



## Experimental studies of thaw consolidation of fine grained permafrost soils from the Mackenzie Valley

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### ABSTRACT

Thawing of permafrost is a major problem for construction in arctic regions. A large-scale laboratory study has been carried out to observe the thaw consolidation behaviour of fine-grained permafrost soils, which are commonly found in the Mackenzie Valley, for a case where the thawing soil consolidates under its own weight. Laboratory results are discussed in comparison to predictions obtained from numerical modeling that was carried out to predict the temperature and moisture migration behaviour, and in comparison to the thaw consolidation theory developed by Morgenstern and Nixon in 1971. Those results were found to be in reasonable agreement.

### RÉSUMÉ

Le dégel du pergélisol est un grand problème quant à la construction dans les régions arctiques. Une étude en laboratoire a été réalisée en mettant l'accent sur le comportement de consolidation durant le dégel du pergélisol à grains fins, qui est fréquents dans la vallée du Mackenzie, pour le cas où le sol est consolidé par son propre poids. Les résultats de laboratoire sont évalués en comparaison avec les résultats obtenus à partir de modèles numériques développés et de la théorie de consolidation lors du dégel développée par Morgenstern et Nixon en 1971. Les résultats sont raisonnablement comparables aux résultats théoriques.

## 1 INTRODUCTION

Permafrost underlies more than 50% of the ground surface in Canada (Johnston, 1981) and underlies most of the Mackenzie Valley (Aylsworth et al, 2000). Thawing of permafrost is a major problem for construction purposes in areas of continuous and discontinuous permafrost. The phenomenon of thawing can be associated with clearing or disturbance of vegetation, forest fires, construction activity, or heat transfer from pipelines.

Warming and thawing of the permafrost leads to thaw consolidation. In 1971, Morgenstern and Nixon proposed a thaw consolidation theory. Many engineering applications in permafrost regions require thaw consolidation theory for proper design and analysis; therefore it is important to verify its every detail. A laboratory study has been carried out with a focus on the thaw consolidation behaviour of fine-grained permafrost. Numerical models were developed to predict the temperature and moisture behaviour of the thawing soil samples. The laboratory apparatus used in this experimental study is discussed and the results are evaluated in comparison with the numerical models and the thaw consolidation theory.

## 2 THAW CONSOLIDATION

Thaw consolidation can be described as a volume reduction or change in void ratio resulting in settlement of frozen soils that are rich in ice, during a thawing period. This section discusses pore water pressures in thawing soils and a related thaw consolidation equation.

### 2.1 Pore Water Pressure

Thawing of ice-rich frozen ground leads to excess pore pressures, thus inducing a loss of strength and stiffness of the thawed zone (Saarelainen, 1999). When the ice in the soil thaws, excess pore pressures are generated due to subjected loading caused by the soils self-weight or a combination of self-weight and applied load. As we have a change in the hydraulic boundary condition of the soil, there is "an excess pore pressure setup relative to the final independent pore pressure state" (Lee et al., 1985).

The rate of settlement during thaw is dependant on the rate of pore water dissipation and compressibility characteristics of the soil (Brown and Johnston, 1970). If thawing occurs at a slow rate, settlement may proceed concurrently with thawing and result in minimal excess pore water pressure. However, if thawing occurs at a faster rate, excess pore pressures generated can be significant and have severe implications (Morgenstern and Nixon, 1971), such as slope instability or differential settlement.

### 2.2 Thaw Consolidation Theory

Thaw consolidation behaviour of a frozen soil is complex. Tsytovich (1960) appears to be the first to perform thaw consolidation tests, almost 50 years ago. Morgenstern and Nixon (1971) explored the settlement of a thawing soil from a theoretical standpoint. Using the theories of heat conduction and of consolidation, equations were formulated to determine the excess pore pressures of a one-dimensional soil configuration.

The following analytical solution of excess pore water pressure was assumed for a soil consolidating under its own weight:

$$u(x,t) = \frac{\gamma' x}{1 + \frac{1}{2R^2}} \quad [1]$$

Where  $u$  = excess pore pressure  
 $x$  = depth measured from the ground surface  
 $t$  = time  
 $\gamma'$  = submerged unit weight of the soil  
 $R$  = thaw consolidation ratio

The thaw consolidation ratio is calculated from Equation 2 below

$$R = \frac{\alpha}{2\sqrt{c_v}} \quad [2]$$

where  $c_v$  is the coefficient of consolidation, a measure of the soil compressibility and hydraulic conductivity.

