INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics
© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5

Process for physical modelling of single pile capacity in thawing ground

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ABSTRACT: Northern climates possess an increased complexity in soil-foundation interactions compared to temperate regions. The continuous and discontinuous permafrost that varies throughout the arctic has a crucial role in pile foundation design. The uncertain quality of frozen soil, and its interaction with an ad-freeze steel pile provides a strong motive to further understand the strengths and bearing capacities of foundations in frozen soil. Centrifuge modelling was used to measure in-situ forces acting on a steel ad-freeze pile in both temperate never frozen soil, and frozen soil. The model pile was designed to recreate the soil-structure interface of ad-freeze piles used in permafrost region foundations. The model piles were tested under a strain controlled, monotonic loading. Results quantify the varying ability of a steel pile to sustain loads in both dry and saturated never frozen temperate soils, as well frozen and thawing soil.

Keywords: centrifuge modelling, pile foundation, ad-freeze, permafrost

1 INTRODUCTION AND BACKGROUND

Permafrost is the term applied to ground that remains frozen (below 0 oC) continuously for at least two years (Dobinski 2011). An active layer, which thaws annually, will vary in thickness with the season and the latitudinal location.

Arctic infrastructure supported on pile foundations are directly dependent on the temperature and the strength of the ice bonds in the frozen soil known as the adfreeze strength. Historic infrastructure foundations in the Arctic were designed assuming perpetually frozen ground and may have lacked scope which included future planning for thawed conditions. Recent temperature data from the Intergovernmental Panel on Climate Change (IPCC) indicate a rise in global mean annual air temperatures, as well a decrease in snow depth and the extent of ground covered by ice (Bernstein, et al. 2007). In the last 50 years the temperatures have risen 3-4 ºC (Hassol and Correl 2006). This increase in air temperature has a direct impact on the ground temperatures in sensitive climate regions such as the Arctic (Sazonova 2003)

Permafrost degradation presents a challenge to Arctic infrastructure and is important to understand to prevent long term economic, environmental, and anthropogenic challenges. The Inuvik to Tuktoyaktuk Highway (ITH) is an all-season highway in Canada which stretches 138 km from Inuvik to Tuktoyaktuk, Northwest Territories. Steel piles have been modelled has been extensively modelled in centrifuges before, for example (Schofield 1980), (Garnier, et al. 2007) , (Li, Haigh and Bolton 2010), (Lundberg, Dijkstra and Van Tol 2012). Steel Piles have been modeled in physical ground quite extensively at 1 G in the field or on the lab floor, for example (Hutchinson 1989), (Adlaeef and Rayhani 2017) (weaver and Morgenstern 1988), and (Nidowicz and Shur 1998). There is also some research that focuses on frozen ground engineering applications in the centrifuge (Nadeau 2019), (Kern-Leutschg and Harris 2008), (Smith 2004). It has been identified that no testing of piles in frozen exists for scaled centrifuge modelling.

A knowledge gap was identified in the assumptions of adfreeze bond strength of frozen soil as well as timing for remediation works for constructed infrastructure. An experimental modelling program was undertaken to investigate pile-soil interaction in warming permafrost and increasing active layer thickness.

2 EXPERIMENTAL SETUP

Pile foundations provide support to the superstructure by mobilizing resistance along the length of the pile shaft, as well as bearing resistance at the pile end. Owing to the relatively small size of the RMC centrifuge it was important to consider the limitations present with the available model geometry and effective radius possible within the centrifuge. Piles are generally a deep foundation with length to diameter ratios typically in excess of 30. In a small centrifuge it is important to maximize this ratio, using the scaling laws to scale a real-world pile foundation into an idealized model pile.

2.1 RMC Centrifuge

For this research a Broadbent Ltd. GT6 small arm beam centrifuge with a diameter of 1.5 m was used. The RMC centrifuge has a maximum soil payload of 20 kg, at an operational radius of 0.750 m, making this a 9 G-tonne centrifuge. The maximum rotational speed of the GT6 is 638 RPM, corresponding to N = 300 g. A velocity of 284 rpm was selected for these experiment, or N = 60 g. While the RMC centrifuge is rated for N = 300 g, the axial loading mechanism used (2D Actuator) was rated for 100 G at 0.660 m effective radius.

