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Brief Communication: Hypergravity Testing of Thawing Rates in Frozen Sand

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Abstract. The active layer above permafrost experiencing seasonal freeze-thaw can range from a few centimeters to tens of meters in thickness, which complicates physical modeling of this phenomenon. This study shows capabilities developed to investigate freeze-thaw in a hypergravity environment that will enable system-level experiments which tie model predictions of permafrost behavior to field observations of permafrost temperature cycling. By leveraging scaling in a hypergravity setting, this research will allow for permafrost layers to be generated on a prototype scale that capture the full thickness of the active layer on the order of tens of meters. We present preliminary results showing requirements and techniques for sample preparation, insulation, and feasible experiment run times in a 1-m radius centrifuge.

1 Introduction

Permafrost—ground which remains frozen at least two consecutive years—plays an important role in the global carbon cycle, natural hazards, and infrastructure performance (Portner et al., 2019). The thickness of the active layer overlying permafrost, which thaws and freezes seasonally, is most affected by air temperatures and precipitation (Murton, 2021). As the global climate changes, associated increases in air temperature and changing precipitation characteristics are likely to induce increased thickness and temperature variability in the active layer. This has substantial implications in terms of infrastructure performance (Hjort et al., 2022) and ground stability (Niu et al., 2016), as well as global carbon release (Schuur et al., 2015), forced migration (Ramage et al., 2021), and diseases (Wu et al., 2022).

Thus, understanding how air temperature and precipitation changes influence both the rate and depth at which permafrost may thaw is important for estimating climate change impacts. The active layer can range from a few centimeters to more than 10 meters in thickness (Murton, 2021), which complicates physical modeling of this phenomenon since laboratory tests only provide element-level measurements of the freezing, thawing, and refreezing processes and it often is not possible to create experiments at field scale. Many field studies have investigated warming-induced impacts on permafrost (for example, Henry and Molau (1997); Salmon et al. (2016); Hicks Pries et al. (2017); Hanson et al. (2017); Nottingham et al. (2020); Qin et al. (2023); Bai et al. (2023)) with tested depths ranging from 5 cm up to 2 m, and planform dimensions up to several meters. Recent work by Wagner et al. (2018) included field experiments at the decameter scale where an approximately 11 x 13 x 1.5

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m soil volume was tested over a period of 63 days. These field tests demonstrate both the potential for further field testing over larger areas and depths to investigate impacts of future climate scenarios on permafrost regions and civil infrastructure while also highlighting the challenges in conducting field-scale experimentation, especially at greater depths.

Understanding how temperature fluctuations propagate through the full soil column, and how these changes impact various aspects of permafrost response would benefit from methods that are able to link field-scale observations to element-level laboratory tests. Here, hypergravity testing in a geotechnical centrifuge is a promising approach that enables testing of a permafrost layer at prototype scale that captures the full thickness of the active layer. While hypergravity testing has found broad applications within geotechnical engineering (Boulanger et al., 2020), it has also previously been applied to permafrost applications. For example, tests have explored soft sediment deformation during thawing (Harris et al., 2000), solufluction during freeze-thaw cycling (Kern-Luetschg and Harris, 2008; Thomas et al., 2009), ice wedge casting (Harris et al., 2005), and periglacial slope stability as a function of soil properties (Harris et al., 2008). More recent tests have investigated contaminant transport as a function of permafrost degradation (Nadeau et al., 2019), thawing in saturated clay around subway tunnels (Zhou and Tang, 2015), and steel piles in frozen and thawing soils (Clarkson et al., 2024). These tests leverage scaling characteristics based on an enhanced gravity field in the centrifuge such that small-scale models can be used to replicate the conditions at field scale. However, when conducting this class of testing, it is important to ensure that boundary conditions do not affect the process of interest in such a way that laboratory conditions do not replicate the prototype configuration of interest. In the case of permafrost testing in the centrifuge, careful consideration must be given to temperature boundary conditions, both in terms of what might be representative conditions for the process at hand, and how the experimental configuration may introduce undesirable temperature sources. As such, it is important to measure temperature in the experiments in such a way that the boundary conditions can be verified and confirmed to provide the necessary temperature conditions.

