

# Modelling embankment temperatures in Arctic highways using thermal modifiers and surface energy balance boundary conditions



Earl Marvin B. De Guzman, Samuel W. Kaluzny, & Marolo C. Alfaro  
*University of Manitoba, Winnipeg, Manitoba, Canada*  
Lukas U. Arenson  
*BGC Engineering Inc., Vancouver, British Columbia, Canada*  
Guy Doré  
*Université Laval, Quebec City, Quebec, Canada*

## ABSTRACT

Highway embankments in the Arctic are typically designed to maintain road geometry requirements with thicknesses that can vary from 2 to 12 m. The thickness of an embankment also influences the thermal regime of the foundation soil where it is desirable to keep the permafrost from degrading to minimize deformations and prevent instabilities. Three years of continuous monitoring of a 5.3 m thick embankment section along the newly-constructed Inuvik-Tuktoyaktuk Highway (ITH) in the Northwest Territories, Canada show that the core of the embankment fill is still frozen since construction. In order to understand the thermal regime in the embankment fill and foundation soil throughout the winter and summer seasons, a thermal numerical model was developed in a commercially-available finite element software using thermal modifiers and surface energy balance (SEB) formulation as boundary conditions at the ground surface. The results of both approaches reasonably simulate the recorded temperatures at the test site and provides confidence that climate change boundary conditions can be implemented for investigating future thermal regimes.

## RÉSUMÉ

Les remblais routiers dans l'Arctique sont généralement conçus pour maintenir les exigences de géométrie de la route avec des épaisseurs pouvant varier de 2 à 12 m. L'épaisseur d'un remblai influe également sur le régime thermique du sol de fondation lorsqu'il est souhaitable d'empêcher le pergélisol de se dégrader afin de minimiser les déformations et d'éviter les instabilités. Trois ans de surveillance continue d'un tronçon de talus de 5,3 m d'épaisseur le long de l'autoroute Inuvik-Tuktoyaktuk (ITH) aux Territoires du Nord-Ouest, montrent que le noyau du remblai est encore gelé depuis la construction. Afin de comprendre le régime thermique du remblai et du sol de fondation tout au long de la saison estivale et hivernale, un modèle numérique thermique a été développé dans un logiciel à éléments finis disponible dans le commerce, utilisant thermal modifiers (TM) et la formulation surface energy balance (SEB) la surface du sol. Les résultats des deux approches simulent de manière raisonnable les températures enregistrées sur le site d'essai et permettent de penser avec certitude que les conditions limites du changement climatique peuvent être mises en œuvre pour étudier les régimes thermiques futurs.

## 1 INTRODUCTION

There are several challenges associated with constructing highways in the Arctic corridor. Embankments in this environment are often constructed during the winter months to preserve the permafrost foundation and minimize environmental impacts during construction. Placement of embankment fill material is easier when the frozen natural ground surface makes movements of construction equipment most effective. Fill material is placed by end dumping, and construction vehicles are prohibited from traveling on or damaging the vegetation mat beyond the limit of the embankment footprint (McHattie and Esch 1983). Thermal disturbance of the permafrost foundation may lead to instabilities in the road embankment and manifest themselves in a variety of ways, ranging from longitudinal cracks at the embankment surface to lateral spreading of the side slopes (McGregor et al. 2010). Embankment thickness (fill height) varies along a project site due to terrain conditions where horizontal and vertical road alignment geometries have to

be satisfied. Embankments thicknesses are typically designed to provide adequate ground insulation and minimize permafrost degradation under known climatic conditions. The permafrost will degrade if the insulating effect provided by the embankment fill is less than the insulating effect of the active layer. On the other hand, the permafrost can rise to the embankment if the insulating effect of the embankment fill is greater than the insulating effect of the active layer.

The completion of the Inuvik to Tuktoyaktuk Highway (ITH) in the Northwest Territories, Canada, has been a long standing goal of the Town of Inuvik, the Hamlet of Tuktoyaktuk, and the residents of the Inuvialuit Settlement Region. The highway has been identified as a priority development by the Government of Canada and Government of the Northwest Territories (GNWT). The ITH, which extends the Dempster Highway past the community of Inuvik to the Arctic Coast, is an all-weather transportation link and completes Canada's road network from the Pacific, to Atlantic, and to Arctic coasts. To comply with vertical geometry requirements, embankment fill

thickness can range from 2 to 12 m. The warming trend in air temperatures due to climate change in the Northwest Territories has and will continue to pose challenges for the transportation system. In order to understand the thermal regime in the embankment fill and foundation soil throughout the winter and summer seasons, a thermal numerical model was developed in a commercially-available finite element software using thermal modifiers and surface energy balance (SEB) formulation as boundary conditions at the ground surface and the results of both approaches are presented in this paper.

## 2 EMBANKMENT CONSTRUCTION AND INSTRUMENTATION

Embankment test sections were constructed along ITH in April 2015. Both test sections have an embankment slope of 3H:1V. Frozen fill material was used to construct the embankment test sections with an average moisture content of 16%. The temperature on site during construction ranged from -35°C to -2°C, with an average temperature of -18°C during fill material end dumping and compaction. Construction was halted when air temperatures were above -10°C. De Guzman et al. (2018) determined the physical properties of this soil as well as its shear strength properties at different environmental conditions. The soil is classified as well-graded sand with silt and gravel to silty sand with gravel based on the Unified Soil Classification System (USCS).

