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# Understanding the role of overburden pressure in the freeze-thaw behavior of silty sand for ground freezing applications

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ABSTRACT: This study examines the impact of applied vertical stress on the thermo-hydro-mechanical (THM) response of a silty sand subjected to a freeze–thaw (FT) cycle, with relevance to artificial ground freezing (AGF) applications in urban environments. Experiments were conducted using a custom heave test apparatus capable of imposing thermal gradients, supplying external water, and applying vertical stresses of up to 500 kPa. Internal temperature sensors and displacement monitoring allowed for detailed observation of the freezing process and frost-induced deformation. A series of three tests was performed on saturated 50 mm-high specimens under vertical stresses of 30, 100, and 500 kPa. Results show that the depth of frost penetration was primarily controlled by the applied thermal gradient, while heave magnitude and rate were governed by applied stress. Total heave decreased from 7.45% at 30 kPa to 3.00% at 500 kPa. External water intake followed a similar trend, with lower inflow under higher stresses, indicating a reduction in cryogenic suction activity. The measured heave was largely attributed to segregation ice growth, supported by the migration of external water toward the freezing front. Increased stress limited this water migration and delayed the development of ice lenses. Segregation potential (SP) values decreased with stress but showed limited sensitivity at low to intermediate loading. These results highlight the coupled nature of thermal, hydraulic, and mechanical interactions during freezing and underscore the need to account for stress-dependent behavior when evaluating heave risk in AGF applications.

KEYWORDS: Artificial ground freezing, freeze-thaw cycle, THM, applied stress, heave test, urban tunneling.

## 1 INTRODUCTION

Urban tunneling and underground infrastructure projects often encounter soft soils and weathered rock formations, which pose significant stability challenges during excavation. Artificial ground freezing (AGF) has proven to be an effective soil improvement method in such contexts, offering increased mechanical strength and reduced permeability through the formation of temporary frozen barriers. However, despite its advantages, AGF can also induce adverse deformations, including frost heave during freezing and settlement during thawing, which can jeopardize structural safety, particularly in densely built urban areas.

Frost heave results from the growth of ice lenses within the soil, driven by cryogenic suction and the migration of unfrozen water toward the freezing front (e.g., Beskow, 1935; Dash et al., 2006; Taber, 1930). The magnitude of this deformation is influenced by a complex interplay between thermal, hydraulic, and mechanical (THM) factors (Joudieh et al., 2025, 2024; Konrad and Morgenstern, 1980; Lu et al., 2021). Among these, overburden pressure from overlying soil layers plays a key role by constraining volumetric expansion and limiting water migration, thereby influencing both ice lens formation and the development of heave (Azmatch et al., 2012; Beskow, 1935; Konrad and Morgenstern, 1982). While the role of overburden stress has been conceptually recognized, its quantitative influence under realistic freezing conditions remains insufficiently explored, particularly in silty sandy soils commonly encountered in urban geology.

This study investigates the THM behavior of silty sand subjected to a freeze-thaw (FT) cycle under applied vertical stresses, using a custom-designed heave test apparatus. The heave test allows for direct observation of the internal temperature evolution and water flux within the soil column, providing enhanced insight into frost heave mechanisms. The test apparatus allows controlled application of vertical stress up to 500 kPa and simulates both open and closed system conditions by regulating external water availability.

All tests were conducted under controlled thermal gradients with continuous external water availability, replicating open-system conditions. The objective is to better understand how overburden stress affects the freezing path, water inflow, and associated deformation mechanisms in silty sand, with the broader aim of informing AGF design strategies in deep excavation environments.

## 2 MATERIALS AND METHODS

### 2.1 *Soil characteristics*

The tested soil was a silty sand obtained from a construction site in Paris where AGF was used for excavation support. It contains 44% sand, 54% silt, and 2% clay, classifying it as silt (USCS). Samples were moistened to the in-situ water content (16.5%) and compacted to a dry density of 1.7 Mg/m³ with a final height of 50 mm.

### 2.2 *Heave test apparatus*

The heave test apparatus (Figure 1) operates as a fully coupled system, integrating thermal, hydraulic, and mechanical components. Sensor data are continuously recorded by a data logger and monitored via connected software. The system includes temperature-controlled top and bottom plates, a sample base plate fitted with a porous stone and dual ports for water supply and drainage, and a filter paper placed between the stone and the specimen to ensure uniform inflow.