To this end, we are developing the capability to investigate permafrost freeze-thaw in a hypergravity environment with a specific focus on insulation requirements to maintain appropriate boundary conditions that maintain a top-down thawing profile where heat exchange only occurs through the top surface of the soil. This will enable system-level experiments which can tie model predictions of permafrost behavior to field-scale observations of permafrost temperature cycling due to temperature fluctuations at the soil surface. Here, we present preliminary results showing requirements and developed techniques in terms of sample preparation, insulation, and feasible experiment run times for maintaining desired boundary conditions in a 1-m radius geotechnical centrifuge. Our experiments focus on how air temperature, sample preparation, and insulation affect thawing rates and spatial evolution of temperatures of frozen soil.

2 Scaling in Centrifuge

We include a brief discussion on scaling in a hypergravity setting to illustrate how soil stress and heat diffusion scale in an enhanced gravity field, or g-field. Further details and many examples of different applications (Boulanger et al., 2020; Garnier et al., 2007; Schofield, 1980) can be found in the literature. The basic premise utilized here is that we test a $1/N$ scale model of a prototype in a g-field enhanced by the same factor, N, to maintain identical scaling of stresses, as shown below. The factor

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N is referenced to the earth's gravitational field, such that the scaled model in the centrifuge will experience a gravitational force N times normal gravity. In the following discussion, scale factors for a quantity will be denoted by the symbol for the quantity with an asterisk. For example, if L is the symbol for length, then the ratio of the length in the model to the length in the prototype would be denoted as L^*.

For hypergravity models of soil, if the desire is to investigate stress-dependent behavior or soil, it is necessary to ensure that the stresses in the scaled model scale identically to the prototype case to ensure the stress-strain response observed in the scaled model is representative of the desired prototype. Thus, the scaling factor for the stress should be one, or $\sigma^* = 1$. Identical materials are used in the model and prototype so that identical mechanical properties are maintained (Kutter, 1995). In doing so, the scaling factor for density will be $\rho^* = 1$. The required scaling factor for gravity can then be calculated as:

$$\sigma_m = \rho_m g_m h_m \tag{1}$$

$$\sigma_p = \rho_p g_p h_p \tag{2}$$

$$\sigma^* = \frac{\sigma_m}{\sigma_p} = \rho^* g^* h^* \tag{3}$$

The subscripts m and p represent the model and prototype respectively, and h is the depth at which the stress is being calculated. Rearranging and noting that h scales the same as any other length, the scaling factor for gravity is established as:

$$g^* = \frac{\sigma^*}{\rho^* L^*} \tag{4}$$

$$g^* = \frac{1}{L^*} \tag{5}$$

Thus, for a model where lengths have been reduced by a factor N, the gravitational acceleration must be increased by the same factor, $g^* = N$, to achieve the desired scaling of stresses. When considering heat diffusion through the soil, conductive heat transfer is described by the heat equation:

$$\frac{\partial u}{\partial t} = \alpha \nabla^2 u \tag{6}$$

where u is the temperature and α represents the thermal conductivity of the medium through which heat is diffusing. Temperature will not depend on gravitational acceleration and we assume that the thermal conductivity of the soil does not change based on g-level since it is a material property. Thus, based on the scaling factors necessary for maintaining identical scaling of stresses, the time rate of scaling of conductive heat transfer will scale to be $t^* = 1/N^2$ (Savvidou, 1988) since the length scaling factor is squared in the Laplacian on the right-hand side of Equation (6). In other words, heat transfer will occur N^2 times faster in the model than in the prototype. This scaling has been experimentally verified by Krishnaiah and Singh (2004).

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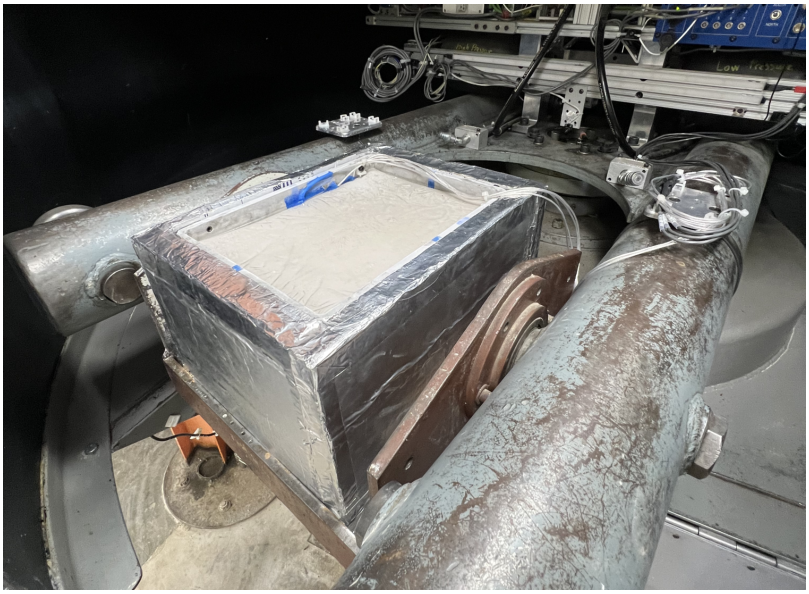

