

# Thermal condition of Kangirsuk airstrip near Ungava Bay Coast, northern Québec, Canada

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## ABSTRACT

Kangirsuk Airport (Nunavik), completed in 1987, is located in the continuous permafrost zone. The runway is 1190 m long and 60 m wide. Thermistor cables were installed in the runway and the natural ground to monitor soil temperatures. Numerical modeling of the thermal regime of the embankment and subgrade has also been performed to reproduce the conditions and trends in the subsurface thermal regime beneath the embankment. Site-specific parameters, such as soil properties, near-surface air temperature, and embankment dimension, were measured and used as input parameters. Particular interest was paid to the foundation soil under the side slope where relatively rapid permafrost degradation was occurring due to snow accumulation. These results help government agencies evaluate the thermal conditions of underlying permafrost and deploy potential adaptation solutions at Kangirsuk, northern Québec.

## 1 INTRODUCTION

Nunavik, located in permafrost regions, constitutes the northern third of the province of Québec, Canada. There are 14 communities in Nunavik; they widely spaced from one another, between 80 and 240 km from the nearest neighbor (Ficheur 2011). Air transportation is essential to ensure communication between local communities and the rest of the province. Ministère des transports du Québec (MTQ) and the Centre d'études nordiques have carried out a research study related to the monitoring of permafrost conditions, during and after the construction of 14 airstrips in Nunavik. Thirteen of 14 airstrips are owned by the MTQ while one is owned by Transport Canada. The majority of the MTQ airstrips are 1090 m long and 44 m wide, covered by gravel material. Of these airports, two are built on sporadic discontinuous permafrost (Kuujuarapik and Umiujaq).

Access roads between the airport infrastructure and local communities were gravel-surfaced during the construction and were paved in the 2000s to improve performance (L'Hérault et al. 2012). During the construction of the MTQ infrastructure in Nunavik between 1984 and 1991, the climate was relatively stable, and permafrost was considered a solid, permanent foundation. However, since the early 1990s, significant climate warming has been observed in Nunavik (Allard et al. 2018).

After the construction of the airport infrastructures, many permafrost studies were carried out by MTQ and researchers from Centre d'études nordiques to provide the information needed for developing adaptation strategies to counter the thawing of permafrost and for future construction and maintenance of runways and access roads in Nunavik.

The specific objectives of this research activity were to quantify the thermal condition of permafrost underneath the airstrip embankment, using numerical modeling techniques. One potential cost-effective adaptation solution was also proposed at Kangirsuk airstrip, in Nunavik.

## 2 STUDY SITE AND FIELD MEASUREMENT

Kangirsuk is located on the coast of Hudson Strait, 420 km northwest of Kuujuaq (61.59N; 71.93W); it is a community of 566 inhabitants (Allard et al. 2007a; Figure 1). The village of Kangirsuk is located 10 km from the Hudson Strait, on the southeastern shore of Wakeham Bay. At Kangirsuk, the averaged air freezing index from 2005 to 2016 was 3151 days  $^{\circ}\text{C}$ , while the averaged thawing index for the same period was 895 days  $^{\circ}\text{C}$ . The warmest year was 2009–2010 with an average of  $-1.8^{\circ}\text{C}$ ; 2014–2015 was the coldest, with an average of  $-5.7^{\circ}\text{C}$ .

The Kangirsuk airstrip, located in the continuous permafrost zone, is 1190 m long and 60 m wide (Allard et al. 2009). It is oriented along a northeast-southwest axis, with an altitude of over 113 m. A section of the airstrip runway was built over ice-rich till that caused settlement when thawed (L'Hérault et al. 2012). This was one of the main geotechnical problems at the airport. By 2004, an accumulated settlement of approximately 0.5 m was observed (Beaulac 2005). Signs of runway degradation were observed during the fieldwork in the summer of 2009.

