PhD thesis
Data-Driven and Physically Informed Surrogate Modelling of Soil–Structure Interaction in Permafrost Conditions

Place: Navier Laboratory, ENPC (77420, Champs-sur-Marne, France)

Duration: 3 years (September 2026 – August 2029)

Salary: ~2350 euros/month (gross salary / salaire brut)

Funding: ANR project PERMACHANGE

Advisors: Lina-María Guayacán-Carrillo, Jean-Michel Pereira and Anh Minh Tang.

Collaborations: Geosciences Environment Toulouse (GET) laboratory
Processes and Engineering in Mechanics and Materials (PIMM) laboratory

Scientific overview:
This PhD thesis aims at studying the impacts of climate change-induced permafrost thaw in the Arctic, by using advanced thermo-hydro-mechanical (THM) modelling capabilities developed in the framework of the PERMACHANGE project. Permafrost is soil permanently frozen in depth, covering a quarter of Northern Hemisphere lands. Due to climate warming, it is experiencing fast and widespread thawing, and this induces essential impacts in the Arctic, both on the environment (e.g., water resources) and on societies (e.g., infrastructure destabilisation). These permafrost thaw impacts are expected to generate significant additional financial costs for maintaining key human activities, up to hundreds of billions of dollars by the end of the century. Moreover, permafrost thaw will likely trigger critical climatic feedback. Thus, anticipating permafrost thaw by numerical simulations is paramount for ensuring the resilience of Arctic environments, societies and activities while controlling the associated costs. Meanwhile, numerical simulations of permafrost dynamics are highly complex and challenging due to the strong non-linearities and couplings involved in the related physics.

The PERMACHANGE project builds on high-performance computing (Orgogozo *et al.*, 2023, Xavier et *al.*, 2024) and hybrid modelling (Chinesta *et al.*, 2020; Champaney *et al.*, 2022) for developing a site-scale (~10's of km^2) permafrost thermo-hydrological hybrid twin, to be coupled with state-of-the-art freezing/thawing soil mechanics machine learning-based surrogate models (Richa *et al.*, 2024, Tristani *et al.*, 2024) using symbolic regression approaches (e.g. Guayacán-Carrillo and Sulem, 2024). By doing so, PERMACHANGE will enable unprecedented high-fidelity and high-efficiency numerical simulations of subterranean heat and water transfers and terrain stability under permafrost thaw.

Objectifs:
This PhD aims at adding soil mechanics (M) simulation capabilities to the TH hybrid twin. The detailed objectives are: (1) simulating the effect of temperature change on geotechnical infrastructures, and (2) building a mechanical surrogate model.

Tasks:
The thesis work is divided into two tasks:

1. <u>Finite element simulations of typical geotechnical infrastructures.</u> This task entails the implementation of numerical modelling across various scenarios to address the effect of

permafrost thawing on typical geotechnical infrastructures (roads, building foundations, slopes, etc.). Extensive parametric studies will be undertaken to examine the thermal and mechanical performance under different scenarios, which encompass soil conditions, infrastructure characteristics, and thermal variations. These parametric studies will critically analyse soil-structure interactions under these diverse conditions. To achieve this objective, numerical thermo-mechanical simulations utilising a finite element code will be executed. It is important to note that the experimental results from prior projects will provide substantial insights for the interpretation and contextualization of new findings. A substantial quantity of numerical data will be produced from these comprehensive investigations.

2. Building a mechanical surrogate model. This task aims to propose a straightforward and definitive tool for expeditious and reliable support. Consequently, in light of the outcomes obtained in the previous task, this tool will be trained on various scenarios to more effectively consider uncertainties primarily associated with soil variability in terms of mechanical and thermal properties. Indeed, recent investigations conducted by the Navier team have demonstrated the efficacy of employing machine learning approaches to furnish engineers with a rapid computational asset for structural design and monitoring. Given that numerical models incorporating multi-physical couplings generally necessitate extensive computational time, the development of machine learning-based surrogate models will be pursued. The subsequent task involves formulating a machine learning-based methodology, encompassing data cleaning and pre-processing, synthetic generation and database creation, culminating in the application of machine tools. Machine learning-based surrogate models will be developed based on the previous endeavours of the Navier team (Richa et al. 2024 and Tristani et al. 2024). Finally, based on symbolic regression approaches, a methodology will be tested to incorporate data from experimental tests and numerical outcomes to derive simple mathematical expressions for evaluating soil-structure interaction, ensuring reliable predictions over time (e.g. Guayacan-Carrillo et al. 2024).

Champaney *et al.*, 2022. *Int J Mater Form* 15, 31. https://doi.org/10.1007/s12289-022-01678-4
Chinesta *et al.*, 2020. Arch Computat Methods Eng 27, 105–134 https://doi.org/10.1007/s11831-018-9301-4
Guayacán-Carrillo & Sulem, 2024. *Comp & Geotech*, 171, 106355. https://doi.org/10.1016/j.compgeo.2024.106355
Orgogozo et al., 2023. *Computer Physics Communications*, 282, 108541, https://doi.org/10.1016/j.cpc.2022.108541
Richa *et al.*, 2024. *In: Geotechnical engineering challenge to meet current and emerging needs of society. Proc. XVIII European Conference on Soil Mechanics and Geotechnical Engineering*. Lisbonne, August 2024. https://doi.org/10.1201/9781003431749-359
Tristani *et al.*, 2024. *Int. J. Num. & Anal Meth. Geomech.* https://doi.org/10.1002/nag.3889
Xavier *et al.*, 2024. *The Cryosphere*, 18, 5865–5885, https://doi.org/10.5194/tc-18-5865-2024

Needed skills and knowledge:
Numerical modelling (experience in Finite Element Methods and/or AI-based modelling)
Collaborative work in a large and diverse international team
Interest in scientific communication and writing
Although not mandatory, a background in geotechnics would be appreciated.

How to apply:
Please send your CV and cover letter to us HERE
Your application will be evaluated, and if you are shortlisted for an interview, we will contact you.

Application deadline: 31st of March 2026