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Laboratory-Scale Investigation of Ice Lens Effects on the Thawing Performance of Closed-Loop Steam-Driven Probe in Permafrost Ground

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ABSTRACT: Ice-rich permafrost ground is highly vulnerable to thermal disturbance, with thaw-induced strength loss posing major risks to infrastructure. As climate-change–driven warming and heat release due to construction activities limit the effectiveness of permafrost preservation techniques, this study proposes a steam-heating–based preconstruction thawing and ground improvement technique as a climate-adaptive foundation strategy. Small-scale experiments were performed on permafrost physical models to investigate the effect of ice lenses on the performance of a closed-loop, steam-driven probe. Two types of models were tested: one consisting of saturated frozen fine sand with only pore ice, and another containing an artificial ice lens in addition to the pore ice. The progression of the thaw front was monitored using temperature measurements from thermocouples, and the steam energy requirement was determined based on the collected condensate. Preliminary results showed that the presence of ice lenses substantially alters the radial propagation of the thaw front in permafrost ground during steam heating. In ice-rich ground, meltwater released from ice lenses surrounding the probe accumulates in depressions formed by soil surface settlement, enhancing lateral heat transfer and increasing the thaw-front radius near the surface. Beneath the meltwater-filled depressions, however, the thaw-front radius decreases. Moreover, for fixed heating durations and equivalent thawed volumes, the collected steam condensate increases with excess ice content, indicating higher latent heat demands and reduced energy efficiency. These findings provide guidance for field-scale steam probe design for pre-construction thawing in ice-rich permafrost regions.

1 INTRODUCTION

Climate warming and construction-induced heat transfer accelerate permafrost degradation, causing ground instability and differential settlement that threaten northern infrastructure, including pipelines, roads, railways, transportation corridors, and airports, particularly in warm ice-rich permafrost regions that are highly vulnerable to minor temperature increases (Fortier *et al.* 2011; Stephani *et al.* 2022; Hjort *et al*. 2022; Afsharipour *et al.* 2024).

To address these challenges, conventional permafrost preservation techniques have been widely employed to maintain frozen ground conditions and reduce maintenance costs (Malenfant-Lepage *et al*. 2012, Remchein et al 2009). However, their effectiveness may be increasingly compromised under extreme warming scenarios and sustained operational heat loads, limiting their long-term reliability (Doré *et al.* 2016; Stephani *et al*. 2022).

Consequently, alternative engineering strategies are being explored to enhance ground stability in permafrost regions. One such approach involves the controlled artificial thawing of permafrost ground, followed by consolidation using ground improvement techniques, and subsequent refreezing with reduced ice content to produce thaw-stable and climate-adaptive ground (Ngo *et al.* 2022). While this method has already been adopted in limited applications, such as gold mining and pile installation, its wider implementation remains constrained by the lack of systematic engineering methods and design guidance, particularly for large-scale ground treatment (Cysewski & Shur, 2012; Esch, 2013; Nouri *et al*. 2025).

This study proposes a novel closed-loop, steam-driven thawing technique that should be capable of controlled, large-scale permafrost thawing with year-round applicability. Earlier investigations examined its performance in frozen, saturated sand with pore ice only (Nouri et al., 2025, under review). The present work extends this ongoing research by examining ice-rich conditions, quantifying the influence of ice lenses on thaw-front development and energy efficiency, with implications for field-scale implementation.

2 EXPERIMENTAL SET-UP

A laboratory-scale wooden cell (520 mm × 480 mm × 340 mm, wall thickness 50 mm) was used to simulate permafrost ground. The external surfaces were insulated with 50 mm of extruded polystyrene and 10 mm of expanded polystyrene to minimize lateral heat fluxes. A serpentine copper tubing network was embedded at the base beneath a thin layer of glass powder to ensure uniform thermal contact. Flexible, impermeable polyethylene sheets were first applied to the inner surfaces to prevent water leakage into the cooling system, followed by a geotextile layer to facilitate uniform saturation (Fig. 1).

Two soil models were prepared from frozen, saturated sand to simulate permafrost ground with and without excess ground ice. The reference model contained only pore ice (model A), while the second model (model B) included a single artificial ice lens between 50- and 90-mm depth, representing excess ground ice conditions (Fig. 2).

