Thermal Numerical Modeling of Transmission Tower Foundations in Northern Manitoba

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ABSTRACT
Design of structural foundations on permafrost requires careful consideration. Changing ground cover affects the thermal regime and may cause permafrost degradation. This may lead to reduced bearing capacity for structures, lateral spreading of embankments, and large settlements. Transmission line towers for the Radisson-Churchill line in Northern Manitoba used synthetic polystyrene (geofoam) in an insulated foundation design. Ground temperatures were monitored during 1987-1990 as part of a thermal monitoring program. Recent studies have improved the understanding of the performance of geofoam insulated foundations. Using the temperature distributions measured earlier, assumed thermal properties, and relevant climate data, numerical modeling was developed to simulate field performance of the foundations.

RÉSUMÉ
La conception de fondations structurelles sur le pergélisol exige des considérations spéciales. La végétation changeante qui recouvre le sol affecte le régime thermique et peut causer la dégradation du pergélisol. Ceci peut mener à une réduction dans la capacité du sol à soutenir les structures, de l'étalage latéral des remblais, et de grands tassements de terrain. Les tours de transmission pour les lignes de Radisson-Churchill au nord du Manitoba ont utilisé du polystyrène synthétique (''Geofoam'') dans leur conception d'une fondation isolée. De 1987 à 1990, les températures du sol au nord du Manitoba ont été surveillées comme partie d'un programme de surveillance thermique. Ces études ont amélioré la compréhension de la performance des fondations isolées par ''Geofoam''. En utilisant la distribution des températures mesurées, les propriétés thermiques supposées, et les données de climat pertinentes, la modélisation numérique a été développée pour simuler la performance réelle des fondations.

1 INTRODUCTION

Frost heave and permafrost degradation are major concerns in foundation design in northern regions. Structural foundations in cold climates must extend below depths of expected frost penetration to protect against frost heaving. In addition, when warm structures are brought in contact with permafrost, the resulting thawing (permafrost degradation) causes reduction in soil bearing capacity and can lead to large settlements.

The most northern line constructed by Manitoba Hydro, the Radisson-Churchill transmission line, extends from Gillam to Churchill (Figure 1). The freezing indices for Gillam and Churchill are approximately 3300°C-days and 3890°C-days, respectively. In comparison, the freezing index in Winnipeg is 1950°C-days. The transmission line traverses areas of both discontinuous and continuous permafrost. The ground is mostly muskeg with thickness varying from a few centimetres to a few metres in depth. The muskeg overlies a mineral clay deposit. Surface drainage varies from fair to poor; the region contains many scattered lakes.

Manitoba Hydro used a guyed tower design for this transmission line and adapted it as necessary for variable soil conditions along the route. The design consisted of a single hollow steel tower founded on wide flange beams connected to a timber footing (Figure 2). Footings were underlain by insulation and granular fill. The steel tower is supported by guy wires.

Manitoba Hydro successfully used synthetic foundations insulated with polystyrene (geofoam) for the towers on the Radisson-Churchill transmission line. The

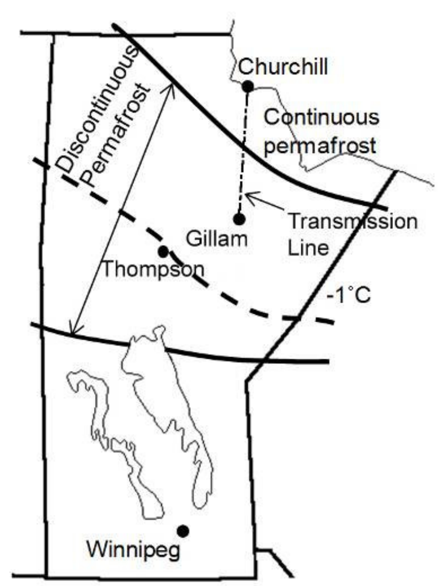


Figure 1. Location of transmission line and permafrost in Manitoba, Canada.

objectives in using the insulation were (1) to reduce permafrost degradation in foundations in the warmer southern portions of the transmission line and (2) to help prevent frost heaving in the colder northern portions.

