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Axial performance of screw micropiles subjected to quick loads in frozen soils

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ABSTRACT

Screw micropiles have been recently introduced to North America as a new foundation type. The screw micropile is a steel pipe pile, threaded and tapered along its lower segment. Due to the unique characteristics, screw micropiles have major advantages such as lightweight, large capacities, reusability, and rapid installation. Screw piles may be a viable solution to foundations in the Canadian Arctic where piles are often backfilled with slurry or gravel. Conventional piles used in the Canadian Arctic require time-consuming freeze-back. However, currently there are no guidelines for the use of screw micropiles in permafrost regions. The present research investigated the engineering behaviour of screw micropiles subjected to short-term loading conditions in frozen ground using the Cold Room Facilities at the University of Alberta. Piles were installed into a smaller pilot hole in the frozen soil, which is intended to simulate the field installation method. The effects of temperature and ice content upon the short-term loading performance of model piles were examined. Preliminary results showed that the pile capacities decreased with the increase in soil temperature. The installation torque was recorded and used to infer the torque required for field installation. The failure pattern of the piles was observed to be located along the edge of individual threads; this pattern suggests that the pile capacities may be greater than conventional pipe piles in the Arctic.

RÉSUMÉ

Les micropieux à vis ont été récemment introduits en Amérique du Nord comme nouveau type de fondation. Le micropieu à vis est un pieu tubulaire en acier, fileté et effilé le long de son segment inférieur. En raison des caractéristiques uniques, les micropieux à vis présentent des avantages majeurs tels que la légèreté, les grandes capacités, la réutilisabilité et une installation rapide. Les pieux vissés peuvent être une solution viable pour les fondations de l'Arctique canadien où les pieux sont souvent remblayés avec du lisier ou du gravier. Les pieux conventionnels utilisés dans l'Arctique canadien nécessitent un gel rapide. Cependant, il n'existe actuellement aucune directive sur l'utilisation des micropieux à vis dans les régions de pergélisol. La présente recherche a étudié le comportement d'ingénierie des micropieux à vis soumis à des conditions de chargement à court terme dans un sol gelé à l'aide des installations de chambre froide de l'Université de l'Alberta. Des pieux ont été installés dans un trou pilote plus petit dans le sol gelé, qui est destiné à simuler la méthode d'installation sur le terrain. Les effets de la température et de la teneur en glace sur les performances de chargement à court terme des pieux modèles ont été examinés. Les résultats préliminaires ont montré que les capacités des pieux diminuaient avec l'augmentation de la température du sol. Le couple d'installation a été enregistré et utilisé pour déduire le couple requis pour l'installation sur site. On a observé que le modèle de rupture des pieux était situé le long du bord des fils individuels; ce schéma suggère que les capacités des pieux peuvent être supérieures à celles des pieux tubulaires conventionnels dans l'Arctique.

1 INTRODUCTION

Piles transmit structural loads to deep soils where the supporting strength of the soil remains relatively stable throughout the life of the structure. In the permafrost regions of Canada, piles are mostly prefabricated and can be installed mechanically, and they do not need an open excavation that could lead to a high thermal disturbance of the ground (Andersland and Ladanyi 2004).

The materials of piles used in the frozen ground generally include timber, steel, concrete, and composite. The selection of a particular pile type in permafrost depends on various factors, such as soil type, temperature profiles, load demand, availability of material, construction equipment, the cost of transportation and pile installation. The most common pile type used in the Canadian Arctic is predrilled steel pipe piles. Straight-shaft pipe piles are placed in a pre-bored hole and the annulus is backfilled with a soil-water slurry or a grout designed to cure at cold temperatures. However, this construction approach and considerable freeze-back may be time consuming. Additionally, predrilled piles may provide a low adfreeze bond strength between the backfill and native frozen soil.