The physical model was constructed within an aluminum swing-bucket with internal dimensions: 300 mm long, 100 mm wide, and 150 mm tall. The geometry of the model setup allowed for a maximum soil heigh of 130 mm. The similitude laws for centrifuge modeling adopted in this study are scaling factors of Ng for model dimensions and displacement, and N^2g for load. Temperature, stress and strain scale 1:1 between model and prototype.

2.2 Model pile and 2D-actuator

In order to accommodate the scaling laws of modelling a deep foundation in a small centrifuge the model pile dimensions were determined to be: 100 mm in length, and 6 mm in diameter. The resulting L/D ratio for this model pile is 16.6, which is greater than 15 therefore satisfies the necessary scaling conflict for modelling piles in a small centrifuge.

The loading mechanism of the pile was a displacement controlled 2D-actuator shown in Fig. 1. The velocity, acceleration, and amount of displacement were required for loading to begin. The pile displacement was measured with a Balluff BIL0004 which was fitted as part of the 2D actuator assembly. This is a magnetic field sensor instrument built into the 2-D Actuator device. A high precision miniature HBM-UC9 1 kN load cell was secured in line with the 2-D Actuator to record the amount of axial load resistance in the pile-soil interface.

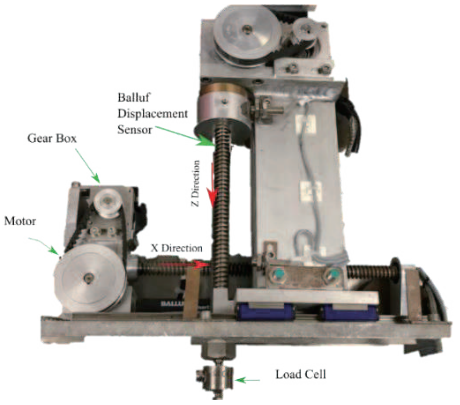

Fig. 1: Picture of the 2D-actuator at RMC

2.3 Thermal measurements

One of the focuses of the research project was the thermal regime of the soil, which necessitated measurement of temperature distribution. Custom built thermistor beads were placed at specific locations to map the model's thermal profile. Soil temperatures in the model were recorded for a long period of time (1-2 hours) to observe the warming of frozen ground process. Temperatures were recorded at the discreet time locations of when a pile was axially loaded to determine the temperature effect of the loading capacity. A 1.5 cm thick layer of insulation was installed along the aluminum surface of the container to reduce the thawing rate

2.4 Material characterization

The material used in this research is referred to as RMC Sand, and was readily available at RMC (Hatami and Bathurst 2005). Hatami & Bathurst characterized the soil to be a uniform rounded beach sand with low fines content. They report friction angle of 40 degrees based on triaxial tests, for unit weight values of approximately 17 kN/m^3.

New characterization was done to confirm the gradation of the soil, for the sample used. The diameter of the pile must satisfy the D/D50 ratio that was defined for geotechnical centrifuge modelling. A wet sieve was conducted to quantify the gradation of the soil. The D_{50} was determined to be 0.24 mm. The D/D_{50} ratio for a 6 mm pile is 25, which satisfies the minimum requirement to maintain the assumption of the soil continuum around a model pile.

3 TEST PROCEDURE

A 3-D printed sand hopper was used to evenly distribute the sand across the model by pluviating sand through a slit which spanned the width of the container. The hopper was manually moved back and forth creating layers approximately 5 mm thick.

