

<https://doi.org/10.32762/eygec.2025.39>

ARTIFICIAL GROUND FREEZING: ROLE OF OVERBURDEN PRESSURE IN THE THERMO-HYDRO-MECHANICAL BEHAVIOR OF SILTY SAND DURING A FREEZE-THAW CYCLE

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ABSTRACT

Artificial Ground Freezing (AGF) enhances soil strength and reduces permeability, but managing frost heave and thaw-induced deformations remains a major challenge. In deep excavations, overburden pressure plays a critical yet complex role in these processes. To investigate this, freeze-thaw (FT) tests were performed on silty sandy soil under applied stresses ranging from 10 to 4000 kPa using a temperature-controlled (TC) oedometer. Results show a strong inverse relationship between stress and frost heave; higher stress limits ice lens formation and associated deformations. Across all stress levels, the FT cycle induces soil densification, resulting in net volume reduction after thawing. However, the post-thaw mechanical behavior depends on the stress applied during freezing. Under low stress (10-30 kPa), FT increases compressibility, weakening the soil despite densification. In contrast, higher stresses reduce compressibility and enhance stiffness, effectively mitigating FT-related damage. Notably, heave is eliminated under 4000 kPa, suggesting the existence of a threshold stress beyond which FT deformations are fully suppressed.

Keywords: artificial ground freezing, freeze-thaw cycle, THM soil behavior, applied stress, post-thaw mechanical behavior.

INTRODUCTION

Artificial Ground Freezing (AGF) is widely employed to improve soils in deep excavations due to its ability to increase soil strength and reduce permeability without introducing chemical additives. While effective, this process induces significant freeze-thaw (FT) deformations, primarily frost heave during freezing and thaw settlement upon melting. These deformations pose serious challenges in AGF applications, as excessive ground movements can compromise the structural integrity of adjacent buildings and underground facilities. Despite significant advancements, accurately predicting and mitigating FT-induced displacements remains a major challenge in geotechnical engineering.

Overburden pressure significantly influences AGF-induced deformations by controlling ice lens formation and water migration. Experimental studies (e.g., Azmatch, 2013; Konrad & Morgenstern, 1982; Zhang et al., 2017) have shown that increasing applied stress lowers segregation temperature, modifies frozen fringe development, and affects soil permeability. However, most laboratory investigations have been limited to stress levels ≤ 500 kPa, leaving the impact of higher stresses on AGF-induced deformations largely unexplored.

To address these limitations, researchers have turned to oedometer-based FT testing under applied stress (e.g., Dalla Santa et al., 2016; Mao, 2018; Viglianti et al., 2023). While these setups provide valuable insights into the mechanical response of frozen soils, they often rely on cold-bath immersion, which does not replicate the controlled thermal gradients typical of AGF applications. As a result, the interplay between applied stress, temperature gradient, and FT-induced deformations under realistic boundary conditions remains an open question. Furthermore, the stress-dependent nature of the mechanical performance of soil following an FT cycle has received limited attention, particularly under high applied stress.

In this context, the present study investigates the thermo-hydro-mechanical (THM) behavior of silty sandy soil subjected to an FT cycle under a wide range of applied stress (10-4000 kPa). A TC-controlled oedometer was developed to simulate upward freezing under controlled thermal gradients, replicating AGF-relevant boundary conditions. The study aims to quantify FT-induced deformations and examine the post-thaw mechanical response as a function of applied stress. The results offer new insight into stress-dependent soil behavior during AGF, with direct implications for shallow and deep urban excavation projects.

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MATERIALS AND METHODS

Tests were conducted using a modified TC oedometer designed for controlled FT cycles. The setup includes a cylindrical sample chamber (H= 20 mm, D= 71.4 mm), a loading piston, a water chamber, and a displacement sensor (Figure 1).

Modifications to the TC oedometer enabled a well-defined thermal gradient with temperatures reaching -10°C at the base and $+3^{\circ}\text{C}$ at the top, simulating upward freezing in AGF applications. Two FT tests were conducted under identical conditions to verify the system's reliability, confirming repeatability with less than 5% variation in displacement measurements. Additional information on the apparatus can be found in Joudieh et al. (2025).

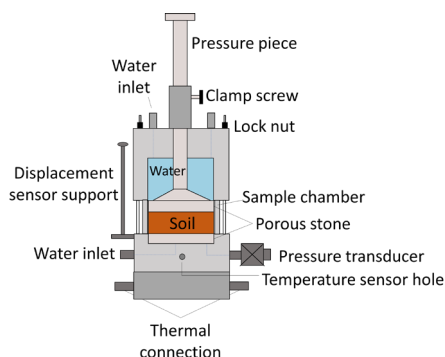


Figure 1 Schematic diagram of the TC oedometer cell

The tested silty sandy soil was sampled from a construction site in Paris, where in situ ground freezing was used for excavation support. The soil consists of 44% sand, 54% silt, and 2% clay, classifying it as silt (USCS). It was processed to a 2 mm grain size and then moistened to its in situ water content of 16.5% for sample preparation. Specimens were mixed and statically compacted to a dry density of 1.7 Mg/m^3 and a height of $20 \pm 0.1 \text{ mm}$.