In their approach, Morgenstern and Nixon found that the excess pore pressure distribution is linear for a given consolidation ratio for the case where the soil is consolidated by its own weight. Figure 1 shows a plot of the normalized values of excess pore pressures that have been computed.

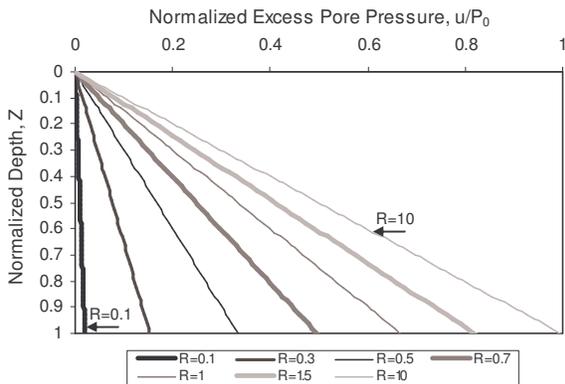


Figure 1. Normalized values of excess pore pressures for different thaw-consolidation ratios

### 3 EXPERIMENTAL STUDY

Through the years, the thaw-consolidation theory developed by Morgenstern and Nixon has been tested and confirmed. However, none have verified the solution of a linear pore pressure distribution for a given consolidation ratio for the case where the thawing soil is consolidated by its own weight. Also, small samples have always been used in laboratory experiments, from 32 mm

height for the analysis of the thaw consolidation theory (Morgenstern and Smith, 1973) to 300 mm height for periglacial solifluction analysis (Eigenbrod et al., 1996). Therefore, it is in our interest to measure excess pore pressures in a larger sample of frozen fine-grained soil (1 m height), which is less affected by the boundary conditions. This section discusses the details about the laboratory device and the experimental procedure.

#### 3.1 Laboratory Apparatus

Freeze-thaw tests have been carried out by developing a laboratory device to measure temperature and pore water pressures throughout a fine-grained soil sample while thawing takes place. The soil sample is contained in a 0.95 metre high and 0.15 metre diameter PVC cylinder, coated with Teflon to reduce side friction.

The device, as represented in Figure 2, allows thawing to take place starting from the top by subjecting the top surface to temperatures above freezing, and exposing the bottom of the soil column to freezing temperatures, as would occur during a natural soil thawing process. A silty clay/insulative system was placed surrounding the PVC cylinder to minimize boundary effects and to ensure uniform thawing from the top down and to reduce heat flow along the sides of the samples, as would occur in natural ground thawing conditions in permafrost regions. The inner layer of this system consists of a silty clay with similar grain size and moisture content as the core sample tested. The outer layer of the system was created using Thermocell loose-fill insulation.

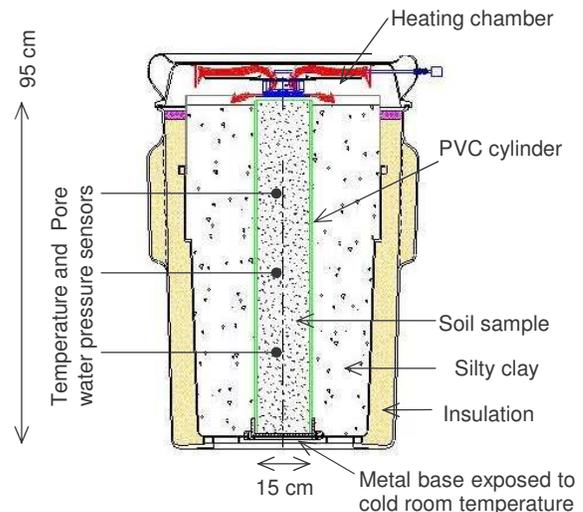


Figure 2. Thaw consolidation experimental device

Three (3) PDCR-81 pore pressure transducers and three (3) K-type thermocouples were inserted along the sides of the sample, at three different depths (i.e., 30 cm, 50 cm and 70 cm from the top), in order to measure pore water pressures and soil temperatures during the course of thawing. The data is collected using a data logger.