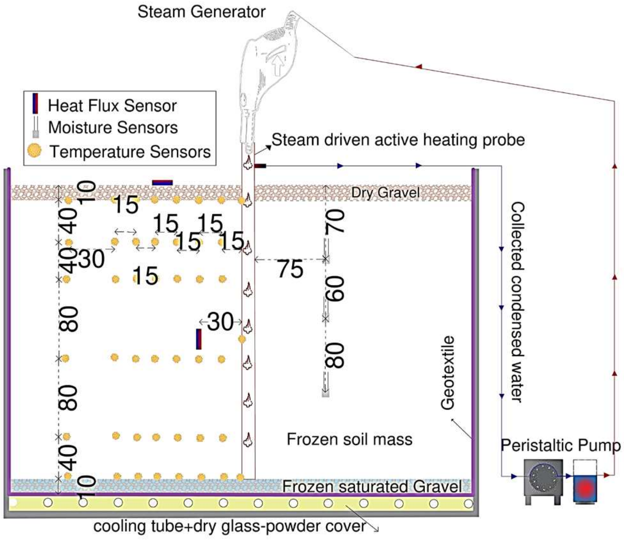


Figure 1. Layout of instrumentation and steam probe configuration (dimensions in mm) for thawing experiments outside the cold room.

In each model, a 10-mm-thick saturated gravel layer was first placed at the bottom to facilitate uniform saturation. Natural fine sand (Groupe Bellemare, #100 mesh) was then placed in 40-mm-thick layers and lightly compacted to a target dry density of 1.57 t/m³ (relative density 50%). The sand was then saturated by upward injection of de-aired water and subsequently frozen. To simulate permafrost ground with an ice lens, model B was prepared by adding a 40-mm-thick artificial ice lens at predetermined depth within frozen, saturated sand layers. Freezing was achieved by circulating ethylene glycol through the base tubing at approximately −10 °C, while the entire box was placed inside a walk-in cold room (0 to −5 °C), resulting in one-dimensional upward freezing (Go *et al.* 2019; Sweidan *et al*. 2022). Finally, a pre-cooled 10-mm-thick dry gravel layer was placed on the surface to reduce heat transfer from the laboratory environment during handling and prevent unintended thawing prior to the start of the tests (environmental heat flux ≈ 70–80 W/m²; surface temperature ≈ 8 °C).

A small-scale steam-driven heating probe (closed-end copper tube, 15 mm outer diameter, 14 mm inner diameter, 300 mm long) was installed vertically at the centre of the model. Saturated steam (105 °C, 0.1 MPa) was injected into the probe at a controlled rate for a duration of three hours, while condensate was continuously collected via a peristaltic pump. Thawing tests were conducted at 21 °C (outside the cold room) to simulate pre-construction ground thawing during summer conditions. Temperature was monitored using T-type thermocouples (±0.1 °C accuracy; 0.01 °C precision) installed at different depths and radial distances from the probe to track the progression of the thaw front. Volumetric water content was measured using CS655 sensors (±3% accuracy; <0.05% precision) at 130 mm depth and 75 mm horizontal distance from the probe. Soil heat flux at the gravel surface was measured with an HFP01 sensor (±3% accuracy).

