EU-DOCS for SmUCS

CO-SUPERVISED SUBJECT PROPOSAL FOR A DOCTORAL CONTRACT

Title of the thesis project Study of the mechanical behavior and stability of partially saturated heterogeneous soils on the seafront	
La Rochelle University Research Unit Laboratoire des Sciences de l'Ingénieur pour l'Environnement (LaSIE)	**Partner university** University of Calgary (Canada) **Cotutelle research unit** Department of Civil Engineering
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Non-academic partner Direction Départementale des Territoires de la Mer (DDTM)	
Main research field: Civil Engineering	
Keywords: Mechanical behaviour of soils, Stability, Capillarity , Shrink-swell of clays, Deep Learning, Discrete Element simulation.	

Scientific description of the research project

In the current context of climate change, the frequency and intensity of storms and extreme weather events are increasing, placing greater and sometimes different stresses on soils, particularly in coastal areas. Under the effect of rapid and intense cycles of water saturation/desaturation, heterogeneous soils may be subject to swelling/shrinking phenomena or undergo significant changes in their mechanical strength, causing damage to the structures (housing or flood protection works) built on them.

The work proposed in this research endeavor aims to improve understanding of the mechanisms of deformation and modification of the mechanical strength of heterogeneous granular soils in coastal areas through the development of appropriate numerical tools and models. Heterogeneous clay soils, whose behavior is more complex, will be addressed in a second phase. This work will help to clarify the possible failure modes that cause complex processes such as soil deformation and the associated loss of mechanical strength, which can damage structures built on top of them (housing or protective structures). It should also lead to a tool for characterizing and predicting possible risks and will improve the design of structures built on heterogeneous soils. **This project is part of the environmental and energy transitions defined in the Néo Terra roadmap, which is a scientific priority for the Nouvelle Aquitaine region.**

Granular soils display intricate constitutive behavior due to their discrete composition, rendering their mechanical properties inherently complex. When both liquid and gas phases are present, forming a three-phase system, this complexity is further amplified, challenging the effectiveness of traditional constitutive models. However, it remains crucial for engineers to develop accessible and practical models to accurately analyze and predict the mechanical behavior and stability of granular soils, especially when subject to wetting and drying cycles at the structural scale.

Recent collaborative research conducted by La Rochelle University and the University of Calgary has successfully combined multiphase Lattice Boltzmann Methods (LBM) with the Discrete Element Method (DEM) to investigate the influence of increased water content and relative humidity on the apparent cohesion of granular soils. For the first time, their study numerically captures a regime transition in partially saturated porous media—from the pendular regime, dominated by capillary doublets between solid particles, to the funicular regime, where most capillary bridges have coalesced. This transition leads to a substantial reduction in capillary forces, triggering a spontaneous decrease in the overall mechanical strength of the granular assembly. While multiphase Allen-Cahn LBM approaches offer the possibility of phase separation and interface dynamics at the pore scale, current computational constraints, even with intensive GPU calculations, limit their ability to simulate the mechanical strength and stability of granular soils at the geostructure scale. To overcome this limitation, this project aims to implement a special scale-shifting technique that integrates small-scale capillary effects, enabling the derivation of mechanical properties at the engineering scale for multiphasic-heterogeneous soils.

To achieve this, we propose the numerical computation of an average stress tensor through homogenization of coupled DEM x LBM simulation results of a highly polydisperse, partially saturated granular assembly. These simulations will encompass three-dimensional models containing several tens of thousands, or even hundreds of thousands, of elementary particles, subjected to a variety of mechanical and hydraulic loadings. This mean stress tensor will be derived from discrete interparticle contact forces and small-scale capillary forces, facilitating the creation of a comprehensive database.

The above-mentioned database will then be utilized to determine the mechanical strength of partially saturated heterogeneous granular soils undergoing wetting and drying cycles. Transitioning to the macroscopic scale will involve coupled MPM x DEM or FEM x DEM numerical simulations at the geostructure scale, supported by Deep Learning techniques to identify a constitutive law tailored to partially saturated soils. Neural network approaches, trained on the previously established database, will play a central role in this scale-shifting process.

PhD student profile and skills required

Applicants should hold a master's degree in engineering or applied mathematics, with a strong background in Continuum mechanics, coupled phenomena in physics, and some knowledges in Machine Learning and/or IA, Applied and computational mechanics, Discrete Element Simulation.

