Observed and Predicted Thermal Regime under an Existing Highway Embankment on Degrading Permafrost

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Temperature changes of ground thermal regimes in permafrost regions can initiate thawing and degradation of permafrost and potentially damage existing infrastructure. Subsequent settlements and lateral spreading can lead to hazardous driving conditions on highways. Future changes in climate will exacerbate thermal degradation and negatively impact the long-term performance of linear infrastructure like highways, runways, rail lines, and pipelines. The paper discusses numerical thermal modeling of an instrumented highway embankment on degrading permafrost, both for simulating current conditions and projecting future behaviour. The embankment is located 18 km north of Thompson, Manitoba on Provincial Road (PR) 391. Thermistors were installed beneath the toe, mid-slope, shoulder and centerline of the embankment. Five years of data have been collected. Earlier papers by the authors outlined the instrumentation and development of a first generation of numerical thermal models for the site. This new contribution describes how projected trends in climate change have been used to assess future behaviour.

RÉSUMÉ
Dans les régions à pergélisol, les variations de la température associées aux régimes thermiques du sol peuvent engendrer le dégel et la dégradation du pergélisol et, ainsi, endommager les infrastructures existantes. Les tassements et déplacements latéraux encourus peuvent induire des conditions de conduite dangereuses sur les routes. Dans le futur, les changements climatiques vont exacerber la dégradation thermique et affecter à long terme les performances des infrastructures linéaires. Cet article discute de la modélisation numérique thermique d'un remblai de route instrumenté qui est construit sur du pergélisol se dégradant. Les conditions actuelles ainsi que le comportement futur ont été simulés. Le remblai se situe à 18 km au nord de Thompson, au Manitoba sur le chemin Provincial (RPS) 391. Des thermistors ont été installés sous le pied du remblai, le milieu de la pente, l'accotement et l'axe du remblai. Cinq années de données ont été enregistrées. Les articles antérieurs présentaient la première génération d'instrumentation, ainsi que le développement du modèle numérique thermique du site. Ce nouvel article décrit comment les tendances de l'évolution du climat ont été utilisées afin de prévoir le comportement futur dans un contexte de changements climatiques.

1 INTRODUCTION

Well-maintained transportation infrastructure in northern Canada is crucial for linking small communities to the rest of the country to the south. The region, though sparsely populated, contains vast quantities of natural resources including minerals, petro carbons, and hydro-electric power generating sites. The development of these resources has the potential to improve the socio-economic well-being of the region as well as maintaining Canada's sovereignty in the Arctic. The presence and behaviour of permafrost may significantly impact development.

Permafrost underlies close to half of the land surface in Canada, primarily in high altitude and northern regions (Brown, 1967). Permafrost varies in both its thickness and its spatial extent. Permafrost can be several hundred metres thick in continuous permafrost regions found further north while thin layers are found in the sporadic discontinuous permafrost regions to the south. Figure 1 shows the coverage of permafrost in Manitoba.

Disturbances of the thermal regime caused by human activity such as road construction can lead to thawing and degradation of existing permafrost. Construction practices in northern Manitoba have typically followed similar procedures used further to the south where permafrost is not found. Construction and maintenance may involve vegetation stripping, changes to drainage patterns, and snow removal. Fill materials often have higher thermal conductivities than the native soils they replace and allow more heat to penetrate the ground. Ground that was considered permafrost prior to construction may consequently thaw and lead to serviceability and possible ultimate failure.

The University of Manitoba (UM), Manitoba Infrastructure and Transportation (MIT), and Transport Canada (TC) have collaborated to study the impact of degrading permafrost on existing infrastructure, specifically a highway embankment, in order to find improvements to the design, construction, and maintenance practices in regions of permafrost through the support of projects that involved field instrumentation, monitoring, laboratory testing, and numerical modelling. This paper presents a thermal model that was developed for an instrumented highway embankment located 18 km northwest of Thompson, Manitoba on Provincial Road (PR) 391 as shown in Figure 1. The thermal model examines the current thermal regime as well as the potential long term behaviour.

