Artificial Ground Freezing: Characterization and Modelling of Thermo-Hydro-Mechanical Behavior

Artificial ground freezing is a temporary soil improvement technique that is becoming increasingly popular, particularly for installing frozen earth walls in deep excavations, tunneling operations, and temporary groundwater control. It is applied in soft or highly weathered soils and rock formations where other temporary consolidation methods may not be safe, suitable, or technically feasible. Frozen soils offer several advantages, including high compressive strength, excellent load-bearing capacity, and low permeability. The ice in the soil pores binds the mineral particles together, similar to how cement holds together concrete (Vitel, 2015). Unlike other soil improvement methods, such as cement or chemical injections, freezing has minimal environmental impact. The cooling liquid is circulated through pipes and either evacuated or recirculated, preventing groundwater contamination (Casini et al., 2014; Greenwood et al., 2014).

Although this method has been studied and used for a long time, several major questions and scientific challenges remain. The first challenge is how to accurately predict the volume deformations (swelling and settlement) of the soil surface during a freeze-thaw cycle (Joudieh et al., 2023,2024, 2025). Second, the creep behavior of frozen soils under the influence of ice pressure, as well as their sensitivity to applied external mechanical pressures. Therefore, a thorough study of swelling rates and creep induced volume deformations appear crucial.

While various models and approaches have been proposed for the numerical modeling of soil freezing, the modeling of coupled and highly non-linear thermal-hydro-mechanical (THM) processes remains complex (Nishimura et al. 2009). Numerous obstacles still exist in determining and optimizing model parameters. Models based on laboratory tests that closely replicate field conditions, or in-situ studies, need to be validated before their parameters can be incorporated into predictive processes for designing structures. A comprehensive study should also include the modeling of the soil-structure interaction during a freeze-thaw cycle. Therefore, thermal-hydro-mechanical coupling (THM) must be considered in numerical modeling applied to real-world scenarios of artificial ground freezing.

Objectives and Methodology of the Thesis

An experimental campaign will be conducted to assess the volumetric deformations (swelling and settlement) of soils during a freeze-thaw cycle. A central focus of this thesis will be the simultaneous analysis of databases from frozen soil sites, enabling a comparison between laboratory results and in-situ soil behavior. This will offer an objective overview of the condition of frozen ground structures, serving as a valuable reference for the design of future structures.

A literature review will analyze and categorize the extensive domain of scientific articles on frozen ground. It will cover various complementary aspects, including the fundamental principles of freezing from both hydrological and mechanical perspectives. Additionally, the review will examine the impact of environmental stresses and provide an overview of the latest advancements in models and design methods for structures in frozen ground, with a particular emphasis on thermal-hydro-mechanical (THM) approaches.

For the experimental setup, laboratory heave and compression tests will utilize saturated and unsaturated soil mechanics methods to objectively investigate the impact of a freeze-thaw cycle on the thermal-hydro-mechanical (THM) behavior of soils. A multi-scale approach will be employed. The microstructural properties of these materials will be studied both before and after stress, using techniques such as mercury intrusion porosimetry and X-ray tomography.

In terms of modeling the behavior of frozen soils and developing a conception method, this thesis will take benefit from LEMTA's expertise in modeling the coupled thermal-hydro-mechanical (THM) behavior of unsaturated soils (Mrad et al., 2005, 2006, 2007; Nowamooz et al., 2008, 2009), and heat and mass transfer in porous media (Boukelia, 2016; Maghsoodi et al., 2020 & 2022). The processes initiated by soil freezing involve heat transfer and the migration of pore water, driven by changes in water potential (suction) during the phase change. The swelling resulting from these processes leads to mechanical effects, such as consolidation and alterations in shear strength. Recent modeling approaches in the field of soil freezing-thawing will be explored to predict the in-situ freeze-thaw behavior.

Successful candidate will engage in interdisciplinary research and will contribute to the research work of LEMTA. The work will be of experimental and/or numerical nature, relying on state-of-the art laboratory equipment and numerical modelling resources of LEMTA. The thesis work will benefit from collaborations with the partners of the EU-funded research program UPGRADE, with the possibility of undertaking long-term research stay.

The doctoral position is set to start not later than the 1st of October 2025. Candidates must own, at the time of the start of the position, a MSc Degree in Civil, Geotechnical or Geological engineering, and have a strong interest in mechanics of geomaterials.

Knowledge of the French language is not mandatory.

