GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

# Influence of snow cover on the ground thermal regime along an embankment built on permafrost: In-situ measurements

Florence Lanouette, Guy Doré et Daniel Fortier
*Québec City, Québec, Canada*
Chantal Lemieux
*Department of Civil Engineering – Laval University, Québec, QC, Canada*
*Department of Geography – University of Montréal, Montréal, QC, Canada*

ABSTRACT
Snow accumulation along linear transportation infrastructures prevents heat to be extracted from the ground in winter. Consequently, the permafrost underneath is degrading and the structural properties of the roadway can be significantly affected. During the winter of 2014-2015, the thermal regime through the snowpack and the ground underlying were monitored at two study sites in Canada. The data collected shows that the ground surface temperature reduction is more important for the first centimeters of snow, then progressively diminishes as the snowpack get thicker and denser. The relationship between the n-factor and the snow thickness that can be explain by a logarithmic equation can quantify this observation. This paper is part of a bigger project whose purpose is to counteract the insulating effect of snow accumulation along transportation infrastructure embankments by adapting the angle of the slopes in the design.

RÉSUMÉ
En empêchant l'extraction de la chaleur en hiver, l'accumualtion préférentielle d'un couvert neigeux en bordure des infrastructures de transport linéaires peut être une cause importante de la dégradation du pergélisol affectant grandement les propritétés structurales de la chaussée. Au cours de l'hiver 2014-2015, le régime thermique dans le couvert nival et le sol sous-jacent a été mesuré à deux sites d'essais. Les données recueillies démontrent que la diminution de la température à la surface du sol est plus importante pour les premiers centimètres de neige, puis, diminue progressivement à mesure que le manteau neigeux devient plus épais et plus dense. La relation entre le facteur-n et l'épaisseur de la neige, que l'on peut expliquer par une équation logarithmique, peut quantifier cette observation. Cet article s'insère au sein d'un projet de plus grande envergure visant à contrer l'effet isolant de l'accumulation de la neige le long des remblais d'infrastructures de transport en modifiant l'angle des pentes lors de la conception.

## 1 INTRODUCTION

In northern regions, transportation infrastructure is essential for the subsistence, the economic development and for the living quality of communities. However, the building of linear infrastructure such as airstrips or roads induces temperature disturbance at the surface of the ground. Combined with climate changes, this alteration of the thermal equilibrium can cause the degradation of underlying permafrost. Then, in ice-rich permafrost environments, the bearing capacity of the subgrade is likely to be affected and significant thaw settlements can cause substantial damages to infrastructures affecting its serviceability and performance.

Snow is an important factor of perturbation associated with linear transportation infrastructure. Dry snow is composed primarily of ice crystals and air. Thermal conductivity of pure ice is around 2.24 W/m·°C, but thermal conductivity of air is very low (0.025 W/m·°C). Thus, the thermal conductivity of snow that contains an important fraction of air varies according to its density. For a low density fresh snow, thermal conductivity can be less than 0.10 W/m·°C and for a dense ripened snow it can be greater than 0.50 W/m·°C. Those values are about five to twenty times lower than any mineral soils (Zhang, 2005). Thus, in comparison with most materials at the surface of the ground, snow is an insulator. After their construction, roads and airstrips stand in the way of the wind favouring accumulation of snow along the downwind side of the embankment. Maintenance of roadways in winter also contributes to increasing the thickness of snow at the toe of the embankment. Thickening this snow cover causes heat retention in the ground during winter because of the insulation properties of snow. As significant heat extraction usually occurs in normal conditions due to the important temperature gradient between cold air temperature and warmer ground temperature in winter, the accumulation of an important snow cover significantly limits ground cooling in comparison with areas where no transportation infrastructures are encountered. These particular conditions are likely to increase permafrost table depth with time, which may cause various problems associated with permafrost degradation.

