Physical Modelling in Geotechnics

Scaled modelling of frost heave of small piles in centrifuge tests

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ABSTRACT: Foundations for solar arrays present unique design challenges, with large numbers of small, closely spaced piles. Since the piles are relatively short, near surface climatic effects, such as seasonal ground freezing, can lead to heaving and structural fatigue of the piles. A range of candidate remedial foundation measures have been proposed, however many of these still require to be assessed. This is being addressed in a study incorporating geotechnical centrifuge modelling. Prior to conducting physical model tests incorporating piles and remedial measures, it is first necessary to ensure that modelling techniques developed to simulate seasonal ground freezing replicate prototype conditions appropriately. The results from a previously reported study of highly instrumented, one-dimensional freezing centrifuge tests (Yang, 1997) have been evaluated using both analytical methods and numerical modelling (using PLAXIS). Predictions of the rate of frost penetration and frost heave for the range of boundary conditions applied in the centrifuge tests during freezing were used to validate the predictive models, allowing the optimization of the design of centrifuge tests on model piles.

Keywords: Piles, frozen ground, centrifuge modelling, finite element model.

1 INTRODUCTION

Foundations for solar power plants often utilize large numbers of small, closely spaced piles. These foundations have relatively low vertical loads and can be subjected to high uplift and horizontal/moment loads from environmental agents. Since the piles are relatively short, near surface climatic effects, such as seasonal ground freezing and wind loading, can lead to heaving of the piles (Levasseur et al, 2015). In addition, since photovoltaic panels are connected, systems are not very tolerant to differential movement between adjacent supports, which can take place during the freezing and thawing stages of seasonal variations. A range of candidate remedial foundation measures have been proposed for use on solar farms, however many of these still need to be fully validated and assessed for long-term use, together with their economic benefits. Physical modelling studies are being conducted by the authors to provide insight into the performance of some of these remedial methods.

In order to design the testing program for physical model tests incorporating piles, it is first necessary to ensure that the techniques developed to simulate seasonal ground freezing in the centrifuge models replicated the prototype conditions appropriately. This requires that the depth of freezing, and the resulting surface heave is accurately estimated *a-priori*, to determine the optimal design of the physical model tests. This study has involved the assessment of appropriate analytical and numerical approaches to enable accurate predictions of the behavior of small scaled physical models of soil and pile frost heave. This has required selecting methods of the appropriate complexity to address the major features of the problem. An analytical approach to this problem has been reported previously, Newson et al. (2021). In this paper a numerical approach using the PLAXIS finite element code (PLAXIS, 2021) is evaluated, in which a constitutive model for freezing and thawing soil has been implemented (Ghoreishian Amiri et al, 2016).

1.1 Physical modelling of frost heave

It is reported that the earliest application of geotechnical centrifuge modelling applied to soil freezing and thawing was conducted by Pokrovsky and Fyodorov (1969). It has also been used for a range of related applications, such as heave of footings (Ketcham et al, 1997), pipelines (Piercey et al, 2011) and retaining walls (Ripley, 2004) and slopes (Zhang et al, 2018). A discussion of the scaling laws relevant to centrifuge modelling of freezing is given in Newson et al. (2021).

To simulate frost heave at small scales it is necessary for the rate of heat loss, rate of movement of water within the freezing soil, and soil overburden effects to all be modelled correctly. Miller and Miller (1956) suggested that this could only be achieved using centrifuge models and later Miller (1990) published a scaling analysis demonstrating the applicability of the technique for modelling frost heave. An assessment of the applicability of these scaling laws was conducted in a series of "modelling of models" experiments at centrifuge accelerations of 20g, 30g and 45g, (Yang, 1997). This study demonstrated that for all three scales there were similar extrapolated prototype quantities of surface heave, depths of freezing, and resulting water contents. The data reported in this study were used for the numerical model assessment reported herein.

1.2 Numerical and analytical modelling of frost heave

Modelling the process of frost penetration into the ground and the resulting heave is highly complex. Various theoretical models have been proposed to predict these phenomena, such as the application of the Clausius-Clapeyron equation by Miller (1972) to develop a "rigid-ice" model and the Konrad and Morgenstern (1980) segregation potential theory. These and various other models have been incorporated into computer codes to predict frost heave, e.g. FROST (Guymon et al. 1993), SSR Model, Saarelainen (1992).

The constitutive model used for predictions in this paper is the Frozen and Unfrozen Barcelona model proposed by Aukenthaler (2016). This has been implemented in PLAXIS by Ghoreishian Amiri et al., (2016). The PLAXIS program provides the additional advantage over numerical techniques developed for predicting frost heave of being able to model complex soil/state profiles and boundary conditions. This permits soil-structure interaction behavior, in addition to frost heave, to be predicted explicitly.

However, to provide accurate predictions these numerical approaches require the determination of a significant number of material parameters that must be measured in laboratory tests, obtained from calibration analyses or approximated from data reported in the literature. This provides considerable challenges; hence validation of the predictive abilities is a necessary step.