Figure 1. Insulated sample place on 1-m radius centrifuge. Aluminium container is surrounded by insulation (silver panels on outside of soil container), while wiring for resistance temperature detectors can be seen emerging from the soil near the back left.

3 Experimental Design

Tests were performed at the UC Davis Center for Geotechnical Modeling using the 1-m radius beam centrifuge. For this set of experiments, cohesionless sandy soils were prepared at two different relative densities to assess the influence of void space on the rate at which thawing occurs in the samples. Furthermore, we tested specimens both in an insulated and uninsulated container to evaluate insulation requirements to create a one-dimensional melting front and temperature profile throughout the majority of the centrifuge container. The model soil depth was 20 cm and tests were conducted at 25 times the earth's gravitational acceleration, or 25g. Thus, in prototype scale the soil depth scales to 5 m. The general configuration for the experiments is shown in Figure 1 and, below, we provide details on different aspects of the experimental setup and measurements taken.

3.1 Soil Preparation and Sensor Placement

F-65 Ottawa Silica Sand (Carey et al., 2020) was used to prepare samples at a relative density (D_R) of 40% and 80% to represent soils in a "loose" and "dense" state, where the loose sample contains more void space to hold water compared to the dense sample of the same volume. Dry soil was air pluviated into a rigid aluminum container (length 35.4 cm $\times$ 26.4 cm width $\times$ 24.0 cm depth) from a specific height that is calibrated based on the desired relative density, air moisture content, and soil type—F-65 in this case. Soil is placed in 2 cm layers to allow for sensor placement within the specimens. For the 40% D_R sample, 4 resistance temperature detectors (RTDs) were placed at the locations shown in Figure 2a to measure temperature change in the sample during testing. Similarly, 16 RTDs were installed in the 80% D_R specimen as indicated in Figure 2b.

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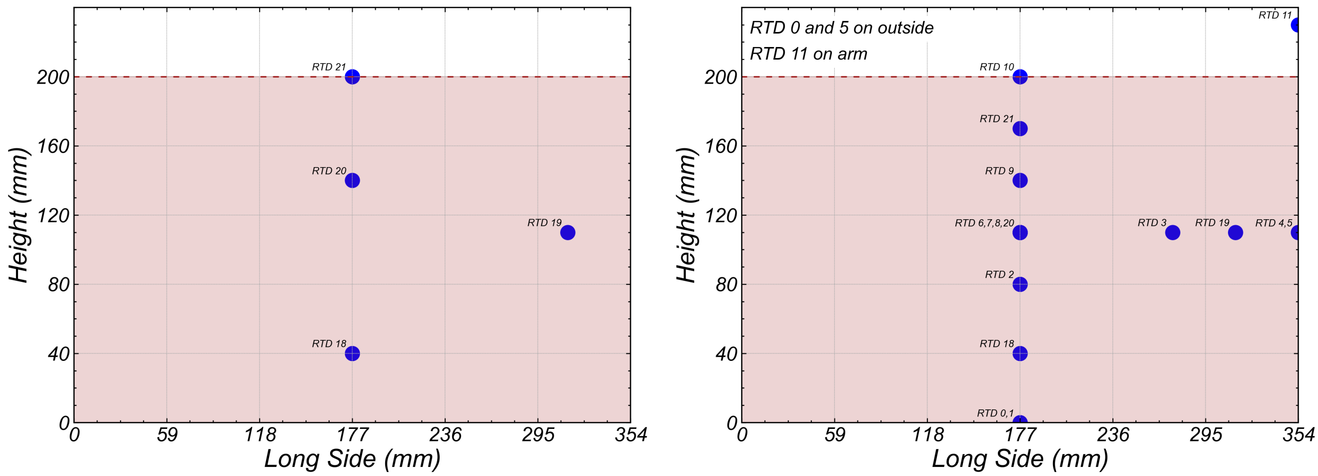

(a) Loose Sample Sensor Placement

(b) Dense Sample Sensor Placement. Note: RTD 6, 7, and 8 are at same elevation as RTD 20, but move progressively closer to the container side. See Gardner et al. (2025) for complete sensor layout.

