Field footing test for foundation settlement estimate of marine saline permafrost in Longyearbyen, Svalbard

Test de pied sur le terrain pour l'estimation du tassement des fondations du pergélisol salin marin à Longyearbyen, Svalbard

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ABSTRACT: A footing test started on February 2020 at Longyearbyen, Norway, where the ground in a large part of the city is Holocene marine deposits. The aim of the field test is to study the time dependent footing settlement, considering the influence of permafrost degradation. Three footing plates, with 300 mm diameter each, were placed on saline clay permafrost at around 4.2 m depth. An equilateral triangle steel frame with an edge length around 4 m is supported by these three legs and used for a loading platform though adding concrete blocks as dead weight. A stepwise loading procedure was adapted to test long term creep settlements for a minimum two years period. We addressed some challenges during the foundation design and construction such as thermal disturbance, insulation, and test implementation. The test is still ongoing, and the simulation for future pile settlement induced by global warming has been conducted based on results of mechanical, thermal, and electrical laboratory testing for the marine permafrost. The short-term (a year scale) and long-term (10-year scale) footing settlement behaviors at permafrost region have been recognized through field test and numerical simulation results.

RÉSUMÉ: Un test de pied a commencé en février 2020 à Longyearbyen, en Norvège, où le sol dans une grande partie de la ville est constitué de gisements marins de l'Holocène. Le but de l'essai sur le terrain est d'étudier le tassement de la semelle en fonction du temps, en tenant compte de l'influence de la dégradation du pergélisol. Trois semelles de 300 mm de diamètre chacune ont été placées sur du pergélisol d'argile saline à environ 4,2 m de profondeur. Un cadre en acier triangulaire équilatéral avec une longueur de bord d'environ 4 m est supporté par ces trois pieds et utilisé pour une plate-forme de chargement en ajoutant des blocs de béton comme poids mort. Une procédure de chargement par étapes a été adaptée pour tester les tassements de fluage à long terme pendant une période minimale de deux ans. Nous avons relevé certains défis lors de la conception et de la construction des fondations, comme les perturbations thermiques, l'isolation et la mise en œuvre des tests. L'essai est toujours en cours et la simulation du futur tassement des pieux induit par le réchauffement climatique a été menée sur la base des résultats d'essais mécaniques, thermiques et électriques en laboratoire pour le pergélisol marin. Les comportements de peuplement à court terme (échelle d'un an) et à long terme (échelle de 10 ans) dans la région du pergélisol ont été reconnus par des essais sur le terrain et des résultats de simulation numérique.

KEYWORDS: Saline permafrost, Creep, Footing settlement, Foundation analysis

1 INTRODUCTION

Globally permafrost warming has been observed due to climate change in recent 50 years (Biskaborn et al., 2019, Aalto et al., 2018). The warming tendency is expected to continue and will result in further permafrost degradation through the 20th century (Karjalainen et al., 2019, Karjalainen et al., 2020). Therefore, some challenges have been aroused for local Arctic communities, such as an increase in number of landslides, ground subsidence and loss of pile bearing capacity (Harris et al., 2009, Yu et al., 2020, Duvillard et al., 2019, Fortier et al., 2011).

In Svalbard, the annual average temperature has increased by 3-5°C during the last 40 years. Thawing of frozen soil reduces the shear strength and leads to larger time-dependent deformations. Frozen marine deposits (saline clay and silt) which are widely distributed in the fjord-valleys in Svalbard are particularly susceptible and vulnerable to thawing under present and future climate conditions. In order to investigate this and to provide a benchmark test for further analytical and numerical analysis of frozen soil, a plate test frame has been founded at the layer of marine permafrost. The frame is loaded with dead weights, and carefully monitored with respect to foundation settlement and ground temperature over time. The legs are designed to resist the external loading only at the foot..

This footing test is a part of the Nunataryuk project, funded by the European Union's Horizon 2020 Research and Innovation Program. The main goal of Nunataryuk is to determine the impacts of thawing land, coast, and subsea permafrost on the global climate and on humans in the Arctic and to develop targeted and co-designed adaptation and mitigation strategies.

2 FOOTING TEST PROCEDURES

Longyearbyen (in figure 1) is the largest settlement with around 2000 inhabitants in Svalbard (Gilbert et al., 2018). Although it is located at remote Arctic region, the town is quite occupied with infrastructures such as a supermarket, bars, church, cinema, school, and even a municipal swimming pool. Besides, the increase in human activity further results in housing crisis in Longyearbyen. Therefore, the permafrost degradation posed a significant risk for the integrity of these infrastructures, and the foundation design principles should hence be revised to meet this challenge.