In fall, when the snow cover is thin, it is mainly heat exchange processes at the snow-air interface that control the thermal regime of the ground. However, as the snow thickness increase during the winter, the ground thermal regime is principally control by conductive heat transfer through the snowpack. The conductive flux (Q) is then function of the thermal conductivity of the snow ($k_s$) and of the temperature gradient expressed as the ratio of the temperature variation across the snowpack ($\Delta T$) and the snow cover thickness ($z_s$) (equation 1).

$$Q = k_s \times \Delta T / z_s \quad [1]$$

In order to minimise the temperature variation between the air and the surface of the ground, the snow thermal conductivity should be higher or the snow cover should be thinner. As previously mentioned, snow thermal conductivity is function of physical properties of snow as density and microstructure and is, obviously, practically impossible to control through design parameters. However, the snowpack thickness can be minimized by using a gentle slope for the embankment. In fact, a gentle slope reduce the turbulence due to the sudden change of slope and allow the wind to follow a laminar flow that can more easily blow the snow away from the embankment. Transportation Association of Canada suggests the use of a slope ratio of 1V:6H (Ficheur and Doré, 2010).

The objective of this study is to develop a thermal stabilization method based on the reduction of heat retention in the ground by limiting the snow cover thickness associated with geometric design parameters of the embankment. The specific objectives of this project are to monitor the thermal regime through the snowpack and the ground at two test sites, to develop a 2D semi-empirical thermal model and, ultimately, to develop an engineering tool to support embankment design while taking into account the impact of preferential snow accumulation on the degradation of embankment built on thaw-sensitive permafrost. Thermal regime in the snow cover and at the surface of the ground will be documented in this paper.

## 2 METHODOLOGY

To address the problem described above, monitoring and analyzing detailed thermal regimes at two test sites has to be done. One test site is along the Tasiujaq airstrip in northern Quebec and the other is along the Alaska Highway near Beaver Creek in Yukon. Data collected at the test sites will be used to develop and calibrate a 2D geothermal model using the modeling software TEMP/W from Geo-Slope International. The purpose of thermal modelling is first to represent the measured heat transfer through the snow, the embankment and the underlying ground at the test sites taking into consideration the specific site conditions. Then, once the finite element model is calibrated, different simulations will allow quantifying the impact of embankment height and slope angle on the thermal regime in the ground and consequently, the possible effect on the mechanical behaviour of embankments.

### 2.1 Experimental Sites

#### 2.1.1 Tasiujaq, Northern Quebec

Tasiujaq is an Inuit community in Nunavik, Quebec located southwest of the Ungava Bay in a zone of extensive discontinuous permafrost (58°71'N, 69°82'W). As many villages in Northern Québec, Tasiujaq airport is the only transportation link in and out of the village, except in summer. However, the runway is known to be affected by permafrost degradation (Doré and Beaulac, 2007). As shown by Allard et al. (2009), one particularity of this site is the great difference of the prevailing winds direction during the year. In summer, the prevailing winds are oriented around 40°N which is almost parallel to the airstrip oriented northeast-southwest (30°N). In winter, prevailing winds are oriented at 290°N and form, consequently an angle of 80° with the runway. Thus, the southeastern side of the embankment is affected by important snow accumulation where the snowpack thickness can reach 175 cm (Allard et al., 2009). Several signs of permafrost degradation under the slopes of the runway have been observed including important water accumulations along the embankment toe.

The Tasiujaq test site was instrumented at the end of September 2014. The monitored transect is located at chaining 5+515, on the southeastern side of the runway. Temperature data were recorded since then every two hours through three different thermistors cables. The D405 Satellite Logger records and transmits the data through a satellite connexion. Figure 1 shows a picture of the instrumentation along the roadway on which a sketch of the thermistors cable has been added. A cable of 18 thermistors, each 1 m apart (red line, Figure 1), measures temperatures at the interface between the snow and the ground. At the mid-slope of the embankment, the thermal regime through 2 m of the embankment and 2.8 m of the underlying ground is monitored by 17 thermistors, 30 cm spaced along the green line (Figure 1). The blue line represents the thermistors cable that allows temperature monitoring in the snow and the underlying natural ground down to a depth of 3.25 m. Above the ground surface, the fiber-glass pole where the thermistors are fixed is 1.75 m high and the sensors are 10 cm apart. The small interval between the thermistors allow more precision while measuring the snow cover thickness considering the important variations of the temperature gradient with snow cover thickness.

