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Experimental study of the frost heave mechanism of solar panel piled foundations in scaled centrifuge models

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ABSTRACT: The increasing demand for clean energy and the pursuit of more efficient systems have led to the establishment of solar panel fields in cold regions. However, prolonged periods with sub-zero temperatures may result in frost heave of the soil, which can in turn generate the uplift of deep foundations by frost jacking and compromise the functionality of the superstructure system. This work investigates the uplift mechanism induced by the frost-heaving phenomena on solar panel pile foundations, typically consisting of individual short driven steel piles, and explores possible mitigation interventions. Two centrifuge tests at an increased gravity of 20*g* and 30*g* were carried out in the geotechnical centrifuge of the Schofield Centre of the University of Cambridge (GEOLAB FROSPER project). They reproduced cold climate by freezing and thawing cycles on different reduced-scale models of solar panel foundations (single piles and connected pile groups). The samples consisted of a saturated clay-sand mixture susceptible to frost heave, comprising 80% Houston Sand and 20% Speswhite Kaolin. The monitoring data collected during the centrifuge tests, including temperatures and displacements of the surface of the soil and the head of the piles, revealed freezing of the shallowest layer of soils and heaving of both the ground and the piles. The settlement of the piles on thawing was always smaller than the heave recorded on freezing, whereas the settlement of the soil surface during thawing was slightly larger than the original heave, resulting in a net uplift of the piles relative to the soil surface on a cycle of freezing and thawing.

1 INTRODUCTION

Carbon neutrality is a short-term climate mitigation strategy focused on limiting the rise in global mean temperature (COP 21, 2015). To meet the net zero target, efficient systems for clean energy production need to be implemented. Deploying solar panels in cold regions is one potential solution to meet the growing demand for clean energy. Environmental temperatures lower than 25°C enhance electricity production from solar radiation (Mussard, 2017). Additionally, large unpaved areas are available in cold regions for installing solar panel fields. The drawback is the extended periods of temperatures below zero degrees. Soils under freezing temperatures may exhibit varying susceptibility to volume expansion and frost heave, depending on their fine content, water availability and freezing rate (Casagrande, 1923). As freezing temperatures penetrate frost-susceptible soils, the soil frost heave may trigger uplift mechanisms of pile foundation (Penner, 1969). This phenomenon, also called pile frost jacking (Liu, 2020), is particularly evident for lightly loaded steel piles such as those of solar panel foundations, compromising the efficiency and functionality of the system (Pagliani *et al.,* 2022, Wang *et al.,* 2022).

The aim of GEOLAB FROSPER project was to investigate the interaction between soil frost heave phenomena and solar panel pile foundations during cold seasons. The pile frost jacking phenomena was reproduced in a geotechnical centrifuge on reduced scaled models at two different levels of increased gravity. In particular, the dependence of the magnitude of pile frost jacking on soil composition, thermal load, pile length, and configuration was explored. Surface-insulating mantels were assessed as a potential mitigation measure against pile uplifting. All the raw experimental data collected during the two centrifuge tests are open-source (Guida *et al.*, 2023).

2 EXPERIMENTAL CAMPAIGN

The two centrifuge tests were conducted at the geotechnical centrifuge of the Schofield Centre of the University of Cambridge with an increased gravity of *N*g, where *N*=20 and 30, respectively. A mixture of Houston sand (80%) and Speswhite kaolin (20%) was chosen as a model frost susceptible soil. The piles were modelled using machined aluminium profiles with 6 mm side H-section and three different lengths of 100 mm, 125 mm, and 150 mm at 20*g* and 67 mm, 83 mm, and 100 mm at 30*g* to replicate 2 m, 2.5 m and 3 m at prototype scale. The beam connecting pile groups was modelled using an aluminium profile with a 8 mm by 1.5 mm rectangular section and a length of 150 mm. The mitigation measure consisted of a 40 mm square polystyrene mantel, 10 mm thick, placed on the soil surface around the pile head.