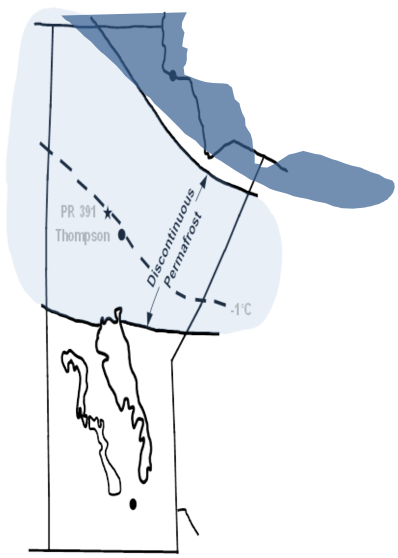

Figure 1: Location of Test Site and Permafrost in Manitoba (Flynn et al., 2013)

2 SITE BACKGROUND

2.1 Site Investigation

PR 391 is located in discontinuous permafrost and is the only road that connects other remote northern communities, hydro generating stations and mines in north-western Manitoba. The highway was initially constructed in the 1960s as a compacted earth road. Upgrades were made in the 1970s and 1980s to gravel and asphalt surface, respectively. However, areas along the highway that were suspected to be permafrost during the initial construction continued to experience irregular deformations. In the 1990s, a 1 m thick stabilizing berm placed along the toe of the embankment in an effort to reduce the lateral spreading. The berm has settled, essentially disappearing into the natural ground surface, and provides no additional support.

Drilling in 2008 and 2012 revealed 6 m of gravel fill beneath the road surface underlain by approximately 14 m of silty clay and gneissic bedrock at a depth of 18 m.

Previous drilling has encountered frozen ground. In 1991, drilling at the toe of the embankment revealed frozen soil between 1.9 m and 10.5 m depth. Frozen soil was again found at the toe between 4.6 m 10.7 m depth during drilling in 2005. However, no frozen soil was found while drilling at the mid slope in 2008. In 2012, drilling encountered frozen and ice-rich soil at the shoulder at depths between approximately 6 m and 9 m beneath the toe as well as between 4 m and 10 m at the centreline.

2.2 Field Instrumentation

Instruments were installed into the embankment in two phases as shown in Figure 2. Instruments installed during the first research phase in 2008 are shown as blue and additional instruments installed in 2012 are shown as green.

Drilling was initially not permitted on the road surface. Consequently, instrumentation was only installed in the toe and the mid slope in October 2008. At that time, 9-noded thermistor strings were installed to monitor the ground thermal regime. Two vibrating wire (VW) piezometers were installed under the toe at 4 m intervals to monitor groundwater conditions. The initial monitoring program provided more than two years of data before it was terminated in April 2011 at the conclusion of that study. Previous publications such as Batenipour et al. (2011) have provided analysis and synthesis of these data.

Permission was given to install instrumentation under the road surface by MIT in September 2012. Instrumentation included 13-noded thermistor strings installed to a depth of 17 m under the shoulder and centreline, four VW piezometers vertically spaced 4 m apart under the centreline, and two ShapeAccelArrays (SAAs); one installed horizontally under the embankment to measure vertical displacements and one installed vertically to measure lateral displacements at the shoulder. The data from the instrumentation have been discussed in Flynn et al. (2013) as well as Flynn (2015).

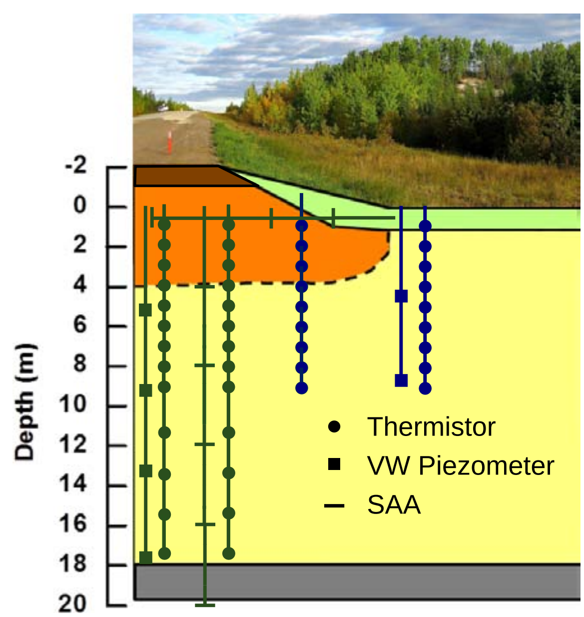

Figure 2: Instrumentation installed. (Note: Blue indicates instrumentation installed in 2008. Green indicates instrumentation installed in 2012). (Flynn et al., 2013).