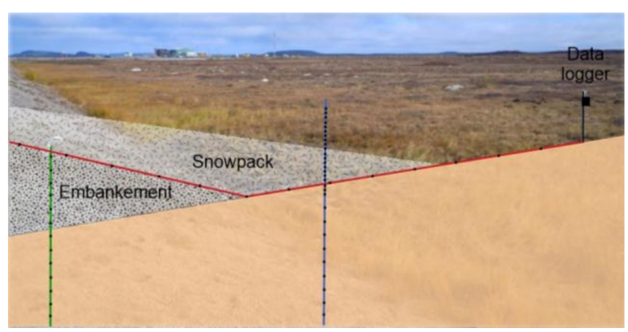


Figure 1. Monitoring along Tasiujaq airstrip.

#### 2.1.2 Beaver Creek, Yukon

This study site is located on a section of the North Alaska Highway located about 8 km south of the community of Beaver Creek (62°20'N, 140°50'W). In this area, the discontinuous permafrost is warm and ice-rich. The climate is continental with long and cold winters and short and dry summers. Snowfall begins annually in September and snowmelt begins in April (De Grangpré et al., 2012). The roadway is oriented northwest-southeast.

For this study, instrumentation has been added to the existing instrumentation of 50 m long reference section. Since October 2008, thermal data are recorded 6 times a day with three vertical thermistor strings to a depth of 15 m from the surface (Lepage and Doré, 2010). They are located along a transect in the middle of the section. Their positions are at the center of the roadway, at mid-slope on the southwest slope and at the toe of the embankment on the same side of the road (southwestern side). Two vertical wooden poles, each 1 m long, are used to fix 10 LogTag temperature recorders, which were installed in August 2014 to monitor the thermal regime through the snowpack and its thickness (Figure 2). Eight of the same sensors were installed at the surface of the embankment and 2 on the natural ground.

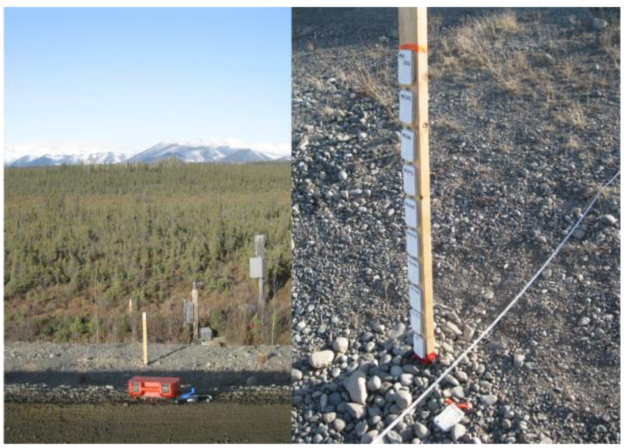

Figure 2. Monitoring of the snowpack along the Alaska Highway near Beaver Creek, Yukon.

## 3 RESULTS AND ANALASYS

The data used for this study were collected between September 2014 and May 2015. Part of the data used was provided by Center for Northern Studies (Tasiujaq) and by Yukon Highway and Public Works (Beaver Creek).

### 3.1 Snowpack evolution

#### 3.1.1 Tasiujaq, Northern Quebec

For the two test sites, the temperature recorded above the surface allows inferring snow depth along a vertical profile. The important influence of the snowpack on the heat transfer between soil and atmosphere impedes ground cooling during winter. Thus, when a temperature sensor is covered by snow, it does not measure the air temperature anymore, but a higher temperature. Therefore, it is possible to determine that a sensor is under the snow when there is a significant difference between the temperature it measures and the air temperature.

At the Tasiujaq study site, thermal data in the snow cover were recorded at 2.5 m from the embankment toe above the natural ground. Figure 3a shows the variation between the mean daily temperature recorded by each sensor and the measured mean daily air temperature. It is possible to observe that, before the end of November, temperature along the vertical pole is the same as the air temperature for all sensors. At that point, no significant snow cover (thicker than 5 cm) was observed. On November 26$^{th}$, the snow cover reached the 15 cm high thermistor but not the one at 25 cm high following a snow precipitation. Thus, at that moment snow cover thickness was estimated around 20 cm. On December 1$^{st}$, another episode of precipitations covered the 35 cm high sensor, therefore the snow thickness was estimated at 40 cm. On December 27$^{th}$, a 60 cm snow cover was estimated. Then, 10 more centimeters of snow were added on January 23$^{th}$, on January 29$^{th}$, on March 3$^{th}$ and on March 31$^{th}$. At this point the 2015 winter maximum snow depth of 100 cm was reached. This snow cover thickness was maintained until snowmelt began on April 15$^{th}$. This observation is not entirely consistent with the assumption made by l'Hérault et al. (2012) for the same test site where snow melting was considered to start half a month later, at the beginning of May. However, like the assumption made in that report, snowmelt lasted about 15 days (from April 15$^{th}$ to May 2$^{nd}$).