An alternative approach for routine engineering design of piles is to employ semi-empirical methods to provide predictions of rates of frost penetration and frost heave. This approach was taken by the authors in a previous study (Newson et al., 2021) and was based on the method proposed by Ladanyi and Foriero (1998) for predicting heave stresses acting on piles. This method predicts frost penetration using the modified Berggren equation, developed by Aldrich & Paynter (1953), and employs empirical data values to predict the frost heave.

2 CENTRIFUGE MODELLING OF FROST HEAVE

The centrifuge model dataset used to validate the analytical and numerical modelling approaches was conducted by Yang (1997). The hypothetical prototype was a 3 m soil deep soil profile subjected to surface freezing temperatures. The water table was maintained at either 0.75 m or 2.25 m below ground surface in an open system. In this paper only models with a water table depth of 2.25 m are considered. The soil used in the experiments was created using sieving of a ground quartz silica material and had a D_{10} = 0.003 mm, D_{60} = 0.023 mm and Cu = 7.6. This compares closely with the values for New Hampshire silt, a soil which is frequently used at CRREL for frost susceptibility tests. The models were formed at three geometric scales - 1:20, 1:30, and 1:45, giving 1D soil columns 150, 100, and 67 mm high. The soil columns were subjected to surface temperatures of -3°C whilst "in-flight" on the centrifuge, whilst the base of the model column was maintained at +3°C. These temperature boundary conditions were held constant for a prototype equivalent of 170 days. Note that this type of "step-freezing" boundary condition is not applicable for a freezing soil body in the field. Full details of the apparatus and experimental procedure can be found in Yang (1997).

3 PREDICTION OF FROST HEAVE IN CENTRIFUGE MODELS

The assessment of the analytical and numerical methods has been conducted by analyzing the centrifuge test results described above. The one-dimensional tests were modelled using both a semi-empirical analytical model based on the modified Berggren formula and a frozen soil analysis using PLAXIS. The predictions of the rate of frost penetration and resulting frost heave for the range of boundary conditions applied in the centrifuge tests during freezing were used to validate both methods, allowing them to be used later to optimize the design of centrifuge tests using model piles subject to frost heave in future Western University studies. Further details of the analytical method can be found in Newson et al. (2021).

3.1 Comparison of measured and predicted results

Material parameters for use in the PLAXIS predictions of the centrifuge experiments were obtained or derived, as appropriate, from values measured or quoted by Yang (1997) and Yang and Goodings (1998), Table 1 (the key parameters), together with values for similar soil quoted in the literature (e.g., Ghoreishian Amiri et al., 2016) and default values provided within PLAXIS. Not presented herein due to space constraints.

In the numerical analysis the soil was modelled as an axisymmetric column 3 m high and with a radius of 0.5 m. The top and bottom boundary conditions were set to seepage conditions, while the left and right boundary conditions were closed, and the water table was located at a depth of 2.25 m (corresponding to the parameters in the centrifuge model tests). The mesh consisted of 650 Quadratic 6-node triangular elements. To model the temperature regime in the centrifuge models, the surface temperature applied to the top boundary was lowered to a temperature of -3ºC in a single step and maintained at this level for the full duration of the analysis. A temperature of +3 ºC was applied to the lower boundary of the column through the analysis. To accurately model the 1D condition in the experiments, the left and right boundaries were fixed horizontally, the top was free, and the bottom fully fixed.

Table 1. Parameters values used in the finite element analyses.

Average moisture content, %	23.8
Latent heat of fusion, L (MJ/m^3)	127.187
Average soil thermal conductivity, k_{av} (W/m.K)	3.724

3.2 Depth of freezing front vs time

Since the temporal development of the depth of freezing in the centrifuge models was not reported by Yang (1997), an assessment of the PLAXIS freezing depth with time prediction was achieved by comparing the numerical predictions with analytical predictions obtained using modified Berggren equation (Newson et al., 2021). Comparison of numerical and analytical predictions in Fig. 1 indicates reasonable agreement between the two techniques. This provides confidence that the material parameters selected for the PLAXIS analysis were appropriate; thus, validating the program and these values for this application.

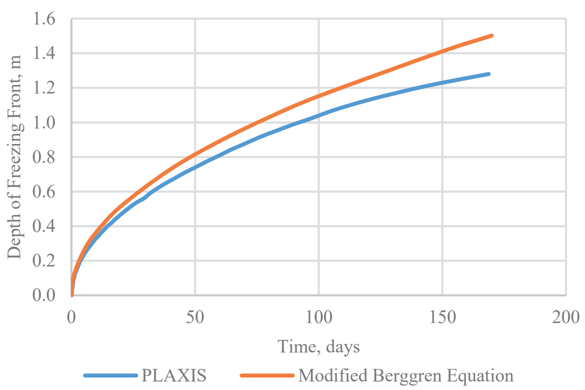

Fig. 1 Depth of freezing front vs time for constant temperature.