The soil specimen is confined laterally within a cylindrical mold composed of six stacked acrylic rings (each 25 mm high, 146 mm in internal diameter), allowing flexibility in specimen height and easy dismantling after testing. Temperature sensors (PT100) are inserted at multiple elevations through dedicated ports in the ring assembly. A constant-head water reservoir (Mariotte system) delivers external water to the specimen base, enabling precise measurement of inflow through a transparent graduated scale.

The thermal control system uses two independent circulating liquid loops: a mono-propylene glycol–water solution (60/40%) controls the top plate (range: −40 °C to +90 °C), and silicone oil controls the bottom plate (range: −40 °C to +165 °C), both with a temperature stability of ±0.2 °C and precision of ±0.02 °C. The external vertical stress is applied through a pressure piece connected to a loading frame, allowing loads up to 500 kPa. Vertical displacements are captured using a high-precision LVDT mounted above the loading assembly.

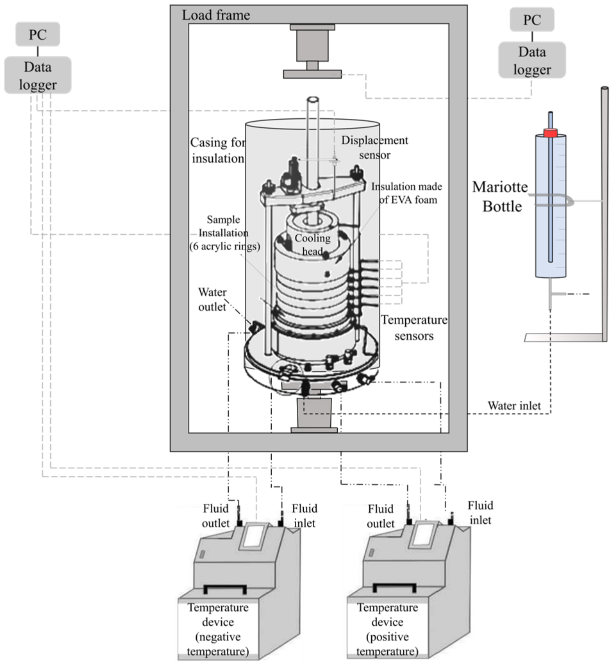

Figure 1. Diagram of the heave test (from Joudieh, 2025).

## 2.3 *Test protocol*

The FT protocol followed the THM loading path shown in Figure 2. Specimens were saturated before loading, then subjected to incremental vertical stress application until the target stress (30, 100, or 500 kPa) was reached. Freezing was initiated from the top downward under a controlled thermal gradient, with the top boundary cooled to −12°C and the base maintained at +6 °C. External water was supplied at the specimen base through a constant-head system to simulate open-system conditions. The freezing phase lasted 48h to allow stabilization of thermal and hydraulic conditions, followed by a 24h thawing phase under constant load. Vertical displacement and internal temperature profiles were continuously monitored throughout the cycle.

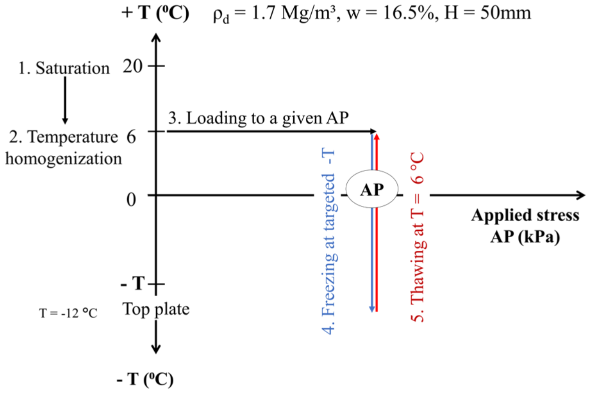

Figure 2. The THM loading path taken during the heave test on soil specimens.

## 3 RESULTS AND DISCUSSION

The following section presents the results of the experimental campaigns, focusing on frost heave evolution, internal temperature dynamics, and the coupled influence of mechanical, hydraulic, and thermal boundary conditions on soil deformation during the FT cycle.

## 3.1 *Thermal Behavior and Freezing Front Progression*

Temperature measurements recorded at four elevations along the soil column allowed the reconstruction of thermal profiles and monitoring of the freezing front during the test. Under all applied stress conditions, freezing initiated at the top boundary and progressed downward in response to the imposed thermal gradient. The evolution of temperature with time and over specimen height is shown in Figure 3.