As it was expected, most of the winter, temperatures measured under the snow were warmer than the air temperature. Thus, the variation of temperature observed on figure 1 are mainly positives. However, some negative values can be observed indicating mild spells during winter.

#### 3.1.2 Beaver Creek, Yukon

Difference of value between sensors temperature recorded at the Beaver Creek test site and the air temperature are presented in Figure 4a (mid-slope of the embankment) and Figure 5a (toe of the embankment). Even if the accuracy of the temperature recorders used is only ± 0.5°C, it was possible to estimate the evolution of the snowpack thickness through the winter (figure 4b and 5b). However, even when there is no snow, a variation up to 1°C can be observed. This value correspond with the maximum measurement of error that can be reach if both data, temperatures measured in the air and along the pole are affected.

According to figure 4a, at the mid-slope of the embankment, the 8 cm high sensor appears to be covered by snow at the beginning of November. Indeed, from that moment, the temperature measured by the 8 cm high sensor presented a difference with air temperature greater than 1°C. Because the 21 cm high sensor does not seem to be covered by snow, the snow thickness was estimated by the mean between the two values (15 cm) (figure 4b). On December 13$^{th}$, the second sensor was also covered by the snow. The maximum snow thickness of 27 cm was reached and stayed until March 17$^{th}$. Snowmelt began on the middle of March lasted for about 10 days.

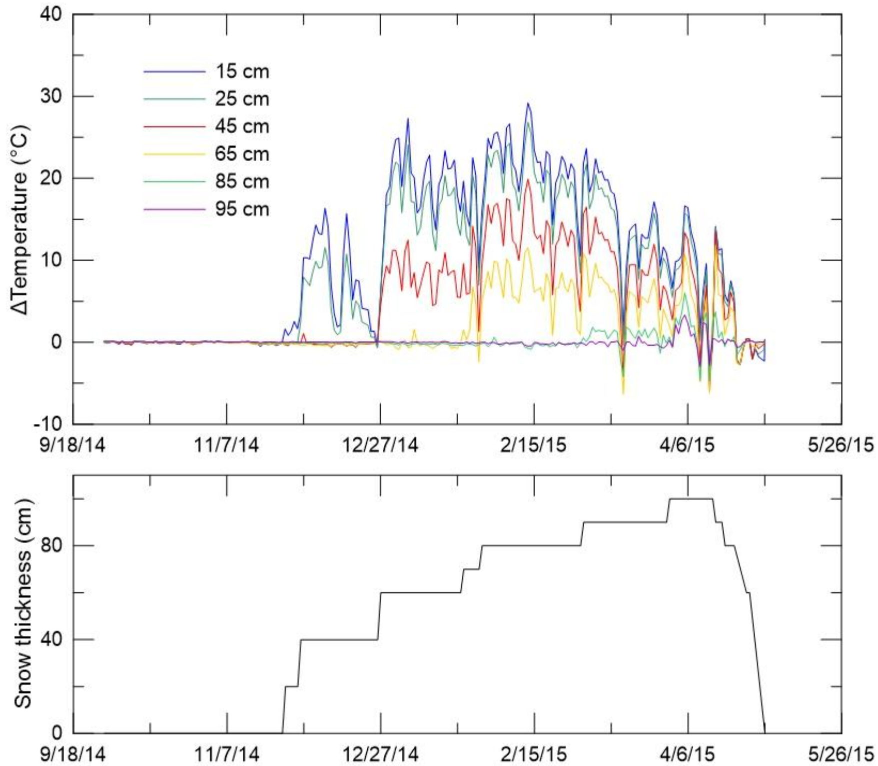


Figure 3. a) Variation of temperatures recorded at the Tasiujaq site along a vertical profile above the ground surface (ΔTemperature = $T_{surface}$-$T_{air}$) (some curves were omitted for a better visibility of the figure); b) Estimated evolution of the snowpack at toe of the embankment.