Empirical methods are often the basis for deciding on the thickness and lateral extent of the insulation in these insulated foundations, though numerical modeling is being used increasingly. Issues that need to be considered during design include factors such as variable surface thermal conditions, soil moisture contents, thermal conductivity, latent heat associated with the changes in water phases, and the complex nature of layered composite systems, among others. A primary issue relates to the structural steel section acting as a heat conductor directly to and from the tower footing. Extensive numerical analysis is required if the interaction between these factors is to be understood. Figure 2 shows a simplified diagram of a typical tower foundation.

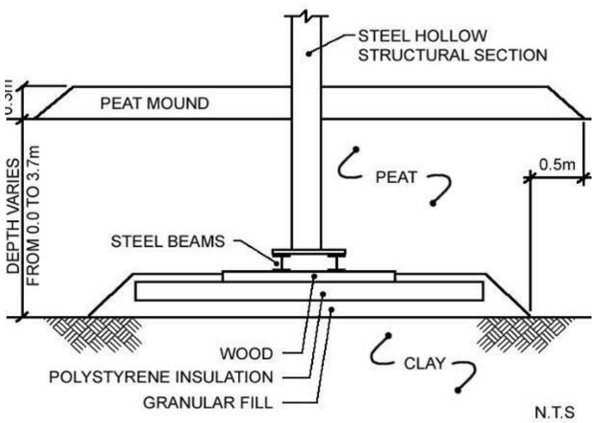


Figure 2. Typical foundation design (re-plotted after Staudzs, 1986).

This study focused on potential permafrost degradation in the foundations for the Radisson-Churchill transmission line towers and the thermal effectiveness of the chosen foundation design. Following sections of the paper present the results of preliminary numerical modeling of the thermal effects of climate on the transmission tower foundations. The results will be expanded in subsequent studies to include effects of groundwater and settlements in the development of an elastic thermo-plastic model.

2 DEFINING THE NUMERICAL MODEL

2.1 MATERIAL PROPERTIES

Thermal modeling of the tower foundations requires input of the frozen and unfrozen volumetric heat capacities (C_F and C_U) and thermal conductivities (k_F and k_U). The in-situ volumetric water content is also required. These preliminary modeling parameters, summarized in Table 1, have been selected from the literature. Data for peat, clay, and gravel were based on publications by Andersland and Ladanyi (2004), the Departments of the United States Army and Air Force (1988), Farouki (1986), Thiessen (2003), and Zhao et al. (2001). The selected values are for materials that were assumed to be near full saturation. Properties of steel were obtained from many of the same sources. Thermal properties of standard high-density expanded polystyrene insulation were taken from Horvath (1995), and Andersland and Ladanyi (2004). Softwood was assumed for the wood/timber layer. The difference in thermal properties between hardwoods and softwoods was viewed as negligible for this application.

Table 1. Material properties and test temperature

Material	C_U (kJ/m^3/°C)	C_F (kJ/m^3/°C)	Vol. WC (m^3/ m^3)
Peat	3707.9	1999.2	0.840
Clay	3408.9	2212.8	0.520
Gravel	4118.0	3380.0	0.140
Insulation	37.5	37.5	0.004
Wood/Timber	1300.0	1300.0	0.020
Steel	3750.0	3750.0	0.000

Material	k_U (kJ/d/m/°C)	k_F (kJ/d/m/°C)
Peat	47.85	155.52
Clay	95.00	157.25
Gravel	242.00	346.00
Insulation	3.00	3.00
Wood/Timber	13.00	13.00
Steel	3900.00	3900.00

2.2 CROSS SECTION AND MODEL DESIGN

Modeling assumed that the foundations were axisymmetric. This simplification allowed efficient modeling and fewer numerical instabilities. Figure 2 shows that footing depths varied from zero (0.0m) to 3.7m. This reflected site variability between Gillam and Churchill. In this paper, 'footing,' refers to the combination of the gravel, insulation, and wood materials. 'Foundation' refers to the whole system, including the footing and surrounding soil.