Figure 2. Resistance Temperature Detector (RTD) sensor placement in section view for loose and dense samples.

General-purpose Pt100 RTDs with a nominal resistance of 100Ω at $0°C$ and a stated measurement accuracy of $\pm1.5\%$ were used. Configured in a 3-wire arrangement, these sensors are representative of low-cost, non-standard RTDs commonly available through online marketplaces. Signal conditioning was performed using a combination of National Instruments NI-9217 and Advantech ADAM-6015 RTD input modules, as well as TWTADE Pt100 transmitters manufactured by Suzhou Taishun Electronics.

Once all sensors are placed and the sample is at the desired height, the soil is slowly saturated. This is done by tilting the container slightly and allowing water to slowly infiltrate from the lowest edge to avoid large pockets of air being trapped in the pore space. Additionally, a sponge is placed on top of the soil to distribute inflow and limit the amount of disturbance from water splashing on the surface.

3.2 Freezing Procedure

The saturated sample is placed in a freezer to completely freeze the soil prior to testing on the centrifuge. In order to minimize disturbance of the soil fabric due to volume expansion of water during the freezing process, the sample is frozen from the bottom up so that water is able to migrate to the surface freely. As illustrated in Figure 3a, this is achieved by placing insulation around the sides and top of the container, while directing airflow within the freezer around the uninsulated bottom of the container. After freezing, excess ice that has formed on the top of the soil is melted away to avoid having an ice buffer that shields the underlying soil during testing. This is done by using a heat gun and a peristaltic pump. Once all excess ice is removed from the top of the sample, it is returned to the freezer to re-freeze the soil near the surface.

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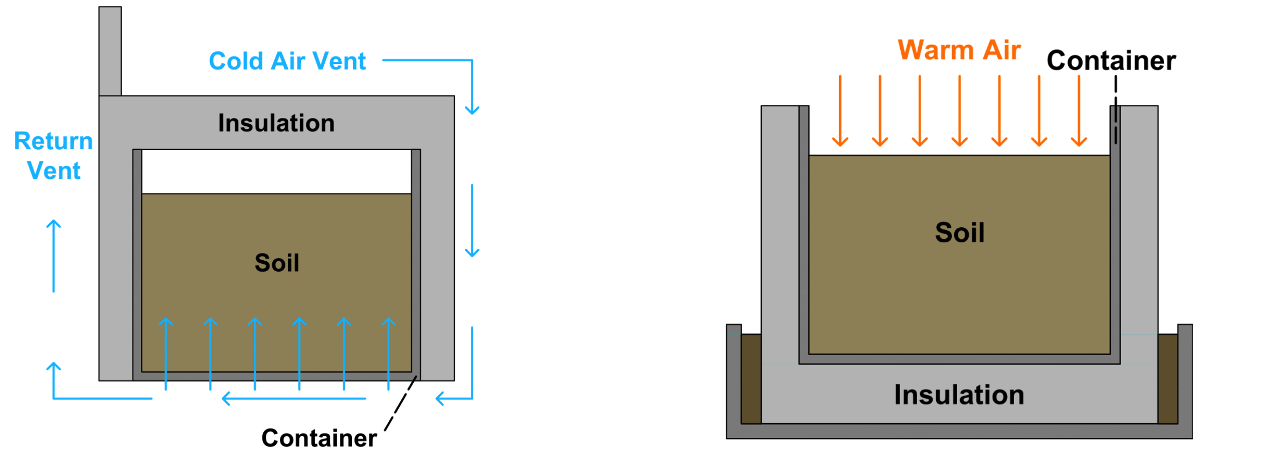

(a) Freezing configuration to ensure models freeze from bottom to top. Airflow is directed next to the uninsulated bottom to ensure heat flux is through the lower portion of the model during freezing.

(b) Configuration of model on centrifuge arm. Bottom and sides of the container are insulated to ensure heat enters the model through the top soil surface.

Figure 3. Schematic illustrating model setup during freezing and during testing on the centrifuge arm.

