

Frost Jacking Phenomena of Solar Panels Piled Foundations Investigated by Centrifuge Scaled Models.

Giulia Guida, Andrea Viglianti, Francesca Casini
DICII, Università degli Studi di Roma Tor Vergata, Italy, giulia.guida@uniroma2.it

Giulia M.B. Viggiani
University of Cambridge, UK

Giuseppe Favata
Enel Green power, Italy

ABSTRACT: Frost jacking refers to the progressive upward movement of foundation elements caused by the frost heave of the soil under freezing conditions. This phenomenon presents a significant challenge for lightweight foundations in cold regions, where it can compromise structural stability and serviceability. In the case of solar panel arrays, frost jacking can cause misalignment, resulting in reduced energy efficiency, and increased maintenance costs, threatening the long-term viability of these systems. This study focuses on frost-jacking mechanisms in the piled foundations of solar panels, which are increasingly deployed in frost-prone areas due to their enhanced efficiency at lower temperatures and minimal visual impact. Two centrifuge tests were performed at increased gravity of 20g and 30g using the Turner Beam Centrifuge of the Schofield Centre, University of Cambridge, to simulate a freeze and thaw cycle on reduced scale models of solar panel foundations in clay-sand soil mixture. The cold climate conditions were reproduced with a vortex cooling system, which rapidly lowered the air temperature below 0°C and stabilised it at -15°C after approximately one hour. The experiments successfully reproduced the expected frost heave phenomena of the soil surface, which induced frost jacking of the piles, despite the frost penetration being limited relative to the total pile length. During thawing, the soil surface either returned to its initial position or experienced minor settlements, while the piles remained slightly uplifted, indicating an accumulation of upward movement. The experimental results are also interpreted by an analytical closed-form solution for calculating the magnitude and the development of adfreeze frost heaving forces acting on the pile, which combines the effects of frost penetration rate, heave rate and soil temperature in time and space.

KEYWORDS: frost jacking, centrifuge models, frost heave, cold regions.

1 INTRODUCTION

Soils subjected to subfreezing temperatures can experience significant volumetric expansion and frost heave, the magnitude of which depends primarily on their fine content, water availability and freezing rate (Casagrande, 1923). Grain size distribution is widely recognised as the key factor controlling frost susceptibility: well graded mixtures of fine sand and silt or clay are particularly prone to frost-induced deformation (Guida *et al.*, 2025). As the freezing front penetrates deeper into the ground, frost-susceptible soils expand, inducing upward displacement that can cumulatively uplift pile foundations (Penner, 1969). This process, commonly referred to as *frost jacking* (Liu, 2020), poses a specific challenge for lightly loaded steel piles, such as those supporting solar panel arrays, as it can compromise the structural efficiency and serviceability of the entire system (Pagliani *et al.*, 2022, Wang *et al.*, 2022).

Cold-climate regions offer unique opportunities for photovoltaic deployment: subzero environmental temperatures can enhance energy conversion efficiency, as electricity production from solar radiation increases at temperatures below 25°C (Mussard, 2017). Furthermore, these regions often provide vast, unpaved land suitable for large scale solar farms. However, the same low-temperature conditions expose short-pile foundations to prolonged freezing periods, increasing the risk of frost jacking

A substantial body of experimental work has been devoted to quantified tangential frost-heaving stresses, which constitute the dominant mechanism driving pile uplift in frozen ground (Tianyuan *et al.*, 2022). The intensity of frost heaves directly governs the magnitude of these stresses: field observations

indicate that peak adfreeze shear stress occurs when the frost heave rate is highest (Liu *et al.*, 2018).

Several mitigation strategies have been developed to reduce the pile uplift in frozen ground. These include the use of enlarged based piles (Sego *et al.*, 2003) or screw piles (Wang *et al.*, 2016), designed to anchor below the maximum frost penetration depth. Other approaches aim to reduce adfreeze bond strength, for example by employing precast composite piles (Fam *et al.*, 2008), or to replace frost-susceptible soils with non-susceptible backfill. The latter, while effective, is often costly and not always feasible in large-scale installation.