To monitor the thermal regime, a thermistor string was installed in 2.9 m deep boreholes under the center of the runway in 2005. It comprised 9 thermistors, with the separation space ranging between 0.1 m and 0.4 m. This string was extended to 6.5 m depth below the embankment-soil interface to monitor the deeper ground thermal regime, in 2016. Data were recorded using a CR10 acquisition system.

In the natural ground, a thermistor string was installed in a 6.5 m deep borehole in 2010. It was located 2 m from the toe of the embankment. There were 10 thermistors, which were spaced by 0.5 m. Data were also recorded using a CR10 acquisition system, which was shared with the thermistor string under the embankment centerline. The thermistor string does not operate well, and limited data were available to analyze the ground thermal regime.

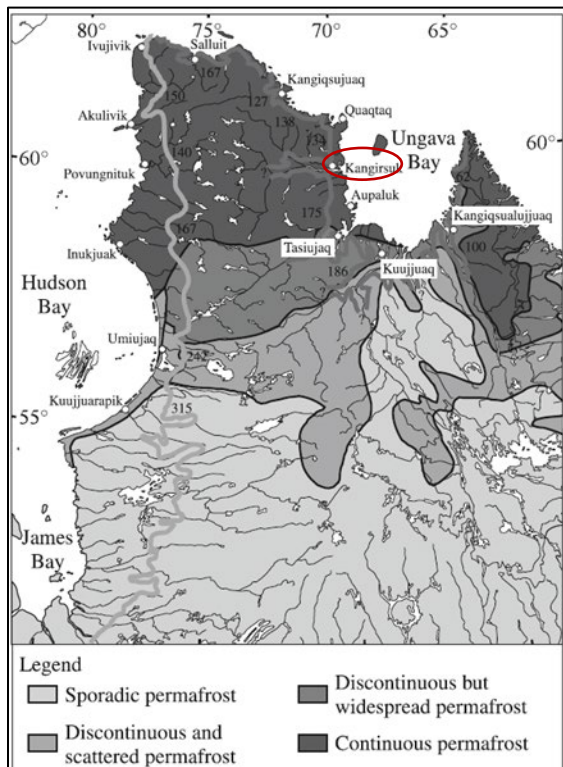


Figure 1. The location of Kangirsuk in Nunavik, Québec (Fortier et al. 2011).



Figure 2. Engineering problem observed at Nunavik, Québec.

Figure 3 illustrates temperature variations under the centerline of the airstrip embankment for 3 years, from November 2016 to August 2018. The embankment thickness was 1.4 m. The interface between the embankment and the natural ground is used as the reference level (0 m), meaning all positive values along the y-axis refer to a position inside the embankment fill. The thawfront penetrated into the natural ground in the summertime from 2016 to 2018. The permafrost table was -0.8 m below the embankment-soil interface in 2016. In the ground, the warming process generally started in June and lasted until November. During winter, there was limited change in the ground temperature from 2016 to 2018. For instance, -1 °C isotherm was located at -2.3 m in 2016 and in 2018.

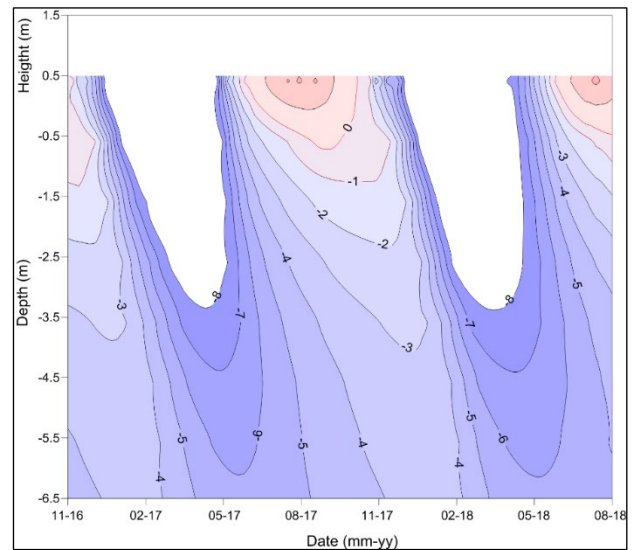


Figure 3. Evolution of embankment and ground temperature with time under the centerline of Kangirsuk airstrip, Nunavik, Canada.