Two configurations, Figures 3a and 3b, were used to reflect the extremes in the design depths. Both maintain a 0.3m peat layer over the foundation and extend 0.5m past the outer edge of the footing (Figure 2). In addition, the foundation was simplified by disregarding the steel beams. Dimensions of the insulating sheet at depth 3.7m were approximately 2.5m x 2.5m. An initial insulation length of 1.25m was used. Construction reports suggested that the area of the insulation varied with depth, though details were not given. Both models were assumed to have the same insulation. The deep and shallow foundation models were primarily analyzed without the addition of the hollow structural steel section shown in Figure 2. Reasons for this decision are discussed in Section 3.2.

The mesh of finite elements in the models extended outwards 20.0m from the centreline of the model and to a depth of 11.5m from the surface. (Only shorter distances are shown in later figures. Small elements were used near the foundation and the ground surface for added precision. To reduce modeling time, larger elements were used away from areas of principal interest.

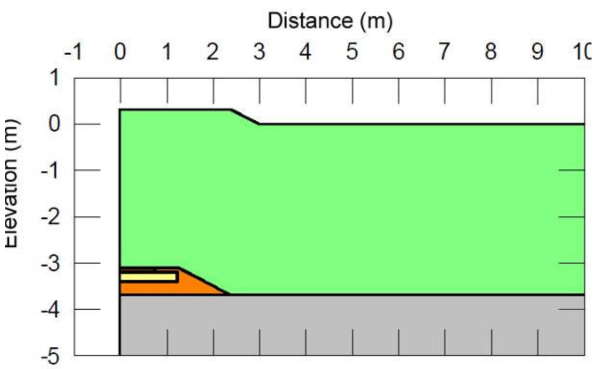


Figure 3a. Model Design, Deep Foundation

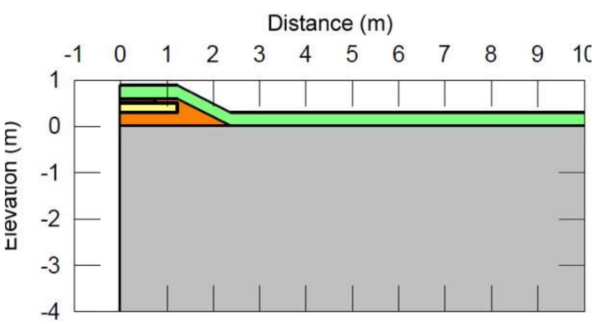


Figure 3b. Model Design, Shallow Foundation

2.3 BOUNDARY CONDITIONS

Modeling was completed in two phases: firstly steady-state and then transient. The first phase was used to obtain initial isotherms for the second phase that used measured climate data. The steady-state analysis assumed zero heat flux (q = 0) along the leftmost (centerline) boundary. The first day's climate data was applied along the ground surface. Constant temperature was assumed along the bottom boundary. .

With increased depth, ground temperatures are affected less by climate and more by the Earth's temperature gradient. The constant temperature boundary condition was chosen from thermistor data from transmission towers near Gillam. The data varied considerably but, based on a slow warming trend in the ground, a range from -1°C to +1°C was chosen. The selected range is discussed further in Section 3.2 which examines differences between frost degradation and ground that is actively freezing.

The transient analysis maintained the top boundary as a climate boundary and the left boundary as having zero heat flux. This allowed fluctuations in temperature, relative humidity, wind and precipitation to be taken into account. The previous constant temperature along the bottom boundary was now replaced with infinite elements. The rightmost boundary at 20.0m from the centreline did not have an applied boundary condition due to the nature of the surface material elements needed for incorporating climate data. Analysis showed that the fluctuations of the 0°C-isotherm, or frost line, along this boundary were minor and considered insignificant (Kurz et al. 2008).