Despite extensive research, to the authors' knowledge no previous studies have specifically examined frost jacking mechanisms in relation to solar panel foundations under controlled centrifuge-scale conditions. The Geolab FROSPER experimental campaign addresses this gap. The study investigates the interaction between soil frost heave and pile foundations supporting photovoltaic systems during cold season. Frost jacking phenomena were reproduced using reduced-scale models tested in a geotechnical centrifuge at two increased gravity levels. The experiments explored the influence of soil composition, thermal loading, pile length, and foundation configuration on the magnitude of pile uplift. In addition, surface insulating mantels were evaluated as a potential countermeasure against frost-induced displacement. All the raw experimental data from the two centrifuge tests are made available as open source (Guida *et al.*, 2023).

The measured temperature fields and surface displacements were further interpreted using the closed form solution proposed by Landanyi and Foriero (1988) to estimate the development of adfreeze induced tangential stresses, incorporating the effects of heave rate, frost penetration depth, and soil temperature profile along the pile shaft.

2 CENTRIFUGE EXPERIMENTAL CAMPAIGN

2.1 Samples

Two centrifuge tests were carried out at the geotechnical Turner Beam Centrifuge of the Schofield Centre at the University of Cambridge, at increased acceleration of Ng , with $N = 20$ and 30 , respectively. The soil used was a frost-susceptible mixture of 80% Houston sand and 20% Speswhite kaolin, selected for its representativeness of transitional soil behaviour. The model piles were aluminium H-section profiles (HE6) with 6 mm sides and three different lengths – short medium and long – designed to replicate prototype pile lengths of 2 m, 2.5 m and 3 m. Accordingly, in the centrifuge model pile lengths were scaled to 100 mm, 125 mm, and 150 mm for the 20g test, and to 67 mm, 83 mm, and 100 mm for the 30g test.

The experimental models were housed in two cylindrical PMMA (polymethylmethacrylate) boxes, each 340 mm tall and 190 mm in diameter. The boxes were filled with a slurry of the clayey sand mixture (water solid ratio of 1:2) and consolidated under a vertical stress of 70 kPa for around 24 h, after which a void ratio $e = 0.7$ was achieved. Both boxes were tested simultaneously inside a larger cylindrical strong box (850 mm in diameter), compatible with the centrifuge swing. Box 1 contained two rows of three connected piles of equal length (Fig. 1a), spaced 60 mm apart and embedded in a heterogeneous soil sample (Fig. 1c) including a shallow pocket of pure Houston sand within the clayey sand mixture. The piles were connected by a 150 mm long aluminium beam (8 mm x 1.5 mm cross-section). Box 2 contained five isolated piles of varying lengths (1 long, 2 intermediate and 2 short, Fig. 1b, d), all embedded in a homogeneous clayey sand mixture.

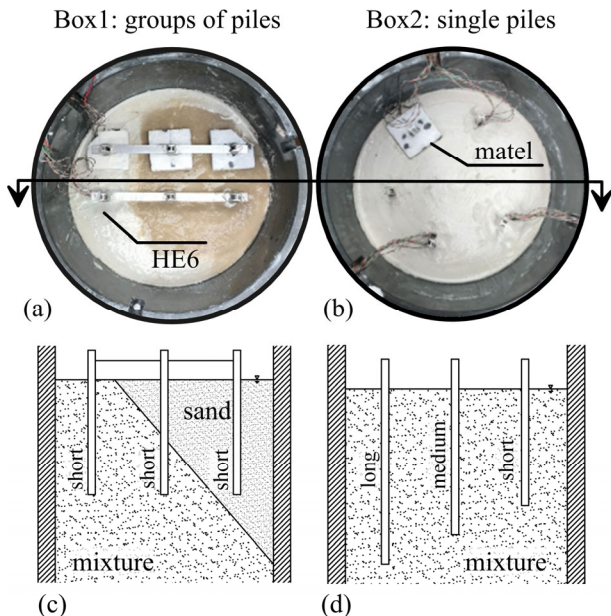


Figure 1. Experimental setup: a-b) plan view of box 1 and 2, c-d) vertical section of box 1 and 2. (The label 1 and 2 identify the two reference piles cited in the results).

To investigate mitigation strategies against frost jacking, a 40 mm square, 10 mm thick polystyrene mantel was applied to some of the piles of Box 1 and 2 to check its effectiveness (see Fig. 1). Vertical displacement of pile heads and the ground surface were monitored using Linear Variable Displacement Transformers (LVDTs). Temperature profiles were recorded with two thermometric rods, each equipped with PT100 sensors at multiple elevations: above the soil surface, at the soil surface, and at depths of 30 mm, 60 mm, and 120 mm. Most piles were

also instrumented with micro-strain gauges at three different depths to assess local forces and reconstruct the tangential stress evolution; however, these gauges failed in both tests.