The ground temperature varies with time due to many factors, including solar radiation, snow thinness, and soil depth. Figure 4 shows the temperature profiles with depth for selected mid-months under the centerline of the airstrip embankment, in 2017. The temperature profiles demonstrate a temperature range of 15.5 °C at 0.25 m below the embankment surface, with the minimum, and maximum temperatures reaching -22.5 °C and 6.2 °C, respectively. The active layer depth was approximately 0.5 m, in August. The soil temperature was still affected by the seasonal ambient air temperature at -6.6 m below the interface, with the maximum temperature and minimum temperature reaching -3.8 °C and -5.8 °C, respectively.

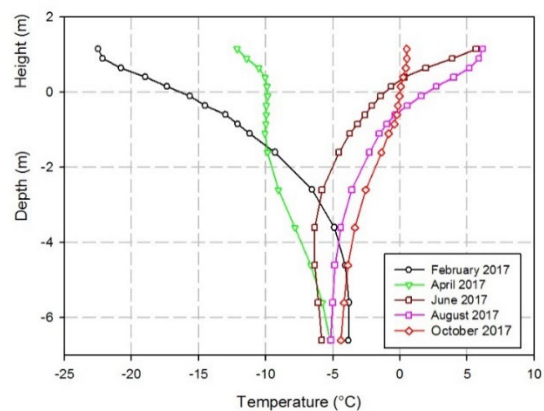


Figure 4. Measured temperature profiles with depth, under the centerline of Klanguirk airstrip, Nunavik, Québec.

### 3 MODEL DEVELOPMENT

A model was developed to reproduce the temperature distribution in the embankment and in the subgrade soil. Site-specific characteristics, such as air temperature and embankment dimensions, were measured and used as input parameters to improve the accuracy of the model.

The physical domain consists of a roadway embankment and an underlying foundation, as shown in Figure 5. The right half of the physical domain was chosen to carry out the simulation, due to the symmetry of the embankment. The physical domain is 65.8 m wide from the centerline of the embankment and extends to a depth of 30.0 m below the original natural ground surface. The embankment thickness is 1.4 m. The computational domain was extended for 30 m from the toe of the embankment, and the lower boundary was located 15 m beneath the ground surface. In the computational domain, part ① is the embankment fill; part ② is the till, with a thickness of 2.7 m; part ③ is the rock, with an ignorable water content of  $0.01 \text{ m}^3/\text{m}^3$ . The thermal properties of embankment fill were estimated through Kersten's equations (1949), with an assumed uniformly water content of  $0.1 \text{ m}^3/\text{m}^3$ . The thermal properties of till and rock were obtained from L'Hérault et al (2012). Table 1 lists the thermal properties of the different materials used in the model.

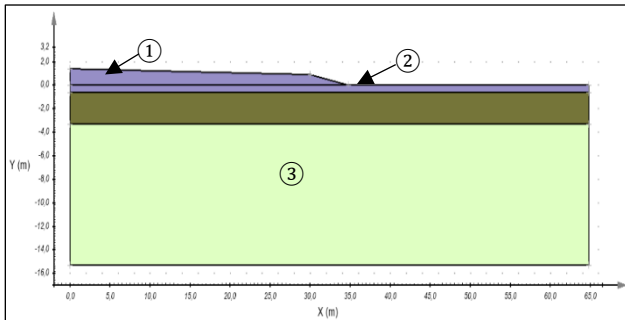


Figure 5. The physical domain of the embankment and foundation.

Table 1. Thermal properties used in the model.