Thawing of the soil sample is generated from a boxed-in heat source and ventilation system, which is located at the top of the sample and silty clay/insulative system, as shown in Figure 2. As this heat source is contained, humidity will build up in the box, therefore additional tubes were installed in the heating box leading to an adjacent room to create air circulation and disposal of this humidity.

### 3.2 Laboratory Testing

Unidirectional thawing tests have been carried out on three samples of disturbed silty clay from the Mackenzie valley. The samples were prepared to have a moisture content of about 40%, which is the moisture content that has been typically observed at depths between the active layer and the permafrost layer. This therefore represents a typical fine-grained soil in the Mackenzie valley, where the upper soil layer undergoes annual freezing and thawing.

The soil specimens were frozen in PVC cylinders under closed system conditions. Freezing took place by placing the freeze-thaw laboratory device in a cold room which kept a constant temperature of -4 degrees Celsius. The samples were allowed to freeze for a period of 15 days or until the thermocouples indicated that the soil temperatures were below -4 degrees Celsius. Once the samples were fully frozen, a boxed-in heat source was applied on the top of the sample to allow thawing to take place. Thawing temperatures were set to 25 degrees Celsius and thawing was complete after 16 to 29 days.

## 4 NUMERICAL MODELLING

Numerical modelling was carried out to predict the temperature and moisture behaviour of the thawing specimens. The models were developed using two finite element software, Temp/W and Vadose/W, developed by Geo-Slope International, which are presented in the following sections.

### 4.1 Temperature Modelling with Temp/W

Temp/W software was used to predict the temperature behaviour throughout the soil samples during the thawing process. Temp/W is a two-dimensional finite element software that simulates the thermal behaviour of geomaterials.

The Temp/W model was developed to represent the experimental system including the core sample and the surrounding silty clay. The boundary conditions were established based on the temperature, heat flow and other conditions imposed on the soil specimens. The soil parameters used in the analysis are presented in Tables 1 to 4, inclusively, and were established based on some laboratory testing and on various sources: Krahn (2004), Das (2004), Terzaghi et al. (1996), Tarnawski & Wagner (1993), Smith and Riseborough (1985), Goodrich (1982), McRoberts and Morgenstern (1974), Isaacs (1974), Zoltai and Pettapiece (1973), U.S. Department of Navy (1971), Penner (1970), and Kersten (1948).

The thermal analysis was conducted in two stages. First, a steady-state model with constant freezing temperatures was setup in order to set the initial temperature conditions for a subsequent transient model. Next, a transient model was setup using the results of the steady state model as its initial conditions. A temperature of -4°C was applied to the lower boundary of the transient model. The climate boundary conditions presented in Table 5 were applied to the upper boundary of the transient model in order to represent the conditions presented from the heating chamber.

Table 1. Soil parameters used in the analysis.

Dry unit weight, $\gamma_d$ (kN/m <sup>3</sup> ) - measured	13.03
Unit weight, $\gamma$ (kN/m <sup>3</sup> ) - measured	18.24
Initial gravimetric water content, w(%) - measured	40
Void Ratio, e - measured	1.03
Specific gravity, $G_s$ - measured	2.7
Hydraulic conductivity, k (cm/s) - estimated	$10^{-5}$ (silt) - $10^{-7}$ (clay)
Coefficient of volume compressibility, $m_v$ (m <sup>2</sup> /kN) - estimated	$1 \times 10^{-5}$
Coefficient of consolidation, $c_v$ (cm <sup>2</sup> /s) - estimated	$1.4 \times 10^{-3}$ - $1.6 \times 10^{-4}$

Table 2: Soil thermal conductivity, K (W/m·°C).

°C	-10	-5	-3	-2	-1	0	1	3
K	2.35	2.27	2.18	2.09	1.91	1.39	1.39	1.39

Table 3. Unfrozen water content function,  $\theta$  (by volume)

°C	-10	-5	-4	-3	-2	-1	-0.5	0	0.2	0.5
$\theta$	0.115	0.13	0.15	0.2	0.3	0.6	0.9	1	1	1

Table 4. Volumetric heat capacity and water content.

Volumetric heat capacity, C (kJ/m <sup>3</sup> /°C)		Volumetric water content, $\theta$
Frozen	Unfrozen	
2050	2450	0.52

Table 5. Climate boundary conditions.