Pile design in frozen soils in most cases is based on the principle of limiting the long-term creep settlement. Creep settlements are a function of the pile-soil adfreeze stress, temperature, and ice content. Weaver and Morgenstern (1981) developed a series of equations for predicting allowable shear stress and pile capacity versus creep settlement. The equations for ice-rich soils were based on the established flow law model for steady-state (secondary) creep in polycrystalline ice. The equations for ice-poor soils were based on an established primary creep law model. Ladanyi and Guichaoua (1985) showed that creep settlement of a slightly tapered pile depends on the pile taper and its diameter, the interface friction and adhesion, and the soil resistance against being pushed aside by the pile axial movement. Foriero and Ladanyi (1990) utilised a viscoplasticity theory to provide a more general approach to the problem of creep in frozen soils. A finite element computer program has been developed to verify the validity of the proposed model. Discussions of methods and recommended pile load test procedures in permafrost are provided by Manikian (1983) and Neukirchner (1988). Methods of analyzing creep rates based on pile load tests are presented by Neukirchner and Nyman (1985). Case studies of pile load tests in saline soils are presented by Biggar and Sego (1994), Miller and Johnson (1990) and Nixon (1988). In order to increase the use of helical piers as a cost-effective foundation alternative, Zubeck and Liu (2003) presented the experience with helical piers in Alaska and gave a design example using the developed finite element analysis and creep results. Liu et al. (2007) presented a computer simulation of the behaviour of helical pier foundations in frozen ground, where the Drucker-Prager yield criterion was used to describe the yield surface for the soil elements.

New pile types have been introduced to the Canadian Arctic in the past decades. For example, helix thermopiles were used as the new foundation type for a building in Inuvik, NWT (Zhang and Hoeve 2015). The helix thermopile is a combination of a thermosyphon and an adfreeze pile which incorporates thin-bladed helixes on the pile surface to increase pile load capacity (Figure 1). A helix thermopile is usually installed in a pre-drilled hole and the annulus is filled with a saturated sand or gravel. Geotechnical evaluations were conducted to estimate the required minimum pile embedment depths considering ground temperature, long term creep settlement, frost heave, and axial shear failure.

Ndofor-EBA (2011) introduced a convection pile which is a steel pipe adfreeze pile to be back-filled outside, but leave the inside pipe open. In this case, convection is anticipated to take place automatically, which will then extract the heat from adjacent soils. This would have a cooling effect on the adjacent ground to improve the pile capacity. Convention would be active during the winter and dormant during the summer. Nevertheless, the effectiveness of the convection pile is not obvious based on the preliminary monitoring data.

Figure 1. Helix thermopiles under a building in Inuvik, NWT.

Most piles in present applications require granular backfills, which may delay the construction of piles. Since the construction season in Arctic region usually starts from May to September, it is critical to finish a foundation construction that is ready to be loaded within this short construction window. The present study introduces a new foundation type that may be suitable for the Arctic construction. Screw micropiles have been recently introduced to North America as a new foundation type. The screw micropile is a type of steel pipe pile, threaded and tapered at the lower segment and installed under the torque. Owing to the difference in pile construction and soil-pile interface, screw micropiles might have many advantages such as lightweight, large capacities, reusability, and rapid installation, in non-frozen soils. Field loading tests of micropiles were conducted by Guo and Deng (2018) who investigated the axial pile performance under monotonic compression and tension loads. Guo et al. (2019) investigated and compared the performance of full-scale screw micropiles under the monotonic and cyclic loads in the axial direction. The effects of axial cyclic loads on the load distribution and unit shaft resistance were studied.

Screw micopiles may present a viable solution for foundations in the Arctic. However, currently there is not any design guideline or research for screw micropiles for application in permafrost regions. The short-term strength and long-term creep rates of the screw micropiles in the frozen ground may be significantly different from conventional predrilled pipe piles, owing to the presumable difference in load transfer mechanisms. Understanding the effects of ground conditions on the axial performance of screw micropiles will provide valuable information for the pile design in permafrost.

This paper is aimed at the engineering behaviour of screw micropiles subjected to short-term loading conditions in frozen soils. The present paper is a part of a broader research program that studies the short-term, long-term, and installability of this pile type in permafrost. A pile loading system was developed in the Cold Room Facilities at the University of Alberta. Segments of full-size screw micropiles with a shaft diameter of 89 mm and a length of 300 mm were loaded under a constant displacement rate in frozen soils to investigate the axial pile capacities and load-transfer mechanism. The effects of temperature and ice content upon the time-dependent deformation of model piles were examined. The soil-pile interaction and load distribution, and installation torque were monitored using strain gauges, load cells and displacement sensors. The temperature profile of the frozen soil was monitored by an array of thermocouples.