The thick embankment section (5.3 m) was instrumented with thermistor strings for temperature measurements and ShapeAccelArrays (SAAs) for deformation and temperature monitoring during the construction as shown in Figure 1. Two thermistor strings were placed horizontally at the top (TS-C1) and along the base (TS-C2) of the thick embankment, and another two strings were vertically installed through the foundation at the centreline (TS-C3) and at the toe (TS-C4). The SAAs are primarily for displacement measurements, but they also provide additional temperature measurements to supplement the thermistor readings.

## 3 THERMAL NUMERICAL MODELLING

Finite element thermal modelling for the embankment sections was carried out using GeoStudio 2018 software TEMP/W (Geo-Slope International, 2018). The modelling procedure and calibration against recorded field values from thermistor strings are presented in this section.

### 3.1 Material Properties

Thermal properties of the embankment fill and foundation soil used in TEMP/W are summarized in Table 1. The embankment fill material ranges from well-graded sand with silt and gravel to silty sand with gravel based on the Unified Soil Classification System (USCS) tests done by De Guzman et al. (2018). The foundation soil is predominantly organic based on the frozen cores obtained

from the centreline and at an offset from the embankment toe during drilling in March 2017. The organic soil is approximately 7 m thick. This is underlain by highly plastic clay with some presence of cobbles based on visual inspection of the grab samples.

Table 1. Summary of TEMP/W model parameters.

Property	Foundation	Fill
Unfrozen thermal conductivity (kJ/days·m·°C)	45	122.5
Frozen thermal conductivity (kJ/days·m·°C)	120	163.9
Unfrozen volumetric heat capacity (kJ/m <sup>3</sup> ·°C)	5282.2	2171.4
Frozen volumetric heat capacity (kJ/m <sup>3</sup> ·°C)	2869.7	1613.9
Volumetric water content (m <sup>3</sup> /m <sup>3</sup> )	5	0.3

Equations proposed by Farouki (1981) were used to determine the unfrozen and frozen thermal conductivities of the embankment fill material as shown in Equations 1 and 2, respectively.

$$k_{\text{unfrozen}} = 0.1442 (0.7 \log w + 0.4) (10)^{0.6243 \rho_d} \quad [1]$$

$$k_{\text{frozen}} = 0.01096 (10)^{0.8116 \rho_d} + 0.00461 w (10)^{0.9115 \rho_d} \quad [2]$$

In the absence of test results, the frozen and unfrozen thermal conductivities were assumed to be similar to peats frequently found in northwestern Canada. De Guzman and Alfaro (2018) used a thermal probe for peat in Northern Manitoba. The unfrozen and frozen volumetric heat capacities for mineral soils beneath the embankment are calculated using Equations 3 and 4, respectively, where  $c_{vw} = 4.187 \text{ MJ/m}^3 \cdot \text{°C}$  and  $\rho_d$  and  $\rho_w$  are the unit mass of the dry soil and water, respectively. The specific heats 0.17, 1.0, and 0.5 correspond to mineral soil, water, and ice, respectively (Andersland and Ladanyi 2004). For organic soils such as peat, the 0.17 is replaced by 0.40.

$$c_{vu} = (\rho_d / \rho_w) (0.17 + 1.0 (w)) c_{vw} \quad [3]$$

$$c_{vf} = (\rho_d / \rho_w) [(0.17 + 1.0 (w_u)) + 0.5 (w - w_u)] c_{vw} \quad [4]$$

The volumetric water content (VWC) is the volume of liquid water per volume of soil and obtained by multiplying the gravimetric water content to the ratio of the density of the soil and density of water. It was assumed that the unfrozen water content ( $w_u$ ) in Equations 3 and 4 is 5% of the VWC as was similarly done in previous studies (De Guzman and Alfaro 2018, Flynn et al. 2016).