2.4 CLIMATE DATA

Climate data were obtained from the Gillam A weather monitoring station on Environment Canada's website. They correspond to 21 years of data between April 1, 1987 and March 31, 2008. The data were compiled and summarized for input into TEMP/W. They include maximum and minimum values of daily temperatures, relative humidities, average daily windspeeds, and total daily precipitation (water equivalent). The latitude of the monitoring station, 56.2° N, was chosen for the modeling. The distribution pattern of the climate over the day was chosen as a Constant Averaged distribution. This pattern is well suited for quick analysis of multiple design options.

The Canadian Centre for Climate Modelling and Analysis (2003) has several models that permit climate prediction and variability. This project will use the Second Generation Coupled Global Climate Model (CGCM2) which couples the atmospheric (AGCM2) and ocean components with the effect of greenhouse gases and other aerosols. Although not presented in this paper, this model will be used to analyse the influence of global warming on future foundation performance. Figure 4 shows reasonable agreement between measured and simulated averaged daily temperatures. The daily temperature range in the area is considerably larger than the average values shown in Figure 4. Extreme values reach +30°C in summer and -40°C in winter.

3 RESULTS AND ANALYSIS

3.1 CALIBRATION

The foundation models were calibrated so their output conformed to temperatures collected from thermistors in

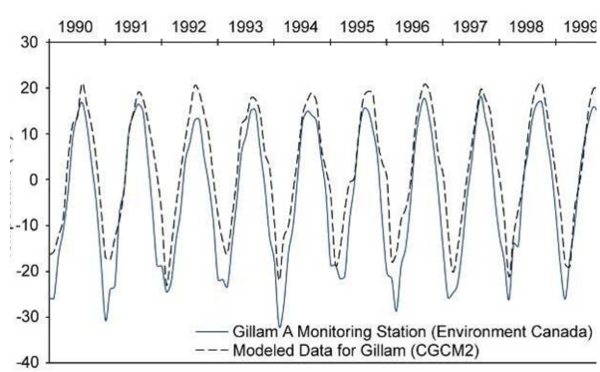


Figure 4. Measured and Simulated Temperature Data, Gillam A Station, Model CGCM2

the earlier field program. As discussed in Section 2.1, the material parameters were all based on previous research on similar materials in the literature. The parameters were then tested in the calibration exercise and adjusted as necessary to improve the agreement between modelled and measured values. Further improvements can only be obtained from laboratory tests on actual materials near the tower foundations. Thermistor data from transmission line tower #45 (Figure 5.) were chosen as the primary basis for model calibration - the data were complete and were considered consistent. Figures 5a and 5b show good agreement between the simulated and measured results.