During the construction and installation of the test setup, we faced several challenges. First, the cost of field test conducted at permafrost region is a big issue due to high expense of human resources, transportation, and materials. For example, we originally designed a hollow concrete column to install extensometer for the measurement of vertical displacement variation along depth under the footing. However, concrete piles/columns can only be casted in the Norwegian mainland and then transported to Longyearbyen, which significantly increases budget. Therefore, available wooden piles were favored and the idea using extensometer had to be abandoned. To supply power during the winter and summer time both wind turbine and solar panel has been installed.

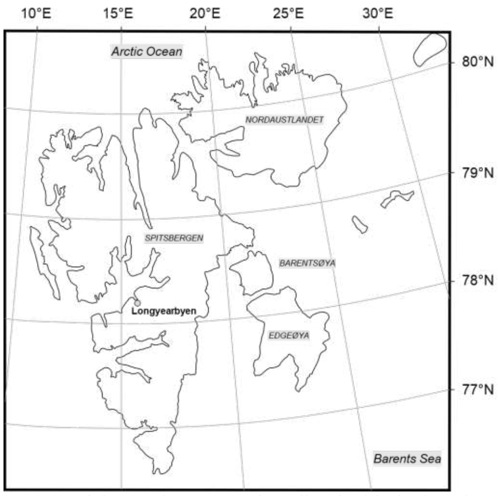


Figure 1. Map of the northern part of Svalbard with the location of Longyearbyen (study area)

The test setup will experience extreme weather condition, and the permafrost is sensitive to thermal disturbance caused by the construction process and by the necessary infrastructure and rigging. Therefore, the evaluation of sensor configurations is essential. Further, the construction must be conducted at the time of subzero temperature, preferably in late fall or winter, to reduce the impact of the construction phase. The permafrost should not experience melting induced by warm air temperature and generated heat during the construction. The measurements showed that it took a few months for the ground temperature to recover back to original field condition, due to the inevitable thermal disturbance during construction. The structures, like the columns and the steel frame, have different thermal properties than the removed soil. Wooden or concrete piles are favored instead of steel pile/beam, since latter is thermally super conductive. The steel frame as loading platform is therefore well covered by a tent shelter to eliminate the adsorption of midnight sun radiation in summertime. The gap between the casing and the column is also thermally insulated to decrease heat exchange due to air convection.

This test is mainly to study time-dependent settlement, with focus of end bearing. However, the infrastructure in permafrost is normally subject to far more complicated state of stress, such as heaving stress with active layer freezing and adfreeze bonding between piles and the ground. Finally, we adopted casings to maintain the borehole and left enough space between casings and piles. All efforts assure the equality between loading force and end-bearing force.

With considering all practical issues and reality in Longyearbyen, final implementation of footing test was conducted on March 2020 according to procedures described below:

1) Three φ320 mm holes have been bored through the active layer and sandy permafrost down to the clay permafrost.
2) Wooden columns are standing at circular footing plates 4.2 m down in the ground, carrying load only at their tip.
3) Casing supports the soil around the boreholes, provides an air gap along the shaft of the piles and prevents leakage of surface water to the columns.
4) Load cells at the top of each pile measures the actual weight loaded to on each wooden column.
5) Vertical displacements are monitored by a wire displacement sensor between each columns and the steel pipe casing that is frozenly bounded to the soil. An unloaded steel bar is fixed 5.5 m down in the ground for reference and checking vertical movements. Movements are also checked against the UNIS building.
6) Temperature sensors are placed at each footing plate.
7) Thermal insulation around the pile at the surface prevents unintended heat leak into the soil, aiming to maintain the natural temperature conditions in the soil and at an undisturbed site.
8) Annual temperature at 4.2 m depth varies from -2.5 ºC to -3.2 ºC through the year. As summer heat takes time to penetrate the frozen soil, the warmest month is February and the coldest month is May at the site.
9) As loading blocks, concrete slabs with weight of 1400 kg each are used. The dead weight went up to 2, 4, and 6 blocks on May 2020, October 2020, and March 2021. Three more blocks are planned to load on July 2021. Some photos regarding test setup, pile installation and dead weight placement are given in figure 2.

a) Footing pile installation

b) Triangular-shape footing setup

c) Dead weight loading

Figure 2. test setup and some key procedures.

Some in-situ samples were well retrieved and tested for determination of unfrozen water content, thermal conductivity, and mechanical testing in a triaxial setup. All these results have been reported in submitted journal articles. These results can be further used to simulate the ground temperature change and pile settlement caused by global warming.