The project site is unconnected to the electrical grid and uses solar energy to power the data acquisition (DA) system and accompanying satellite system to allow data collection from any location.

3 MODELLING

The authors developed a thermal model to simulate the ground thermal regime under the highway embankment at the PR 391 project site. The thermal model used the TEMP/W software package from Geo-Slope International Ltd. The following section includes the development of the thermal model, comparisons to actual ground temperature data, and assessments about long-term behaviour of the ground thermal regime.

3.1 Geometry

The development of the model geometry was based on previous models (Batenipour, 2012; Kurz, 2014; Flynn et al., 2014), and observations during drilling in 2008 and 2012. The geometry chosen was a half cross-section of the embankment. Each side of the embankment has differences in solar radiation, slope, snow accumulation, and vegetation, but for was assumed to be symmetrical for this model. A full cross-section was not modelled to reduce the quantity of nodes and computing time, and also because only half of the embankment had instrumentation. The model geometry extended 30 m laterally from the centreline, and to a depth of 12 m below the natural ground surface. The author tried models that increased the lateral extent to 40 m, but the isotherms (temperature contours) beyond 30 m remained unchanged. The model was cut off at a depth of 12 m because the temperatures below stayed relatively constant over a full year. The initial square finite element mesh remained coarse (1 m by 1 m) until the thermistor and simulated data were in closer agreement. Subsequent models used a mesh element size of 0.5 m by 0.5 m to calculate the isotherms of the ground thermal regime.

3.2 Material Properties

All materials in the thermal model used a full thermal model, which requires intrinsic properties in frozen and unfrozen states including: unfrozen volumetric water content, unfrozen and frozen thermal conductivities (k_u and k_f), unfrozen and frozen volumetric heat capacities (c_u and c_f), and in-situ volumetric water content (VWC). Material properties used in the thermal modelling are summarized in Table 1.

Temperature dependent functions in TEMP/W calculated thermal conductivities and unfrozen volumetric water contents. The functions required the soil type, and frozen and unfrozen material properties. TEMP/W assumed the material properties changed as temperature passed through the freezing point of 0°C in the full thermal model. The unfrozen volumetric water content function assumed 5% similar to relationships found in Andersland and Ladanyi (2004) and Farouki (1986) as used in thermal modelling by Batenipour (2012) and Kurz (2014).

Unfrozen volumetric water content is the percentage of water that remains unfrozen and is absorbed on the surface of the particle at temperatures below 0°C. Some water remains unfrozen in fine-grained soils at temperatures below 0°C because of the large surface areas.

Thermal conductivity reflects of the ability of the soil to transmit heat between the matrix of soil particles and pore fluids (both water and ice) through direct contact or indirectly through the soil pore fluids. Thermal conductivity is a function of the water content, degree of saturation, soil type, soil density, and temperature. Kurz (2012a) carried out thermal conductivity laboratory tests on the silty clay. The unfrozen thermal conductivities of the clay specimens were between 1.18 and 1.51 W/(m·°C) while the frozen thermal conductivities ranged from 1.21 to 2.42 W/(m·°C).

The volumetric heat capacity and in-situ volumetric water content calculations used the relationship between dry densities and measured water contents. Heat capacity in soil is the quantity of heat required to raise the temperature of the soil by 1°C (Andersland and Ladanyi, 2004) and depends on the heat capacities of the solid, water, ice, and air components of the soil proportional to their mass. Volumetric heat capacity expresses heat capacity as unit of volume rather than mass while also integrating specific heat, the density of dry soil, the heat capacity of water, and moisture content. Frozen volumetric water content requires both the natural gravimetric water content and unfrozen water content.

Thermal property tests for the gravel were not performed and values were selected from Harlan and Nixon (1978). Each year, new gravel is placed on the highway for maintenance over the existing gravel that was assumed to have become fully saturated. The authors assumed the gravel applied during maintenance had a dry density of 1900 kg/m^3 and a gravimetric moisture content of 3% for the new gravel. The gravel likely had a higher moisture content when compacted, but the value was chosen to distinguish the new 'dry' gravel from the saturated gravel already present in the embankment.