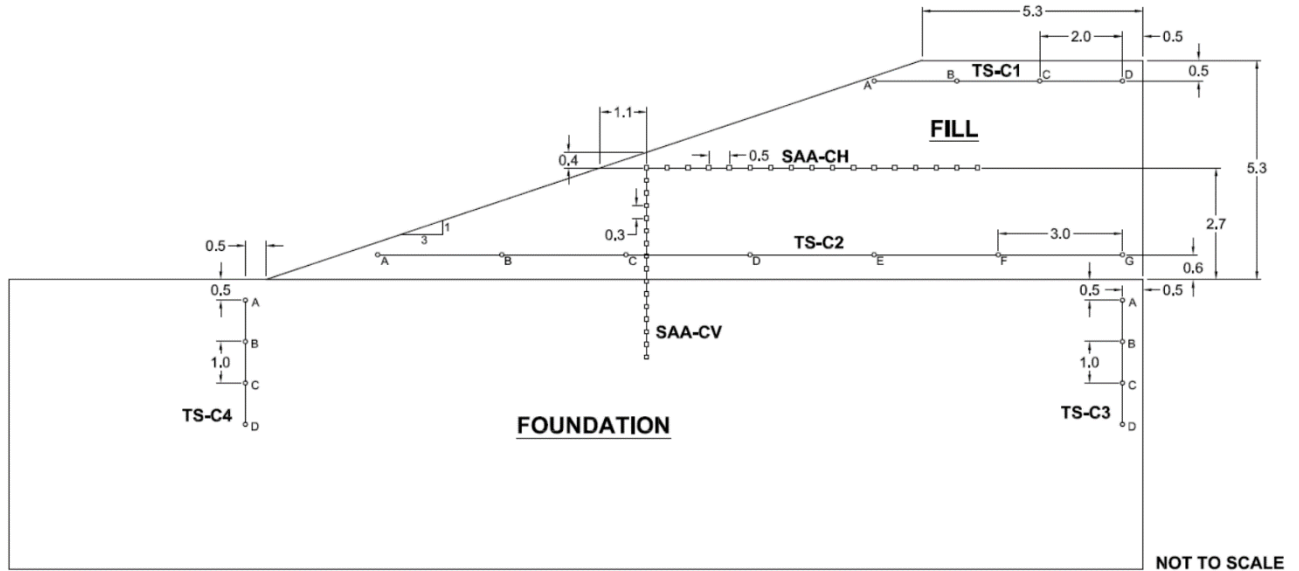


Figure 1. Cross-section and location of temperature sensors in the embankment test section.

### 3.2 Embankment Geometry and Boundary Conditions

The cross-section of the embankment model in TEMP/W for the thick embankment section is shown in Figure 2. The surfaces of the embankment fill and foundation soil interacting with air temperatures are subdivided accordingly. The road surface is labelled as *Top*, while the slope is divided into three regions because of the different snow depths that can accumulate in these regions. The foundation soil immediately at the base of the embankment is labelled as *Toe*, and outside this the foundation surface is labelled as *Prairie*. Air temperatures at the research site were obtained from satellite measurements provided by the National Aeronautics and Space Administration (NASA). The rightmost and leftmost boundaries are no flow boundaries, while a constant temperature of  $-4.3^{\circ}\text{C}$  was applied at the base of the foundation soil based on temperature readings nearby the research site from 2015 to 2018. Only half of the embankment was modelled because of symmetry. A global mesh size of 0.3 m with triangular elements was used.

### 3.3 Modelling Approach

Because the thermistor strings and SAAs were installed during the construction phase and temperature monitoring was easily available during that period, a predefined temperature field can be added in the numerical model where the initial temperature analysis can be anchored. Temperature readings on April 19 and April 20, 2015 were used as spatial functions in a transient analysis. These spatial functions were only applied to the first model and subsequent models were created in a tree analysis using the previous model as its parent analysis but with the revised air temperatures applied and spatial functions removed. No intermediate steps were applied in between the three-year monitoring period once the model was ran for analysis. The analysis period ran from April 20, 2015 to August 31, 2018.

For embankment modelling where there are no temperature sensors to provide an initial condition, a spin-up analysis is typically required in order to reach equilibrium for the embankment fill and foundation soil with an applied constant sinusoidal boundary condition representative of the temperatures expected where the embankment will be situated. Average sinusoidal functions are applicable in this case because the same boundary condition is being applied repeatedly until steady-state is reached where otherwise the actual temperatures will provide erratic changes. Spin-up analyses were done for the embankment sections and it was found that there is no significant difference between a 5-year and 10-year spin up in comparison with a predefined temperature field in the embankment discussed previously. Parametric studies for different embankment heights and air temperature conditions however will require such analyses to satisfy initial thermal equilibrium. Care should also be exercised in selecting the thermal boundary conditions to be applied with respect to the existing conditions at the site.

The governing equation in TEMP/W is shown in Equation 5 where the forced-convection heat transfer and the latent heat of vaporization are ignored. The default physical processes involved in TEMP/W include conduction heat transfer and changes in stored sensible energy and latent heat of fusion (Geo-Slope International, 2018). In Equation 5,  $C_p$  is the volumetric heat capacity,  $h_{sf}$  is the latent heat of fusion,  $k$  is the thermal conductivity,  $\rho_w$  is the density of water, and  $\theta_{uwc}$  is the unfrozen volumetric water content. The parameter  $\theta_{uwc}$  is a function of temperature that controls the rate of change in the latent energy of fusion per degree of temperature change. The volumetric heat capacity and the thermal conductivity are both defined for frozen and unfrozen states.

$$C_p + \rho_w h_{sf} (\partial \theta_{uwc} / \partial T) = \partial [k(\partial T / \partial y)] / \partial y \quad [5]$$