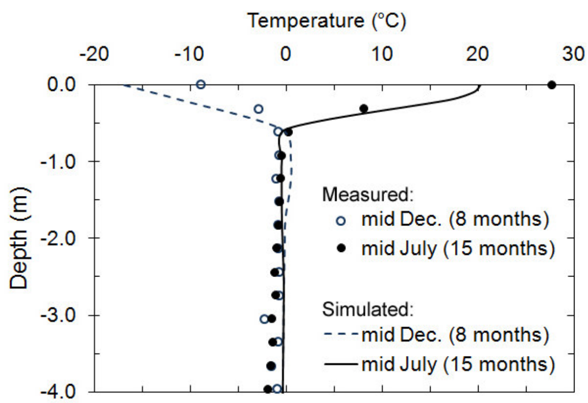


Figure 5a. Model Calibration, Deep Foundation

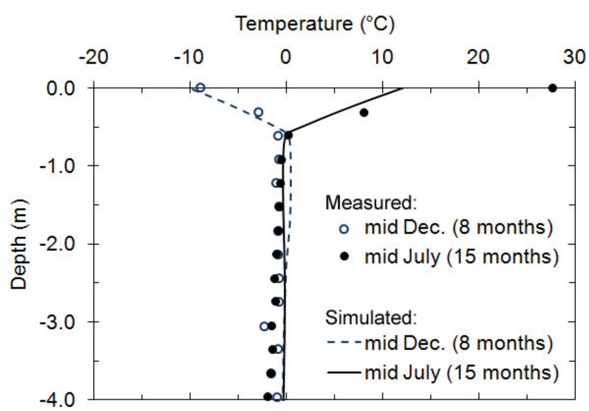


Figure 5b. Model Calibration, Shallow Foundation

3.2 PARAMETRICS

Parametric studies were used to better understand the effects of the modeling parameters on the foundations of the towers. The primary study stems from the original foundation design and the range of footing depths shown in Figures 3a and 3b. A second parametric study involved increasing the length of the insulation layer by 60 per cent and analyzing potential frost degradation as a function of footing depth.

Models were analyzed with and without the hollow structural steel sections (Figure 2) to investigate the possible effect of direct heat input and output on the foundation. These models also analysed radial thawing and freezing above the footing due to heat transfer along the length of the steel section. The steel sections were not included in the base models because data regarding the impact of direct sunlight, climatic effects, and heat dissipation on the steel have not been quantified.

Varying the temperature boundary condition at the bottom of the models between -1℃ and 1℃ allowed analysis of frost degradation and frost penetration. With a -1°C boundary, the models were assumed to be frozen. This allowed analysis of potential permafrost degradation in the tower foundations. Application of a 1℃-boundary allowed analysis of frost penetration and ground freezing due to the onset of winter.

The final parametric study involves alteration of the climate data between measured values and values predicted by the CGCM2 climate model. This will allow simulation of future performance of the foundation. This work is still in progress and is not presented here.

3.3 RESULTS

3.3.1 DEEP FOUNDATION

The models for the deep foundation (depth 3.7m) indicated no permafrost degradation, outside of the active zone, that would cause an adverse effect on the performance of the superstructure. With no steel in the foundation, the maximum depth of the active zone, below ground surface, was observed to be 1.3m near the footing and tapered off to approximately 1.65m further from the centreline. This difference of nearly 0.4m in the elevation of the frost line is attributed to the insulating effect of the peat mound placed on the ground over the tower foundation. With the exception of the model with steel in the foundation, an increase in insulation length was found to have a negligible effect on the deep foundations.

As mentioned earlier, the addition of steel allows transfer of heat directly to and from the foundation of the tower. Figure 6 illustrates the effect of steel on the foundation after summer heating. The modeled isotherms indicate that the insulation is sufficient to resist applied

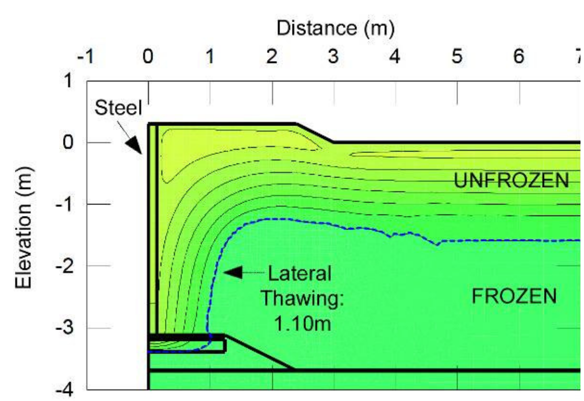


Figure 6. Deep Foundation, Steel, mid Sept.

heat from the climate data. Heat is, however, radiated laterally into the peat to a distance of 1.1m from the steel. The results show that the applied heat is not sufficient to flow around the insulation length of 1.25m and cause thawing beneath the footing. With the onset of winter, the steel acts as a heat sink, allowing the heat in the ground to dissipate faster. This permits the ground adjacent to the tower to freeze more quickly. An increase in the insulation length for this model helps maintain the frozen ground beneath the footing.