2 EXPERIMENT PROGRAM

2.1 Test materials: soil and pile

The test soil was a 2:1 mixture of Devon Silt and Silica sand. The particle size distribution (Figure 2) was designed to be similar to silty sands observed in a number of Arctic communities near the MacKenzie River delta, where the surface soil tends to be silty.

Screw micropiles can vary in the length and diameter. The original pile with the length of 1.5 m and diameter of 89 mm was provided by the industrial partner. Note that the dimensions of this pile type can be varied for the practical use in the field. Owing to the limitation of lab testing equipment, the pile was cut into three segments (Figure 3) and tested separately. A straight threaded segment was used in this study. The threads on the pile segments have the width of 12 mm and thickness of 2 mm. The spacing between each thread is 50 mm ± 2mm. The pile is made of structural steel which has the elastic modulus of 210 GPa and a yield strength of 248 MPa.

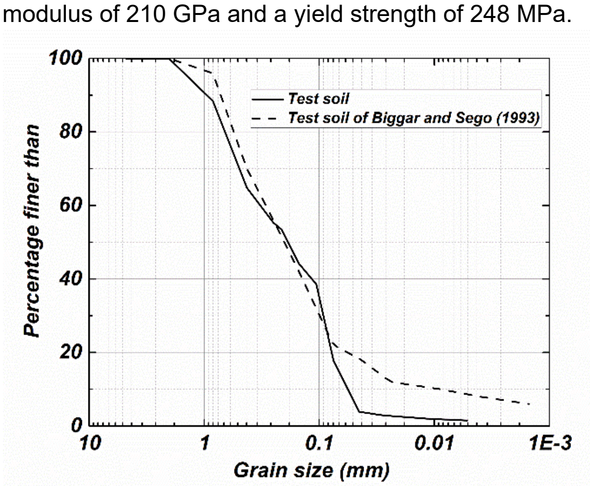


Figure 2. Particle size distribution of test soil.

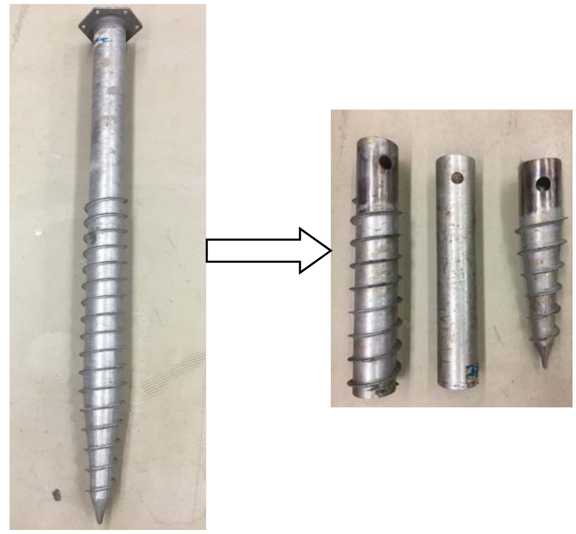
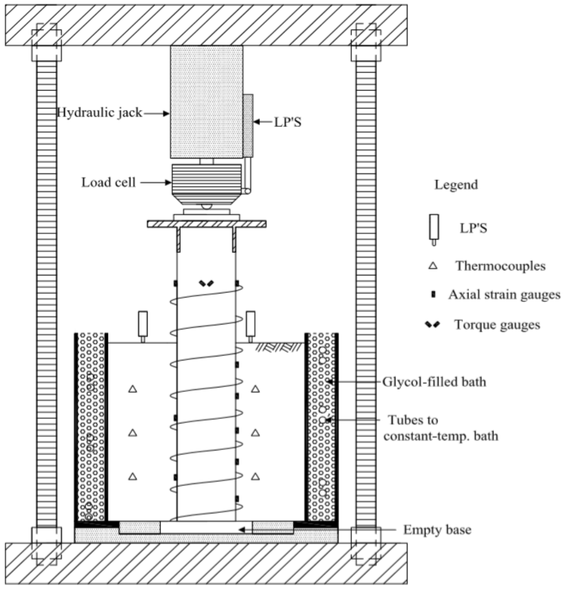


Figure 3. A prototype screw micropile that was cut into test pile segments.