3 FIELD TEST RESULTS

Two less accurate thermistors (T2) were amounted at the bottom of plate 1 and plate 2 respectively and started measurement at the middle of May 2020. On July 2020, three well-calibrated thermistors (T1) were placed down to the bottom of column 1~3 through plastic pipes which were pre-attached to the columns before installation on March 2020. The footings have been subject to three stepwise loading events since the construction. Two concrete blocks (≈2.8 ton) were loaded on early May 2020, while the recording system started working after one week. Therefore, the instant settlement for 1st loading was not recorded in the dataset presented in figure 3. The second loading event (L2) took place at the end of October 2020 when two more concrete blocks were added (up to 5.6 ton). The third loading (L3) followed on the March 2021. In this event, all previous loads (4 blocks) were firstly removed, and dead weight (6 blocks) was added again after 24 hours. We observed 1 ~ 2 mm footing rebound and faster settlement after placing heavier dead weight. Except that, several observations are highlighted according to test results up to May 2021 shown in figure 3.

1) Although T2 are less accurate sensors, they show a nearly constant offset (≈0.35 ℃) with well-calibrated sensors, T1. The T2 recording indicates that construction event conducted at wintertime 2020 resulted in the additional cooling of the studied permafrost from around -3.1±0.3 ℃ down to below -5 ℃. This thermal disturbance took 3 ~ 4 months to gradually recover back to original temperature before construction.

2) Temperature and load dependent settlement rate were found. During the March 2020 ~ September 2020, ground temperature was relatively low (below -3.5 ℃), and only two concrete blocks (≈2.8 ton) were loaded. Except plate 2, both plate 1 and 3 experienced very little settlement. On October 2020, the dead weight rose to 5.6 ton, and temperature continued rising from -3.5 ℃ to -2.8 ℃ until January/February 2021. Settlement rate accelerated for all three plates. After this, the temperature reduced until May 2021. Although higher load was added (8.4 ton), settlement rate still reduced.

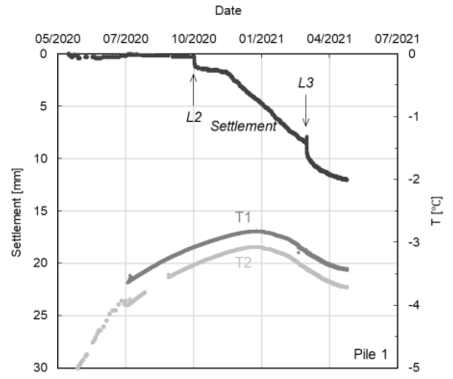
3) Uplifting has not been observed so far, especially in wintertime due to heaving forces. It indirectly indicated that we managed to keep disconnection between the columns and the casings.

4) Plate 1 and 3 show similar amount of settlement and are only half of the settlement of plate 2, up to the May 2021 (12~14 mm vs. 28 mm). This difference might come from the slight difference of embedment depth and/or variability in frozen soil mechanical properties.

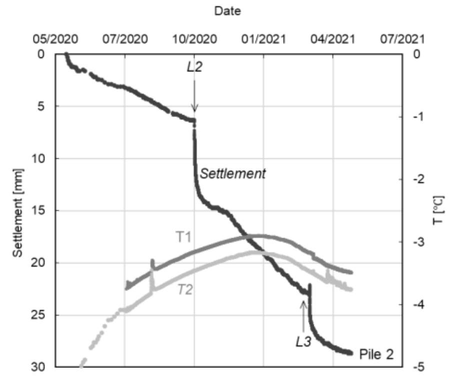
4 THEORETICAL FRAMEWORK AND NUMERICAL SIMULATION

4.1 *Theoretical framework*

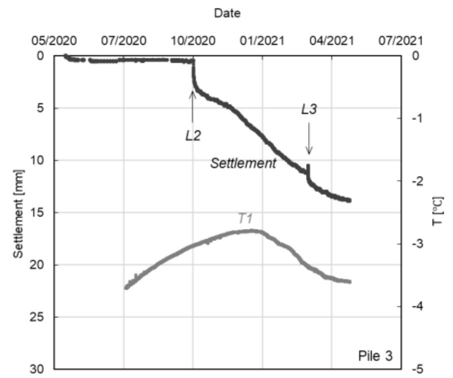
A constitutive model is essential to simulate thawing and creep deformation of permafrost. In the literature in general two approaches have been adopted and developed to model the mechanical behaviour for frozen soils: total stress based models and two stress-state models. The former model faces some significant difficulties although it has been widely used. For example, it is challenging to connect the total stress based frozen soil model with the effective stress based unfrozen soil models to simulate thermo-hydro-mechanical coupling. It is very important in the process of permafrost thawing. As a more efficient model, the two stress-state approach was initialized by Nishimura et al. (2009) to develop an elastic-plastic model for saturated frozen soils. Inspired by classical unsaturated soil mechanics (Fredlund and Morgenstern, 1977), this method employed the cryogenic suction and net stress as two stress variables in the model. Alternatively, the elastic-viscoplastic model, proposed and implemented in PLAXIS by Ghoreishian Amiri et al. (2016), uses solid phase stress and cryogenic suction to describe the frozen soil. This theoretical framework is inspired by the Barcelona Basic model (Alonso et al., 1990) that is widely used for unsaturated soils.