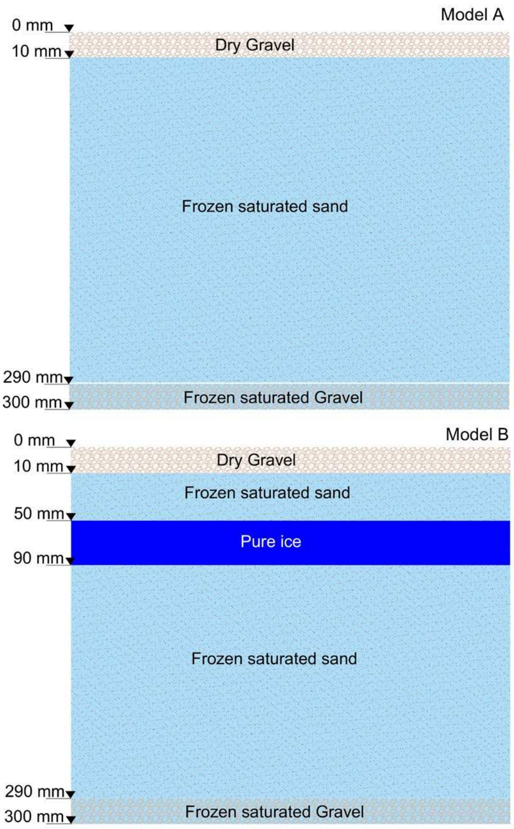
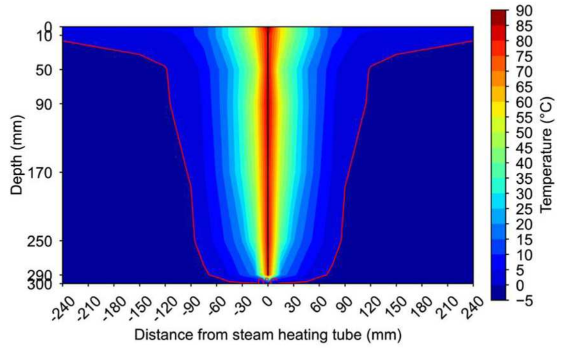


Figure 2. Schematic of soil and ice layer arrangements used in permafrost physical modeling.

3 RESULTS

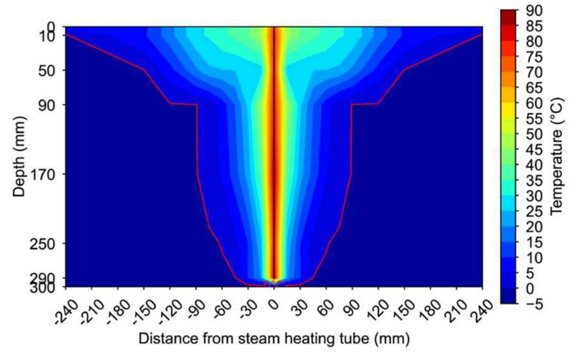
Figure 3 indicates the spatial temperature distributions at the end of steam heating for models A and B.

Model A contained only pore ice (28.23 × 10⁶ mm³, 39% of the frozen volume). The thaw radius decreased with depth, measuring 240 mm at 10 mm, 119 mm at 50 mm, 114 mm at 90 mm, 96 mm at 170 mm, 85 mm at 250 mm, and 72 mm at 290 mm. The total thawed volume was 11.32 × 10⁶ mm³ (15.64% of the frozen volume), including 4.42 × 10⁶ mm³ of melted pore ice, corresponding to approximately 4.05 L of water. The measured condensate mass was 1.4 kg.



Model A

V^0_{frozen}: 72.384×10^6 mm³
$V^0_{pore\ ice}$: 28.23×10^6 mm³ (39% $V_{t,\ frozen}$)
$V^0_{unfrozen\ pore\ water}$: 2.17×10^6 mm³ (3% $V_{t,\ frozen}$)
$V_{t,\ thawed}$: 11.32×10^6 mm³ (15.64% V^0_{frozen})
$V_{pore\ ice \to water}$: 4.42×10^6 mm³ (6.11% V^0_{frozen})



Model B

V^0_{frozen}: 72.384×10^6 mm³
$V^0_{total\ ice}$: 32.65×10^6 mm³ (45.11% $V_{t,\ frozen}$)
$V^0_{ice\ lens}$: 7.24×10^6 mm³
$V^0_{pore\ ice}$: 25.41×10^6 mm³
$V^0_{unfrozen\ pore\ water}$: 1.96×10^6 mm³
$V_{t,\ thawed}$: 10.91×10^6 mm³ (15.08% V^0_{frozen})
$V_{total\ ice \to water}$: 5.62×10^6 mm³ (7.8% V^0_{frozen})
$V_{ice\ lens \to water,\ total}$: 2.24×10^6 mm³
$V_{pore\ ice \to water,\ total}$: 3.38×10^6 mm³

Figure 3. Spatial temperature distribution at the end of thawing test for Models A, and B. The 0 °C isotherm, indicated by the red line, represents the thaw front.