Table 1: Thermal Material Properties

Material	Vol. Heat Capacity [kJ/(m^3·°C)]		Thermal Conductivity [W/(m·°C)]		In-Situ VWC [m^3/m^3]
	c_u	c_f	k_u	k_f	
Silty Clay	2760	1960	1.24	1.86	0.41
Clayey Silt w/ Organics	2850	2050	1.42	2.42	0.41
Gravel Sat.	2505	1958	2.70	3.80	0.28
Gravel Dry	1591	1472	1.50	1.00	0.06

3.3 Boundary Conditions

Boundary conditions applied in the model included the initial conditions of the ground thermal regime, heat flow along the bottom boundary of the model geometry, and air temperatures at the ground surface.

Transient analyses are in a constant state of change and require a start time to establish the initial conditions. September 25, 2010 was selected as the model start date to allow the initial conditions to equilibrate; two years prior to the start of data collection from the field instrumentation. A spatial function established the initial temperatures on the start date. A krigged surface interpolates isotherms based on temperatures applied to specified points in the two-dimensional domain to illustrate the ground thermal regime. The specified temperatures took thermistor string data from September 2010 for the toe and mid slope and from September 2012 for the shoulder and centreline. The thermistor string data from the toe were also used on the right extent of the model so the initial isotherms were horizontal to the ground surface.

A constant unit heat flux representing the geothermal gradient was applied to the bottom extent of the model (depth of 12 m). Geothermal gradients vary by location but generally range between 0.9 and 3.3°C per 100 m (Brown, 1963). A constant unit flux of 3 kJ/m^2·day was used based on the unfrozen thermal conductivity of the silty clay and a geothermal gradient of 3°C per 100 m.

3.3.1 Air Temperature Boundary Condition

The thermal boundary condition applied to the ground surface was developed using a sine function approximation of daily average air temperatures from Environment Canada and a projected temperature trend from a climate model developed by the Canadian Centre for Climate Modelling and Analysis (CCCma).

Air temperature data was used from the Environment Canada weather station at the Thompson airport located 10 km from the project site. Numerical instabilities may develop when daily average temperatures are applied directly to the ground surface of a thermal model due to the large, and occasionally erratic, day-to-day changes in average temperature. A sine function provides a useful approximation of the yearly cycle of daily average temperatures. Equation 1 shows a sine function first used for thermal modelling of this site by Kurz et al. (2012b).

[Eq. 1] $T = A + B \times \sin\left[2\pi\left(\frac{t+C}{365}\right)\right]$

where A = Mean Annual Average Temperature (a temperature shift calculated as -2.8°C), B = a constant (amplitude calculated as 20.9°C), t = time in days, and C = constant (a time shift calculated as 155.2 days). The sine function was based on the Environment Canada weather data between September 2010 and 2014 and ‘smoothed out’ the erratic nature of the actual data to capture the essence of the day-to-day temperature changes.

Air thawing and freezing indices are the annual summation of the difference between the mean daily average air temperatures and the freezing point over the thawing and freezing seasons. The average air thawing and freezing indices between September 2010 and 2014 were 2014°C·days and 3015°C·days, respectively. The sine function calculated air thawing and freezing indices as 1939°C·days and 2950°C·days respectively for the same time period. The percent difference between thawing and freezing indices of the daily mean temperatures and the sine function was acceptable at 4%. The sine function generates a slightly cooler summer but warmer winter.

The Canadian Centre for Climate Modelling and Analysis (CCCma) developed several models to predict climate changes and variability in Canada. The CCCma Third Generation Coupled Global Climate Model (CGCM33.1/T47) provided projected air temperature data from January 1, 2001 until December 31, 2100. An average air temperature of 0.76°C was projected for the project site between September 2012 and September 2037 while the average temperature between September 2037 and September 2062 was 1.89°C. The overall average air temperatures equated to an increase of 0.0365°C annually. The increasing trend was applied to the sine function in Equation 1 to represent projections of air temperature used in the thermal model and is shown in Equation 2.

[Eq. 2] $T = A + B \times \sin\left[2\pi\left(\frac{t+C}{365}\right)\right] + 0.0001t$

Figure 3 shows the projections for air temperatures over the next ten years. For example, the average air temperature after ten years would have been 0.365°C warmer than day 1. The air temperature projections are limited because the model does not account for changes in precipitation, vegetation, hydrology, or extreme weather events such as prolonged cold spells and heat waves which could all potentially affect ground temperatures in the future.

