of your work.

Strong scientific English skills are essential.

Project advantages

- **High-quality supervision** provided by a joint team from Ineris and the University of Lorraine.
- **Attractive remuneration**, gross annual salary of €27,530 (€2,130 × 12.5 + €905 bonus).
- **Contract**, 39-hour workweek; 18 RTT days in addition to 31 days of paid leave; meal vouchers.
- **Mobility and networking opportunities**, including travel within France and internationally as well as participation in scientific conferences.

Your research will be carried out within the Natural Hazards, Structures and Storage unit at Ineris, as part of a THMC modeling team (ten engineers, including three habilitated to supervise research (HDR), and one PhD candidate), specializing in geomaterials behavior and the design of structures in both continuous and discontinuous media.

Application profile

- **Application deadline: July 1, 2026**
- **Required documents:**
  Curriculum vitae – Copies of the certificates for each university degree and the corresponding transcripts – Motivation letter – Any recommendation from your professors and/or supervisors. Knowledge of COMSOL Multiphysics (mechanics/flow) and mechanics/hydraulics of fracture is an asset.
- **Eligibility:**
  All intra-EU candidates – Non-EU candidates who already hold student status in France – Holders of a Master's degree or equivalent – Skill in French and/or English: written and spoken.

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About Ineris

Ineris (the French National Institute for Industrial Environment and Risks), employing around 500 staff, is a leading national institute under the Ministry for the Environment, dedicated to research and risk prevention.

Joining Ineris offers the opportunity to apply and further develop one's skills through research, support, and expert assessment missions carried out on behalf of public authorities and industry. Ineris operates 30,000 m^2 of laboratories and testing facilities equipped with a wide range of state-of-the-art technologies.

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