a) Plate 1: settlement and temperature at plate level



b) Plate 2: settlement and temperature at plate level



c) Plate 3: settlement and temperature at plate level

Figure 3. Field footing test results

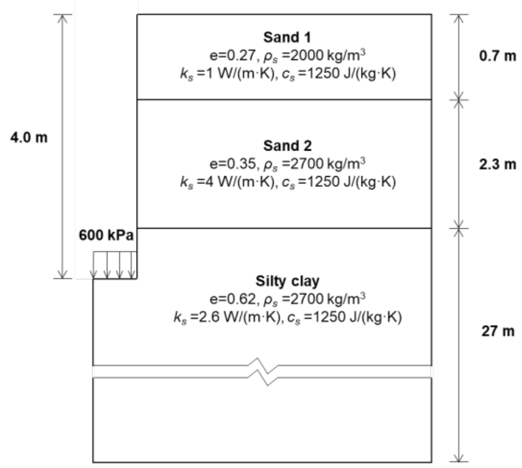
4.2 *Numerical simulation*

This study adopted the elastic-viscoplastic framework in PLAXIS to simulate a long-term footing settlement with the consideration of global warming. A systematic laboratory test has been conducted to measure unfrozen water content, thermal conductivity, shear strength and creep rate as a function of temperature for undisturbed frozen soil samples. Mechanical test results were further used to calibrate parameters in the elastic-viscoplastic model, matching strain-stress curves in both shear and creep tests. All test results have been documented in submitted journal articles. Figure 4(a) shows the geometry of simulation domain and the relevant soil properties of each soil layer. The low ρ_s value for Sand 1 layer is because of high organic content. The 600 kPa was added at 4m depth, and the settlement at the period of 2021~2060 is simulated according to different warming scenarios, RCP2.6, RCP4.5 and RCP8.5 reported by Hanssen-Bauer et al. (2019). The scenario RCP2.6 indicates the slowest air temperature rising rate and RCP8.5 suggests the quickest condition. The figure 4(b) shows footing settlement versus time and highlighted several interesting observations:

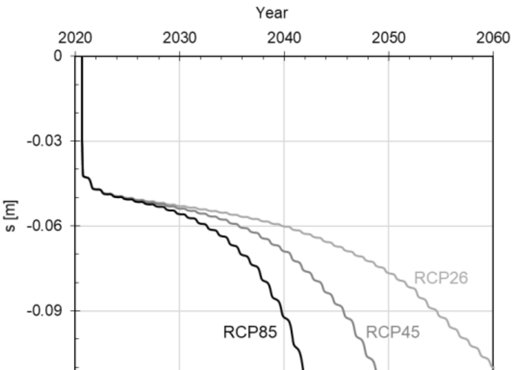
1) The settlement with time can be divided into three stages for all three climate change conditions: instant settlement at the time load was added, moderate settlement rate (up to 2030~2040, depends on warming scenarios) and accelerated settlement (after 2030~2040).

2) Stepwise settlement is found in one-year period, which follows the time variation of ground temperature.

3) As expected, the warming scenario plays important role in footing settlement and service time of infrastructure. This influence would become more visible after first 10 years. The time for transition from moderate settlement to accelerated settlement varies with temperature warming rate, around year 2030 for RCP8.5 vs. 2040 for RCP2.6.



(a) Stratigraphy with soil index properties. (Note: e: void ratio, ρ_s: soil grain density, k_s: soil grain thermal conductivity, c_s: soil grain thermal capacity)



(b) Footing settlement according to different warming scenarios

Figure 4. Soil stratigraphy in the simulation and settlement estimate

5 CONCLUSIONS

This study addressed some engineering challenges for the conduction of field footing test in remote permafrost region and have so far achieved satisfying test result. Although the test is in progress, several interesting conclusions can still be drawn from test results and numerical simulation.

1) Thermal disturbance is evitable during the construction and long-term field test. This is one of main reasons to initialize to build setup in wintertime. It causes an additional cooling of the adjacent ground, and several months were spent to recover back to the original ground temperature. Besides, some other efforts, such as the use of wooden piles and a tent as shelter, have been made to minimize the effect of artificial structure on permafrost disturbance during the test.

2) Temperature and load dependent settlement rate were found. Seasonal temperature variation and the tendency of future temperature rising result in the stepwise settlement in a short-term period (a year scale) and accelerated settlement rate in a long-term period (10-year scale).

3) As expected, the warming scenario plays important role in footing settlement and service time of infrastructure. This influence would become more visible after first 10 years. The time for transition from moderate settlement to accelerated settlement varies with temperature warming rate, around year 2030 for RCP8.5 vs. 2040 for RCP2.6.

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