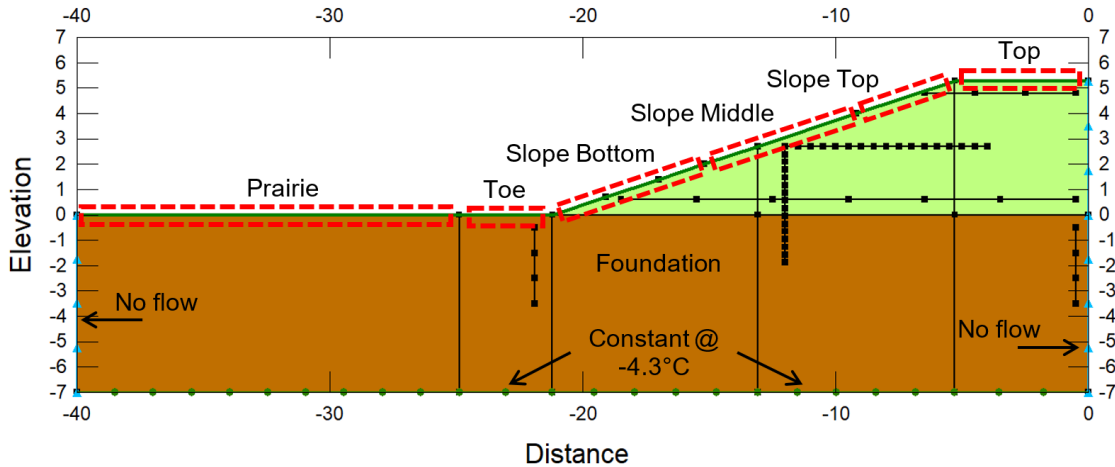


Figure 2. Cross-section of an embankment model in TEMP/W and location of boundary conditions.

In the following two subsections, two approaches are discussed regarding the temperature applied at the ground surface. The air temperatures from satellite data obtained from NASA for the period of April 2015 to August 2018 are directly applied in the model. Previous studies (e.g. Kong et al. 2019, De Guzman and Alfaro 2018, Flynn et al. 2016) have applied a fitting sine function to the temperature data. The sine function takes into account the day-to-day fluctuations and resolve them to an average; however, the smoothing curve ignores the extreme data sets during the peak summer and winter conditions which may both be helpful or detrimental in the analyses. This is extremely important in the context of climate change as an average sine function will ignore the warming trend which underestimates both the summer and winter months in a short-term analyses (typically less than 5 years).

### 3.3.1 Thermal Modifier (TM)

The thermal modifier (TM) approach, commonly known as the n-factor approach, is where an empirically determined n-factor is used to translate the air temperature to the ground surface temperature typically to a depth of 100 mm from the soil surface which accounts for the net radiation, vegetation, snow cover, and ground thermal properties (Andersland and Ladanyi 2004). It is defined as the ratio of the of the ground surface freezing or thawing indices to the air freezing or thawing indices, respectively. Table 2 summarizes the thermal modifiers used in the numerical model. The values in the specific locations where they were applied are typical of literature values and were adjusted accordingly to best match the results from the field. The varying  $n_{\text{freezing}}$  for the slope accounts for the change in snow depth where the thickest snow is at Slope Bottom. Table 2 shows that the freezing and thawing n-factors for the toe and prairie are significantly less than that of the n-factors applied to the embankment fill. As discussed earlier, peat/vegetation is a great insulator and thus prevent significant thawing in the summer months. In the winter months and because of the presence of snow, the  $n_{\text{freezing}}$  factors are somehow reduced and with greater depth of snow at the toe the freezing air temperature cannot easily penetrate through the snow layer and the foundation soil.

Table 2. Thermal modifiers used in TEMP/W model. Values based on local calibration

Location	$n_{\text{freezing}}$	$n_{\text{thawing}}$
Top	0.95	1.00
Slope Top	0.92	1.00
Slope Middle	0.83	1.00
Slope Bottom	0.55	1.00
Toe	0.20	0.55
Prairie	0.20	0.45

### 3.3.2 Surface Energy Balance (SEB)

The surface energy balance (SEB) approach uses the energy transfer between the ground surface and the atmosphere. TEMP/W has a well documented approach for incorporating these energy transfers in a thermal model and as such only a general overview of the numerical solution is presented here. The surface energy balance equation for heat transfer analysis is given in Equation 6.

$$(q_{\text{ns}} - q_{\text{nl}}) = q_{\text{sens}} + q_{\text{lat}} + q_{\text{g}} \quad [6]$$

In Equation 6,  $q_{\text{ns}}$  and  $q_{\text{nl}}$  are the net solar (shortwave) and net terrestrial (longwave) radiations,  $q_{\text{sens}}$  is the sensible heat flux,  $q_{\text{lat}}$  is the latent heat flux, and  $q_{\text{g}}$  is the ground heat flux. The boundary condition applied to the ground surface is calculated by determining  $q_{\text{g}}$  (as a function of the ground temperature) in Equation 6 and is taken as the remaining energy flux once all the other fluxes are satisfied. The net solar radiation is the difference between the downwelling and upwelling shortwave radiations. The reflected portion of the downwelling shortwave radiation is known as albedo ( $\alpha$ ) which is highly dependent on the surface characteristics. In TEMP/W, the downwelling shortwave radiation ( $q_{\text{s}}$ ) can be estimated based on the latitude of the project site, day of the year, and time of day. Combined with  $\alpha$ ,  $q_{\text{ns}}$  can be determined (Equation 7). A highly reflective surface such as fresh snow will have an albedo close to unity while a black body that absorbs all radiation will have an albedo of zero.

