CENTRALE NANTES GeM Institut de Recherche en Génie Civil et Mécanique RÉGION PAYS DE LA LOIRE

Final year Master internship offer

On the role of extreme drying-induced surface soil degradation on contaminant transport in the vadose zone: A numerical investigation

keywords: vadose zone, partially saturated porous media, contaminant transport, advection-diffusion, phase field modeling.

Context & problem statement

According to the "*Bulletin de situation hydrogéologique*" released by the french geological survey bureau (BRGM) by end of the replenishing period in 2022, the risk of drought on groundwater in the Pays de la Loire (PdL) region in France is classified as high to very-high (see figure 1). This trend continued in 2023 and the spatial zone of high to very-high risk has spread across the various regions in France. This is a trend that is expected to exacerbate as the extreme drying events occur at increased frequencies and in fact this is not localized to France. The Intergovernmental Panel on Climate Change (IPCC) AR6 Synthesis Report: Climate Change 2023 (Lee and Romero, 2023) claims a 1.1°C increase in global surface temperature by 2011-2020 compared to 1850-1900.

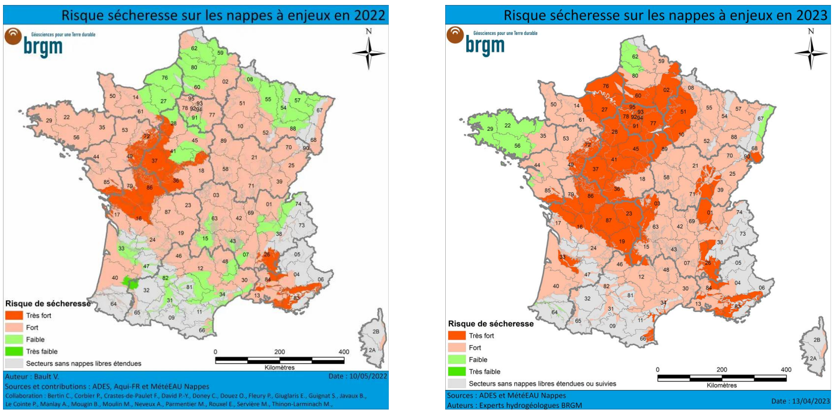

Figure 1: Drought risk on groundwater aquifers in France in 2022 and 2023 as released by BRGM.

The direct impact of extreme drying is the formation of drying cracks that propagate vertically into ground and have an effect of increasing the global conductivity of the soil mass, and in such sense, degrading the surface soils. Consequently, various contaminants find new pathways to reach groundwater much faster and in higher quantities. This endangers the security of already depleted water sources. **What is the impact of surface soil degradation on the contaminant transport mechanism?** This is the problem statement that the current internship project aims to address.

Scientific approach & internship objectives

The approach to above stated problem involves three steps: (1) building a suitable damage model that describes drying induced fracturing/ remodeling of surface soil, (2) building a suitable coupled model that is capable of describing the transport phenomena of both infiltrating water (solvent) and contaminant (solute) across an *a priori* remodeled soil layer and finally (3) Implementing appropriate numerical schemes that are capable of resolving the above two problems (soil degradation & contaminant transport). The loading and initial conditions associated to the two mechanisms naturally necessitate two distinct boundary-value problems preferably needing two distinct modeling strategies.

Soil degradation driven by extreme drying is a topical subject extensively studied both experimentally (Tang et al., 2021) and numerically. In the current work phase field modeling of fracture will be employed to describe the complex fracture initiation/ propagation. There exist two prevailing paradigms that intend to explain surface fracture initiation in drying soils, tensile stress-state driven (Peron et al., 2009; Cajuhi et al., 2018) and capillarity driven (Shin and Santamarina, 2010; Ommi et al., 2022b). The current study intends to make a comparative investigation between the capillarity driven and the total stress-state driven (Heider and Sun, 2020; Luo et al., 2023) damage mechanisms. Another aspect to treat is the evolution of permeability with fracture opening and more importantly the assessment of fracture aperture in phase-field modeling where fracture geometry is described diffusely with a continuous field. In this context, recent strain-based methods (Miehe et al., 2015; Fei and Choo, 2025) seem to be particularly adapted. These techniques will need to be extended to the context of partially saturated porous media that is the drying soil layer.

The state of degraded soil after the drying cycle is to be considered as an initial condition for the contaminant transport problem. Here, two transport mechanisms will be considered: advection due to the infiltrating water flow and diffusion of the contaminant within the water phase. These two transport mechanisms can be modeled using the advection-diffusion equation, where the advective flux is driven by the Darcy-like velocity of the infiltrating water. A generalized Darcy's law modeling such velocity and the resulting complex topological changes in liquid-gas interactions (fingering, pinching & coalescence) during an unstable infiltration have been well-captured through a fourth-order in space extended Richard's equation in the recent work (Ommi et al., 2022a) of the current internship advisors. It remains to be investigated if the unstable infiltration results in a preferential and thus an accelerated transport of the contaminant. Moreover, the modified permeability field due to the preceding drying cycle is expected to accelerate the triggering of the infiltration instabilities. The numerical implementation will be done in Python language employing the open-source finite element library FEniCS (Baratta et al., 2023).

To summarize, the internship objectives are:

- Familiarize with existing phase-field models for drying-induced fracturing of saturated soils.
- Investigate on the possible extension, to partially saturated porous media, of the strain-based fracture aperture assessment and its consequence on the local permeability.
- Numerical implementation and simulation of drying(drainage) induced degradation of the surface soils.
- Familiarize with the phase-field model (Ommi et al., 2022a) for flow instabilities during wetting-induced infiltration of dry soils.
- Numerical implementation of infiltration of dry soils coupled with advection-diffusion equation for contaminant transport.
- Numerical investigation of the impact of surface soil degradation during drying cycles on the contaminant transport during wetting cycles.

Required competences

- Strong skills in continuum mechanics (familiarity with porous media mechanics is an advantage).
- Strong skills in finite element method.
- Familiarity with numerical methods for coupled problems.
- Strong programming skills using Python and Matlab.
- Fluent in written/spoken English.

Internship advisors

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Additional information

- The internship will be conducted in its entirety at the Institut de Génie Civil et Mécanique (GeM), Ecole Centrale de Nantes, 1, rue de la Noë, 44321 Nantes cedex 03, FRANCE.
- The internship will last 6 months (February-July 2025).
- The gratification will be 4.35 €/hour (≈ 600 €/month) according to the French law.
- The internship is in part funded by the Projet TRANSEC (*TRANsport de contaminants dans les géomatériaux influencé par des conditions de SEChage extrêmes*) financed by the region PdL.

N.B. A Curriculum Vitae and the transcript of academic records must be accompanied with the email to candidate for this internship. The e-mail must be sent to siddhartha-harsha.ommi@ec-nantes.fr and giulio.sciarra@ec-nantes.fr

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