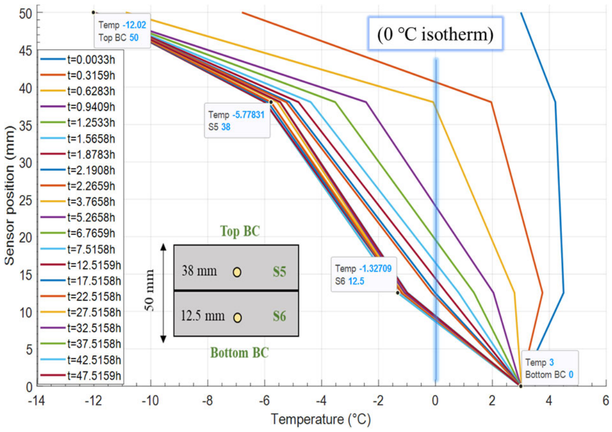

Figure 3. Example of temperature distribution profile over specimen height for an FT cycle under 30 kPa.

Figure 4 presents the evolution of 50 mm soil specimens during freezing under vertical stresses of 30, 100, and 500 kPa. Figure 4A shows the final temperature profiles at steady state, distinguishing frozen and unfrozen zones. The temperatures correspond to measurements from sensors located at 12.5 mm (Sensor S6) and 38 mm (Sensor S5) along the specimen height. Figure 4B shows the progression of the freezing front over the 48h freezing period. In all cases, the 0 °C isotherm advanced through the soil during the transient phase and stabilized thereafter, marking the onset of the steady state. Under identical thermal boundary conditions (−12°C at the top, +6 °C at the base), the depth of frost penetration was similar for the 100 and 500 kPa tests, with approximately 55% of the specimen height below 0 °C. In contrast, the test under 30 kPa, conducted with a lower base temperature of +3 °C, exhibited a deeper freezing front, with 80% of the specimen reaching subzero temperatures. frozen. These results show that frost penetration is governed primarily by the thermal gradient, rather than the applied mechanical stress.

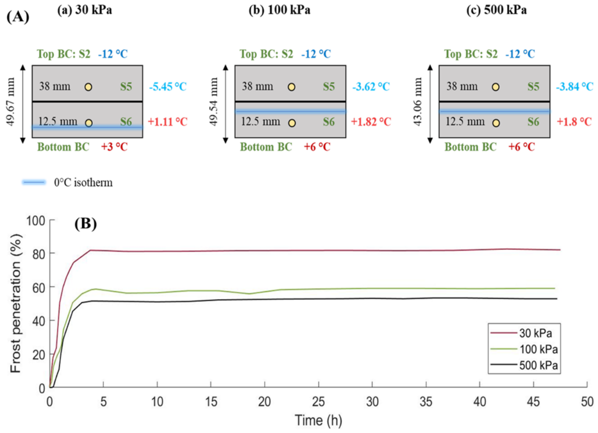

Figure 4. Freezing behavior of specimens under 30, 100, and 500 kPa. (A) Final temperature profile at steady state; (B) Freezing progression during 48h.

## 3.2 *Effect of Applied Stress on Heave Development and Phase Change Behavior*

Figure 5 presents the heave deformations measured over the 48h freezing phase for specimens subjected to applied stresses of 30, 100, and 500 kPa. The results indicate an inverse relationship between applied stress and frost-induced deformation. At the end of the freezing period, total heave reached 7.45% under 30 kPa, 4.45% under 100 kPa, and 3.00% under 500 kPa. Measurements of external water intake during the tests support this interpretation. After 48h of freezing, the specimens absorbed 75, 70, and 30 mL of water under 30, 100, and 500 kPa, respectively. These values suggest that increasing vertical stress reduces the cryogenic suction gradients that drive water migration toward the freezing front. As a result, the amount of water available for ice segregation is diminished, leading to lower heave amplitudes. These findings point to the importance of applied stress in controlling the hydraulic response of the soil during freezing, particularly in open-system conditions where external water is accessible.