Physical variable	$K_f$ (W/m- $^{\circ}\text{C}$ )	$K_u$ (W/m- $^{\circ}\text{C}$ )	$C_f$ (MJ/m $^3$ - $^{\circ}\text{C}$ )	$C_u$ (MJ/m $^3$ - $^{\circ}\text{C}$ )
Embankment fill <sup>a</sup>	2,65	2,00	1,67	1,92
Till <sup>b</sup>	2,34	2,32	2,23	3,21
Rock <sup>b</sup>	1,70	1,70	2,49	2,49

Note:  $k_f$  = frozen thermal conductivity;  $k_u$  = unfrozen thermal conductivity;  $C_f$  = frozen volumetric heat capacity;  $C_u$  = unfrozen volumetric heat capacity. <sup>a</sup> Values obtained from Kersten's equations; <sup>b</sup> Values obtained from L'Hérault et al. 2012.

The thermal boundary conditions consisted of temperature functions applied to the embankment and natural ground. A constant heat flux boundary was applied to the bottom, right, and left boundaries. At the left-hand and right-hand boundaries, a zero-heat flux was applied, considering the negligible temperature variation. A geothermal heat flux of  $0.03 \text{ W/m}^2$  was applied at the bottom, considering its limited effect on the permafrost temperature. The near-surface temperature is applied on the top boundaries of the physical domain. The thermal regime of permafrost is strongly affected by the snow thickness and density (e.g., Jorgenson et al. 2001), due to its insulation effect. A field investigation was done to assess the snow accumulation at Kangirsuk airstrip. Based on field measurements, the snow cover thickness was 60 cm to 75 cm (Allard et al. 2007b). The n-factor is the ratio of air temperature to surface temperature. Lanouette et al. (2015) developed the logarithmic relationship between the n-factor value and the snowpack thickness, based on the measured snow thickness and air temperature, near-surface soil temperature in Nunavik. To simplify the mode, an even snow depth of 65 cm was assumed to estimate the n-factor on the side slope of Kangirsuk airstrip. The thawing n-factor for the embankment surface and side slope was 1.86. Table 2 summarizes all the n-factors used in the model.

Table 2. Summary of n-factor used in the model.

Surface type	Thawing n-factor	Freezing n-factor
Natural ground surface	0.25	0.36
Embankment surface	1.86	1.0
Embankment side slope	1.86	0.28

### 4 NUMERICAL CALIBRATION AND DISCUSSION

The meshing element size ranged from less than 1.0 m in the embankment fill to approximately 1.5 m in the subgrade, covering the domain shown in Figure 5. To obtain a better solution of the active layer and the top part of permafrost, a density meshing was assigned at the natural ground surface layer.

The measured data from 2016 to 2018 were available and used for model calibration. The model was run with an automatic step of less than 1.0 days. Figure 6 shows the 2-year average measured and simulated maximum, averaged, and minimum soil temperature profiles with the depth under the centerline of the airstrip embankment at Kangirsuk, Nunivak.

The results indicate that the modeled average temperature was larger than the measured temperature with a maximum temperature difference of  $0.2 \text{ }^{\circ}\text{C}$  at the depth of  $-1.1 \text{ m}$  below the embankment-soil interface. Below  $-1.1 \text{ m}$ , the modeled average temperature fitted well with the measured average temperature. For the maximum temperature, the modeled temperature was higher than the measured temperature in the subgrade until the depth of  $-4.6 \text{ m}$ , with a maximum temperature difference of  $0.9 \text{ }^{\circ}\text{C}$  occurring at  $-1.1 \text{ m}$  above the interface. At the depth of  $-6.6 \text{ m}$ , the modeled temperature was lower than the measured

temperature, with a difference of 0.1 °C. Comparison between the modeled minimum temperature and measured minimum temperature indicates that the measured temperature was higher than the modeled temperature in the embankment and subgrade, with the difference becoming smaller with depth. The maximum and minimum difference was 3.3 °C and 0.4 °C, respectively.