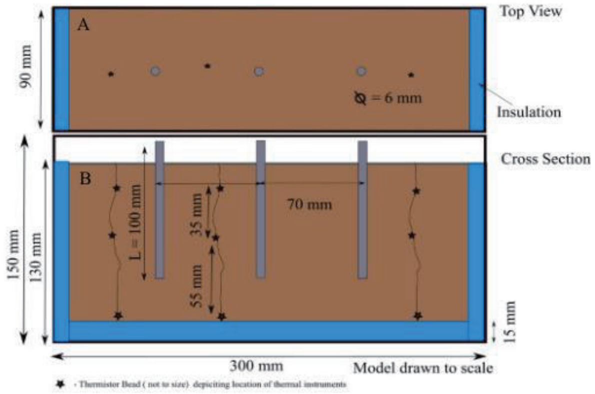

Fig. 2: A) Plan view sketch of physical Model B) cross section sketch of physical model

Once the sand was backfilled to the desired model height, a CO_2 saturation was conducted. This process successfully removed any air bubbles in the voids, which could not be dissolved in water. Immediately following the CO_2 saturation, the model was fully saturated with de-aired water (H_2O) from the base of the model upward.

The piles were then placed inside the model along the centreline of the container. A stickup height of approximately 20 mm was used, and the piles were distanced by 70 mm to avoid interaction between the loading of adjacent piles, as well as any boundary effects from the model container. The benefit to loading two or three piles under the same conditions was gave confidence in the repeatability of the test when the results showed the same behaviour within the same test model. The alternative was to allow varying thaw periods to assess the effect the change in temperature had on the strength of the pile. For frozen test samples, the model container was placed in a freezer immediately following pile placement and allowed to freeze for a minimum of 12 hours.

The tests were performed over the course of an hour or more, depending on whether frozen tests were conducted. Never frozen tests were completed within half an hour including spin up, and spin down. Frozen tests were allowed to thaw in-flight, and for extensively warmed models this sometimes lasted several hours. Data was recorded at 10 Hz for most tests.

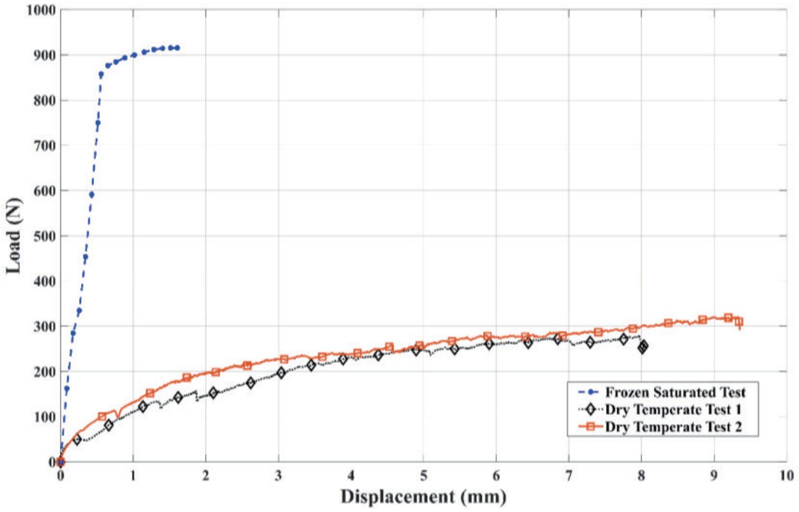

Fig. 3 Load vs displacement for dry-temperate sand and frozen saturated sand

4 SIGNAL PROCESSING OF TEST DATA

Upon completion of a centrifuge test, the data stored in the on-board DAS was extracted as a .dat file and uploaded into a numerical processing program; in this case Matlab. The raw data was calibrated and filtered to remove signal noise using signal processing.

A butterworth filter was used to eliminate signal noise, by analyzing the signal frequency components using a fast fourier transform (fft), which is a built-in signal processing function in Matlab. The load and temperature data produced results with high-precision and a low signal-to-noise ratio, and therefore did not need to be filtered; however, the displacement data collected from the Balluff BIL displacement sensor was filtered to remove the observed noise.

5 TEST RESULTS

The first two centrifuge tests were conducted at the temperate and dry state shown in Fig. 3. All results are presented at model scale. These individual piles were embedded 8 cm into an air-dried temperate sand (21ºC). For the two tests shown at the dry temperate state an initial stiff response softens until maximum load is achieved at maximum displacement. Consistent results from repeat tests show the range of maximum load is 277-310 N, at model scale.