Linear Variable Displacement Transformers (LVDT) were used to measure the vertical displacements of the heads of the piles and of the soil surface. Temperatures were monitored using PT100 sensors fixed on a steel bar at different heights: in the air above the soil, at the soil surface away from the piles, and at depths of 30 mm, 60 mm, and 120 mm. Two thermometric rods were installed in each box.

Cold air was applied at ground surface with a vortex tube system, which generates cold air, subdividing the forced compressed air into a cold and hot flux through a generation chamber, spinning the air at a high rate of speed (1,000,000 rpm) into a vortex.

As shown in Figure 1, the models were prepared in two cylindrical PMMA (polymethylmethacrylate) boxes, each 340 mm high and with a diameter of 190 mm. A permeable hole at the base allowed water drainage. The two cylinders were tested together, placing them in another cylindrical strong box with a diameter of 850 mm, which could be hosted on the swing of the centrifuge.

Box 1 contained two rows of three connected piles of the same length (Figure 1a), immersed in a heterogeneous soil profile (Figure 1c) composed by a pocket of pure Houston sand, acting as a non-frost-heave-susceptible soil, realized in the initially homogeneous clayey sand mixture. Box 2 contained five isolated piles with different lengths (Figure 1b, d) immersed in the homogeneous clayey sand mixture.

A polystyrene mantel was placed to protect all piles of one of the pile groups in Box 1, and one of the single piles in Box 2.

The boxes were insulated laterally with rock wool, placed between the boxes and the cylindrical tub, and hydraulically connected to a standpipe that provided the water supply.

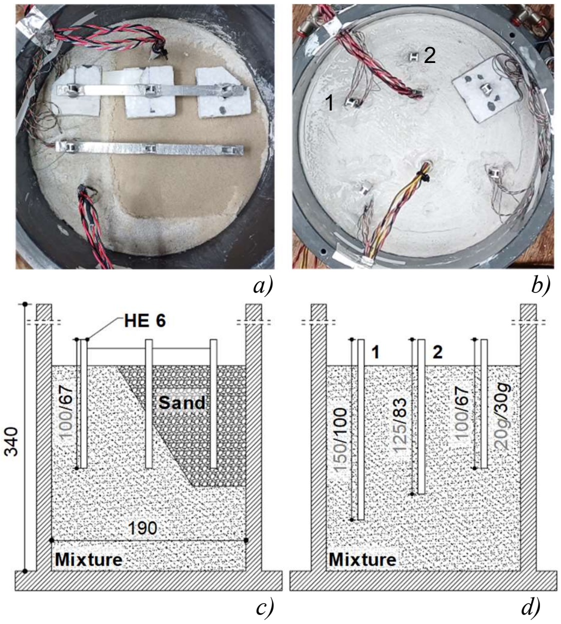

Figure 1: Experimental setup: a-b) plan view of box 1and 2, c-d) vertical section of box 1 and 2. (The label 1 and 2 identify the two reference piles cited in the results).

3 TEST PROCEDURE

The soil samples were prepared in two layers of approximately 100 mm, each obtained by consolidating a slurry mixture of sand and kaolin. The slurry preparation consisted of dry mixing 9.6 kg of sand with 2.4 kg of kaolin for 5 minutes, then adding 6 litres of water and continuing mixing for half an hour. The single layer was obtained by pouring 7.5 litres of slurry in each box and consolidating at a total vertical stress of 70 kPa for 24 hours to achieve a void ratio e = 0.7, starting from an initial void ratio $e_0 \cong 1.2$. The load was applied gradually at a rate of 0.004 kPa/s to prevent slurry from squeezing from the top. Figure 2 illustrates the typical evolution of the void ratio with applied vertical stress during the consolidation of one layer.