Cold air was applied at soil surface via a vortex tube system, which uses compressed air (6 bar) to generate separate hot and cold streams by spinning the air at high speed (up to 1,000,000 rpm) into a vortex chamber. Later, insulation with rock wool was placed between the PMMA boxes and the cylindrical strong box, while a drainage system connected to a standpipe ensured water supply at the base of the models.

The centrifuge test comprises three main phases:

- Swing-up: gradual increase from 1g to target acceleration (20g or 30g),
- Freezing/thawing: activation/de-activation of the vortex system,
- Swing-down: return to 1g.

For further details regarding the sample preparation and the test procedure, refer to Viglianti *et al.* (2024).

2.2 Experimental results

This contribution focuses on the results related to the single piles, therefore on those related to Box 2. Fig. 2 compares the vertical displacements of the soil surface and the heads of the single pile measured during the centrifuge tests at 20g and 30g. Positive values of vertical displacement correspond to heaves.

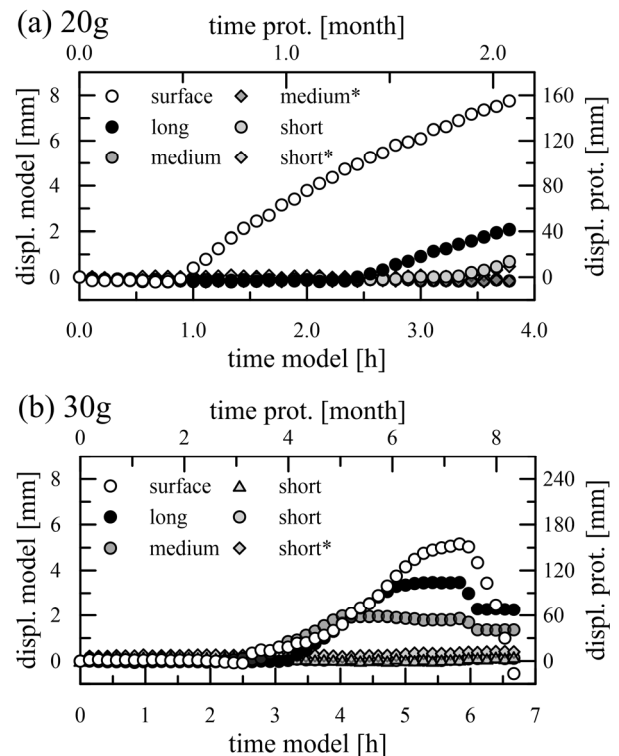


Figure 2. Time evolution of displacements of the pile heads and soil surface for (a) 20g and (b) 30g tests. (*) with insulation mantel. The second axis shows the displacement and time at the prototype scale. In the physical model time scale as $1/N^2$ and length as $1/N$.

In both tests, during the freezing phase, the soil surface experienced the greatest heave. In contrast, the single piles exhibited a reduced response, with a particularly pronounced time delay in the 20g test (Fig. 2a), while in the 30g test (Fig. 2b) the delay is less marked. This behaviour is consistent with the nature of frost jacking forces, which must overcome both the self-weight of the pile and the lateral resistance mobilised in the bottom anchored portion. In the 20g test (Fig. 2a), the surface heaved by approximately 8 mm over a freezing period

of about 4 hours. The pile exhibiting the larger displacement was the long pile, which moved upward by 2 mm, while the other piles displaced by 1 mm or less. Fig. 2b shows the displacements recorded during the 30g tests, in which the freezing phase lasted 6 hours. During the final hour, the vortex system was switched off to allow the model to thaw. Soil surface heave began approximately 2.5 hours after the onset of freezing. Initially, the long and medium-length piles followed the same trend as the soil, showing similar displacements for almost one hour. Thereafter, their responses diverged: the long pile reached a plateau at around 3.5 mm and the medium pile at approximately 1.5 mm, while the soil surface continued heaving up to 5.5 mm. The insulation mantel effectively mitigated the effects of freezing, as the protected piles (* in Fig. 2) showed negligible displacements throughout the tests. During thawing, the soil surface settled slightly more than it had previously heaved, resulting in a net settlement of about 0.6 mm. In contrast, the long and medium-length piles experienced settlements smaller than their heaves during freezing, leading to residual uplifts of 2.3 mm and 1.4 mm, respectively. These values correspond to net heaves relative to the soil surface of 2.9 mm and 1.7 mm. Notably, the longer piles consistently exhibited the greatest uplift in both centrifuge tests, compared to the shorter piles. This outcome contrasts with the initial expectation, which predicted that shorter piles would be more susceptible to frost-induced uplift due to their lower self-weight and reduced shaft resistance. This behaviour may result from a combination of factors, including the influence of strain gauge wires on the pile–soil interface and the heat transfer mechanisms along the pile shaft.