The results observed in the dry temperate tests resemble the stress strain of a loose sand, gradually trending toward the peak states. The first dry-loose test (Dry test 1) experienced a peak load of 310 N at 9 mm displacement, and a yield load of about 175 N at 2 mm. The second dry-loose test experienced a peak load of 277 kN 8 mm. The yield strength of this test is approximately 150 N at 2.5 mm. The results in the saturated temperate tests show similar peak strengths with much less displacement, resembling stress strain results of a dense soil, displaying a more peaked yield point, where the loading transitions from elastic to inelastic deformation, continuing to increase to the ultimate state, before trending toward the constant volume state.

Table 1. Model poperties and tst rsults

Test	Dry Unit Weight (kN/m^3)	Porosity	Ultimate Load (N)	Displacement at ultimate Load (mm)
Dry-1	16.2	0.338	310	8.76
Dry-2	16.1	0.344	277	7.98
Frozen 1	15.9	0.350	910	1.5

The soil state parameters for the two axially loaded pile tests shown in table 1 are internally consistent with the soil state parameters for the tests prepared using the same methodology. The repeatability in the preparation of the model, and the similarities in the load displacement response for piles loaded under the same conditions demonstrate the effectiveness of this testing procedure. Also shown in Figure 3 is the load vs displacement response for a pile axially loaded in frozen ground. At nearly comparable porosity, the frozen test showed an ultimate resistance 3x times higher than the temperate tests.

6 DISCUSSION

The experimental results were compared to theoretical pile capacity design for frozen ground as well as non-frozen pile capacity. The non-frozen pile capacity was compared to best practices using the beta method, as outlined in the Canadian Foundation Engineering Manual (CFEM, 2010). For the non-frozen tests (those measured at +22 degrees Celsius), a back analysis was performed using the applied ultimate load capacities, scaled to prototype. With a scaled ultimate load, pile radius, and length, the beta value, which is an empirical coefficient relating the vertical stress and bearing capacity, can be back calculated. For the experimental ultimate loads, the corresponding beta values were calculated between 0.45 to 0.65. These correspond to the approximate range of values for the soil characteristics used in the experimental model, when compared to design tables in CFEM indicating that the experimental results for temperate tests match well with design guidelines that use a beta-method approach.

For the frozen pile analysis, the ultimate load capacities can be translated into a shaft resistance, as shear strength. These shear strengths are analogous to the adfreeze bone strength for frozen pile design. For the temperatures tested in the experimental program, the soil-pile interface shear strengths are approximately 1.5 to 2x the maximum adfreeze bone strength reported by available frozen pile design charts (Weaver and Morgenstren, 1981), however those design charts are limited in the lowest temperature reported which is minus 4 degrees Celsius. Both the frozen test results and the non-frozen test results are shown as ultimate load capacity at varying test temperatures across the frozen to non-frozen spectrum.

7 CONCLUSIONS

The methods and materials used in these experiments were able to effectively model a single steel pile in varying ground conditions inside the centrifuge. Steel piles axially loaded in frozen ground has not been modeled in a centrifuge before, it was important to establish the required materials and methodology for a pile experiment in the centrifuge at a temperate state first. Once the methodology was shown to be successful the process was applied to the application of frozen ground. The goal for this research was to expand the understanding and capabilities of steel piles axially loaded in frozen ground. The extreme difference in load capacity for frozen piles compared to the same pile in a temperate state can be attributed to the high strength parameters of the pile-frozen soil interface.

The piles loaded in both temperate dry and frozen conditions displayed results consistent with values established through the design limit states provided by the foundation guide for geotechnical engineers in Canada. The beta method for piles in temperate ground show consistent estimates with these results and the piles shaft ad-freeze resistance estimates based on temperature for the test performed in frozen soil. The load capacities for piles in varying amounts of cold and warming frozen ground will continue to be analyzed through physical modelling in the centrifuge. The goal will be to quantify the effect the warming ground temperature has on the strength of the pile.

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