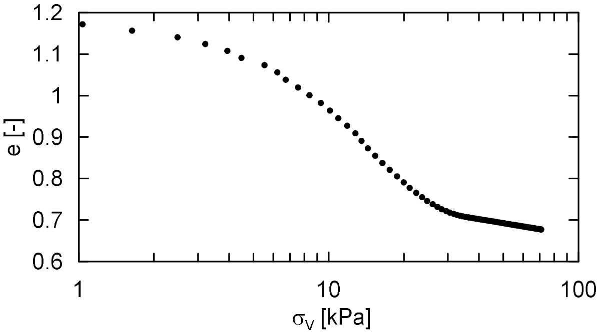

Figure 2: Void ratio evolution during the consolidation

The sand pocket in the heterogenous layout (Figure 1c) was realised after consolidation of the clay-sand mix by substituting a portion of the mixture with hand-compacted saturated sand. The piles were finally hand-driven in the model at 1*g* according to the configurations shown in Figure 1.

The centrifuges tests consisted of the following phases:

- Swing-up: The models were accelerated up to the target increased gravity *N*g (in 5 minutes at 20g and 10 minutes at 30g), and settlements were left to stabilise. This lasted 10 and 17 minutes at 20g and 30g, respectively.
- Freezing phase: obtained by activating the vortex tube by injecting compressed air at 6 bar. The duration of this phase depended on the achievement of the expected effects.
- Thawing phase: obtained by turning off the vortex tube for approximately 1 hour. During this phase, the temperatures inside the model rose above 0°C. The thawing phase was only performed in flight for the test at 30*g*.
- Swing down to 1*g*.

4 EXPERIMENTAL RESULTS

Figure 3a shows the evolution with time of the measured temperature at different depths for 30*g* test. According to the scaling laws, a 6-hour freezing phase corresponds to a cold season of about 7 months at this level of increased gravity. The measured air temperature dropped rapidly from 15°C to -5°C, gradually approaching -10°C afterwards. In contrast, the temperature of the soil decreased more slowly, starting from an average value of 13 °C and reaching a range between -2.5°C and 7°C at the end of the freezing phase. The frozen front reached a maximum depth of 23 mm, corresponding to 0.7 m in the prototype scale.

The thawing phase lasted 1 hour, during which the air temperature quickly rose, while the soil surface temperature, characterised by a higher thermal inertia, became greater than 0 °C only after one hour.

Figure 3b shows the evolution of the vertical displacements of the soil surface with time at an increased gravity of 20*g* and 30*g*. Positive values of vertical displacement correspond to surface heave. The subscript „p“ indicates the prototype scales.

In both experiments, the soil surface started heaving when the freezing front had penetrated a depth of ~10 mm. This occurred after about 1 hour in the test at 20*g* and after about 2.5 hours at 30*g*. The maximum recorded vertical displacements were 7.75 mm and 5.2 mm at 20*g* and 30*g*, respectively. The corresponding displacements at the prototype scale, are 155 mm at 20*g* and 156 mm at 30*g*.