2.2 Test setup

This research will characterize the axial behaviour of screw micropiles subjected to quick loads in the frozen soils, using the Cold Room Facilities at the University of Alberta. A model pile testing program is developed in the Cold Room laboratory where the room temperature can vary from 20 to -20 ºC. The testing system consists of test pile segments, test cell, loading system, servo-control system and data acquisition system. A schematic and photo of the testing apparatus are shown in Figure 4.

The test cell was composed of two concentric chambers while the soil sample was placed in the inner chamber and the ethylene glycol was placed in the outer chamber. In order to maintain the soil mass at a constant temperature, ethylene glycol from a constant temperature bath was circulated through copper coils located in the outer chamber. At the bottom of the test cell, an aluminium base plate was inserted during consolidation stage. During load testing, a PVC base plate with a center hole replaced the aluminium base plate. The hole in the base plate was slightly larger in diameter than the pile to allow failure to occur. Pile head load and displacement were recorded by a load cell and a linear potentiometer. The load cell and linear potentiometers were calibrated before use. A hydraulic jack was connected with a servo-control system which can provide a constant hydraulic oil pressure. A ball bearing was placed between the load cell and pile cap to eliminate loading eccentricity and bending moment.



(a)

(b)

Figure 4. (a) Schematic of testing apparatus; and (b) a photo of testing apparatus.

2.3 Instrumentation

In order to examine the load transfer mechanism during loading period while the pile segment needed to be embedded in the soil and kept intact as one piece during loading, the most effective way to measure the internal axial loads is to use strain gauges. A strain gauge is a sensor whose resistance varies with applied force. It converts force or torque into a change in electrical resistance which can be measured as a voltage change. The strain gauges were manufactured by Micro-Measurement with the model number CEA-060-250UT-350. Eight locations were marked on the instrumented pile at different levels. On each station, two strain gauges were attached to the pile shaft surface and connected to a data acquisition system to form a half Wheatstone bridge circuit (Figure 5). Three layers of protective coating (Epoxy, modelling clay and aluminium foil tape) were applied to prevent the strain gauges and wires from being torn off during pile installation. Strain gauge stations were calibrated against axial load or torque before use.

Figure 5. Axial and torsional strain gauges instrumentation.

Six thermocouples were embedded in different layers and at different radial distances from the pile shaft to measure the soil temperatures during the entire test progress. In order to measure torque during pile installation, four torsional strain gauges were installed on the pile head surface and connected to form a full Wheatstone bridge that can provide sensitivity and guaranteed linearity of results.

2.4 Test design

The short-term displacement rate was 20 mm/32767 s, which is the slowest rate servo-control system can achieve. The rate value was commonly used to the quick loading test in permafrost (Biggar and Sego 1993; Notlingham and Christopherson 1983; Parameswaran 1978; Ladanyi and Guichaoua 1985). The ice content, temperature, salinity of 0 PPT, and soil type are selected to cover the range of conditions encountered in coastal Arctic communities (Majid-EBA 2004 and Ndofor-EBA 2011). The installation method was pre-drilled hole which had a slightly smaller diameter of 79 mm than the pile shaft diameter of 89 mm. In this case, backfilling is not needed. Straight threaded pile segment was used in this study. Detailed design of the tests is listed in Table 1.

Table 1. Test matrix

Test ID	Soil Temperature	Water content
SL01	-1 ºC	35%
SL02	-1 ºC	20 %
SL03	-5 ºC	35 %
SL04	-5 ℃	20 %

2.5 Model construction and test procedure

Silty sand from a mix of Devon silt and silica sand was dried in an oven. Dry soil was placed in a heavy duty soil mixer and was mixed with the approximate amount of distilled water. Wet soil was placed in the buckets with lids to seal and was stored in a moisture room until ready for use.