The experimental procedure followed the THM loading path illustrated in Figure 2, consisting of four main stages: saturation, consolidation, FT cycle, and post-thaw mechanical testing. First, specimens were saturated at 3°C (Step 1). They were then consolidated to their target stress, which remains constant throughout the FT cycle (Step 2). Freezing was initiated by applying a temperature gradient: for 48 hours, with 3°C at the top and $-10^{\circ}\text{C} \pm 1^{\circ}\text{C}$ at the base, allowing for controlled bottom-up freezing (Step 3). Thawing was followed by raising the base temperature to 3°C for 24 hours (Step 4). Once thawed, specimens were loaded incrementally to 4000 kPa, then unloaded back to 30 kPa, to evaluate their post-thaw mechanical response (Steps 5 and 6). All tests were performed under drained conditions.

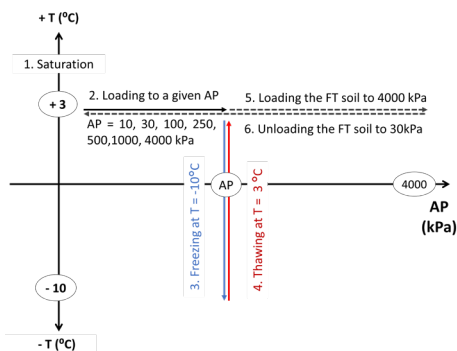


Figure 2 THM path during FT tests. AP = applied pressure, T = temperature

FREEZE-THAW RESPONSE OF SILTY SAND UNDER DIFFERENT APPLIED STRESSES

Figure 3 presents soil specimens after 48 hours of freezing under 30 and 1000 kPa, illustrating the effect of applied stress on ice lens formation. Under 30 kPa, the soil exhibits pronounced heave, accompanied by the development of thick, well-formed ice lenses. In contrast, under 1000 kPa, ice lenses appear much thinner and less developed, and the overall heave is visibly reduced. This suggests that increasing stress modifies the freezing pattern by limiting ice lens growth.

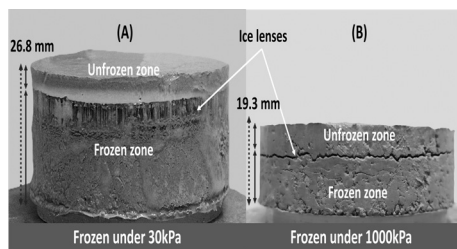


Figure 3 Photograph of specimens after 48h of freezing under 30 and 1000 kPa

Figure 4 quantifies these observations, showing the evolution of frost heave across applied stresses from 10 to 4000 kPa. Under low stress levels (10 and 30 kPa), frost heave is most pronounced, as minimal resistance allows unrestricted ice lens formation. As stress increases, frost heave is progressively reduced. Between 10 and 100 kPa, a 43% decrease in heave is observed, confirming that increasing overburden pressure restricts ice lens development. However, the suppression of heave is not linear. Under 1000 kPa, heave is reduced by 77% compared to 10 kPa, yet a measurable displacement of 1.62 mm (8.5% of the specimen height) persists, indicating that cryogenic suction and water migration still plays a role in ice lens formation even under significant applied stress.

Overall, the results emphasize the crucial role of applied stress in regulating frost heave. Higher stress limits ice lens formation and the associated volume expansion, yet measurable heave persists even at relatively high stress levels (e.g., 500-1000 kPa), indicating that water migration continues to contribute to freezing-induced deformations.

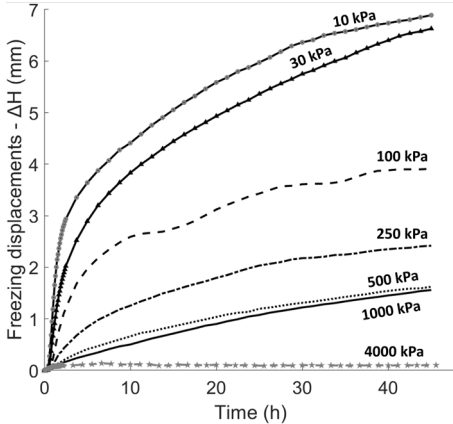


Figure 4 Freezing displacement (ΔH) under different applied stress as a function of time

Figure 5 illustrates the evolution of dry density (ρ_d) under different applied stresses before and after the FT cycle. Initially, increasing stress compacts the soil, reducing the bulk density from 1.70 Mg/m³ at 10 kPa to 1.95 Mg/m³ at 4000 kPa. After thawing, all specimens exhibit a net increase in bulk density, highlighting the densification effect induced by the FT cycle. However, the extent of this densification varies with stress. Under low stresses (10-100 kPa), ice lens formation expands the soil structure during freezing (Figure 4), but upon thawing, water drainage and particle rearrangement lead to significant compaction. For instance, following an FT under 100 kPa, the final dry density reaches 1.82 Mg/m³, nearly matching that of soil pre-consolidated at 250 kPa without freezing. This suggests that the FT cycle replicates the densification effect of mechanical preloading. Under higher stresses (500-1000 kPa), the change in density before and after the FT cycle becomes less pronounced. This is likely due to the suppression of ice lens formation, which limits structural expansion and particle rearrangement. Under 4000 kPa, the FT cycle has an almost negligible effect, indicating that extreme overburden pressure effectively prevents significant FT-induced deformations.