Fig. 3 shows the time evolution of the measured temperatures in the air, at the surface and at depth. The delayed heaves observed in the 30g tests compared to 20g tests (Fig. 2) can be attributed to the variation in the air temperature between the two experiments.

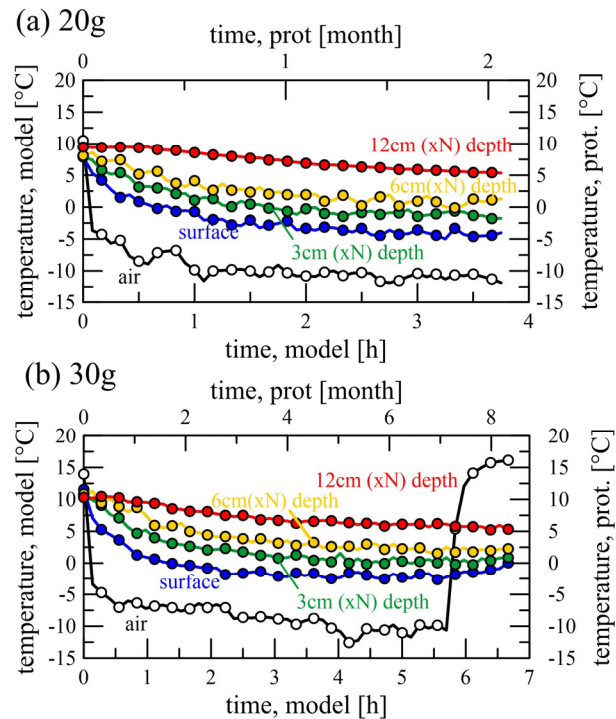


Figure 3. Time evolution of measured temperatures during (a) 20g and (b) 30g tests. The second axis shows the time and the temperature at the prototype scale. In the physical model time scale as $1/N^2$ and temperature as $1/N^0$.

In both tests, the air temperature dropped rapidly from an initial 10°C to -5°C , gradually reaching -10°C , within 1 hour in the 20g test and 2.5 h in the 30g test. The temperature of the soil decreased more slowly, reaching a range between -5°C and 5°C at the end of the freezing phase. The frozen front (corresponding to a temperature of 0°C) extended to a depth between 30 mm and the surface in both tests. The thawing phase was performed only in the 30g test and lasted 1 hour. During this time, the air temperature increased rapidly, while the soil surface, due to its higher thermal inertia, reached temperatures above 0°C only at the end of the thawing phase.

3 ANALYTICAL MODEL

3.1 Calculation steps

The experimental results were interpreted using the closed-form equation introduced by Landanyi and Foriero (1988), which provides a framework for predicting the evolution of adfreeze forces acting on pile foundations. The model relates the mobilised adfreeze stress $\tau_{a,i}$ along the pile shaft to the corresponding frost heave rate s'_i through a temperature dependent creep shear modulus $\tau_{c,\theta i}$. The equation is based on the creep theory for frozen soils developed by Johnston and Landanyi (1972), originally formulated to interpret the behaviour of grouted rod anchors installed in permafrost. Indeed, when ground temperatures are only a few degrees below the melting point of ice, the presence of unfrozen water content and the weakness of ice bonds promote excessive creeps. Under these conditions, frozen soil failure is typically governed by ductile plastic deformation rather than by the formation of distinct strain discontinuities (Sayles & Haines, 1974). The relationship of the mobilised adfreeze stress is expressed as:

$$\tau_{a,i} = \tau_{c,\theta i} \left(\frac{n-1}{\gamma'_c} \right)^{\frac{1}{n}} \left(\frac{s'_i(t)}{a} \right)^{\frac{1}{n}} \quad (1)$$

where a is the pile radius, n is the creep exponent and γ'_c is a reference shear strain rate. The effect of temperature on the creep behaviour of frozen soil is incorporated in the creep modulus $\tau_{c,\theta i}$ through empirical formulations. Among the several models proposed by Landanyi (1972), the following power law relationship is adopted in this work:

$$\tau_{c,\theta i} = \sigma_{c0} \left(1 + \frac{|\theta_i|}{\theta_0} \right)^w \quad (2)$$

where $\theta_0 = 1^\circ\text{C}$, θ_i is the temperature at the pile depth i , w is the experimental temperature exponent and σ_{c0} is the general creep modulus. The parameters used in Eqs. (1) and (2) are listed in Table 1, based on literature data for very ice-rich soils (Andersland and Landanyi, 1994, Tab. 5.3). Given a time-dependent evolution of surface temperature $T_s(t)$, the frost penetration x_0 can be estimated using the Modified Berggren formula developed by Aldrich and Paynter (1966). This expression corrects the classical Stefan solution by introducing a correction factor λ , under the assumption that the latent heat L of soil moisture is the primary source of released energy as temperatures fall to or below freezing point:

$$x_0 = \lambda \sqrt{\frac{2k_{av}}{L} I_{sf}} \quad (3)$$

In Eq. (3), I_{sf} is the freezing index obtained by integrating the surface temperature over the freezing period and $k_{av} = 0.5(k_f + k_{th})$ is the average thermal conductivity of frozen “f” ($k_f = 2.35 \text{ W/m/K}$) and thawed “th” ($k_{th} = 1.71 \text{ W/m/K}$) soil evaluated as reported in Eq. (4):

$$k_{f/th} = k_s(1 - \phi) + k_{ice/w}\phi \quad (4)$$

where $k_s = 2.5$ W/m/K, $k_{ice} = 2.14$ W/m/K and $k_w = 0.6$ W/m/K are the thermal conductivities of solid grains, ice and liquid water and $\phi = 0.41$ is the porosity ($e = 0.7$).

Table 1. Model Parameters at the prototype scale.

Parameter	20g	30g	Unit
k_{av}	2.62	2.62	W/m/K
c_v	3.53	3.53	MJ/m ³ /K
L	334	334	MJ/m ³
I_{sf}	174	188	°C day
t	48	120	days
α	2.74	6.38	–
μ	0.04	0.02	–
λ	0.78	0.75	–
σ_{c0}	103	103	kPa
γ'_c	9×10^{-5}	9×10^{-5}	1/h
n	3.0	3.0	–
w	0.37	0.37	–

The correction coefficient λ is obtained from the abacus in Fig. 4 (after Anderland & Landanyi, 1994), as a function of two dimensionless parameters:

- Thermal ratio $\alpha = v_0 t / I_{sf}$, where v_0 is the initial undisturbed temperature of the subsoil ($= 10^\circ\text{C}$), I_{sf} is the freezing index already defined on Eq. (3) and t the freezing duration.
- Fusion parameter $\mu = c_v I_{sf} / (Lt)$, where c_v is the soil volumetric heat capacity, calculated as the average between the frozen, ($c_{v,f} = 2.66$ MJ/m³/K) and thawed ($c_{v,th} = 4.41$ MJ/m³/K) conditions. The individual values are estimated as a composition of the volumetric heat capacities of the different phases, similarly to Eq. (4), considering c_v equal to 2.16 MJ/m³/K and 2.60 MJ/m³/K, for sand and clay, and to 1.93 MJ/m³/K and 4.19 MJ/m³/K for ice and liquid water, respectively.

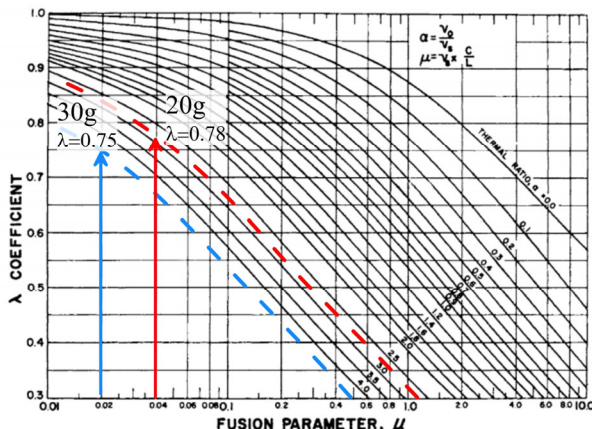


Figure 4. a) Evaluation of the correction coefficient λ in the modified Berggren equation (after Anderland & Landanyi, 1994, p.71).