$$q_{ns} = (1 - \alpha) q_s \quad [7]$$

The net terrestrial radiation is given in Equation 8 where  $\epsilon_s$  is the surface emissivity assumed to be 0.95 in TEMP/W,  $\sigma$  is the Stefan-Boltzmann constant ( $4.903 \times 10^{-9}$  MJ/K<sup>4</sup>/m<sup>2</sup>/day),  $T_g$  is the absolute temperature of the ground surface,  $\epsilon_a$  is the air emissivity, and  $T_a$  is air temperature.

$$q_{nl} = \epsilon_s \sigma T_g^4 - \epsilon_a \epsilon_s \sigma T_a^4 \quad [8]$$

Sensible heat is the energy required to change the temperature of a substance with no phase change while latent heat is the energy that is supplied or extracted to change the state of the substance without changing its temperature. Sensible heat flux represents the loss of energy by the surface by heat transfer to the atmosphere. It is positive when directed away from the surface into the atmosphere. Latent heat flux on the other hand represents a loss of energy from the surface due to evaporation. For practical purposes, TEMP/W requires the wind speed to estimate the heat transfer coefficient ( $h$ ) at a reference height of 2 m to determine  $q_{sens}$  (Equation 9). The wind speed at the test site was also obtained from satellite data of NASA. The latent heat flux is related to the actual evapotranspiration on site of which no data is available and thus was ignored in the model. It is further assumed that the latent heat flux is zero during the winter months.

$$q_{sens} = h (T_g - T_a) \quad [9]$$

The presence of snow in the winter months alters the SEB and modification to Equation 6 is required. TEMP/W assumes that the  $q_{snow}$  is equal to the ground heat flux and that the snow has no capacity to store energy. The energy flux through the snow is given by Equation 10 where  $k_{snow}$  is the thermal conductivity of snow,  $T_{snow}$  is the temperature at the snow surface,  $T_g$  is the temperature at the ground surface, and  $h_{snow}$  is the depth of snow. The snow depths on site are estimated over a monthly period based on the snow depth readings observed from the images obtained from camera traps installed around the research site and also measured from previous site visits during the winter season.

$$q_{snow} = -k_{snow} [(T_g - T_{snow})/h_{snow}] \quad [10]$$

Combing Equations 7, 8, 9, and 10 (if snow is present) in Equation 6 the ground temperature can be solved as the applied boundary condition at the ground surface. In summary, the parameters required for an SEB analysis in TEMP/W requires the air temperature, wind speed, solar radiation (measured or estimated), albedo, relative humidity, and snow depth.

Tables 3 and 4 summarize the albedo and snow depth at different locations in the embankment, respectively. The albedo values selected in the model were taken from NASA and adjusted accordingly to best match the results of the recorded field values over a monthly period. The higher the albedo, the more reflective the surface is. As mentioned earlier, the snow depths in Table 4 were estimated based on the survey rod readings from images taken by camera traps at the research site. The thermal conductivity of snow at the Toe and Prairie surfaces is 15 kJ/days·m·°C, and taken as 55 kJ/days·m·°C for the Slope Top, Slope Middle, and Slope Bottom. The top surface is always cleared off from snow precipitation either mechanically (snow dozers) or naturally (drift). These values are within the range of snow thermal conductivities from Sturm et al. (1997) for different densities.

Table 3. Albedo applied to the model at different locations.

Month	Top	Slope Top	Slope Middle	Slope Bottom	Toe	Prairie
Jan	0.12	0.15	0.35	0.70	0.70	0.70
Feb	0.12	0.15	0.35	0.70	0.70	0.70
Mar	0.12	0.15	0.33	0.65	0.65	0.65
Apr	0.15	0.20	0.20	0.65	0.65	0.65
May-Sept	0.10	0.10	0.10	0.10	0.25	0.25
Oct	0.12	0.12	0.12	0.18	0.25	0.25
Nov	0.12	0.15	0.22	0.80	0.80	0.80
Dec	0.12	0.15	0.25	0.75	0.75	0.75

Table 4. Snow depth at different locations of the embankment (units in metres).

Month	Top	Slope Top	Slope Middle	Slope Bottom	Toe	Prairie
Jan	0	0.16	0.30	0.55	0.60	0.55
Feb	0	0.20	0.40	0.60	0.65	0.60
Mar	0	0.20	0.47	0.70	0.73	0.70
Apr	0	0.10	0.20	0.65	0.65	0.60
May-Sept	0	0	0	0	0	0
Oct	0	0.03	0.05	0.07	0.07	0.07
Nov	0	0.04	0.07	0.20	0.20	0.20
Dec	0	0.06	0.17	0.50	0.50	0.48

### 3 RESULTS AND DISCUSSION

Figures 3 to 6 show the recorded field values from the thermistor strings during the three-year monitoring period and the results of the thermal modelling using both TM and SEB approaches. Modelled results of select thermistor nodes at the top of the embankment (TS-C1) are shown in Figure 3. TS-C1 shows that there is uniform warming across the top of the embankment in response to the ambient air temperatures. Both approaches reasonably simulate the recorded field values as well as the fluctuation in daily mean air temperatures.