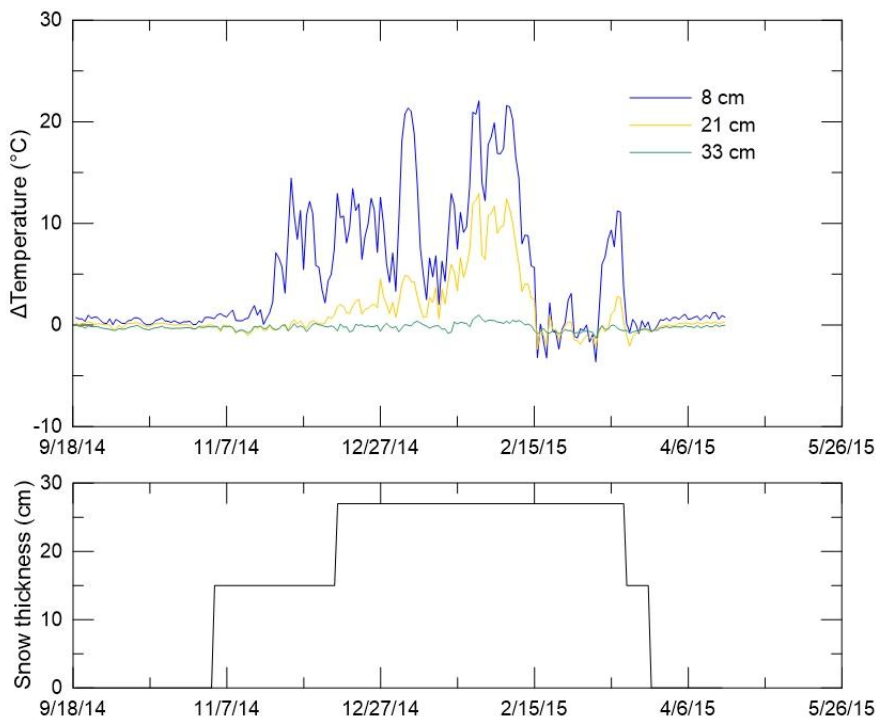


Figure 4. a) Variation of temperatures recorded at the Beaver Creek site along a vertical profile at mid-slope above the ground surface (ΔTemperature = $T_{surface}$-$T_{air}$); b) Estimated evolution of the snowpack at mid-slope of the embankment.

At the toe of the embankment, even without snow, variations of temperature between the sensors along the pole were sometimes greater than 1°C reaching up to 2.5°C (absolute value). Therefore, in this case, snow accumulation was inferred when the temperature variations were over this last value. It is also important to note that the lower temperature sensor (0 cm high) was kept in ice because of a water accumulation that occurred at the bottom of the wooden pole. Because of the high heat capacity and high latent heat of water, those data can barely be used to estimate the snowpack evolution when the thickness is less than 19 cm. Indeed, according to figure 5a, snow would have covered the 0 cm high almost immediately after the installation of the instrumentation. Observations on the field confirmed that there were no snow accumulations at that point. However, on November 26th the 12 cm high sensor was covered. Thus, the snow thickness was estimated at 19 cm until the end of December when the 25 cm high sensor was under the snow surface and snow thickness was estimated at 31 cm (figure 5). Finally, on February 12th, the maximum snow thickness of 43 cm was reached until the snowmelt beginning on March 20th. The snowmelt lasted around 15 days according to thermal data and field observations.