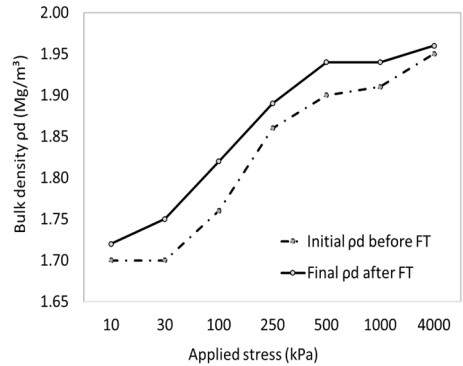


Figure 5 ρ_d of specimens before and after FT

POST-THAW BEHAVIOR OF SILTY SAND UNDER APPLIED VERTICAL STRESS

The previous section demonstrated that the FT cycle leads to soil densification by the end of thawing, regardless of the applied stress. This section investigates the repercussions of this densification on the post-thaw mechanical behavior of the soil. Figure 6 presents the compression curves before and after an FT cycle for 2 tests conducted under 30 and 1000 kPa, representing the effects of FT under low and high applied stress. The dashed lines indicate the initial state compression curve, while the solid lines correspond to the frozen-thawed soil. The results for all other applied stresses are available in Joudieh et al., (2025).

Under 30 kPa, the specimen experiences a marked increase in void ratio during freezing, rising from 0.58 to 1.12 due to significant frost heave (Figure 4). Upon thawing, the void ratio decreases to 0.54, indicating partial reconsolidation from water drainage and particle rearrangement. Notably, the post-thaw curve closely follows the reference virgin compression curve, even at stress levels lower than the pre-consolidation pressure ($\sigma'_p \approx 55$ kPa). This suggests that the FT cycle fundamentally resets the soil's mechanical behavior by inducing structural disruption, which changes its subsequent compression behavior. The post-thaw soil exhibits increased compressibility, resembling a remoulded or structurally weakened/degraded soil.

Under 1000 kPa, the total heave is significantly reduced to 162 mm increasing the void ratio from 0.41 to 0.54. The thawed specimens remain densified, with final void ratios stabilizing at 0.39 (Figure 6). Upon reloading, the specimen exhibits a notable reduction in compressibility, with the compression index (C_c) decreasing from 0.13 in the reference state to 0.067 post-thaw. This shift indicates a transition to a denser, less compressible soil structure, as high stress suppresses ice lens growth and pore expansion, thereby minimizing heave and limiting the disruption of the original soil structure.

Another key observation from Figure 6 is the consistency in unloading behavior. Despite the variations in applied stress, the stress-strain response during unloading converges onto a common path across all tests. This suggests that while the FT cycle changes the compressibility of the soil, it does not significantly affect its elastic recovery upon unloading.

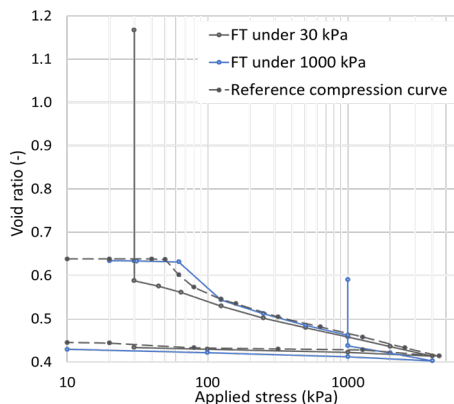


Figure 6 Void ratio evolution with applied stress for specimens subjected to an FT cycle under 30 and 1000 kPa

CONCLUSIONS

This study investigates the impact of applied stress on soil behavior during an FT cycle, focusing on frost heave, thaw settlement, and post-thaw mechanical properties. FT tests on silty sand from a tunnel excavation in Southern Paris were conducted using a TC oedometer across a stress range of 10–4000 kPa to capture the THM response under varying confinement levels. Key findings include:

Higher stress limits ice lens formation and heave but does not fully eliminate it, indicating continued water migration even under strong confinement.

Regardless of the applied stress, the FT cycle promotes particle rearrangement, resulting in a net decrease in void ratio and an increase in dry density.

The impact of FT on post-thaw behavior varies with applied stress. Under low stress (10, 30 kPa), FT weakens the soil and increases compressibility. Under high applied stress levels, it enhances stiffness and reduces compressibility, mitigating FT-induced damage.

Effective AGF implementation requires careful consideration of site-specific properties and overburden pressure. Under low stress, frost-susceptible soils remain highly prone to heave. Under high stress, heave is significantly reduced but not fully eliminated, reinforcing the need for laboratory testing to evaluate the magnitude of FT-induced displacements.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Bouygues Travaux Publics for supporting and funding this research, which was part of the first author's PhD thesis.

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