Temperature (°C)	Relative Humidity (%)	Wind (m/s)	Precipitation (mm)	Potential evaporation (mm/day)
25	50	3	0	8

As the effectiveness of the insulation was unknown, two different models were tested to represent the temperature behaviour in the thawing soil. The first model was developed by applying temperature boundary conditions to the sides of the model, which would represent a case without insulation. The second model

was developed with applying a no heat flow condition to the lateral boundaries, which would be the case if the insulation would have been fully efficient. The results were expected to fall within the envelope created by these two models.

4.2 Moisture Modelling with Vadose/W

Vadose/W software was used to predict the hydraulic behaviour throughout the soil specimens during thawing. Vadose/W is a two-dimensional finite element software that simulates the behaviour of water flow through saturated and unsaturated geometerials by taking into account of evaporation, evapotranspiration, and other environmental parameters.

The Vadose/W model was developed to predict the hydraulic behaviour of the core sample. The soil parameters used in the analysis are those presented in Tables 1 to 4.

The hydraulic analysis was also conducted in two stages. First, a steady-state model was setup in order to set the initial moisture conditions (40%) for a subsequent transient model. Next, a transient model was setup using the results of the steady state model as its initial conditions. A temperature of -4°C was applied to the lower boundary of the transient model and the climate boundary conditions given in Table 5 were applied to the upper boundary.

As presented in Table 1, the hydraulic conductivity used for the analysis ranged from  $10^{-5}$  cm/s to  $10^{-7}$  cm/s, which represents typical values for silt and clay. The results for the silty clay samples were expected to fall within this range.

5 RESULTS

A heave of 4.2 cm, 3.5 cm and 2.8 cm was observed at the end of the freezing process and a settlement of 9.3 cm, 5.0 cm and 8.4 cm was observed at the end of the thawing process, for sample #1, sample #2 and sample #3, respectively. The heave and settlement values were measured with respect to the initial top of the soil columns (i.e., 95 cm height).

This section provides an analysis of the moisture, temperature and pore pressure results obtained during the laboratory experiments with respect to numerical and theoretical predictions.

5.1 Moisture migration

Figures 3 and 4 present the volumetric moisture content measured within the silty clay soil in sample #1 and #2 after 16 days of thawing, and in sample #3 after 29 days of thawing, respectively, which is the amount of time the samples were allowed to thaw.

Both figures present an upper limit case and a lower limit case for the silty clay, corresponding to the hydraulic conductivity values of clay and silt, respectively, as well as a dashed line representing the numerical results with a hydraulic conductivity that best fit the experimental data.

The figures illustrate that Vadose/W was successful in predicting the moisture conditions observed during the

laboratory experiments. From the shape of the curves, it is shown that the soil is relatively dry at the top of the soil column following the thaw consolidation process, which is a result of evaporation. A crust in the upper portion of the soil sample was observed after the test. This was the result of soil moisture loss. The soil moisture loss also caused substantial settlement of the soil columns mentioned earlier.

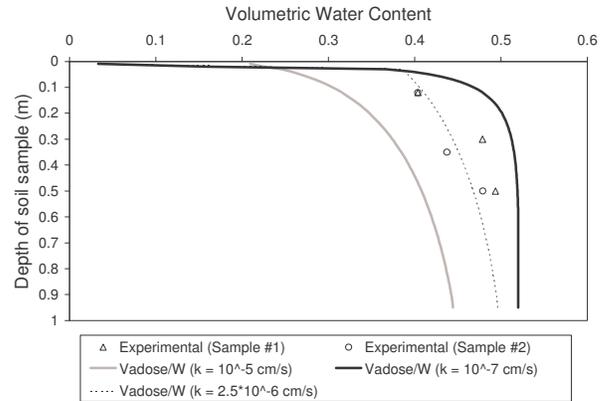


Figure 3. Experimental (samples #1 & #2) and theoretical moisture contents after 16 days of thawing