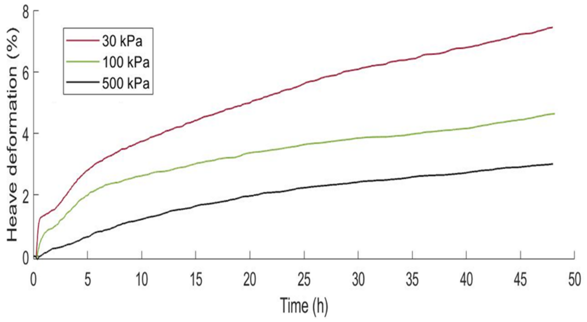

Figure 5. Heave deformation over time during freezing under varying applied stress values.

The influence of stress is also reflected in the evolution and magnitude of the heave attributed to porewater phase change. Theoretical deformation due to the 9% volumetric expansion of water upon freezing was estimated using Equation (1). $H_{PW}(t)$ represents the heave due to phase transition; $n$ is the volumetric porosity, calculated from the bulk dry density ($\rho_d$) and particle density ($\rho_s$), and $S_r$ is the degree of saturation, taken as 0.98 based on preliminary saturation tests. The variable $x(t)$ denotes the depth of frost penetration at time t, derived from the temperature profiles presented in Figure 3.

$$H_{PW}(t) = 0.09 \cdot n \cdot S_r \cdot x(t) \tag{1}$$

The results, shown in Figure 6, indicate that the phase change–induced heave developed rapidly under low stress, reaching completion within the first 3h under 30 kPa. In contrast, under 500 kPa, this component of heave progressed more slowly and extended over approximately 10h.

These observations suggest that higher applied stress delays the advancement of the freezing front and reduces the availability of water for phase change during the early stages of freezing. As a result, both the evolution and magnitude of the heave associated with porewater freezing are affected.

When considered together, the deformation and water intake data emphasize the coupled nature of mechanical stress and hydraulic behavior during freezing, with stress acting as a controlling parameter on both ice lens development and the progression of the freezing process.

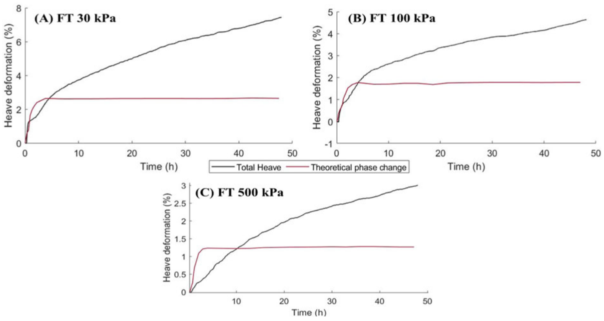

Figure 6. Evolution of total heave and estimated phase change–induced heave during freezing under 30, 100, and 500 kPa.

## 3.3 *Segregation Potential*

To complement the heave and phase change analyses, the segregation potential (SP) was evaluated for each test condition as a means to quantify the soil's ability to draw external water into the freezing zone (Equation 2). Originally proposed by Konrad and Morgenstern (1980), SP remains one of the most widely used parameters for assessing frost susceptibility. It is defined as the ratio between the water intake velocity $v_0$ and the temperature gradient grad(T) across the freezing front:

$$v_0 = SP\,\mathrm{grad}(T) \tag{2}$$

This formulation offers a direct measure of cryogenic suction activity in the active freezing zone. The model has evolved to incorporate the effect of confining pressure on frost heave development. An extended formulation (Equation 3), proposed by Konrad and Morgenstern (1981, 1982), relates SP to the applied effective pressure using an exponential decay law (Konrad, 2005; Konrad and Morgenstern, 1982, 1981).

$$SP = SP_0 . e^{-\alpha P_e} \tag{3}$$

Where $SP_0$ is the value of SP obtained for zero applied pressure, Pe is the applied pressure (or effective overburden pressure), and α is a soil constant. All of these parameters can be obtained directly from macroscopic frost heave testing in the laboratory.

The model has been applied to a range of engineering problems, including frost heave prediction beneath buried frozen infrastructure (Konrad and Morgenstern 1984). However, subsequent studies (e.g., Nixon, 1987, Ishizaki and Nishio, 1988) have noted that it does not fully capture ice lens formation in thermally unstable or heterogeneous conditions, and does not explicitly account for fundamental soil properties (Li and Chen 2000). Nevertheless, it remains a useful macroscopic indicator of soil response to freezing under defined boundary conditions.

