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Hypergravity testing of thaw-dependent stiffness in permafrost under shallow foundations

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ABSTRACT: This study introduces new capabilities under development to investigate freeze-thaw processes in a hypergravity environment, enabling system-level physical modeling of permafrost and active-layer dynamics and their implications for shallow foundation performance. Conventional laboratory tests provide only element-scale measurements and cannot reproduce field-scale stress states, natural ice morphology, or the time-dependent consolidation that accompanies progressive thawing. By leveraging centrifuge scaling laws for heat transfer and stress similitude, the proposed approach enables the capture of thaw-dependent stiffness changes that are otherwise unobservable within practical laboratory timescales. Preliminary results demonstrate the practical requirements for frozen-soil sample preparation, boundary insulation installation, and achievable run times in a 1m centrifuge needed to generate a controlled, one-dimensional thawing front from the surface downward. Using these capabilities, the approach successfully captures thaw-dependent stiffness degradation beneath a shallow footing, showing more than an order-of-magnitude reduction in foundation stiffness as thaw progresses, from approximately 1390 MN/m to below 56 MN/m, and enabling settlement to be quantified as a function of thaw depth and the evolving thickness of the active layer.

1 INTRODUCTION

Rising global temperatures have accelerated permafrost thaw, leading to thicker active layers and threatening ground stability and infrastructure (Hjort et al., 2022). As frozen soil thaws, its mechanical stiffness decreases significantly, compromising the stability of foundations in cold regions. Understanding how soil stiffness evolves during progressive thawing is therefore essential for assessing the long-term performance of infrastructure in permafrost regions (Niu et al., 2016). The objective of this study is to determine how progressive thawing reduces soil stiffness beneath shallow foundations by replicating a downward-moving thawing front in a geotechnical centrifuge under realistic stress conditions. To achieve this, a fully frozen sand deposit was prepared and instrumented within an insulated container, and then thawed from the ground surface downward. During thaw progression, the shallow footing was subjected to repeated loading cycles to measure the evolution of stiffness as the active layer thickened.

2 TEST DESIGN

The centrifuge test was conducted at the UC Davis Center for Geotechnical Modeling using the 1m centrifuge. All dimensions are presented in prototype units following conventional scaling laws described by Kutter (1995). Ottawa F65 silica sand was prepared at a relative density of 40% and pluviated into a rigid aluminium container (8.9 m in length × 6.6 m in width × 6.0 m in depth). Following Gardner et al. (2025), insulations having different thicknesses were installed along the container boundaries to provide one-dimensional thawing: 2.5 cm of interior insulation, 3.8 cm along the exterior sidewalls, and 6.5 cm along the exterior bottom, with thermal resistances of 1.1, 1.7, and 2.9 $m^2 \cdot K/W$, respectively, in model scale.

Resistance temperature detectors (RTDs) were installed at 0.5 m spacing near the top and bottom, and at 0.75 m spacing in the middle region (Figure 1). After preparation, the model was saturated with deionized water and frozen from the bottom upward to minimize air entrapment. Once fully frozen, a shallow foundation (1.25 m × 1.25 m) with a contact stress of 80 kPa was placed at the center of the model surface. The model was then spun to 25g and gradually thawed from the surface downward under a 1D profile. As thawing progressed, 17 loading events were applied, each consisting of a full loading-unloading sequence (0-130-0 kN). This paper presents results only from the 2^{nd} to 5^{th} loading events (Loads 2-5). Temperature was recorded throughout the test, and the sequence continued until all RTD readings exceeded 0°C, enabling measurement of the thaw-dependent change in soil stiffness.

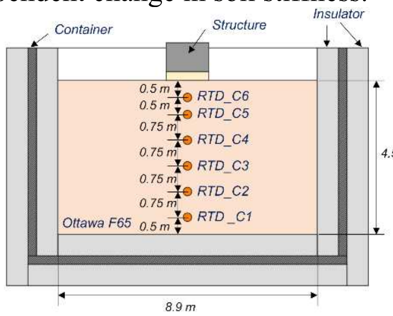

Figure 1. Cross-sectional view of the centrifuge model.

3 RESULTS

The temperature changes with time, measured by RTDs during the test, are shown in Figure 2. All sensors initially recorded subfreezing temperatures. Thawing initiated at the uppermost sensor (RTD_C6) and progressed systematically downward. This clearly indicates a one-dimensional thawing front developing from the surface downward, consistent with the vertical thawing pattern observed in field conditions.

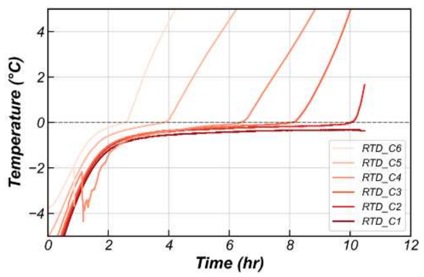

Figure 2. Temperature variation with time (time shown in model scale).

To evaluate stiffness change during thawing, the force-displacement response of the foundation was plotted for loading events (Loads 2-5) in prototype scale in Figure 3. Here, force refers to the vertical load applied to the foundation, as measured by the load cell. The Chin-Kondner method (Fellenius, 1990) was used to estimate the stiffness of the soil. The initial loading (Load 2) showed a high stiffness of 1390 MN/m, reflecting the rigidity of the frozen soil. As thawing advanced, the measured stiffness gradually decreased to about 139 MN/m (Load 3), 98 MN/m (Load 4), and 56 MN/m (Load 5). This trend indicates a progressive reduction in soil stiffness correlated with the extent of thawing. Based on these results, the current work focuses on estimating settlement under shallow foundations as a function of the thickness of the active layer and the zone of influence of foundation loads.

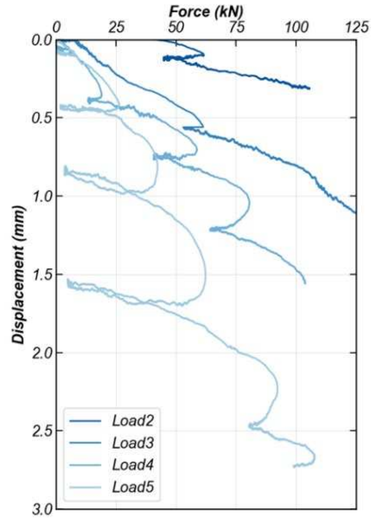

Figure 3. Force-displacement responses of the foundation during the loading events.

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