The soil and thermocouples were placed into a test cell. The test cell was left in a cold room with a temperature of 2 °C for at least 24 hours, to allow for even distribution of moisture content throughout the soil, self-weight consolidation and stabilization of the soil. Consolidation load plate was placed on top of the soil and an 80 kPa consolidation pressure was provided. Load and deformation were recorded until 95% consolidation was achieved. A PVC cylinder was left in the middle of the soil chamber during the 80 kPa consolidation process; this tube would be removed before we installed the test pile segment. The PVC tube had a diameter of 79 mm, to simulate a pilot hole that is smaller than the actual piles in the field installation. The small pilot hole is intended to eliminate the needs of backfilling and enable the immediate loading after installing piles.

Ethylene glycol was circulated through the outer chamber until the thermocouples indicated that the soil was completely frozen. Cold room temperature was set to the desired test temperature. The sample was left for a further 24 hours to allow for temperature equilibration.

The pile segment was screwed into the soil using an electric driver (Figure 6). The torque was measured during the installation process by using the torsional strain gauges.

Figure 6. Method of pile segment installation.

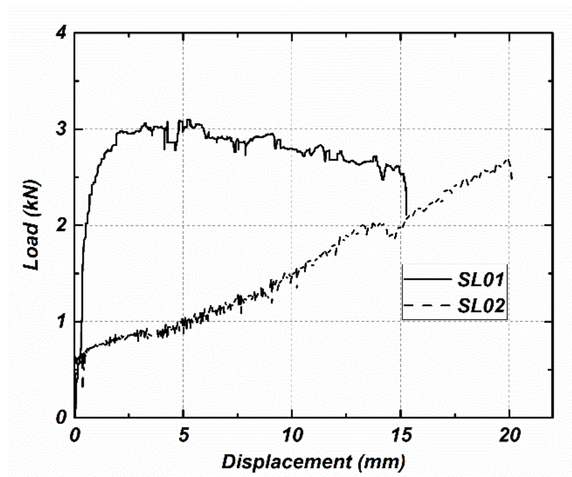
After the test, the soil and pile segment was pushed out of the chamber and was excavated with care. Failure pattern was observed between the pile surface and adjacent soil. Frozen soil was removed to measure the density and moisture content.

3 TEST RESULTS

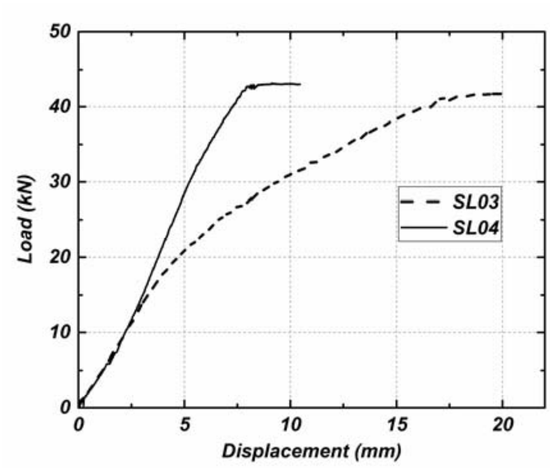
3.1 Axial load vs. displacement curve

The axial load and pile head displacement were recording during the short-term loading tests. As shown in Figure 7, the pile load capacities increase significantly from 3 kN to 42 kN with the decreasing of temperature from -1 ºC to -5 ºC which shows the temperature has a marked effect on the mechanical behaviour of pile because of temperature's direct influence on the strength of intergranular ice and the amount of unfrozen water in frozen soil. The samples with the same temperature experienced a similar yield strength, whereas the samples with the higher ice content behaved a strain soften trend. It can be concluded that ice content has a significant effect on the patterns of elasticity on load and displacement curve rather not limit state capacity.

In general, a decrease in temperature results in an increase in strength of frozen soil, but at the same time, it increases its brittleness, which is manifested by a larger drop of strength after the peak and an increase in the ratio of compressive strength to tensile strength. (Sayles and Haines 1974; Haynes and Karalius 1977; Haynes 1978). At the temperature near the freezing point of the pure water, adfreeze bonds are weak and the soil is highly susceptible to time-dependent deformation.



(a)



(b)

Figure 7. Axial load vs. displacement curves of (a) SL01 and SL02, and (b) SL03 and SL04.

Figure 8 shows the average soil temperture from three thermocouples embedded in different layers for two samples. It is shown that the soil temperature remains stable during the loading period with the fluctuation less than 1 ºC which means the constant temperature bath and styrofoam isolation work effectively during the test progress.

