Multiscale modeling of maritime dikes under cyclic hydraulic loading

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The University of Calgary, the University of La Rochelle and INRAE are pleased to invite applications for a PhD position (3 years) to model the mechanical behavior of granular materials subjected to cyclic hydraulic loading and to analyze the induced instabilities. This PhD project is part of the StabDigue project supported by the French Region Nouvelle Aquitaine on the analysis of both the stability and durability of dikes and retaining structures along the coastline. The PhD candidate will benefit from both a French-Canadian double PhD degree and the International Research Network *Multi-Physics and Multi-scale Couplings in Geo-environmental Mechanics* (GDRI CNRS GeoMech).

Context and motivations

In a context of climate change, coastal structures such as dikes will be subjected to increasingly more extreme loads in the future. This PhD project aims at improving the understanding of the mechanical behavior of these protective structures as well as the soil beneath them for a better management of their structural integrity and failure. A distinctive feature of these hydraulic structures is that they are subjected to cyclic hydraulic loadings that can ultimately reduce their bearing capacity.

In this PhD project, a multiscale approach will be developed. Indeed, at the microscale, earthen dikes and soils can be modeled as granular materials. These materials are porous and water infiltrates in between the grains. One of the peculiarities of granular materials on the coastline is that they can be found in either fully or partially saturated states under the action

Figure 1: Modeling view of a coastal dike subjected to hydraulic cyclic loading (tides or waves). In its core the saturation line fluctuates, resulting at microscale in varying degrees of saturation and local capillary stresses.

of waves and tides (see Fig. 1). The issue at hand in the project is to understand the impact of saturation/drying cycles on the mechanical stability of granular materials.

To achieve this, a numerical and analytical approach will be employed, through the use of both discrete element simulations and micromechanical models [20, 23]. This will enable us to analyze the microscale mechanisms occurring during the saturation/drying cycles as well as homogenizing the resulting mechanical behavior to bridge the gap between the local physics and the overall mechanical stability of the hydraulic structures.

The long term objective of this PhD project will be to exploit computational tools in order to better assess and predict the stability and durability of coastal dikes.

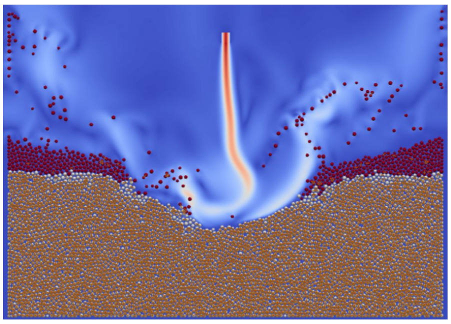
A brief state of the art

Instabilities in granular materials: Since its introduction by Hill in 1958 [8], the second-order work criterion has proved to be a versatile tool to identify unstable states at the material point scale [13, 14]. The vanishing of the second-order work for some incremental loading directions has been shown to be the instability criterion that is first reached in granular materials before Rice-Rudnicki's condition for strain localization and the plastic limit condition [18]. This criterion has become more and more clear for dry granular materials [13, 21, 22], but its application to unsaturated and fully saturated material remains elusive. Indeed, since the introduction of the effective stress concept by Terzhagi in the early 1920s [19], failure in geomaterials has always been assessed with respect to the dry material. The stress tensor to be considered in the writing of the second-order work (total or effective stress) will be elucidated in this project for the first time.

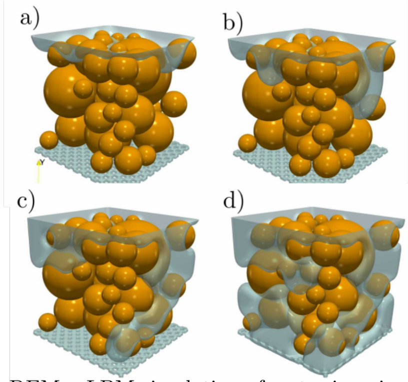
Capillarity effects in granular materials: So far, considerable effort has been devoted to the modeling of the behavior of granular materials in the pendular regime, i.e. when the degree of saturation is sufficiently small so that a distinct capillary bridge exists only between pairs of particles. Much fewer studies have been devoted to the funicular and capillary regimes corresponding to the existence of liquid bridges between several particles (more than two as illustraded in Figures 1 and 2) [3, 4, 11, 10, 12, 15, 17] and the effect of the coalescence of liquid bridges [5, 6, 7] that can trigger for instance static liquefaction. A correct modeling of capillary forces during wetting and drying cycles remains, thus, a challenge today. To tackle this open issue, the PhD candidate will benefit from ongoing work of the various collaborative research teams involved in the project exploring the coalescence of liquid bridge at the scale of a few grains of soil (mesoscale) from numerical, analytical and experimental viewpoints. In addition, to capillary effects in "sandy" granular materials, more complicated phenomena occur while considering "clay" granular materials. In materials composed of clay aggregates, the water effect is acting at different scales: between clay platelets through Van der Waals forces and between clay aggregates through capillary forces. Accounting for this double scale modeling of saturation/drying for such clay aggregates remains an open challenge.