Model B contained an ice lens at 50–90 mm depth (7.24×10^6 mm³) and pore ice (25.41×10^6 mm³), corresponding to 32.65×10^6 mm³ of total ice (approximately 45% of the frozen volume). The thaw radius increased to 150 mm at 50 mm, then decreased with depth, measuring 90 mm at 90 mm, 90 mm at 170 mm, 66 mm at 250 mm, and 45 mm at 290 mm. The total thawed volume was 10.91×10^6 mm³ (15.1% of the frozen volume), including 5.62×10^6 mm³ of melted ice (3.38×10^6 mm³ pore ice and 2.24×10^6 mm³ ice lens), corresponding to 3.10 L of water from pore ice and 2.05 L from the ice lens. The measured condensate mass was 2.0 kg.

In both models, the thaw-front radius is largest in the upper 50 mm, reflecting the combined effects of ambient laboratory heat flux at the soil surface (~70–80 W m^{-2}) and the substantially higher heat flux from the probe wall (~1200–1500 W m^{-2}). The presence of an ice lens fundamentally alters thaw patterns. Model A, without an ice lens, shows a continuous decrease in thaw-front radius with depth. In contrast, model B, which contains an ice lens, exhibits non-uniform, depth-dependent behaviour. At shallow depths (<90 mm), the thaw-front radius in Model B was larger than in Model A. This is attributed to thawing of the ice lens surrounding the probe, which induces surface settlement. Meltwater released during thaw accumulates in near-surface depressions, where its high specific heat capacity enables it to store and gradually release thermal energy, enhancing lateral heat distribution primarily through conduction. Between 90 and ~170 mm depth, the thaw-front radius in model B remains nearly constant and smaller than in model A. Residual ice within the 50–90 mm lens continues to consume latent heat, increasing local thermal resistance and limiting radial thaw-front propagation. Beyond ~170 mm depth, the thaw-front radius decreases more rapidly than in model A, indicating a reduced downward heat flux.

The presence of an ice lens also significantly increases the steam energy required to achieve a given thaw volume. Estimates based on measured condensate masses indicate that model B required approximately 4.54 MJ of steam-released energy, compared with 3.18 MJ for model A, corresponding to a ~43% increase. These values represent lower-bound estimates, as they do not include heat transferred by uncondensed steam within the probe or the sensible heat of the condensate prior to collection. Melting 4.05 kg of ice in model A requires the input of approximately 1.35 MJ of latent heat of fusion, whereas the higher ice content in model B (5.15 kg, including the ice lens) increases the latent heat requirement to approximately 1.72 MJ (~27%). Additional sensible heat is consumed in warming frozen soil to 0 °C and raising the temperature of thawed soil above 0 °C, with model B further affected by the accumulation of ~2.05 L of surface meltwater, which acts as an additional thermal sink. Together, the higher latent heat of the ice lens and the additional energy needed to heat the surface meltwater explain why the overall energy demand in model B is higher.

Comparison of thaw efficiency and energy efficiency highlights the impact of excess ice on thawing performance. Although models A and B were heated for the same duration and achieved similar thawed volumes, model B required ~43% more energy to reach a slightly smaller thawed volume, reducing energy efficiency by approximately 33%. In contrast, thaw efficiency in terms of thawed volume per unit time remains similar between the two models. These results indicate that pre-construction thawing techniques in ice-rich permafrost ground should account for the additional energy required to maintain energy efficiency, even when thaw rates are comparable.

These results indicate that, for field-scale steam-probe testing in ice-rich permafrost ground, site-specific characterization of ice content and distribution of ice lenses is essential, as ice lenses can alter thaw patterns and increase energy demand. Incorporating these insights into pre-thawing strategies can improve energy efficiency, promote uniform thaw, and reduce operational risks.

4 CONCLUSIONS

Laboratory-scale testing demonstrated that a closed-loop, steam-driven probe can effectively thaw permafrost within a controlled zone, enabling subsequent drainage, consolidation, and strengthening of the ground prior to infrastructure construction. However, its performance is strongly influenced by the presence of excess ground ice, which increases the steam energy required to thaw the target area. In soils containing ice lenses, meltwater released from the lenses surrounding the probe accumulates in depressions formed by soil surface settlement, enhances lateral heat transfer, and increases the thaw-front radius at shallow depths, while layers below the meltwater-filled depressions may exhibit a smaller thaw-front radius compared to soils without ice lenses. These findings highlight the critical role of ice lens distribution in controlling thaw dynamics, affecting both thaw geometry and energy requirements for controlled permafrost ground thawing.