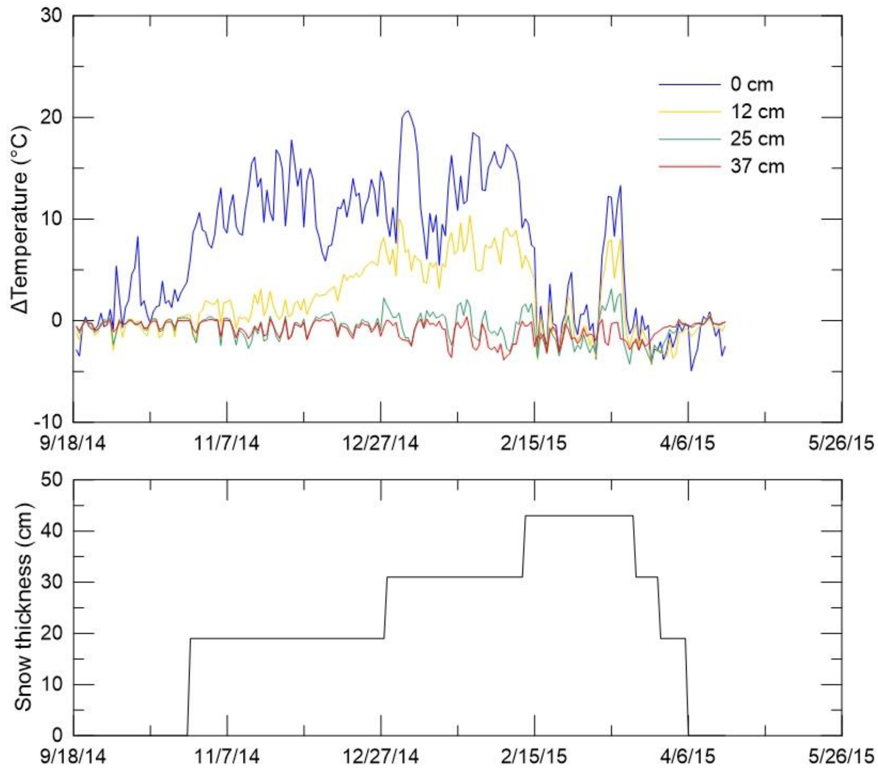


Figure 5. a) Variation of temperatures recorded at the Beaver Creek site along a vertical profile at the toe of the embankment above the ground surface (ΔTemperature = $T_{surface}$-$T_{air}$); b) Estimated evolution of the snowpack at the toe of the embankment.

According to the snowpack evolution estimated, the snow is accumulated earlier and lasted longer at the toe of toe embankment (figure 5b) than at the middle of the embankment (figure 4b). This fact is due to the presence of vegetation at the toe of the embankment that prevented the snow to be blown away and protected it from solar radiation at the end of the winter. Thus, the maximum snow thickness was greater at the toe of the embankment.

Generally, the winter of 2014-2015 at the Beaver Creek test site was characterised by a late snow cover building and an early snowmelt beginning.

## 3.2 Ground surface temperature

In order to determine a ground surface temperature corresponding to a certain snow thickness, two parameters have been used.

### 3.2.1 Temperature variation

In the first place, estimated snow depths have been related to the variation of temperature between the bottom ($T_{surface}$) and the top ($T_{air}$) of the snowpack. Figure 6 presents the variation of temperature ($T_{surface}$ - $T_{air}$) as a function of the snow thickness estimated for the lowest temperature measurement of each day. All data collected above the ground (at mid-slope and at the toe of the embankment in Beaver Creek and at the toe of the embankment in Tasiujaq) are presented. For each snow thickness measured, the average temperature value is presented as well as the standard deviation associated.

The general trend shows that for a small amount of snow (less than approximatively 40 cm), the increase of snow thickness has a great impact on the variation of temperature between $T_{surface}$ and $T_{air}$ in winter. This effect progressively decrease as the snow thickness increase. This observation is consistent with the conclusion of Zhang (2005) which suggests that over an optimal snow thickness of 40 cm, the effect of the snow cover on the ground surface temperature is more subtle. This relationship can be represented by a logarithmic equation (figure 6). However, the coefficient of determination associated with this function is relatively low at 0.25. An asymptotic curve could also express the general trend showing a maximum variation of temperature of 24°C independently of the snowpack thickness. In fact, it seems that the compaction and the metamorphism of the snow changing its density and microstructure diminish the insulating properties of snow. However, important snow accumulation is only observed at the Tasiujaq test site. Consequently, it is hard to base an empirical relationship only on one experimental site.