Microscale modeling of partially and fully saturated granular materials: Thanks to increasing computation power, the behavior of granular material is now often simulated directly at the microscale thanks to the use of discrete element methods (DEM)[2]. Initially developed for dry granular materials, this method has been coupled with other numerical schemes to incorporate the action of interstitial fluid in between grains. Among these methods, Lattice Boltzmann Methods (LBM) or Pore scale Finite Volume (PFV) methods have proven to be relevant to model interstitial fluid flow in fully saturated granular materials, and some numerical schemes exists to account for the saturation/desaturation of granular materials [24]. To this respect, Figure 2 provides two illustrations of the method capabililities. However, so far most of the studies still address these coupling problems in 2D because of computational cost issues. In this respect, the PhD candidate will benefit from recent developments made at INRAE by carrying out DEM-LBM simulations on GPUs [1] so as to speed up the computations.

Homogenization in granular materials: In order to model the mechanical behavior of granular materials at the engineering scale (at the scale of a dike for instance), there is a need to replace their discrete nature with enriched equivalent homogeneous materials. This upscaling process results in the definition of a constitutive behavior, i.e. a mathematical relation between the constitutive variables of the material (a minima between stress and strain). The change in scale



DEM – LBM simulation of an impinging jet



DEM – LBM simulation of water invasion

Figure 2: DEM-LBM simulations in fully and partially saturated conditions. Simulation of an impinging jet with a GPU accelerated DEM-LBM code [25] and water invasion in the pore space of an initially dry granular assembly [9].

is usually achieved by averaging local quantities either by volume or statistical averaging. In the first case, a representative volume element of material is considered (for instance with DEM) and macroscopic variables are defined by averaging over the considered volume. In the second case, a collection of mesostructures of a few grains are considered under different geometric configurations. For each of these mesostructures, local definition of macroscopic variables are expressed in terms of micro quantities, while the macroscopic variables are recovered by averaging over the collection of microstructures. In recent years, micromechanical models were proposed to homogenize the mechanical behavior of granular materials. Compared to DEM direct homogenization, the microstructure of granular material is simplified, but these models show very good prediction capability provided that the driving physical processes are captured by the considered mesostructures. The PhD candidate will benefit from the recent developments of micromechanical models achieved at the University of Calgary and at INRAE [23, 16]. In particular, these recent developments enable us to account for capillary forces in different capillary regimes.

Required knowledge and skills

The candidate should have a master or an engineering degree in geomechanics, civil engineering or mechanical engineering. As the PhD subject will be at the interface between solid and fluid mechanics and will involve multiple scales, notions in fluid mechanics and homogenization will be greatly appreciated. A good level of scientific English (speaking and writing) is mandatory.

Depending on the candidate skills and interest, some laboratory testing may be included in the project (microscale capillary force measurements in micro-gravity environment).

Application

In order to apply for this position, CV and cover letter (in English or French) must be sent by e-mail to all members of the supervising team (wan@ucalgary.ca, olivier.millet@univ-lr.fr, antoine.wautier@inrae.fr, and francois.nicot@inrae.fr)

Terms and contract

The PhD candidate will benefit from a CNRS contract that is scheduled to start in October 2020 (with some flexibility) for a period of 36 months. The PhD candidate will benefit from a French-Canadian double PhD degree and will be enrolled at the two following doctoral schools: École Doctorale EUCLIDE and Schulich School of Engineering. As a result the PhD candidate will split his/her time between 18 months in Calgary and 18 months in France between La Rochelle and Aix-en-Provence.

The PhD candidate will be paid by the University of Calgary and by the CNRS with a gross salary of 2700 €/month for the period in France and 1800 CAD/month for the period in Canada.

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