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REFERENCES

Afsharipour, M.H., Gheysari, A.F., Bouaanani, N., Boudreault, R., & Maghoul, P. (2024). A Review on Small Modular Reactors for Energy Transition in Northern Canada: Some Geotechnical Considerations in the Context of Climate Change. *Geotech Geol Eng*, 42, 6697–6725. https://doi.org/10.1007/s10706-024-02915-0

Cysewski, M. H., & Shur, Y. (2012). Pre-thawing: From mining to civil engineering; A historical perspective. In *Cold Regions Engineering 2009* (pp. 22–31). American Society of Civil Engineers. https://doi.org/10.1061/41072(359)4

Doré, G., Niu, F., & Brooks, H. (2016). Adaptation methods for transportation infrastructure built on degrading permafrost. *Permafrost and Periglacial Processes*, 27(4), 352-364. https://doi.org/10.1002/ppp.1919

Esch, D. (2013). Thawing techniques for frozen ground. In *Thermal analysis, construction, and monitoring methods for frozen ground* (pp. 239–257). American Society of Civil Engineers. https://doi.org/10.1061/9780784407202.ch07

Fortier, R., LeBlanc, A. M., & Yu, W. (2011). Impacts of permafrost degradation on a road embankment at Umiujaq in Nunavik (Quebec), Canada. *Canadian Geotechnical Journal*, 48(5), 720-740. https://doi.org/10.1139/t10-101

Go, G. H., Lee, J., Shin, H. S., Ryu, B. H., Jin, H. W., & Kim, D. W. (2019). Evaluation of one-dimensional freezing behavior for ice-rich sandy soil. *International Journal of Heat and Mass Transfer*, 130, 960-967. https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.017

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., & Luoto, M. (2022). Impacts of permafrost degradation on infrastructure. *Nature Reviews Earth & Environment*, 3(1), 24-38. https://doi.org/10.1038/s43017-021-00247-8

Malenfant-Lepage, J., Doré, G., Fortier, D., & Murchison, P. (2012, June). Thermal performance of the permafrost protection techniques at Beaver Creek experimental road site, Yukon, Canada. In *Proceedings of the 10th International Conference on Permafrost* (pp. 261-266). The Northern Publisher Salekhard, Russia.

Ngo, H. P. T., Sveen, S. E., & Gjerløw, E. (2022). Artificial thawing of frozen ground: a review. *Journal of Cold Regions Engineering*, 36(4), 04022006. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000280

Nouri, A., Fortier, D., Roustaei, M., Arenson, L., Pereira, J. M., Tang, A. M. & Maghoul, P. (2026) Physical Modelling of a Closed-Loop Steam-Driven Thawing Technique for Permafrost Ground [Manuscript accepted for publication]. Submitted to *Géotechnique Letters*.

Nouri, A., Maghoul, P., Fortier, D., & Roustaei, M. (2025, June). Performance Evaluation of a Novel Steam-Based Thawing Method for Permafrost Regions. In *3rd International Conference on Energy Geotechnics 2025*.

Remchein, D., Fortier, D., Dore, G., Stanley, B., Walsh, R. (2009). *Cost and Constructability of Permafrost Test Sections Along the Alaska Highway,* Yukon. Proceedings of Transport Association of Canada Annual Conference, Vancouver, October 2009, 1-20

Stephani, E., Lepage, J. M., & Doré, G. (2022). *An overview of major engineering challenges for developing transportation infrastructure in northern Canada*. The School of Public Policy Publications, 15(1). https://doi.org/10.11575/sppp.v15i1.73187

Sweidan, A. H., Niggemann, K., Heider, Y., Ziegler, M., & Markert, B. (2022). Experimental study and numerical modeling of the thermo-hydro-mechanical processes in soil freezing with different frost penetration directions. *Acta Geotechnica*, 17(1), 231-255. https://doi.org/10.1007/s11440-021-01191-z