3.3 Insulation

Insulated and uninsulated tests of both the dense and loose samples were tested to evaluate the insulation required to maintain a one-dimensional melting front throughout the container during testing. Thus, the samples were first placed in the centrifuge uninsulated and temperature data was collected as soil thawed due to ambient temperatures during spinning. After this test, samples were re-frozen and placed on the centrifuge with insulation around the sides and bottom of the container, as shown in Figure 3b. Insulation consisted of 3.81 cm thick insulation sheets with an RSI-value of 1.69 $m^2 \cdot K/W$ placed around the sides, and two sheets (one 3.81 cm and one 2.54 cm sheet for a total thickness of 6.35 cm) on the bottom of the container to account for loss of insulation due to compression during testing at 25g.

4 Results

Here, we present key results and a summary of observations; however, all data is available in the published data set (Gardner et al., 2025).

4.1 Insulation Requirements

The time-varying temperature for both the insulated and uninsulated cases for the loose sample are shown in Figure 4a, and for the dense sample in Figure 4b—note that all values are shown in prototype scale. For the uninsulated tests, the order in which the temperature increases at different sensor locations clearly indicates that the sample is heating from all sides and that the

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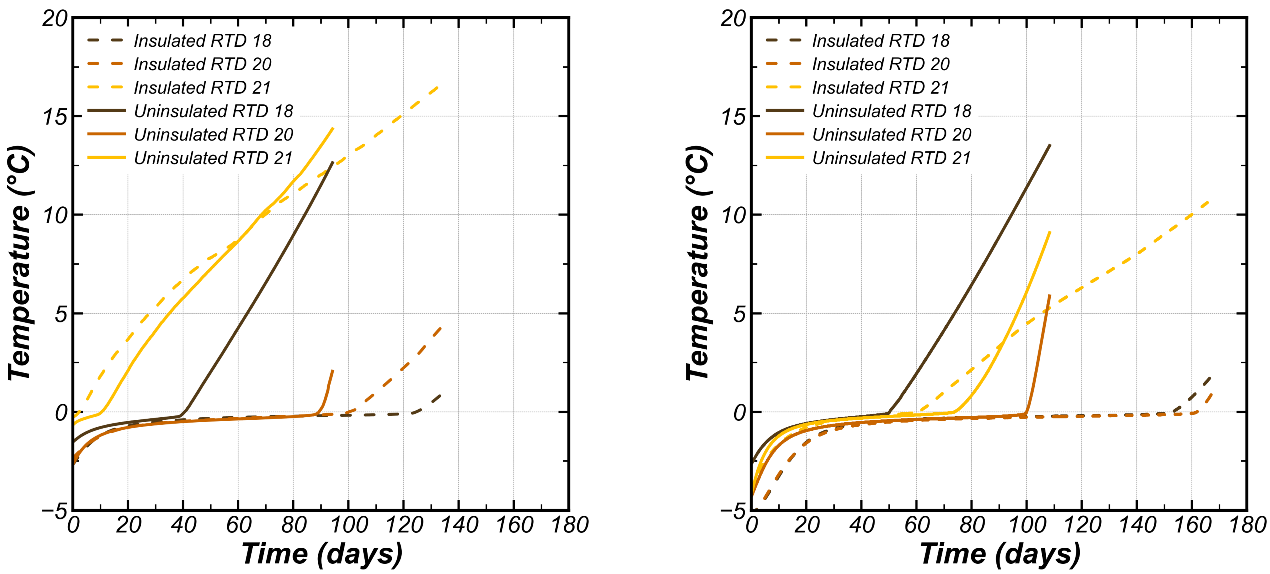

(a) Loose Sample

(b) Dense Sample

Figure 4. Recorded temperatures for dense and loose sample preparations. For both sample preparations, results are shown for insulated and uninsulated tests. Substantial benefit of insulation can clearly be seen in both cases, where a one-dimensional thawing profile is maintained for 120 days for the loose sample and 150 days for the dense sample when insulated.

center of the sample is the last to fully thaw—the influence of the exposed aluminum container in particular can be seen in the slope of the uninsulated tests where it is able to efficiently transfer heat from the warm air in the centrifuge rotunda directly into the soil. For these uninsulated tests, it is thus not possible to maintain a one-dimensional, top down thawing profile for any reasonable amount of testing time and results from these tests would not be representative of what anticipated conditions would be in the field.