Conditions

Starting date: not later than 1.12.2025

Duration: 36 months, fixed term contract

Gross Salary: 2 200 € per month plus social benefits

Institution: LEMTA (http://lemta.univ-lorraine.fr/comp_thmc_sols.html)

Université de Lorraine (www.univ-lorraine.fr)

How to apply?

Send by e-mail before 31 October 2025 April 2025 a CV (2 pages max), the MSc thesis (abstract only if it is on-going), and the name of one referee to both supervisors:

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Références

Boukelia A. (2016) - Modélisation physique et numérique des géo-structures énergétiques. Thèse de doctorat – Univ. de Lorraine.

Casini F. Gens A., Olivella S. (2014). Artificial ground freezing of a volcanic ash: laboratory tests and modelling. Institution of civil engineers.

Greenwood, W., Green, C., Partenio, M. (2014). ground-freezing implementation-in-the-field. www.geoengineer.org: https://www.geoengineer.org/education/web-class-projects/cee-542-soil-site-improve-winter-2014/assignments/ground-freezing#implementation-in-the-field

Joudieh, Z., Cuisinier, O., Abdallah, A. & Masrouri, F. 2025. Impact of overburden pressure on the thermo-hydro-mechanical behavior of silty sand during a freeze-thaw cycle in the context of Artificial Ground Freezing. Engineering Geology 350, 107992.

Joudieh, Z., Cuisinier, O., Abdallah, A., Masrouri, F. (2023). AGF: A review of the effect of applied stress on the soil freezing. 11th International Symposium on Ground Freezing – London. UK.

Joudieh, Z., Cuisinier, O., Abdallah, A., Masrouri, F. (2024) Artificial Ground Freezing – on the soil deformations during freeze-thaw cycles, Geotechnics 2024, 4(3), 718-741, https://doi.org/10.3390/geotechnics4030038

Joudieh, Z., Cuisinier, O., Abdallah, A., Masrouri, F., 2025. Impact of overburden pressure on the thermo-hydro-mechanical behavior of silty sand during a freeze-thaw cycle in the context of Artificial Ground Freezing. Eng. Geol. 350, 107992. https://doi.org/10.1016/j.enggeo.2025.107992

Maghsoodi, S., Cuisinier, O., Masrouri, F., 2020. Effect of Temperature on the Cyclic Behavior of Clay–Structure Interface. J. Geotech. Geoenvironmental Eng. 146, 04020103. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002360

Maghsoodi, S., Cuisinier, O., Masrouri, F., 2021. Non-isothermal soil-structure interface model based on critical state theory. Acta Geotech. 16, 2049–2069. https://doi.org/10.1007/s11440-020-01133-1

Mrad, M., Abdallah, A., Masrouri, F. (2007). Modélisation numérique du comportement d'un sol gonflant chargé soumis à des variations hydriques. Revue Française de Géotechnique, n° 120-121, pp. 121-130.

Mrad, M., Abdallah, A., Masrouri, F., Vaunat, J. (2006). Finite-element implementation of BExM elastoplastic model for swelling unsaturated soils. In Geotechnical Special Publication. https://doi.org/10.1061/40802(189)163

Mrad, M., Cuisinier, O., Abdallah, A., Masrouri, F. (2005). Modelling of the hydromechanical behaviour of unsaturated swelling soils under high suctions | Modelisation du comportement hydromécanique des sols gonflants non saturés sous fortes succions. In Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering: Geotechnology in Harmony with the Global Environment (Vol. 2), Osaka, Japan, 12th-16th September

Nishimura, S., Gens, A., Olivella, S. Jardine, R. J. (2009). Géotechnique 59, No. 3, 159–171 [doi: 10.1680/geot.2009.59.3.159] : THM-coupled finite element analysis of frozen soil: formulation and application.

Nowamooz, H., Mrad, M., Abdallah, A., Masrouri, F. (2008). Experimental and numerical studies of the hydromechanical behaviour of a natural unsaturated swelling soil. In Unsaturated Soils: Advances in Geo-Engineering - Proceedings of the 1st European Conference on Unsaturated Soils, E-UNSAT 2008.

Nowamooz, H., Mrad, M., Abdallah, A., Masrouri, F. (2009). Experimental and numerical studies of the hydromechnical behavior of a natural unsaturated swelling soil. Canadian Geotechnical Journal, 46(4): 393-410, doi: 10.1139/T08-127, ISSN:1208-6010.

Vitel M. (2015). Modélisation thermo-hydraulique de la congélation artificielle des terrains. Géosciences, ressources naturelles et environnement. Thèse de l’école nationale supérieure des mines de Paris.