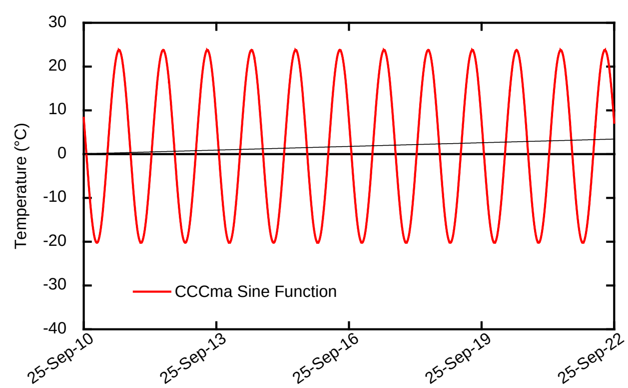

Figure 3: Mean Daily Temperature Fitted Increasing Sine Function from September 25, 2010 until September 25, 2022 with 0.0365°C/year trend line.

TEMP/W analyses require empirically based modifying factors (n-factors) when a temperature based function is applied to the ground surface (Geo-Slope, 2010). The n-factor is used to estimate ground temperature based on air temperature and is calculated as the ratio between thawing and freezing indices of the ground surface and the air (Johnston, 1981). A series of models were run solely to back-calculate n-factors to uniquely fit the site. The authors note that the n-factors are lower than the typical values found in literature. N-factors are impacted by differences in snow accumulation, solar radiation, vegetation, and other factors (Johnston, 1981). Table 2 summarizes the n-factors selected for the locations.

Table 2: Modifying Factors (n-factors)

Material	Thawing n_t	Freezing n_f
Road Surface	0.3	0.3
Mid Slope	0.1	0.6
Toe	0.01	0.73

4 RESULTS AND DISCUSSION

Numerical convergence can be an important issue because computations in TEMP/W thermal models are highly non-linear. Several versions of the thermal model were developed and improved through modifications of the boundary conditions, material properties, and geometry. The modelled data were compared to the ground temperatures recorded by the thermistor strings from the toe, mid slope, shoulder, and centreline of the embankment. For brevity, only plots at the toe and shoulder are shown comparing the measured thermistor data to the thermal model based on the CCCma projected air temperature trend.

Thermistor strings recorded sub-zero ground temperatures every month since September 2012 under the shoulder and centreline of the embankment at the same depths encountered during the drilling. This region was found between depths 6 to 9 m under the shoulder and between depths 4 to 10 m under the centreline and was subsequently referred to as the frost bulb region. The warmest temperatures under the embankment were observed at the toe which is consistent with previous research stating permafrost degradation of embankments began at the toe (Alfaro et al, 2009). All thermistors recorded above-zero temperatures for the first time in the fall of 2014 which indicates degrading permafrost.

Figure 4 and Figure 5 show temperatures plotted against depth on specific days at the toe and shoulder of the embankment. The dates include April and October of 2014 which represent, in general, the coldest and warmest ground temperatures during the year, respectively. Measured data from the thermistor strings (shown as a symbol) were compared with the simulated values from the thermal model (shown as a dashed or solid line).

Figure 4 demonstrates that there is generally good agreement between the measured data and the thermal model for the toe. The agreement also improves with depth. A similar statement could be made about the comparison of simulated and measured ground temperatures at the mid slope.

There is less agreement between the simulated temperatures and the measured ground temperatures further into the embankment. Figure 5 shows the temperature-depth profile at the shoulder. The thermal model was able to capture the seasonal variability in the upper 5 m, but was consistently warmer. The same could be stated for the frost bulb region. Measured ground temperatures in the frost bulb region fluctuated by very small amounts over a yearly basis and were only marginally below 0°C. The lowest recorded temperature in the frost bulb was -0.25°C. The thermal model was able to simulate fairly constant temperatures over a year, but was unable to achieve sub-zero temperatures. The discrepancies between measured and simulated ground temperatures were accentuated at the centreline and differed by about 2°C.

The thermal model was run for twenty seven years; two years allowed for the initial conditions to equilibrate and twenty five years to simulate projected temperatures for the ground thermal regime under the embankment. The CCCma climate model projected air temperatures applied to the ground surface of the thermal model to rise by 0.0365°C annually which equated to an increase of approximately 1°C after twenty five years.