Once the frost penetration depth is known, the frost heave can be evaluated as a fraction of that depth according to Eq. (5):

$$s = Kx_0 \quad (5)$$

where K is a proportional parameter which depends on the type of soil and site-specific conditions. The distribution of temperature, frost heave and frost heave rate with depth are assumed to vary linearly from the surface to the frost penetration depth.

3.2 Model vs Prediction

The model of Landanyi and Foriero (1988) was applied to the results of the centrifuge tests at prototype scale. An average value of the temperature at the soil surface, measured by the two thermometric rods installed in each box, was used to evaluate the surface freezing index I_{sf} during the examined freezing period t .

Fig. 5 shows the resulting frost penetration (evaluated according to Eq. (3) for the 20g and 30g tests. A direct comparison with monitored data was not possible because the first temperature sensor was located at 30 mm depth and its temperature did not clearly drop below zero degrees during the tests. Even if with a different rate, frost penetration achieved similar depths among the two tests at prototype scale.

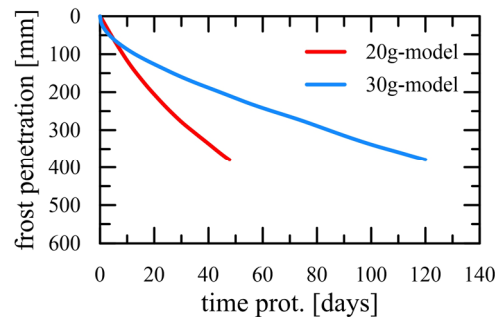


Figure 5. Prediction of frost penetration on 20g and 30g tests at prototype scale.

Fig. 6 reports the evolution of frost heave at the prototype scale for both centrifuge tests obtained by the frost penetration trend. The parameter K in Eq. (5) was calibrated in two different ways: (i) by best fitting the entire curve and (ii) by matching the ultimate value of displacement. For the 20g test, both methods yielded the same value as $K=0.40$. In contrast, for the 30g test, where the frost heave trend at the soil surface is less uniform and its shape deviates from the predicted model, the two approaches provided different results. When calibrating K based on the ultimate displacement, the value obtained ($K=0.4$) is the same as that of the 20g test; on the other hand, the best-fit calibration resulted in a lower K value of 0.31.

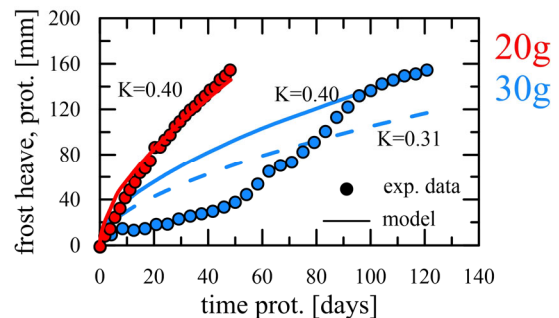


Figure 6. Frost heave: predicted vs data (at prototype scale).

3.3 Adfreezing shear stress and uplift force

A simple Matlab® code was developed to evaluate tangential stresses and the overall uplifted force acting on the pile as a result of soil frost heave. Fig. 8 shows the distribution of adfreeze tangential stress along the pile depth at different instants of time, according to Eq. (1) and the parameters listed in Tab.1. The adfreeze tangential stress develops along the pile-soil interface due to the relative displacement between the frost-heaving soil and the pile shaft. Because tangential stress depends on the rate at which the frozen soil “drags” the pile via adfreeze bonding (Eq.1), its magnitude is directly related to both the frost heave rate and to the creep modulus of the frozen soil-pile interface. Consequently, stresses are highest at the pile head, where the heave rate is maximum, and decrease with depth, reaching zero at the frost penetration front, where no displacement occurs. At the surface, the frozen soil is able to sustain non-zero tangential stresses because the adfreeze bonding imparts an effective cohesion. Average tangential adfreeze stresses are greater in the 20g test, consistent with its higher frost heave rate (slope of the curve in Fig. 7) compared to the 30g test. The time instants reported in Fig. 8 correspond to three equally spaced points within the freezing stage at prototype scale: 30, 60 and 90 days for 30g test and 13, 27 and 40 days for 20g test. The calculated stresses, on the order of hundreds of kPa, are higher than the shaft resistance mobilised in the unfrozen soil layer for piles that experienced uplift.