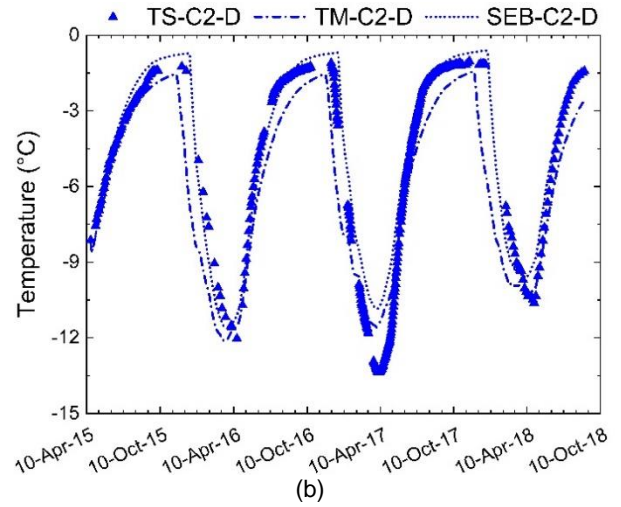
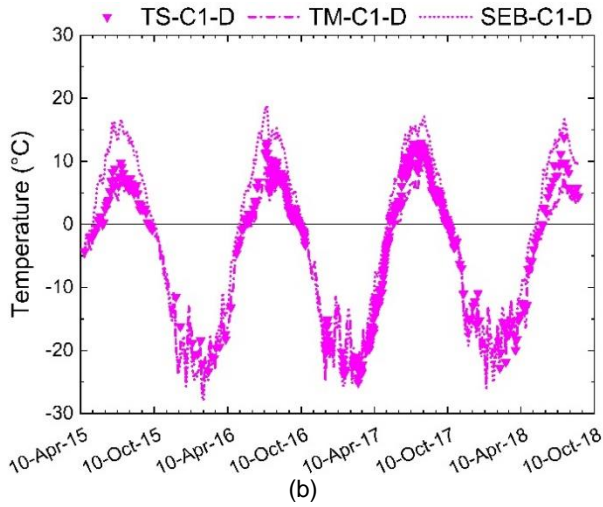
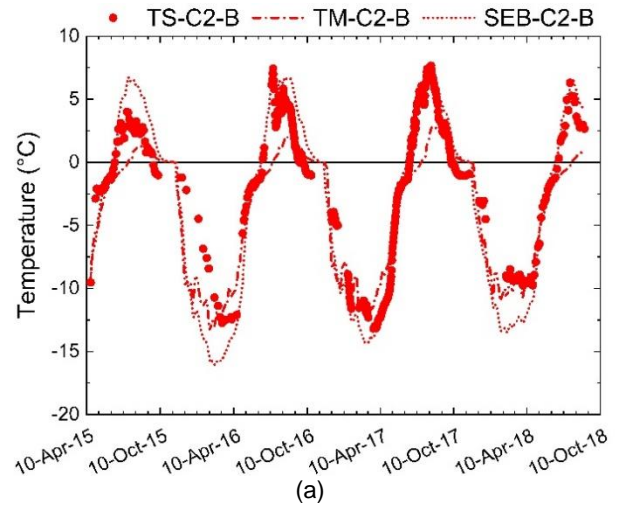
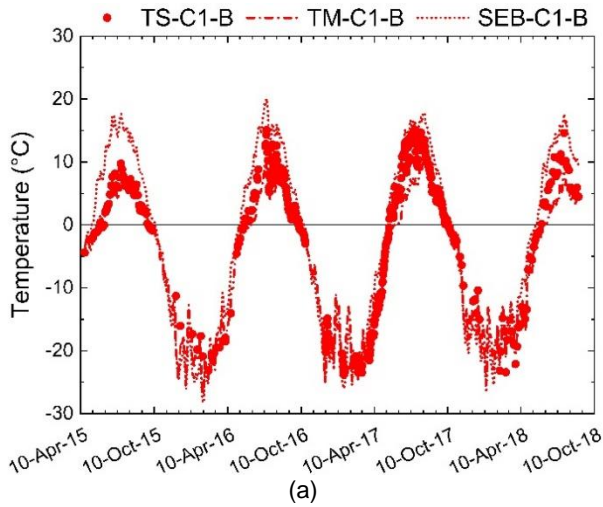


Figure 3. Comparison of measured and modelled temperature values using TM and SEB approaches at the top of the embankment: (a) C1-B and (b) C1-D.