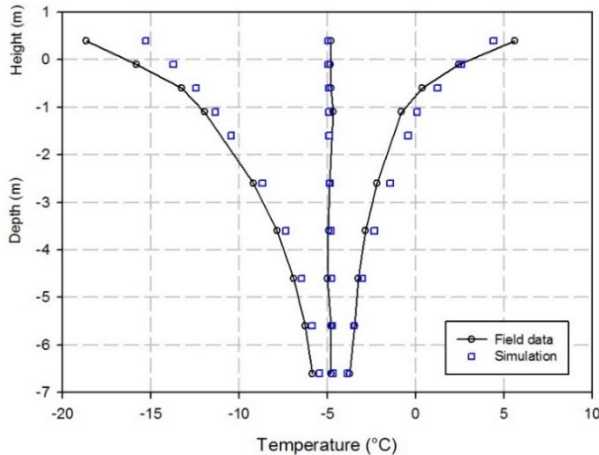


Figure 6. Comparison between the averaged field data (2016–2018) and numerical simulation of the maximum, minimum, and average temperature profiles with depth, under the centerline of Tasiuaq airstrip, Nunavik.

For the natural ground, the temperature measurement was not continuous, and the averaged temperature was unable to be obtained. Figure 7 shows the 2-year averaged measured and simulated maximum and minimum soil temperature profiles with the depth in the natural ground. Comparison between the modeled maximum temperature and measured maximum temperature indicates that the simulated soil temperature generally fitted the measured soil temperatures well, with the maximum difference less than 0.5 °C. For the minimum temperature, the measured temperature was colder than the measured temperature in below the depth of -1.0 m below the interface. The maximum difference of 1.3 °C occurred at -2.5 m. As a whole, the developed model was judged reasonable and satisfactory to reproduce the thermal regime at Kangirsuk, Nunavik.

Climate change can lead to negative impacts on the underlying permafrost, causing degradation of the infrastructure in Nunavik. In this paper, our specific interest was paid to the thermal stability of permafrost under the airstrip shoulder using the model developed at Kangirsuk, Nunavik. Batenipour et al. (2010) indicate that the thermal stability of permafrost can be assessed based on the thermal gradient of mean annual ground temperature between the embankment-soil interface and the soil depth with zero soil variation. A positive mean annual thermal gradient is an indication of warming and degrading permafrost. The modeled mean annual soil temperature at the interface under the side slope was 1.8 °C, indicating a positive thermal gradient and unstable permafrost condition. The current work is in the early stage of designing

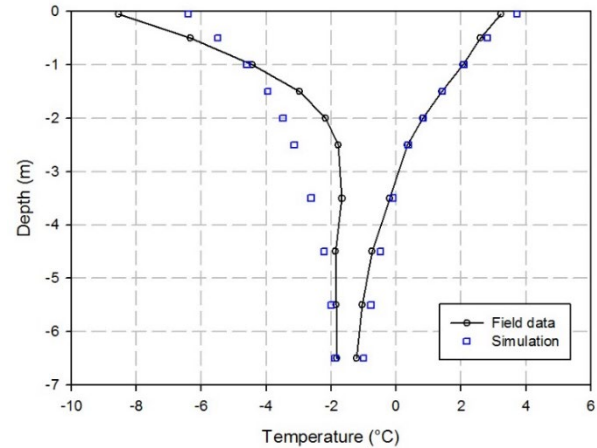


Figure 7. Comparison between the field data and numerical simulation of the maximum, and minimum temperature profiles with depth, in the natural ground.

adaptation techniques to preserve the degrading permafrost under the airstrip shoulder at Kangirsuk, Nunavik.