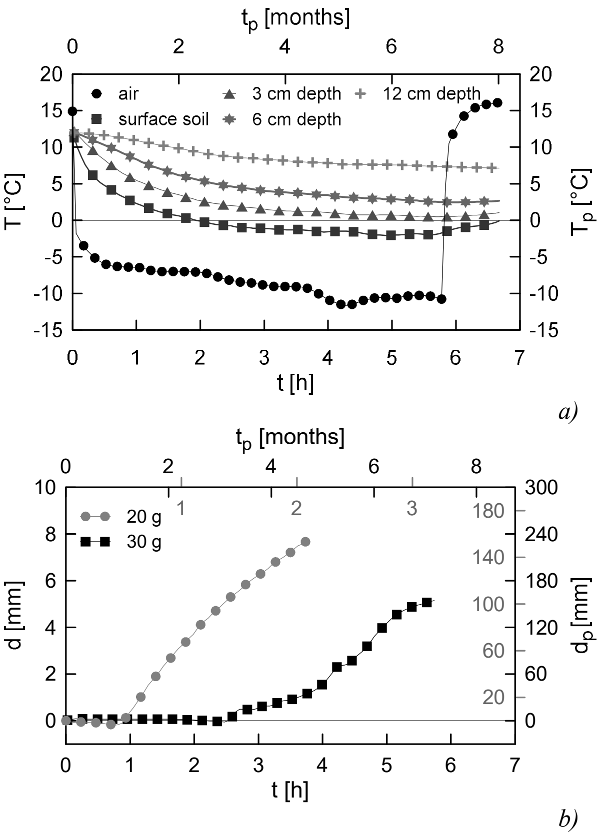

Figure 3: a) Temperature evolution with time at 30 g, b) Surface displacement with time during the freezing phase

Figure 4a compares the vertical displacements of the soil surface and the pile's heads measured in the test at 30*g*. The piles exhibited a delayed and limited heave compared to the soil surface, 3.5 mm and 2 mm for Pile 1 (100 mm length) and 2 (83 mm length), respectively. Indeed, the frost-jacking actions need to overcome the self-weight and the lateral resistance in the bottom anchored portion of the pile.

On thawing, the settlement of the soil surface was slightly larger than the heave on freezing, with a final cumulated settlement of 0.6 mm. In contrast, the settlements of Pile 1 and Pile 2 during thawing were smaller than the heave during freezing, with a residual heave of 2.3 mm and 1.4 mm, respectively, corresponding to a net heave relative to the soil surface of 2.9 mm and 1.7 mm. The insulation mantel effectively mitigated the effects of freezing and thawing, as the protected piles showed negligible displacements throughout.

Figure 4b shows the time evolution of the displacements of the pile groups recorded in the experiment at 30*g*. The pile embedded in the mixture heaved by 1 mm (Figure 1c), while those installed in the sandy layer and the piles with the insulation mantel showed negligible displacements.

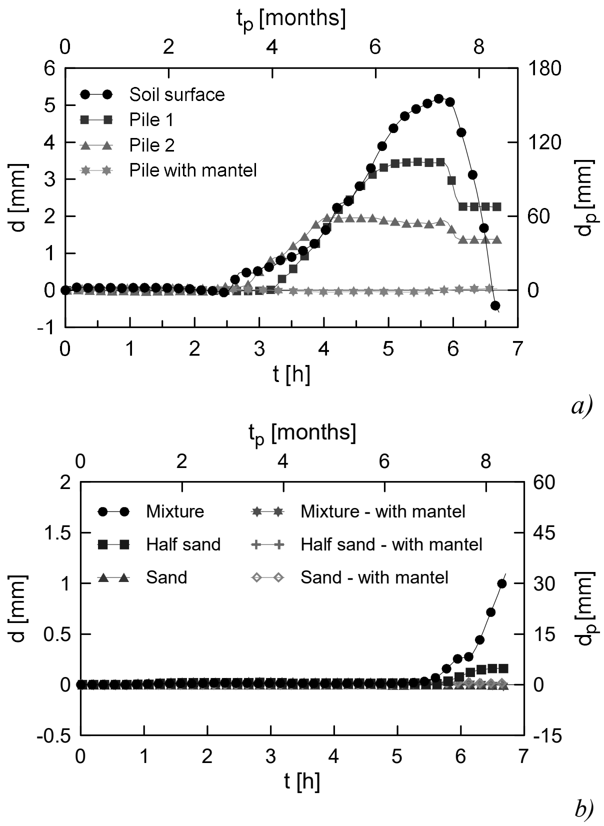

Figure 4: a) Displacement evolution with time of piles and soil surface at 30g, b) Piles group displacement with time at 30g.

5 CONCLUSIONS

The centrifuge tests successfully replicated the phenomenon of frost jacking for piled foundations of light structures. Freezing was induced using a simple vortex system powered by 6-bar air pressure. The piles began to uplift only after the soil surface started heaving. The piles remained irreversibly uplifted during thawing, while the soil surface recovered all the heaving displacements. The adopted insulating mantels effectively served as a mitigation intervention.

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