The thermistor nodes along the base of the embankment (TS-C2) are shown in Figure 4. Node C2-B (Figure 4a) is approximately 1.3 m directly below the slope face and model results show that the seasonal freezing and thawing temperatures can penetrate at this location. Node C2-D (Figure 4b) is 3.3 m directly below the slope face above it and the temperature recorded and modelled are sitting close at  $-1.5^{\circ}\text{C}$ . Node C2-G (Figure 4c) has 4.7 m of embankment fill above it and results indicate that the core of the embankment is still frozen. The temperature recorded at C2-D and C2-G is colder by approximately  $1.4^{\circ}\text{C}$  in the second year of monitoring but  $1.5^{\circ}\text{C}$  warmer in the third year compared to the first year. In general, the SEB approach reasonably simulated the summer peaks for the three thermistor nodes presented, while the TM approach slightly underestimated it. The SEB approach slightly overestimated the winter temperatures for C2-B. Both TM and SEB approaches underestimated the winter temperatures at the core of the embankment by about  $1.5^{\circ}\text{C}$ .

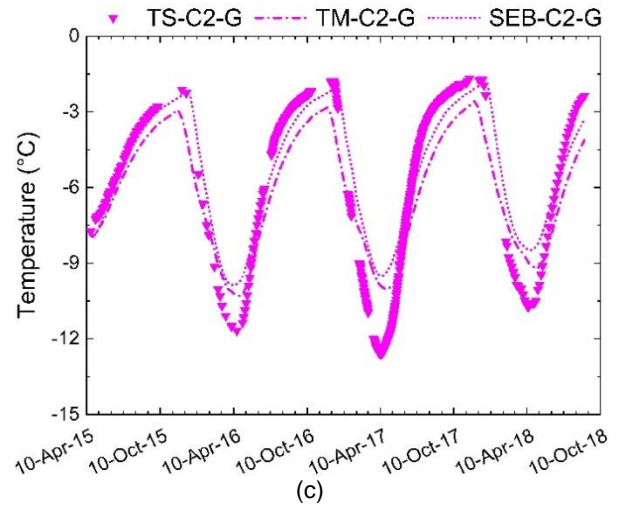


Figure 4. Comparison of measured and modelled temperature values using TM and SEB approaches along base of the embankment: (a) C2-B, (b) C2-D and (c) C2-G.

The thermistor nodes at the foundation centreline (TS-C3) are shown in Figure 5. The thermistor nodes presented indicate the foundation soil where the warmest recorded temperatures reach close to  $-4^{\circ}\text{C}$ . The SEB approach shows good agreement in the summer to winter turnover but overestimates the winter to summer turnover. The trend in between periods are comparable to the field results. Although the TM approach slightly underestimates the warmest temperatures in the summer to winter turnover, the winter to summer turnover temperatures are simulated well. It is interesting to note that the recorded temperatures in the field have shown a warming trend since construction completion and captured by both approaches as well. This warming trend is a result of both the observed warming air temperatures in the region as well as the possibility that the embankment is still undergoing changes to reach thermal equilibrium. Although the full height of the embankment is insulating the foundation centreline, climatic changes are still contributing to the warming temperatures in the foundation soil.

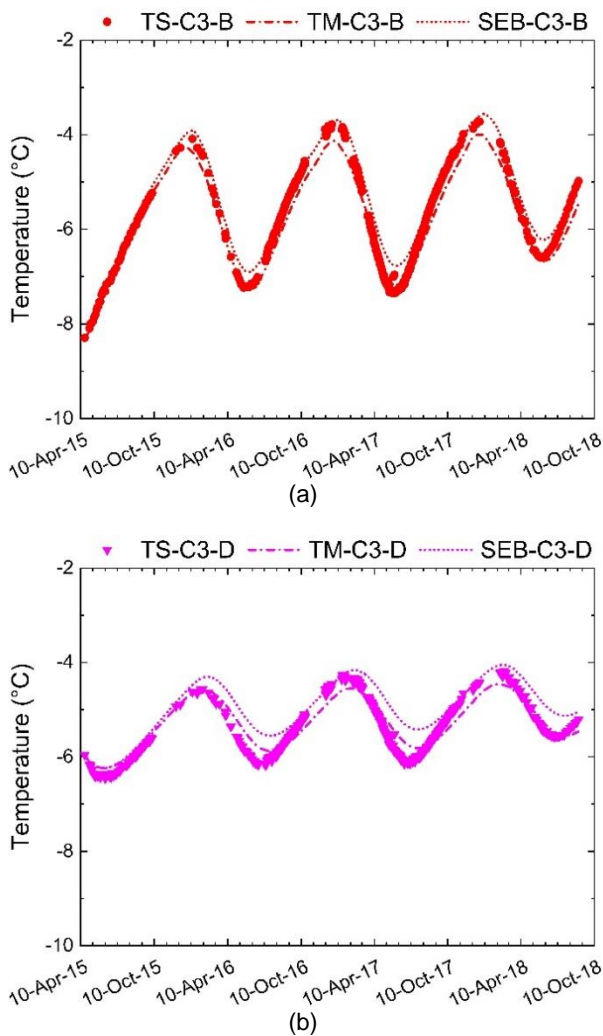


Figure 5. Comparison of measured and modelled temperature values using TM and SEB approaches at the foundation centreline: (a) C3-B and (b) C3-D.