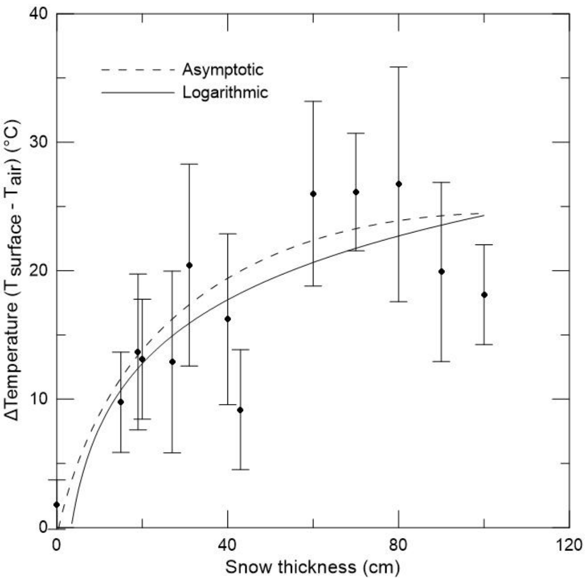


Figure 6. Temperature variation ($T_{surface}$-$T_{air}$) as a function of the snowpack thickness for the lowest temperature measurement of each day. Three different fit curves are proposed.

### 3.2.2 n-factor

The n-factor was calculated from the mean daily temperature measured from the end of September to the beginning of May. This period of time is approximately equivalent to the half of the climatologic year usually used to calculate the freezing n-factor. Here, the freezing n-factor ($n_f$) is express as the ratio of the near surface temperature ($T_{sfc}$) and the associated air temperature ($T_a$) (equation 2).

$$n_f = T_{sfc}/T_a \quad [2]$$

In order to smooth out short-term fluctuations and highlight longer-term trends, moving means of the air temperature and of the near-surface temperature were used. Each of those was calculated on a period of ten days using the negative average daily temperature value during the cold season.

Thus, multiples n-factor were obtained at the toe of the embankment for Tasiujaq test site as the winter goes on. Those values were expressed as a function of the instantaneous snow thickness ($z_s$) also represented by a moving average (figure 7). The relationship seems well explained by a logarithmic fit curve (equation 3).

$$n_f = -0.204 \times \ln(z_s) + 1.142 \quad [3]$$

The trend observed is that the reduction of $n_f$ is more important for the first centimeters of snow, then progressively diminishes as the snowpack get thicker and denser. This general conclusion is consistent with the findings of L'Hérault et al. (2012). Their study, based on 12 measurements along the Tasiujaq airstrip, also suggested that a logarithmic equation explained the relationship between the freezing n-factor and the snow cover thickness at the end of the winter which was considered as the maximum value (equation 4).

$$n_f = -0.424 \times \ln(z_{s(max)}) + 2.525 \quad [4]$$

Ultimately, the general trend is the same for both relations except that the one found in this study is more pronounced. Moreover, it seems that this last relation considerably underestimate the n-factor for a given snowpack thickness in comparison with L'Hérault et al. (2012) results. This difference is more pronounced for low snow depths. For example, if the snow thickness is 40 cm, equation 3 gives an n-factor of 0.39, whereas equation 4 gives an n-factor of 0.96. Those two values are significantly different.

In the case of the Tasiujaq test site, the robustness of equation 3 is quite good because the coefficient of determination is relatively close to 1 (0.80) and because when there is no snow thickness ($z_s$=0) the n-factor is very close to one. Furthermore, it is supported by the findings from previous studies suggesting the high influence of the first 40 cm of snow cover on ΔT ($T_{surface}$-$T_{air}$) and, consequently, on the n-factor.

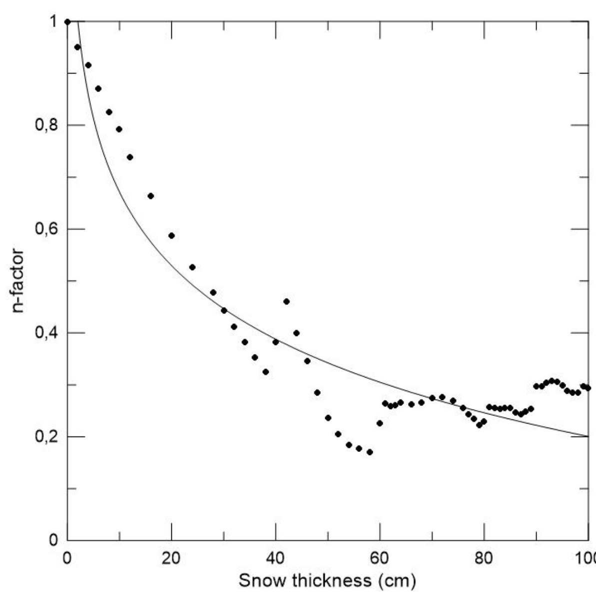


Figure 7. The logarithmic relationship between n-factor value and snowpack thickness at the Tasiujaq test site.