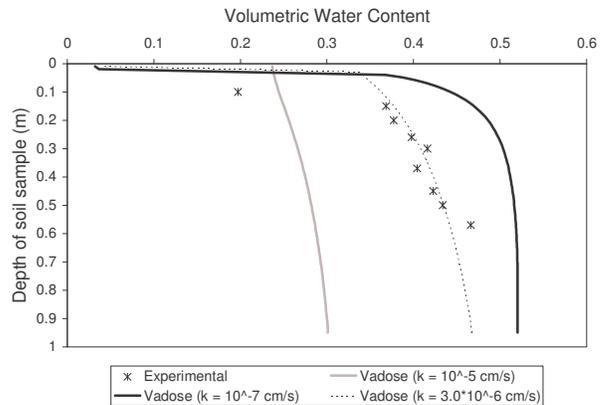


Figure 4. Experimental (sample #3) and theoretical moisture conditions after 29 days of thawing

5.2 Thermal behaviour

Figures 5 and 6 present the temperature results that were obtained from the k-type thermocouples embedded in the silty clay soil in sample #1 and #2 and in sample #3, respectively, as well as the cold room temperature during the course of thawing. In addition, Figure 6 presents the temperature in the heating chamber during the test period. The results from sample #1 and sample #2 are very similar as they were performed at the same time, under the same freezing and thawing conditions.

As expected, the soil closest to the heating chamber was thawing more rapidly. From Figure 5, it was determined that the thaw front had reached 30 cm and 50 cm after 3.1 days and 9.2 days of thawing, respectively, in both sample #1 and sample #2. From Figure 6, it was determined that the thaw front had reached 30 and 50 cm after 2.95 days and 10.75 days of thawing, respectively, in sample #3. Both figures show that the thaw front had not yet reached 70 cm when the soil temperatures had stabilized.

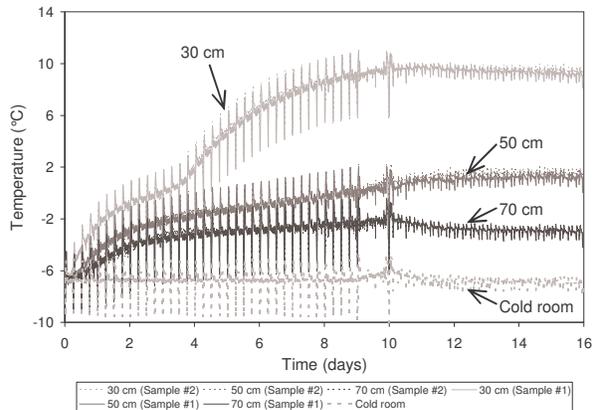


Figure 5. Experimental temperature results during thawing of samples #1 and #2

From these results, it was found that the soil located at 30 cm depth was thawing almost four time quicker than the soil located at 50 cm depth. For example, the silty clay from sample #3 was thawing at rates of 1.1°C/Day and 0.3°C/Day for soil located at a depth of 30 cm and 50 cm of the soil column, respectively.

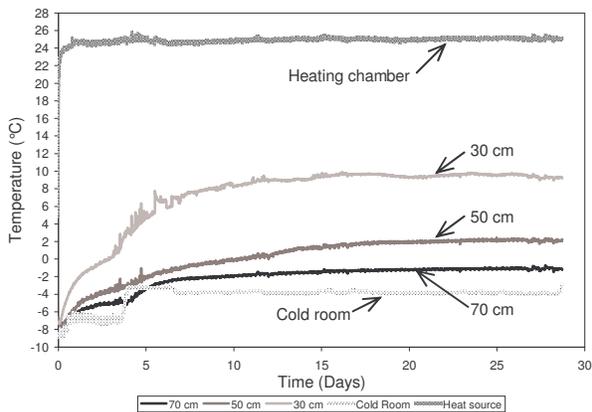


Figure 6. Experimental temperature results during thawing of sample #3

Figures 7 and 8 present these temperature results in comparison to the results obtained from the Temp/W analysis for samples #1 and #2 and for sample #3, respectively.

From these figures, it is shown that the thawing was taking place as anticipated in all soil samples, as all experimental data points fell within the thawing temperature envelope that was obtained from the finite element models with two extreme insulation cases. Furthermore, the results indicate that the insulation system that was established only worked to a certain extent.