Scientific alignment with EU-DOCs for SmUCS objectives

In today's climate change context, the frequency and intensity of storms and extreme climatic events are on the increase, placing greater and sometimes different demands on soils and surfaces subjected to sea spray and rain/wind, particularly along the seafront. Under the effect of rapid and intense water saturation/desaturation cycles, heterogeneous soils can be subjected to swelling/shrinkage phenomena or undergo significant changes in their mechanical strength, resulting in damage to structures (housing or sea defenses) resting on them. The results obtained in this proposed research should lead to a numerical tool for characterizing and predicting possible risks and will improve the design of structures built on heterogeneous soils.

This project is in line with the environmental and energy transitions defined in the Néo Terra roadmap, which is a scientific priority for the Nouvelle Aquitaine region. **Therefore, it aligns perfectly with SmUCS objectives.**

Societal and economic challenges and contributions

An important application with a strong socio-economic impact concerns the modeling of the stability of partially saturated granular soils, as part of the New Aquitaine Region's *Néo-Terra* roadmap *for a green and sustainable world*.

The Direction Départementale des Territoires et de la Mer[1] (DDTM) in La Rochelle is heavily involved in this thesis project. It will host the doctoral student at its La Rochelle site for a period of three months.

The results obtained in this thesis should lead to a numerical tool for characterizing and predicting possible risks and will improve the design of structures built on heterogeneous soils (housing or coastal protection structures). In situ applications on sites identified with the DDTM are planned as part of this work. The benefits for government services in optimizing risk prevention, as well as investment and maintenance costs for the region, are extremely significant.

Partnership context

The thesis will be carried out under a joint supervision agreement between the University of La Rochelle and the University of Calgary, in intensive collaboration with the DDTM in La Rochelle. The PhD student will spend several periods at the DDTM for a total duration of three months. He will spend also at least 6 months in Calgary University.

Complementarity of teams and Universities and their areas of expertise

La Rochelle University: The thesis will take place at Laboratoire des Sciences de l'Ingénieur pour l'Environnement (LaSIE), UMR CNRS 7356, La Rochelle University. The LaSIE brings together a wide range of expertise with integrated approaches from the atomic scale to materials, buildings, and their environments, across different time and spatial scales. It establishes a continuum from the development of mathematical tools to applications, through numerical models, simulations, and experiments. The doctoral student will be affiliated with the M2N team (Mathematical and Numerical Methods for Transfer Phenomena), whose work focuses on the development of mathematical and numerical models in mechanics in general, and transfer phenomena in particular.
The researcher contributing to this project is recognized for their work on multiscale approaches to solid mechanics and geomechanics, numerical simulations of two-phase fluid mechanics, studies of capillary bridges and their stability, micromechanical analysis of dry and partially saturated granular materials and soils, homogenization of reactive transfers in porous media.

University of Calgary: The University of Calgary's contribution focuses on the micromechanics of three-phase granular media, with an extension to clayey materials. A central objective is to understand how stresses are partitioned among the grain skeleton, water phase, gas phase, and the various interfaces within unsaturated media. The Calgary research team has developed precise mathematical formulations that capture these stress distributions at the pore and grain scales, accounting for the topology and statistical variability of the constituent phases.
Simulations are initially conducted at La Rochelle University and continue in Calgary using the WestGrid high-performance computing network. These coupled Discrete Element Method (DEM) and Lattice Boltzmann Method (LBM) simulations generate detailed micro- and meso-scale data, which serve as a critical bridge between computational modeling and machine learning. The analytical expressions developed in Calgary are rooted in micromechanical principles and, thus, can be directly integrated into machine learning frameworks to ensure they are physics informed.
In the extension to unsaturated clay materials, the Calgary team has also developed micromechanical models that incorporate dominant physico-chemical forces at the microscale. These interactions are explored through homogenization techniques, enabling the upscaling of small-scale physics to the macroscopic level. This leads to a micromechanically-enriched constitutive model for clays that captures behavior down to the nano-scale and below.
Given the depth and alignment of this collaborative work, the student is expected to spend more than six months in Calgary. This exchange complements the broader project framework, which includes: (1) Mathematical and numerical modeling, along with experimental investigations at La Rochelle University, (2) Direct engagement with engineering and societal challenges through the Departmental Directorate for Territories and the Sea in La Rochelle, and (3) An international research dimension, leveraging Calgary's expertise in micromechanics of three-phase granular materials, including nano-scale clay behavior.

DDTM: The Departmental Directorate for Territories and the Sea (DDTM) is an interministerial department responsible for carrying out missions of the Ministry of Spatial Planning and Ecological Transition. Acting under the authority of the Prefect, it oversees the Charente Maritime dyke plan, which has a total budget of €250 million. It carries out activities to protect populations in flood-prone areas by developing natural risk prevention plans and keeps a record of dikes and retention structures. In addition, it manages the public maritime domain and pays close attention to the challenges of coastal erosion.

HR EXCELLENCE IN RESEARCH