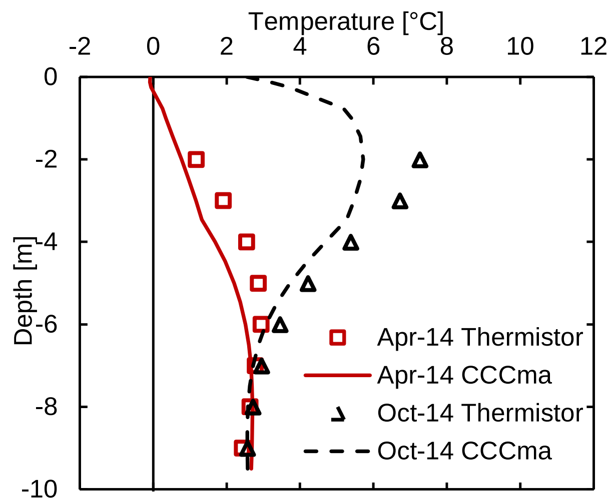

Figure 4: Comparison between the measured (symbol) and modelled (line) ground temperature data at the toe in April and October of 2014.

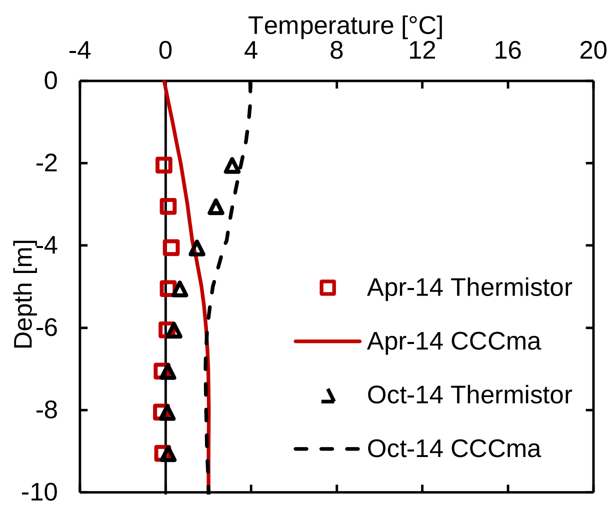

Figure 5: Comparison between the measured (symbol) and modelled (line) ground temperature data at the shoulder in April and October of 2014.