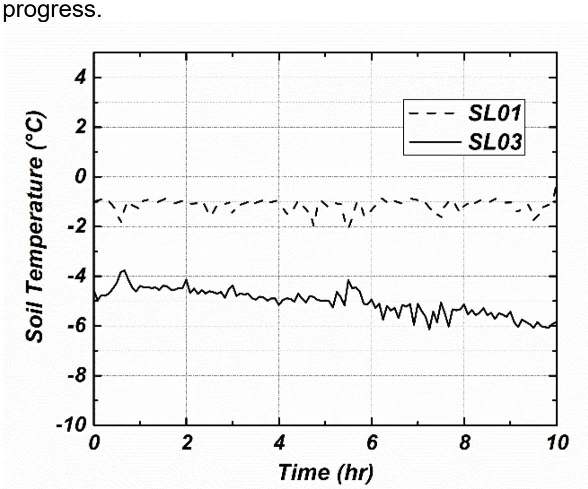


Figure 8. Soil temperature during axial loading tests.

3.2 Installation torque

The installation torque is one of the primary parameter in the evaluation of axial capacities for screw piles. Empirical or theoretical torque-capacity correlation can be used for the pile design purpose. Guo and Deng (2018) proposed a theoretical torque model to estimate the torsional resistance of screw micropiles installed in cohesive soils. Nevertheless, there has been no research in the torque-capacity relationship for screw micropiles in frozen ground.

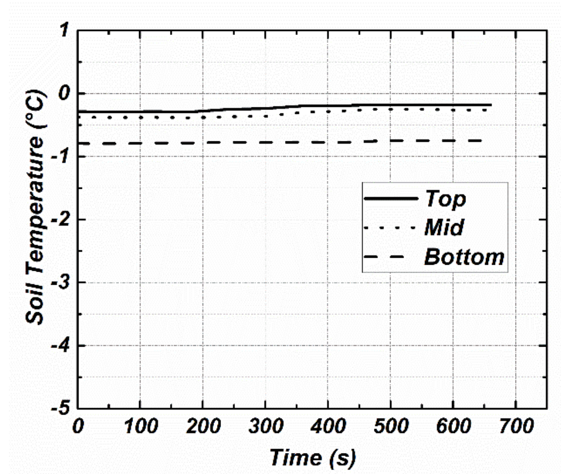


Figure 9. Time history of the soil temperature at different layers during installation (Test ID: SL01).

Figure 9 and 10 show the time history of soil temperature and torque during pile segment installation with the sample ice content of 35% under the temperature about -0.5 °C on average. The maximum torque during installation was 110 N*m.

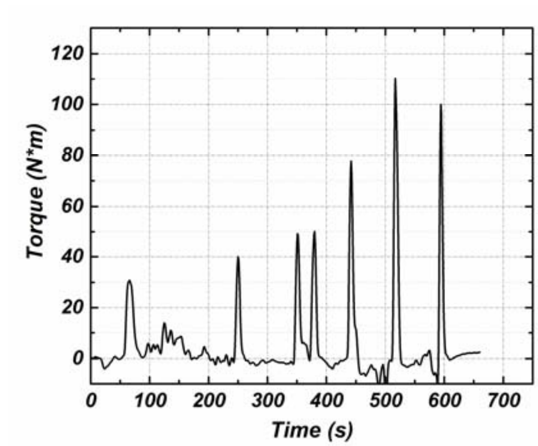


Figure 10. Time history of torque during installation (Test ID: SL01).

In order to obtain torque vs. penetration depth corelation, the torque data shown in Figure 10 was picked manually. The interval depth of the segment was chosen by using final depth (30 cm) divided by 6 since the pile segment was driven consistently and it took approximate 6 cycles to drive test pile the segment to the end. The torque values were selected from the peak of the Torque-Time plot. Figure 11 shows the relationship between installation torque and penetration depth. It is seen from the plot that the installation torque increased with the increasing embedment of pile segment.

The peak installation torque is about 110 N*m (Figure 11). If a pile of 5 m length and the same diamter is to be install to a warm permafrost at -0.5 °C, the installation torque required would be about 2200 N*m, which is proportional to pile length in theory. This torque of 2200 N*m can be achieved using a common torque head according to the experience of the authors in this pile type.