Use of a -1°C boundary condition indicated that the active zone in the peat would slowly decrease by less than 0.05m per year. As expected with the thermal properties of the peat and clay, these materials promote ground freezing. Use of a +1°C boundary condition indicated comparable results, but with an increase in the active zone due to ground freezing. These results are discussed further in Section 4.0.

3.3.2 SHALLOW FOUNDATION

The models of shallow foundation (depth 0.0m) suggest degradation of annual frost that may potentially have adverse effects on the performance of the superstructure. Due to the shallow depth of the foundation, the maximum depth of thawing is decreased from a depth of approximately 1.7m at a distance of 4.0m from the centreline to about 1.1m below the footing (Figure 7a). Thawing that takes place in the summer months, and the possibility that the frost line will be uneven, may result in differential settlement of the tower foundation.

Given the relatively high thermal conductivity of the gravel base beneath the footing, lengthening the insulation would provide a longer path for the heat to travel from the surface into the ground beneath the centreline of the foundation, thereby dissipating heat more quickly. Figure 7b indicates that lengthening the insulation by 60 per cent results in an additional decrease of 0.5m in the maximum depth of thawing. The thickness of the thawed soil is 0.6m.

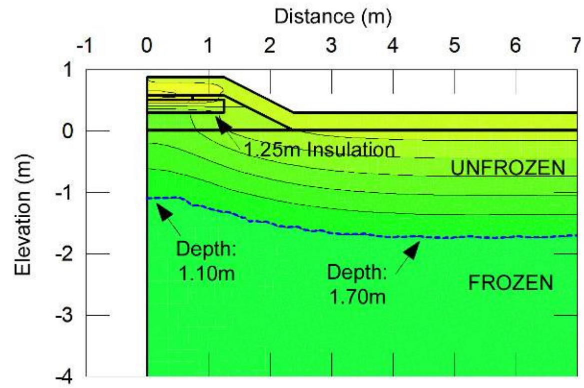
As expected with the addition of steel, lateral heat radiation was not observed as it was in the deep foundations, due to the depth of the footing. Analysis shows that the application of steel has negligible effect on the isotherms (Figures 7b, 7c). The isotherms beneath the footings for each of the respective lengths of insulation were nearly identical to the models with and without steel.

Use of both a -1°C and +1°C boundary condition indicated similar results to that of deep foundations and the promotion of ground freezing.

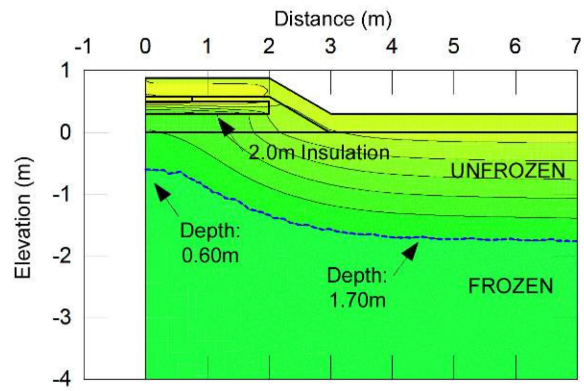
4 DISCUSSION AND RECOMMENDATIONS

The numerical modeling adequately reproduced seasonal ground temperatures of tower foundations for the Radisson-Churchill transmission line. The models assumed typical thermal properties for the foundation soils. Parametric studies indicate key areas that warrant more study.