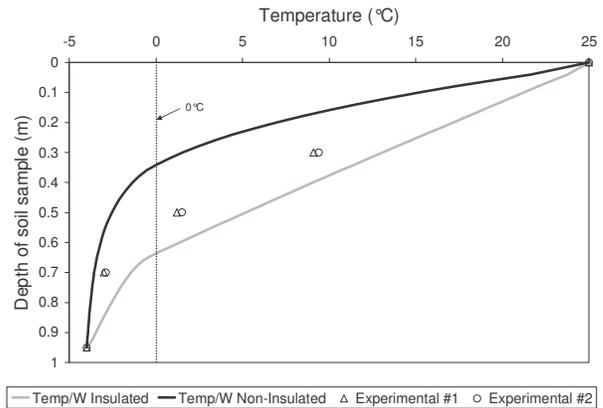


Figure 7. Thawing temperature envelope and results for samples #1 and #2 after 16 days of thawing

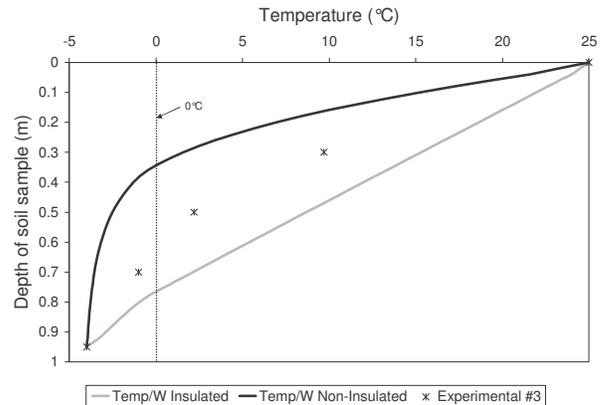


Figure 8. Thawing temperature envelope and results for sample #3 after 29 days of thawing

From the temperature results, the position of the thaw front at a certain time during the course of thawing was calculated using the following Neumann solution:

$$X(t) = \alpha \sqrt{t} \quad [3]$$

Where  $X$  = depth to the thaw plane  
 $\alpha$  = a thermal constant determined in the solution of the heat conduction problem  
 $t$  = time

Table 6 presents the average value of  $\alpha$  that was determined for known values of  $t$  and  $X$  for a surface temperature of 25°C for the third thaw consolidation test. The results show that the  $\alpha$  value is higher for the soil located at the 30 cm depth than for the 50 cm depth. It should be noted that the relationship between thaw depth and time is a complex issue that can be affected by various other conditions, e.g., boundary temperatures, soil moisture changes and other soil property changes due to consolidation. Discussions about this are beyond the scope of this paper. Due to limited data and for simplicity, Equation [3] is used here as adopted by Morgenstern and Nixon (1971) in derivation of their thaw consolidation equations. Further discussions about this issue can be found in Nixon and Morgenstern (1973).

Table 6. Thermal constant determination.

$X$ (m)	$t$ (year)	$\alpha$ (m/y <sup>1/2</sup> )
0.30	0.0079	3.3656
0.50	0.0280	2.9881

### 5.3 Pore pressure

This section presents an analysis of the excess pore water pressure (pore water pressure reading minus the static pore water pressure) results obtained during the third thaw consolidation test. Figure 9 presents the experimental results obtained during the thawing period.

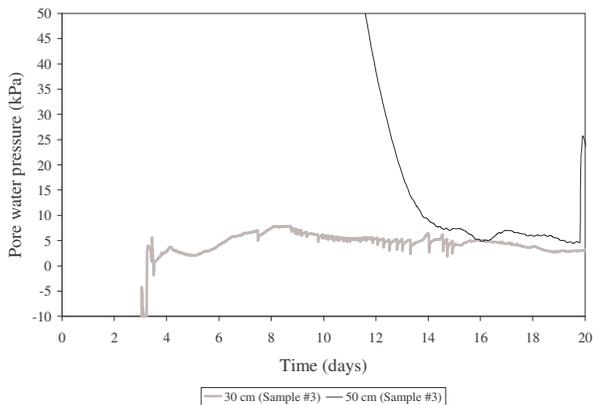


Figure 9. Pore water pressure results at 30 cm and 50 cm depths during thawing of sample #3

From Figure 9, it is shown that the sensors did not begin to pick up pore pressure until after 3.3 days and 14.5 days of thawing, at 30 cm and 50 cm depth, respectively. This is longer than the time it took for the soil to reach the 0°C isotherm at those two locations, as discussed in section 5.2. From the temperature analysis, it was found that the soil at 30 cm depth was thawing

almost four times quicker than that at 50 cm depth. It is therefore reasonable to state that it was taking much longer for the pore ice to turn to pore water at 50 cm depth than at 30 cm depth.