The thermistor nodes of the foundation toe (TS-C4) are shown in Figure 6. Node C4-B (Figure 6a) is 1.5 m below the ground surface and it can be seen that the warmest recorded permafrost temperature is close to  $-1^{\circ}\text{C}$ . The TM approach overestimates the winter to summer turnover close to the ground surface, but showed agreeable results for the first two years of monitoring for C4-D (Figure 6b). The field results however are  $1.3^{\circ}\text{C}$  warmer compared to the model results in the third year and  $1.8^{\circ}\text{C}$  warmer compared to the previous year field values. In between transition periods especially from summer to winter the SEB and TM approach respond differently but both reach the same turnover temperatures. The SEB approach model results are closer to field values in between transitions periods. The difference in results during the summer to winter turnover is possibly due to the volumetric water content of the foundation soil. It is possible that there is more water present on site than anticipated during the thawing season for which the latent heat will take longer to be removed.

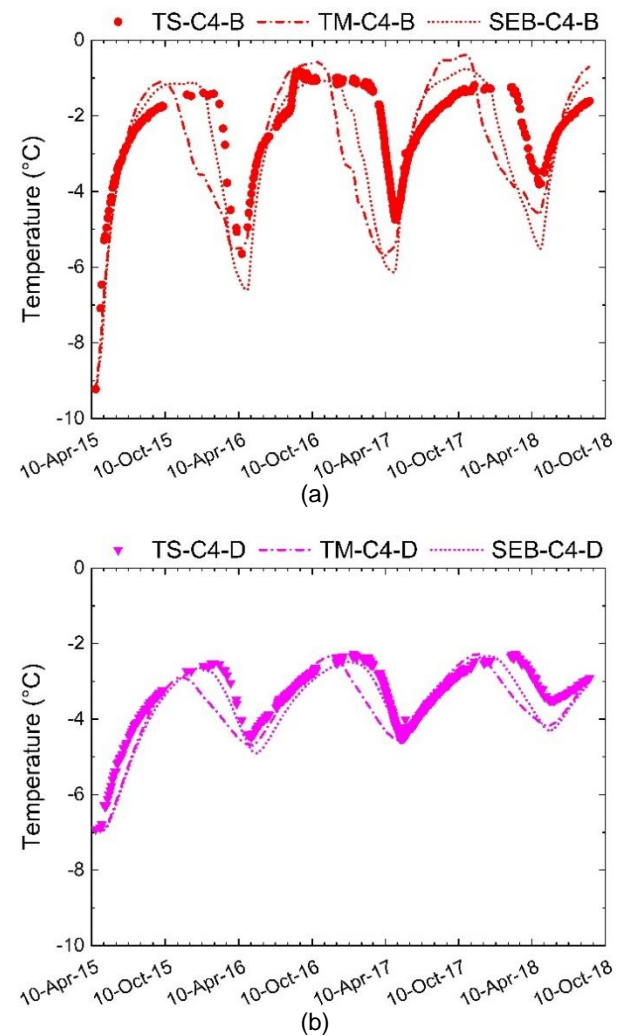


Figure 6. Comparison of measured and modelled temperature values using TM and SEB approaches at the foundation toe: (a) C4-B and (b) C4-D.

Although the TM approach provided comparable results with the monitored field values, the factors selected were still empirical which required numerous simulations in order to match the field values. The authors however are confident that because of the simulations done for an embankment in Arctic conditions, these values provide an initial estimate of behaviour which can be supplemented by instrumentation at site to further refine embankment performance prediction. The SEB approach led to more accurate behaviour for the embankment fill and foundation soil especially during the turnover periods, but is more demanding on input parameters and requires more computational time to complete an analysis in comparison to the TM approach. Furthermore, accurate field measurements for the SEB approach require specialized equipment and thus translate to cost in large infrastructure projects, but otherwise available from satellite data.

#### 4 SUMMARY

Thermal numerical models using thermal modifier and surface energy balance approaches have been developed for a thick embankment section along ITH calibrated with three years of monitored temperature data since 2015. The thermistors and SAAs installed at the test section greatly contributed to rational calibration of the thermal models. Embankment thermal design should account for reasonable assumptions on material properties and expected temperature boundary conditions to best simulate thermal performance. Supplementing the model with measured field values can greatly improve its reliability.

The results of the thermal model are highly dependent on the modelling approach selected. The thermal modifier approach uses empirical values that lump all factors together to transform the air temperature to ground surface temperatures, while the surface energy balance approach requires complex input parameters that require sophisticated instrumentation to obtain accurate values. The difference in soil temperatures between the two models is an inherent variable a designer should assess. The snow depth and albedo was assumed to be constant throughout the analyses for the surface energy balance approach which may not be accurate for future conditions but nevertheless provide reasonable estimate in assessing thermal performance of embankments in the Arctic.

#### ACKNOWLEDGEMENTS

The work presented in this paper was supported by the Department of Infrastructure (formerly Department of Transportation) of the Government of the Northwest Territories and Transport Canada. E. Gruben's Transport Ltd. was the contractor for the north-side construction of the highway and provided logistical support with Department of Infrastructure personnel at the construction site and formed a critical part to the successful construction of the test section. The assistances of Kerry Lynch and Aron Piamsalee during the installation of instrumentation in April 2015 are greatly appreciated.

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