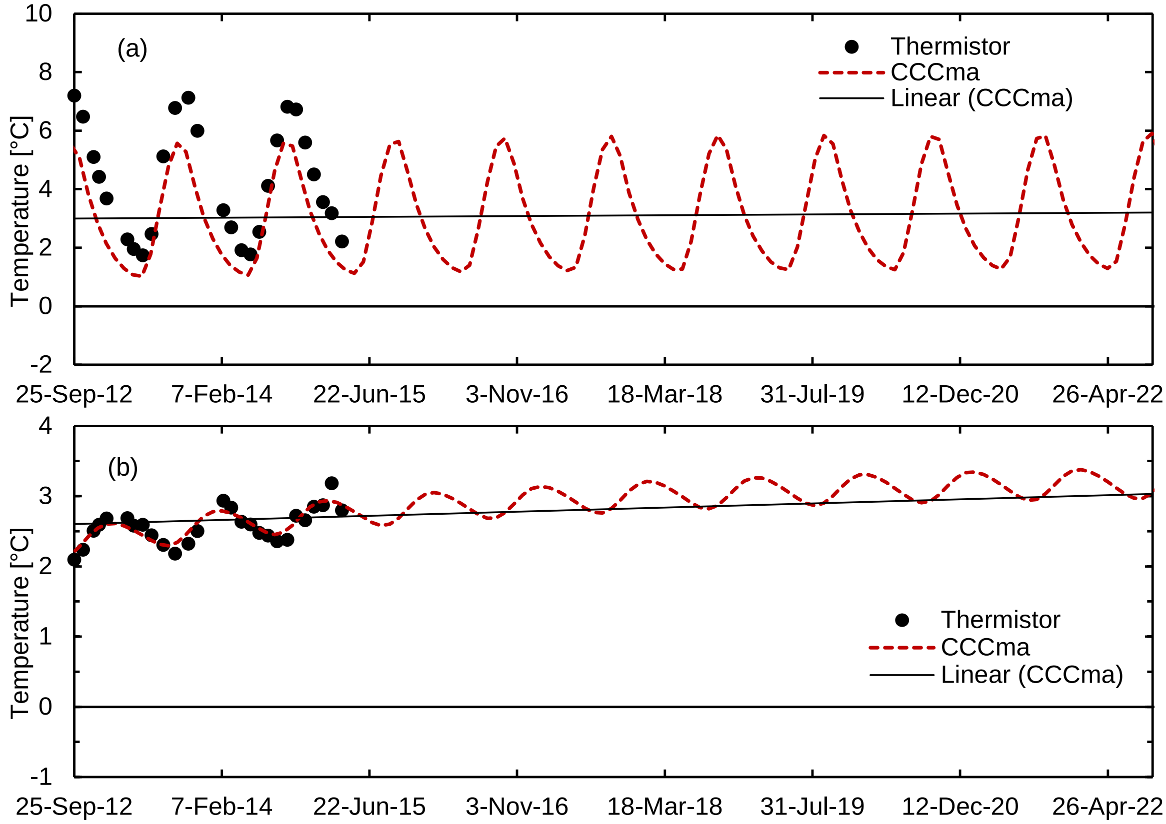

Figure 6: : Temperature versus time for 10 years at (a) 3 m and (b) 8 m below the toe of the embankment

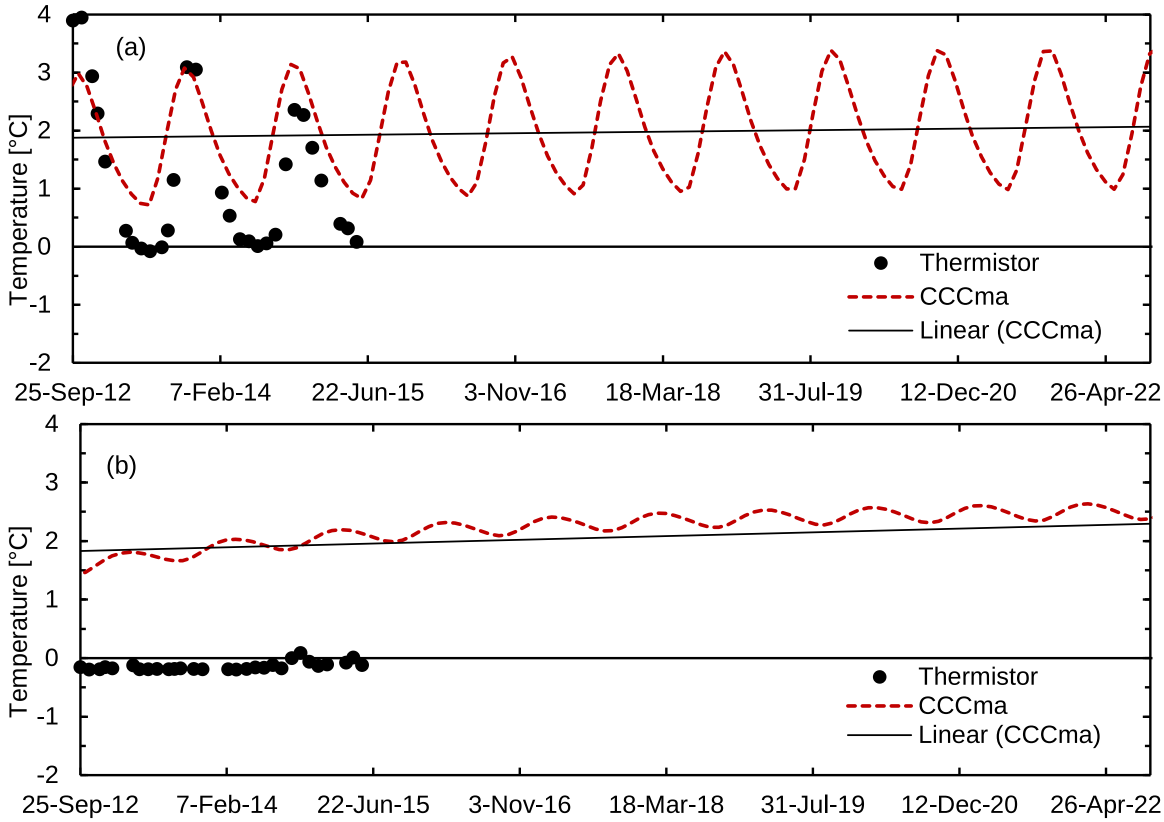

Figure 7: Temperature versus time for 10 years at (a) 3 m and (b) 8 m below the shoulder of the embankment

Figure 6 and Figure 7 represent the results of the forward projected ground temperatures from the thermal model plotted against time since the start of data collection in September 2012.The figures only show the first ten years of simulated ground temperatures to make it easier to compare to measured ground temperatures since September 2012.