Comparatively, when placing insulation around the sides and bottom of the container, the order at which thawing is observed at the different sensor locations indicates that the sample thaws from the surface downward. This better approximates the thawing process that would be observed in the active layer. For the prototype scale tested, the one-dimensional melting profile can reasonably be maintained for approximately 150 days for the dense sample and 120 days for the loose sample, where reported times are in prototype scale. Considering the scaling approach used for these tests, if the tests were conducted at higher g-levels, the prototype times tested could be extended. Of course, this would also mean that the prototype depth of the active layer would be increased, so consideration would need to be given to both the desired prototype depth and time that is being modeled. In the case of our experiments, we were restricted to a 1-m radius centrifuge; however, larger systems would expand the range of scenarios that could be tested.

Figure 5 shows contours of the temperature over both time and the depth at the center of the model to illustrate how temperatures evolve in both the insulated and uninsulated tests. In this preliminary testing, the impact of simply placing insulation

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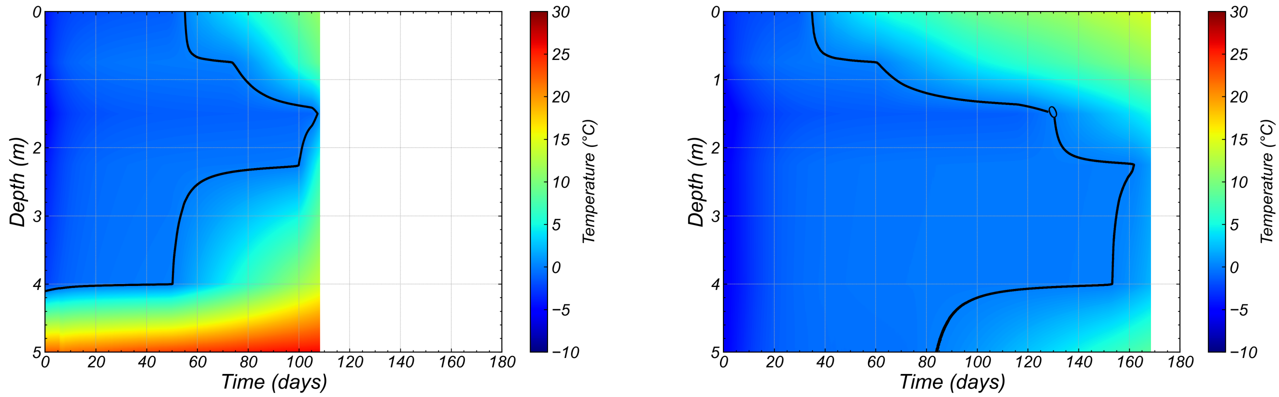

(a) Uninsulated Test

(b) Insulated Test

Figure 5. Contours of temperature along the depth at the center of the dense model over time. The black line shows the $0°C$ contour over time. (a) The rapid increase in temperature at the bottom of the model in the uninsulated tests can be clearly seen. (b) The efficacy of the insulation is evident; however, the influence of heat entering the insulated model through the aluminum container can be seen through the increasing temperature at the bottom of the model.

around the sides and bottom of the aluminum container can be clearly seen. However, a small portion along the top of the container was still exposed to the surrounding air in the insulated tests. This small exposure of the top of the aluminum container, which has higher heat conductivity, provided a pathway for heat to flow into the container and introduce undesirable heat to the bottom and sides of the frozen sample, partially compromising the one-dimensional thawing profile of the test. While this did not compromise our tests entirely, it did reduce the feasible run times for which a top-down thawing profile could be maintained. This boundary effect can be seen in Figure 5b. Future testing specifically addresses this issue by ensuring the aluminum centrifuge container is completely wrapped in insulation on both sides, with exposure only where instrumentation must be secured for testing.

4.2 Soil Density Effects

The relative density of the soil was observed to have a strong influence on the rate at which thawing occurs within the samples during testing. Figure 6 shows a comparison of the time-varying temperature in the dense and loose samples for the insulated tests. As shown, the loose soils thawed consistently faster than the dense soils at all measured locations. Similar trends were observed in the uninsulated tests, but are not shown here. The difference in the thawing rates between the dense and loose soil preparations can be explained by considering the difference in thermal conductivity of the soil particles and ice, and their relative amounts present in each of the soil samples. For dry, silica-rich sandy soils, the thermal conductivity ranges from approximately 0.1-1.0 W/mK (Chen, 2008; Tarnawski et al., 2009; Tetteh et al., 2024) while the thermal conductivity of ice ranges from approximately 2.1-2.6 W/mK (Bonales et al., 2017). The relative amount of ice present in the loose sample compared to the dense sample is higher since the volume of the pore space is greater and completely filled with ice. As such,