Poorly graded rocks with a high porosity are used to facilitate convection in an air convection embankment (ACE). Shoulder air convection embankments (ACEs) are proven to be an effective technique to counter the effect of snow accumulation on the side slope of northern infrastructure embankments (e.g., Goering 1998; Coulombe et al. 2012; Darrow and Jensen 2016). This technique has also been successfully employed to preserve underlying permafrost at Puvirnituk airstrip, Nunavik (Figure 8).

The design chart of shoulder ACE to stabilize permafrost was proposed in the previous research, and it should be used with the heat balance analysis charts for unprotected embankment (Figure 9; Kong and Doré 2021).  $L$  is the embankment thickness (Figure 9a).  $\Delta T$  is the temperature difference between the mean annual winter air temperature and permafrost temperature (Figure 9b).



Figure 8. Application of ACE at Puvirnituk airstrip, Nunavik, Québec.

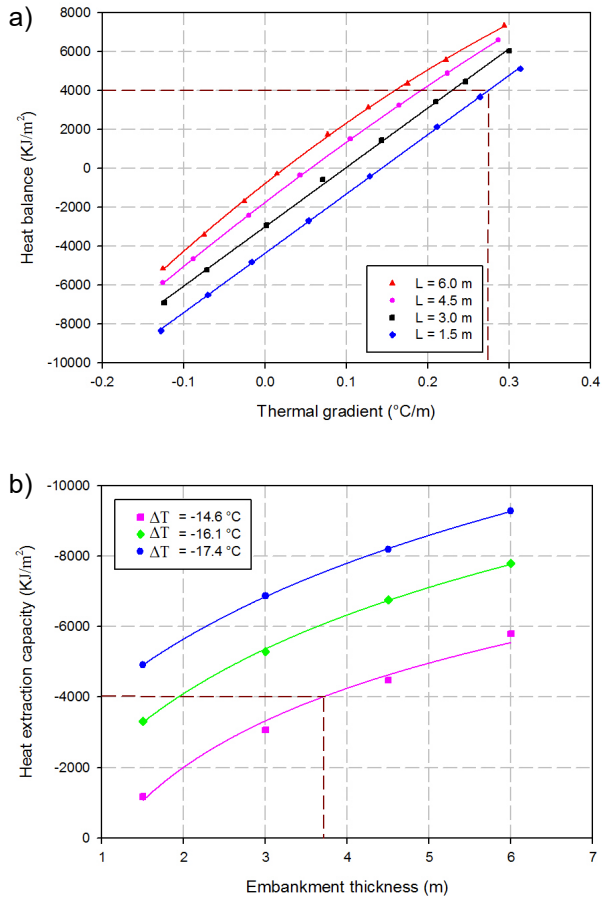


Figure 9. Thermal analysis of permafrost stability under the side slope of embankment: a) heat balance assessment chart for conventional embankments; b) heat extraction capacity chart for shoulder ACE.

## 5 CONCLUSIONS

A geothermal model was developed to reproduce the thermal regime of underlying permafrost beneath an embankment at Kangirsuk airstrip, Nunavik. Field measurements of ground temperature from 2016 to 2018 were available and used to calibrate the model developed. The modeled average temperature fitted with the measured average temperature closely, with the maximum temperature difference of 0.2 °C, supporting the reasonable accuracy of the developed model. After a satisfying calibration, the model was used to calculate the soil temperature at the embankment-soil interface under the side slope, to determine the thermal stability of underlying permafrost. The analysis of the thermal gradient indicates that the side slope of the airstrip embankment was thermally unstable. Considering the ongoing climate warming in Nunavik, the thermal degradation appears to continue, and effective adaptation techniques are required to preserve the Kangirsuk airstrip. Air convection embankment (ACE) provides a good option to mitigate the degrading permafrost, based on measured thermal performance in Nunavik. Future work will focus on 1) investigating the

future thermal regions under different climate change scenarios using the model developed, and 2) developing of adaptation solutions to adapt to the projected thermal degradation of permafrost underneath Kangirsuk airstrip, in Nunavik, Canada.

## 6 ACKNOWLEDGMENTS

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