Figure 6 demonstrates that the agreement between measured and simulated ground temperatures improved with depth. . Figure 6 also shows that warm temperatures at the toe will continue to contribute to permafrost degradation under the embankment over the next ten years. Figure 7 shows that the thermal model reasonably simulates ground temperatures at shallower depths while the discrepancy grows in the frost bulb region. The author noted that the measured temperatures under the shoulder and centreline above the frost bulb had increased during the winter and spring of the second monitoring season (2013-14) compared to the same time period in the first monitoring season (2012-13). The average temperature at 3 m depth at the shoulder, as measured by the thermistor strings, between March and August 2014 increased by 0.06°C compared to March and August 2013. Meanwhile, thermistor strings recorded an increase of 0.34°C was observed at a depth of 2 m below the centreline between the two same periods. The thermal model predicts that the temperatures at all locations under the embankment will increase above 0°C within the next twenty five years.

The heat capacities of liquid water and ice are 4.18 and 2.09 Joules per gram per degree Celsius, respectively. Consequently, frozen ground requires more energy to increase the temperature compared to unfrozen ground. Warmer temperatures simulated in the region just above the frost bulb would allow more energy to reach the frost bulb and possibly initiate thawing in the future. The latent heat of fusion of water, the heat released during the phase change between ice and water, affects the thermal behaviour of the soil and is equal to 333.9 Joules per gram (Lide, 1994). As a result soil is more difficult to re-freeze once thawed. Two years is a small sample to evaluate long-term trends, but the general warming trends projected by the thermal model do not make it unreasonable to suggest that the frost bulb under the embankment may disappear entirely within the next 25 years.

Further work is required to obtain better agreement between modelled and measured values, particularly below the shoulder and centreline of the embankment. The TEMP/W models experienced trouble simulating the constant marginally sub-zero temperatures observed in the frost bulb. The difficulties are accentuated under the centreline because the frost bulb is thicker at that location. The frost bulb appears less vulnerable to seasonal cyclic changes than the regions closer to the ground surface. The measured temperatures in the frost bulb remain relatively stable year round and fluctuate less than 0.1°C which is the same as the manufacturer stated tolerance of the thermistor strings.

Assumptions about the divisions of sub-surface materials and their properties were mostly based on judgement from drilling and available literature. Only thermal conductivity tests on the silty clay had been carried out for the PR 391 site (Kurz, 2014). Testing the thermal properties of all relevant materials shown in Table 1, such as the gravel fill, would be useful to understanding its role in heat transfer in winter and summer. Modifications to the thermal properties of the soil and understanding the behaviour of the soil at temperatures close to freezing may enhance the thermal model. Unfrozen water may still be present in fine-grained soils at temperatures below 0°C (Farouki, 1986). The amount of water in a soil impacts the energy requirements to increase or decrease ground temperatures.

5 SUMMARY

This paper outlines the observed temperatures measured under an instrumented highway embankment in degrading permafrost and compares them to long-term projections of expected behaviour under the road. Thermistor strings recorded sub-zero ground temperatures every month since September 2012 under the shoulder and centreline of the embankment at the same depths encountered during the drilling. This region was found between depths 6 to 9 m under the shoulder and between depths 4 to 10 m under the centreline and was subsequently referred to as the frost bulb region. Positive temperatures were detected in the frost bulb for the first time in the fall of 2014, indicating degrading permafrost.

There was generally good agreement that improved with depth between the simulated model values and the measured thermistor data at the toe and mid slope of the embankment. The simulated modelled temperatures were still close to the thermistor data at shallower depths at the centreline and shoulder of the embankment. Discrepancy between the simulated and measured ground temperatures data increased at the frost bulb depths under shoulder and centreline. There are indications the cold winter temperatures are not penetrating the soil as thoroughly as in the past since the temperatures just above the frost bulb depths have increased over the two years. It becomes more difficult for soil to re-freeze after it has been thawed. Warming trends projected by the thermal model may lead to the degradation and possible disappearance of the frost bulb in the next twenty five years. Excessive deformations may impact the performance of the highway embankment and lead to increased maintenance and rehabilitation costs.

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