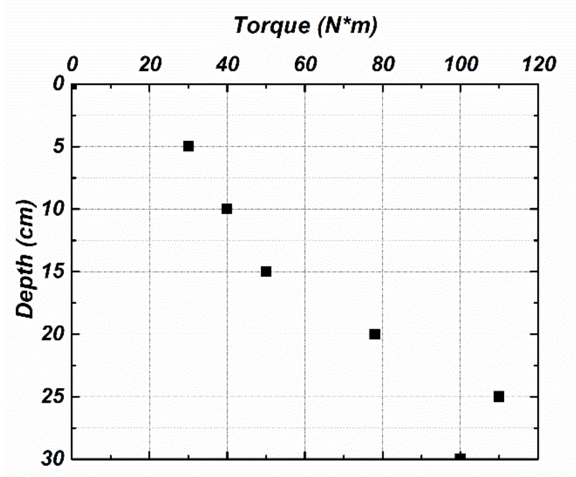


Figure 11. Torque vs. penetration depth (Test ID: SL01).

3.3 Failure mode observation

Two hypothesized failure modes might be applicable to the straight thread shaft in the non-frozen soils: cylindrical shear mode (CSM) and individual bearing mode (IBM). Guo and Deng (2018) concluded that soils around the straight thread segment fail in the CSM at the limit state. The substantially increased limit capacity is caused by the shear plane was pushed outward to the edge of the threads.

Figure 12 shows that the failure occurred locally at the soil beneath the pile threads instead of at the soil-shaft shear surface. In this case, the end bearing resistance q_b (in a unit of kPa) was dominated whereas the adfreeze strength q_s (kPa) should be considerably smaller than q_b. The soil between threads was pushed down by axial force and there is no apparent global failure found.

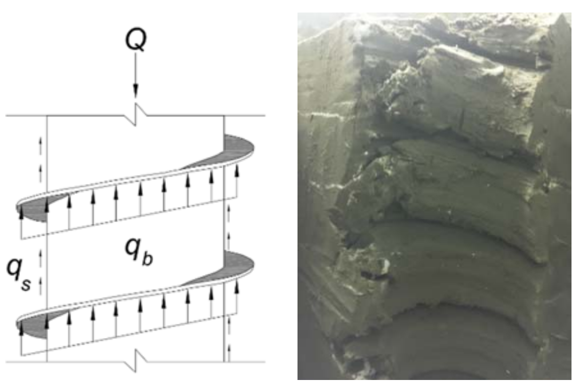


Figure 12. Failure pattern observation after loading test (Test ID: SL01).

The individual failure mode of all other tests in the present work was also observed. This was owing to a strong soil-pile engagement as a result of the cavity expansion when the pile segment was installed by applying a torque. Presumably the end bearing resistance is much greater than the shaft adfreeze for piles in frozen soil, the failure mode of screw micropile segment in this research suggests a potential advantage of this pile type over conventional predrill-backfilled piles.

4 CONCLUSIONS

Screw micropiles may render a viable solution to pile foundations in the Canadian Arctic. A pile loading test program is developed in the Cold Room Facilities at the University of Alberta. In total, four axial quick loading tests are reported in the present paper, and the measured pile capacity and strain gauge readings were used to evaluate the load-transfer mechanism between the pile and soil. Following conclusions can be drawn:

1. Temperature has a significant effect on the pile capacity in frozen soils. Pile capacity increases dramatically with the decreasing of the temperature. Ice content affects the patterns of elasticity on load and displacement curve rather not limit state capacity.

2. The pile can be installed into a smaller pilot hole in a warm permafrost. The installation torque was recorded and used to infer the torque required for field installation.

3. The failure pattern of the piles was observed to be located along the edge of individual threads. This pattern suggests that the pile capacities may be greater than conventional smooth piles used in the Arctic.

Notably, several limitations exist in the present research.

1. Only one size of pilot hole was used. The torque values and pile capacities may change with pile hole diameter.

2. The pile segment was only installed under the warm permafrost about 0 °C, owing to the limitation of lab installation technique.

3. The long-term creep settlement rate under a constant load is not assessed in the present paper.

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