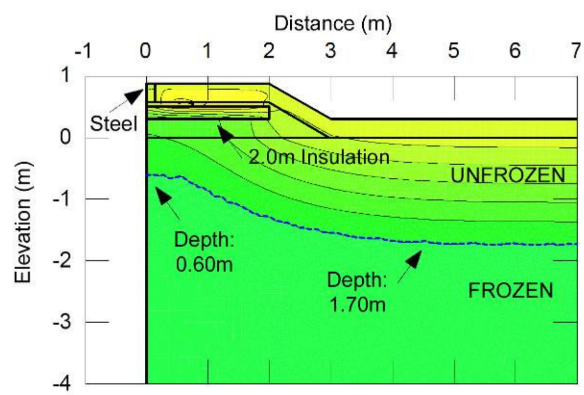
The deep foundation (depth 3.7m) appeared adequate. Analysis suggested negligible effects on the permafrost aside from annual fluctuations in the active



igure 7a. Shallow Foundation, Base Model, mid Sept.



igure 7b. Shallow Foundation, Lengthened Insulation, nid Sept.



igure 7c. Shallow Foundation, Steel and Lengthened nsulation, mid Sept.

zone. Fluctuations in the 0°C-isotherm were entirely contained within the peat layer.

The shallow foundation (depth 0.0m) presented results that the active zone can reach a depth of 1.7m in unaltered soil but is limited to no more than 1.1m below the tower footing. This difference is attributed to the insulation preventing the input of heat into the foundation from the climate data. Additional research into deformations and stability of the foundations and towers is required, with respect to temperature gradients. This will help to determine if annual thawing of the soil near the tower footings may be troublesome.

Increasing the length of the insulation in the shallow foundation models produced a significant reduction in the depth of thawing. The models show that heat flows over a longer path, thereby providing more time to dissipate. It also reduces the potential for thawing beneath the foundation. In contrast, increasing the length of the insulation in the deep foundations apparently had no effect. This means that foundation designs can be altered to account for the areal dimensions of the insulation as a function of the foundation depth. Shallow and deep foundations can use larger and smaller areas of insulation, respectively. This may permit optimization of construction costs.

Introducing steel members had little effect on isotherms beneath the insulation for both deep and shallow foundations. However, the steel did significantly affect temperatures in soil above the footing. Future changes in surface climate and inclusion of a heat source, will alter results of the numerical modeling. Additional research is recommended to quantify the thermal effect of steel in the foundations, identify potential stability or drainage issues related to radial thawing, and identify possible remedial measures.

The significance of the various climate data parameters needs to be established. Despite reasonable correlation between simulated and actual temperatures, there are differences between the predicted climate model and actual climate data. Effects of humidity, wind speed, and precipitation require further study.

Thiessen (2003) described the insulating effect of a peat layer on permafrost and the relationship between the thermal conductivity and high water content. Considering that the modeled peat layer has high volumetric water content and that the latent heat of fusion for water is approximately 334 kJ/kg (at 0°C), it becomes evident that peat absorbs more heat energy and requires more time to thaw than other soil types in the model. As indicated in Table 1, more heat flows when the peat is frozen (k_F = 155.52 kJ/d·m·°C) as opposed to thawed (k_U = 47.85 kJ/d·m·°C). These thermal conductivities, however, depend strongly on the water content of the soil material. This modeling assumed full saturation of the peat and resulted in the peat layer promoting ground freezing. Similar results were encountered with the clay material. If peat, or clay, is to be used as an insulating layer, more precise thermal properties should be obtained and the material treated as engineered material with a specific purpose. Field investigations are currently underway to obtain soil samples near several tower foundations to establish actual thermal conductivities in the laboratory following ASTM D 5334-05, *Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure.*

5 SUMMARY

Numerical simulation of ground temperatures using past climate data can provide information about long-term serviceability and maintenance schedules for northern structures in areas of continuous or discontinuous permafrost. This preliminary modeling of the effects of climate on transmission tower foundations is being extended to include effects of groundwater and deformations. Ongoing projects are examining how warming affects the stress-strain behaviour of foundation clays and deformations of highway embankments. Combining data from these projects will lead to the development of an elastic thermo-plastic model.

ACKNOWLEDGEMENTS

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