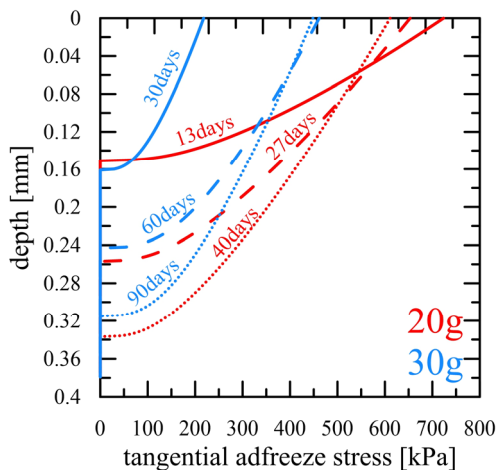


Figure 7. Tangential adfreeze stress along the pile shaft at different time instants for the 20g and 30g tests.

By integrating the tangential adfreeze stress along the frozen portion of the pile shaft, the uplift force induced by soil frost heave was calculated. Fig. 9 shows the time evolution of the predicted uplift force for the two tests, based on a no-slip assumption at the pile-soil interface. The calculation accounts for the non-circular pile cross section by using its actual perimeter, which, assuming a wall thickness of 1 mm, equals $24(xN)$ mm. The irregular trend of the plots reflects the experimental scatter nature of the temperature measurements, on which the creep modulus values (Eq. 2) are based. Pile uplift occurs when this force exceeds both the shaft resistance mobilised in the lower unfrozen portion of the pile and the pile’s self-weight.

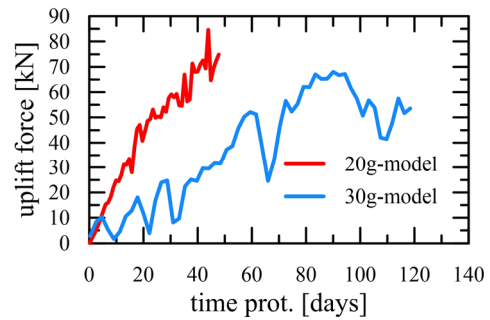


Figure 8. Time evolution of the uplift force generated by soil frost heave.

4 CONCLUSION

This study represents one of the first centrifuge experimental investigations addressing frost jacking phenomena on solar panel pile foundations. Remarkably, the reduced-scale model successfully reproduced the expected mechanical response of the pile-soil system under freezing conditions, despite the absence of previous experimental work of this kind reported in literature. The adopted vortex-based freezing system effectively froze the soil, inducing frost heave and multiple pile uplifts. Furthermore, the insulation mantels used as a mitigation strategy against frost jacking performed well, highlighting the promising effectiveness of the approach, which still warrants further investigation. During the subsequent thawing phase, the soil largely recovered its upward displacement, in some cases even exhibiting minor settlements, whereas piles which displaced under freezing did not fully return to their initial position and remained slightly uplifted. This behaviour can be explained by the loss of tangential adfreeze stresses once the soil thawed: while these stresses had previously exceeded the shaft bearing capacity and generated uplift, their disappearance left the residual shaft resistance preventing the soil-pile system from completely reverting to its original state.

The application of the closed-form solution by Landanyi and Foriero proved to be a valuable tool to interpret the measured adfreeze stresses on pile shaft. The results clearly showed that the highest tangential stresses are mobilised where the frost heave rate is greatest, in agreement with field observations and previous studies. The integrated uplift forces obtained from the predicted distribution of the tangential adfreeze stress were of the same order of magnitude as values reported in the literature for similar soil type and thermal loads (e.g., Ottawa site after Landanyi and Foriero, 1988).

Future work will build on these results by predicting the evolution of soil resistance in the unfrozen portion of the pile and coupling these observations with a thermo-mechanical numerical model capable of capturing the coupled processes of heat transfer, phase change, and soil-pile interaction, in order to further validate and generalize the conclusions drawn from the present centrifuge campaign.

5 ACKNOWLEDGEMENTS

The authors acknowledge GEOLAB facilities access (<https://project-geolab.eu/>), enabling free-of-charge 2-weeks of centrifuge tests at the Schofield Centre of the University of Cambridge. The GEOLAB project has received funding from the European Unions Horizon 2020 research and innovation programme under Grant Agreement No. 101006512. In addition, the authors acknowledge Dr. Ahmed Alagha and the technicians of the Schofield Centre who supported the design and the setup of the tests.

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