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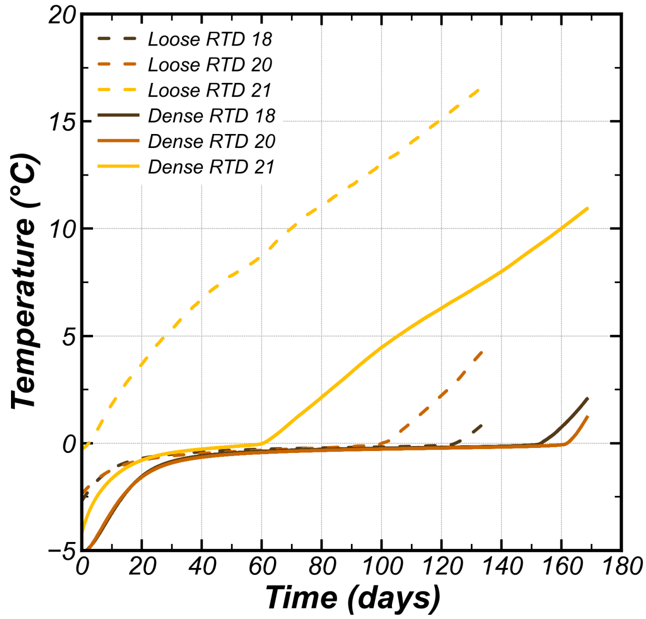

Figure 6. Thawing rate comparison for dense and loose sample preparations for insulated tests. The dense sample shows a substantially slower thawing rate compared to the loose sample.

estimating the equivalent thermal conductivity as a function of the relative amounts of soil particles and ice present in a given soil volume would yield a higher value for the loose sample compared to the dense sample. Thus, the loose sample is able to conduct heat at a faster rate compared to the dense sample and will show faster phase transition and temperature increase compared to the dense sample.

5 Conclusion

Hypergravity testing in a geotechnical centrifuge provides a means by which to conduct system-level experiments that tie element level phenomena to field scale observations. To investigate the application of this approach in modeling the active layer in permafrost regions, we developed and tested capabilities for conducting hypergravity testing on thawing rates of frozen soil in a 1-m radius geotechnical centrifuge. Specifically, we show that a one-dimensional thawing profile that approximates how soil melts during higher air temperatures at the soil surface can be achieved without active cooling by adequately insulating the sides and bottom of the centrifuge container. When insulating the container, careful consideration must be given to potential heat entry points, as heat flows readily through the aluminum container and can lead to undesirable thawing patterns.

Further, we conducted experiments with two different soil sample preparations—one relatively dense and one relatively loose sample—that show the influence of soil fabric on the rate at which it thaws. For the two specimens prepared with the same silica sand, the influence of the soil density and associated void space was shown to influence the rate at which heat can

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flow through the sample. Thus, it should be expected that heat flux will be highly dependent on soil fabric and type, both of which will vary spatially in the field. Our results here consider only a very limited set and further research is necessary to establish how heterogeneity influences spatially variability in soil thawing rates. An important consideration for this aspect would be to consider the influence that sample freezing may have on the desired soil fabric. In this work, we ensured that the prepared fabric was minimally disturbed by freezing the sample from the bottom up. Since the sandy material is free-draining, this allowed water to migrate to the top of the sample as ice formed below it without substantial expansion within the soil pore space.

The capabilities and procedures discussed here illustrate the basic requirements to maintain temperature boundary conditions for conducting hypergravity testing of frozen soil, and the spatial and temporal scales that may be considered using this approach. Considering these preliminary results, there are opportunities for substantial expansion on how this approach can be applied. In our work, we did not implement an active cooling system and thawing rates could not be controlled by maintaining a specific temperature at the top soil boundary. However, current research is specifically focused on creating testing capabilities that provide active cooling such that temperature conditions of the centrifuge container and soil samples can be directly controlled, enabling testing of thawing and freezing cycles.

Data availability. Data are publicly available and can be accessed on the NSF NHERI DesignSafe repository through the following DOI: https://doi.org/10.17603/ds2-mwar-sp11.

Author contributions. MHG and JTD conceived the study; SB, SH, and HK conducted the centrifuge experiments; all authors analyzed the experimental results together and contributed to writing the manuscript.

Competing interests. The authors declare that they have no competing interests.

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