PhD Proposal

Giving Cohesion to Granular Matter: When Liquid Foam Meets Grains

February 24, 2025

Context and Problem Statement

The injection of liquid foam into granular materials is involved in numerous processes, particularly in soil decontamination and remediation [1, 2, 3], as well as in the stabilization of sandy soils excavated by tunnel boring machines [4, 5]. In another context, the production of construction blocks can be considered using granular materials from recycling streams, by binding the grains together with an initially liquid foam [6]. Foam granulation is a process that transforms powders into granules, where the liquid foam acts as an agglomeration agent. With respect to the use of pure liquid [7], this approach allows for better control of particle humidification and granule formation [8]. In several applications, it is crucial to precisely control the rheological behavior of foam-grain mixtures to ensure the efficiency of the process. However, this aspect remains largely unexplored and poorly understood.

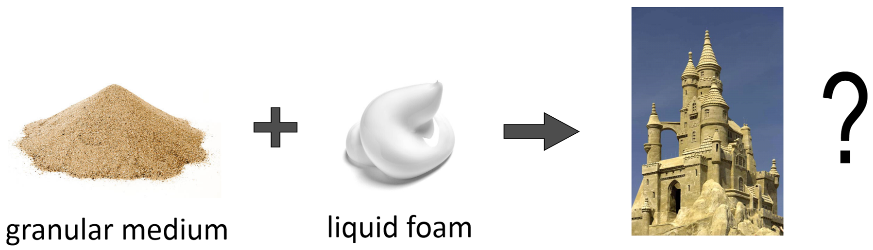

Figure 1: How much cohesion can liquid foam provide to granular assemblies?

The study of the foam-grain system is scientifically interesting because it combines two classes of materials with complex behaviors. Granular media exhibit specific mechanical properties, with transitions between solid and liquid states depending on the applied constraints. Liquid foam is intrinsically cohesive: its bubbles are held together, more tightly when the foam has a low liquid content. This cohesion is further enhanced when the bubbles are small. However, foam is a material subject to aging: over time, gas diffusion between bubbles leads to an increase in their size [9, 10]. To what extent do the grains mixed with the foam benefit from this cohesion? And how does it influence the transition between the solid and liquid states of the medium? Is the cohesion observed in flow conditions the same as in a static system? Does this system evolve over time, and if so, according to what dynamics? These are all questions that deserve further investigation.

Objectives of the PhD

This PhD project aims to investigate the mechanics of granular materials interacting with liquid foams, focusing on:

- the cohesion of grain packings impregnated with foam, as well as the critical stress (or yield stress) that triggers their flow. These parameters will be studied as a function of the liquid volume fraction, grain size, and bubble size. The temporal evolution of these quantities will also be analyzed, particularly in relation to foam aging.
- We will establish the relationship between stress and deformation rate (shear) governing the flow of these systems, taking into account the aforementioned parameters.
- Furthermore, the microstructure of the packings will be characterized to identify correlations with the derived flow laws. Particular attention will be given to the evolution of bubble size between the grains, both in static conditions and under shear.
- Finally, we will measure the so-called *local law*, which characterizes the interaction between neighboring grains immersed in liquid foam. The influence of the liquid fraction, as well as grain and bubble sizes, will be quantified. These findings can then be incorporated into discrete element numerical simulations to explore the overall behavior of foam-impregnated grains.

Methodology

- The preparation of foam-grain systems will build on the laboratory's extensive and unique expertise in this field [11, 12, 13, 14]. We will be able to precisely control the composition of the samples in terms of volume fractions (liquid/gas and grains) and sizes. To simplify the study, the grains will have a uniform size, as will the bubbles, at least in the initial phase.

- Experiments aimed at determining the rheological properties of the systems will be conducted using a specially developed osmotic cell, mounted under a rheometer. This cell will allow us to fix the liquid fraction during measurements and analyze its impact on rheology.
- Volumetric imaging and microstructural characterization of the systems will be carried out using our X-ray microtomograph. Additionally, an ultra-fast tomography campaign at the Soleil synchrotron will enable the study of the system's dynamic aspects.
- A force measurement device, developed in the laboratory, will allow direct access to the local interaction law between two grains immersed in liquid foam.
- A physical modeling approach will be conducted to account for our observations and propose laws that can later be used to predict the rheological behavior of these doubly complex systems.
- Finally, discrete element simulations will be implemented to reproduce the macroscopic behavior of the systems based on the experimentally determined local interaction law.

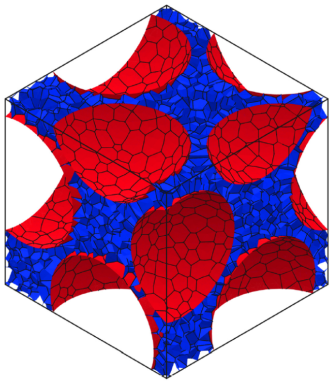

Figure 2: Illustration of the foam bubbles (in blue) located between the spherical grains (in red). The grains are hollowed out to allow observation of the interior, particularly the bubbles in contact. V. Langlois [15]

Working Environment

This PhD will be conducted at the Navier Laboratory, a joint research unit of the Ecole Nationale des Ponts et Chaussées (ENPC), the Gustave

Eiffel University and the National Center for Scientific Research (CNRS), located in the Cité Descartes in Marne-La Vallée (Champs-sur-Marne). Our researchers study mechanics and physics of materials, structures and geomaterials, and their applications to geotechnics, civil engineering, transport, geophysics and energy. Our research focuses on several societal challenges, including sustainable construction, natural hazard management, environmental preservation, and the energy transition. The project will be supervised by **Olivier Pitois** and **Abdoulaye Fall**, both researchers in the Rheophysics and Porous Materials team, experts respectively in foam and wet granular materials, ensuring strong interdisciplinary expertise.

Expected Profile

We are looking for a student with a Master's degree (M2) in physics, physical chemistry, or materials science, with hands-on laboratory experience, particularly through a research internship.

References

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