From Equation [1], the simplified pore pressure equation derived by Morgenstern and Nixon (1971), the respective excess pore water pressures were calculated for the two depths measured in the laboratory (i.e.,  $x = 30$  cm and 50 cm depth from the soil surface).

The pore pressures were calculated using the coefficient of consolidation range given in Table 1 and the  $\alpha$  values presented in Table 6. The range of excess pore pressure calculated for each depth are plotted in Figure 10, along with the actual excess pore pressures measured experimentally.

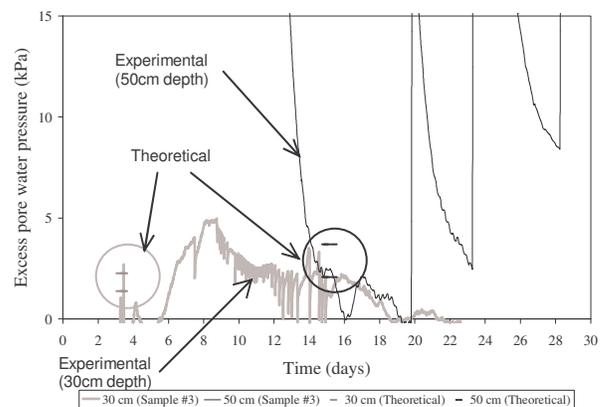


Figure 10. Theoretical and experimental excess pore water pressure

The excess pore pressures calculated from Equation [1] represent the initial value of excess pore pressure that is generated at the moment when the pore ice changes to water. Figure 10 shows that the generated excess pore pressures were equal to about 2.69 kPa for the 30 cm sensor and 2.45 kPa for the 50 cm sensor after 3.45 days and 15.00 days of thawing, respectively. Figure 10 provides evidence that these values fall within the excess pore pressure range calculated from Equation [1].

It can be seen from the shape of the pore pressure curves that there were sudden spikes and drops of pore pressure throughout the thaw consolidation process. The exact reason for this behaviour is unclear, however it may be due to the ice-water phase change, the formation of a crust at the top of the soil sample caused by evaporation, shaft friction between the soil and the PVC column, and/or the accuracy of the sensors.

It should be noted that the thaw consolidation theory by Morgenstern & Nixon (1971) does not take into account the behaviour of water flow through unsaturated soils, which is the case in the field as well as with the laboratory models discussed in this paper. However, the

theory is considered conservative for engineering applications.

## 6 CONCLUDING SUMMARY

The thaw consolidation theory developed by Morgenstern and Nixon (1971) calculates thaw induced excess pore water pressures by considering two loading conditions: (1) soil consolidates under surface loading excluding the material self weight; and (2) soil consolidates under its own weight. Laboratory verification of the first part of the equation was previously reported by the original developers. This paper presented a laboratory verification of the second part of the equation with relatively large scale soil columns to simulate thaw consolidation of the soil under its own weight. Finite element models were used to verify the effectiveness of the laboratory models. In particular, the thermal and soil moisture migration conditions were simulated numerically to understand the boundary effect with the laboratory model. The numerical results confirmed that the laboratory model could simulate the field conditions reasonably well for the purpose of verifying the thaw consolidation theory. The thermal behaviour and the soil moisture condition changes of the laboratory models are within the expected range. The boundary conditions applied to the laboratory model are effective to a reasonable extent. Given the uncertainties associated with the boundary constraints, accuracy of the pore water pressure sensors and the ice-water phase change behaviour, the laboratory results obtained are reasonably agreeable with the theoretical values.

However, it must be recognized that the thaw consolidation theory is based on idealized thawing conditions, i.e., assuming ice changing to water at the 0°C thaw line. In reality, there is a phase change zone around the 0°C isotherm, within which pore ice only partially changes to water. While the remaining ice is melting, pore water pressure dissipates as well. Therefore, pore water pressures measured at the thaw front should not be expected to exactly match the theoretical values.

It was observed from both the laboratory models and the numerical analysis results that the upper layer soils become unsaturated due to evaporation. This is almost always the case in the active layer in permafrost ground. Further development of the thaw consolidation theory is therefore necessary to take into account water flow through unsaturated soils.

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