## 4 CONCLUSION

This paper presented a preliminary analysis of the temperature data collected at two test sites for the winter of 2014-2015. Along the Tasiujaq airstrip, it was possible to estimate with confidence the evolution of the seasonal snowpack with a precision of less than 5 cm. In the case of the Alaska Highway at the Beaver Creek test site, the low measurement accuracy of the temperature loggers caused temperature variations without the presence of snow. However, it was also possible to estimate the snow thickness when temperature variations were greater than 1°C at the middle of the slope and 2.5°C at the toe of the embankment.

Using thermal data and estimated snow cover thickness, it was possible to establish empirical relation between ground surface temperature of the embankment and the snow depth. First, a relationship between variation of temperature above and under the snowpack and the corresponding snow thickness shows a poor statistical correlation between both variables. Secondly, a relationship between the freezing n-factor and the snowpack thickness could be expressed by a logarithmic equation. However, this relationship was only based on measurements from the Tasiujaq test site. Therefore, both relationships tend to demonstrate that the effect on the temperature offset ($\Delta T$) or ratio (n) between air temperature and ground temperature is more important for the first centimeters of snow, then progressively diminishes as the snowpack get thicker and denser.

In the near future, the previous relation between the n-factor and the snow thickness will be used to fix the temperature at the surface of the ground (top boundary conditions) in a 2D semi-empirical thermal model. Once calibrated according to field conditions, the purpose of this model will be to run simulations with different slope angles. From those results, abacus will be created in order to propose a slope angle that will assure the maintenance of the underlying permafrost for given site conditions.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of all partners of the Arquluk Program. They would also like to thank Tasiujaq and Beaver Creek communities for their contribution and cooperation.

## REFERENCES

Allard, M., Doré, G., L'Hérault, E., Verreault, J. and Sarrazin, D. 2009. Investigations géotechniques, caractérisation du pergélisol et stratégie d'adaptation pour les aéroports du MTQ au Nunavik, Rapport d'étape 2, Centre d'études Nordiques, Université Laval, 83pp.

De Granpré, I., Fortier, D. and Stephani, E. 2012. Degradation of permafrost beneath a road embankment enhanced by heat advected in groundwater, *Canadian Journal of Earth Sciences*, 49: 953-962.

Doré, G. and Beaulac, I. 2007. Impact de la fonte du pergélisol sur les infrastructures de transport aérien et routier du Nunavik et adaptation, Rapport de l'université Laval, remis au ministère des transports du Québec. 240pp.

Ficheur, A. and Doré, G. 2010. Expérimentation de techniques de mitigation des effets de la fonte du pergélisol sur les infrastructures de transport du Nunavik: Aéroport de Tasiujaq, Rapport final. Réalisé pour le compte du ministère des transports du Québec. Département de genie civil, Université Laval. 197pp.

Lepage, J. and Doré, G. (2010), Experimentation of mitigation techniques to reduce the effects of permafrost degradation on transportation infrastructures at Beaver Creek experimental road site (Alaska Highway, Yukon), *Proceedings of the Join 63 rd Canadian Geotechnical Conference & 6 th Canadian Permafrost Conference,* Calgary, Alberta.

L'Hérault, E., Allard, M., Barrette, C., Doré, G. and Sarrazin, D. 2012. Investigations géotechniques, caractérisation du pergélisol et stratégie d'adaptation dans un contexte de changements climatiques pour les aéroports du MTQ au Nunavik, Rapport d'étape 1: État d'avancement du projet et résultats préliminaires. Réalisé pour le compte du ministère des Transports du Québec. Centre d'études nordiques, Université Laval, Québec. 71pp.

Zhang, T. 2005. Influence of the seasonal snow cover on the ground thermal regime: an overview, *Review of Geophysics*, 43: 1-23.