In this study, SP was calculated for each applied stress condition based on steady-state heave rates obtained during the freezing phase using Equation 4.

$$SP = \frac{dh/dt}{gradT} \tag{4}$$

where $dh/dt$ is the measured vertical heave rate (mm/s), and gradT is the temperature gradient (°C/mm) across the frozen fringe. Due to the limited number of embedded temperature sensors, the exact thickness of the freezing front could not be directly measured. To overcome this, four possible fringe intervals were considered: [0, −0.5 °C], [0, −1 °C], [+0.5, −0.5 °C], and [+0.5, −1 °C]. Based on the temperature profiles in Figure 3, the vertical positions of the −1, −0.5, 0, and +0.5 °C isotherms were identified. These measurements made it possible to determine the thickness of the frozen fringe for each interval. The corresponding temperature gradients were then calculated by dividing the temperature difference by the estimated fringe thickness. Results showed that the variation in gradient values across the four configurations was small, and the calculated SP values remained consistent. Therefore, for each test, a single representative SP value was computed using the average temperature gradient. The SP values obtained for each applied stress condition are summarized in Table 1.

Table 1 shows that increasing the applied vertical stress from 30 to 500 kPa leads to a marked reduction in total heave deformation, from 7.45% to 3.00%, and a decrease in external water intake from 75 to 30 mL. In all cases, the theoretical deformation associated with porewater phase change remains well below the observed heave, suggesting that the majority of the deformation arises from water migration into the freezing front, rather than from in-situ freezing of pore water.

The calculated SP values follow the same overall trend, decreasing with stress from 4.62 × 10$^{-5}$ to 3.03 × 10$^{-5}$ mm$^2$/s°C between 30 and 500 kPa. While this decrease is consistent with a reduction in cryogenic suction under higher stress, it is worth noting that SP values remain nearly unchanged between 30 and 100 kPa, despite a substantial difference in heave magnitude (67%). This discrepancy may point to certain limitations of SP when used as a sole indicator of frost susceptibility under load. As it is derived from steady-state heave rates, SP primarily reflects the rate of water inflow during advanced freezing stages and may not fully capture earlier transient phenomena, such as the onset of ice lens formation or stress-dependent phenomena in the soil. These results suggest that while SP remains a valuable parameter for assessing the capacity for water migration during freezing, it does not directly translate to the soil's potential for heave, which is more strongly governed by the coupled THM response. Therefore, interpreting SP alone may lead to incomplete assessments. A more robust evaluation should consider SP in conjunction with total heave, external water intake, and mechanical boundary conditions to more accurately characterize soil behavior during freezing, particularly in AGF contexts where stress plays a central role.

Table 1. Summary of the heave response and calculated segregation potential under different applied stresses during freezing.

| Applied stress during FT (kPa) | Heave deformation (%) | Theoretical phase change (%) | External water intake (mL) | SP (mm$^2$/s.°C) |
|---|---|---|---|---|
| 30 | 7.45 | 2.65 | 75 | 4.62 x 10$^{-5}$ |
| 100 | 4.45 | 1.78 | 70 | 4.45 x 10$^{-5}$ |
| 500 | 3.00 | 1.27 | 30 | 3.03 x 10$^{-5}$ |

## 4 CONCLUSIONS

This study investigated the THM response of a silty sand subjected to a single FT cycle under varying applied vertical stresses. Laboratory experiments were conducted using a heave test apparatus equipped with internal temperature monitoring and external water supply, allowing simultaneous observation of thermal evolution, vertical deformation, and water migration.

The results indicate that while the depth of frost penetration was primarily controlled by the applied thermal gradient, the magnitude and timing of frost heave were strongly influenced by the applied vertical stress. Higher stress levels led to a reduction in total heave, delayed the progression of phase change–induced deformation, and limited external water intake during freezing.

Theoretical estimates of porewater phase change confirmed that the majority of observed deformation was driven by water migration rather than in-situ freezing. Segregation potential values followed the same decreasing trend with stress, though their limited sensitivity between low and intermediate stress levels suggests that SP alone may not capture the full complexity of stress-dependent frost susceptibility.

Taken together, the obtained results highlight the coupled role of thermal conditions, water availability, and mechanical loading in controlling frost-induced deformation. In the context of artificial ground freezing, these interactions should be considered when assessing heave potential and defining design parameters, particularly in urban environments where ground movement must be tightly controlled.

## 5 ACKNOWLEDGEMENTS

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