The temperature gradient at the final time step of the PLAXIS analysis (i.e. at 170 days) is displayed in Fig. 2, together with the suction gradient. As would be expected from laboratory and field investigations (e.g. Andersland and Ladanyi, 2004), freezing causes soil suctions which lead to the development of ice lenses in the soil that contribute to heave. Since the shear strength and stiffness of the interface between a pile and freezing soil will be a function of both the temperature of the soil and the effective stress (Davies et al., 2021), it is important that both temperature and pore pressures are correctly replicated in both physical and numerical models.

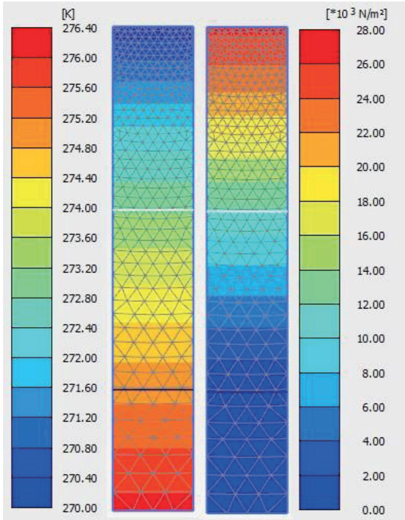

Fig. 2 Temperature gradient (left) and suction gradient (right) for model at final time step using constant temperature boundaries.

3.3 Surface heave vs time

Comparisons of measured surface heave with time with numerical and analytical predictions are presented in Fig. 3 (error bars are for the experimental replicates). It can be seen that the development of heave with time recorded in the physical experiments was closely modelled in both sets of the predictions.

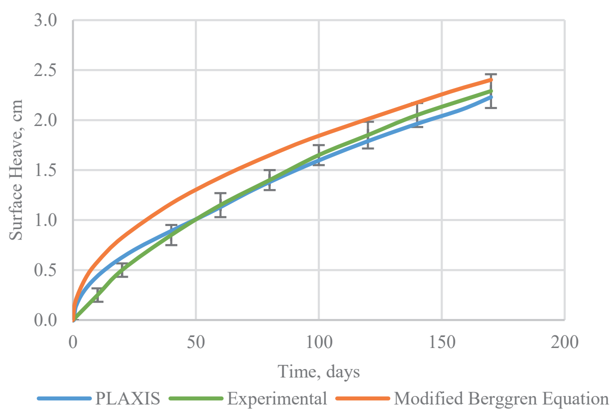

Fig. 3. Comparison of predicted and measured surface heave vs time (experimental data after Yang, 1997).

Since the coefficient of proportionality between surface heave and depth of frost penetration, K, used for the analytical predictions was obtained directly from the surface heave measured in the experiments, the predicted and measured values of surface heave at the end of the experiments should have similar values. However, the excellent agreement between the numerical and centrifuge model data provides further assurance about the parameters selected for the numerical analysis.

These comparisons also provide confidence in the application of PLAXIS to inform the design of centrifuge models of frost heave on piles. To demonstrate this capability, the analysis was repeated with a temporal variation in surface temperature obtained from field data, as shown in Fig. 4. The greater heave in this case (than in Fig. 3) is because the freezing index (i.e., the sum of the negative degree days) is larger than in the centrifuge model predictions, above. The delay in the initiation of the heave due to the slower rate of temperature change is also noticeable. This shows the importance of including cyclic sinusoidal temperature boundary conditions in centrifuge simulations to provide more realistic long-term soil-pile heave responses.

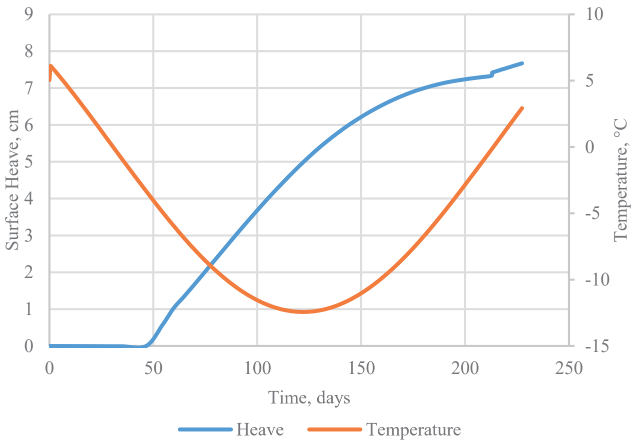

Fig. 4 Simulated daily temperature variation used in field prototype analysis (based on data for Sleepy Hollow, Alberta, Canada provided by Government of Canada) and resulting surface heave predicted using PLAXIS.

4 CONCLUSIONS

The results of the analyses indicated a good comparison between the measured and predicted rates of frost penetration and frost heave. This provides confidence in the use of both the analytical and numerical approaches to enable accurate predictions of the frost heave phenomena that will facilitate the design of centrifuge models to investigate frost heave on piles.

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