Initial Results from Temperature Monitoring in a Culvert under Winter Conditions in Permafrost

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ABSTRACT
Culverts installed across road embankments maintain natural drainage conditions and minimize hydrological impacts. In northern applications where permafrost is present, culverts are installed during winter, such as the case of the newly-opened Inuvik-Tuktoyaktuk Highway (ITH) in the Northwest Territories. This means the fill material is placed and compacted in frozen condition. Culverts affect the thermal stability of road embankments. They act as heat conduits during summer, but depending on its diameter can trap heat during winter. Thawing of soil around and below the culvert will lead to differential settlements and longitudinal cracks at the road surface and embankment slopes. In order to study the effects of culverts on the thermal behaviour of surrounding soil, a 5-noded thermistor string was installed inside an 800 mm diameter culvert along its length. Temperature readings along the culvert from the time of installation and during the winter months are presented in this paper.

RÉSUMÉ
Les ponceaux installés dans les remblais routiers maintiennent les conditions naturelles de drainage, limitant ainsi les impacts hydrologiques. En région de pergélisol, les ponceaux sont installés durant la saison de construction hivernale, comme le long de l'autoroute Inuvik-Tuktoyaktuk (ITH) aux Territoires du Nord-Ouest, où le matériel de remplissage est alors constitué de sol gelé. Les ponceaux sont des éléments structuraux qui influencent la stabilité thermique des remblais de route. En été, ils permettent la circulation de chaleur et peuvent piéger celle-ci durant l'hiver, dépendant de leur diamètre. Le dégel du pergélisol autour et sous un ponceau engendre des tassements et des fissures longitudinales à la surface de la chaussée et dans les pentes du remblai. Pour étudier ce comportement thermique, un câble à thermistances avec cinq capteurs a été installé à l'intérieur d'un ponceau de 800 mm de diamètre, couvrant toute sa longueur. Les températures mesurées le long du ponceau depuis l'installation et incluant les mois d'hiver, sont présentées dans cet article.

1 INTRODUCTION

The completion of the Inuvik to Tuktoyaktuk Highway (ITH) has been a long standing goal of the Town of Inuvik, the Hamlet of Tuktoyaktuk, and the residents of the Inuvialuit Settlement Region (EIRB 2011). The construction of the ITH will help address the goals of Northern economic development, enabling future natural resource exploration, development, and production (such as the natural gas and oil reserves in the Mackenzie Delta and Basin), and reinforcing Canadian sovereignty objectives (EIRB 2011, Infrastructure Canada 2015).

Detailed road alignment, environmental data gathering, and engineering design were conducted in the 1960's and 70's and has been continuously revised to address the concerns of local communities and other stakeholders during an extensive environmental review process, leading to the development of the route alignment alternatives in 2009. 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, will be an all-weather transportation link and will complete Canada's road network from the Pacific, to Atlantic, and to Arctic coasts. Figure 1 shows the constructed alignment of the highway.

The warming trend in air temperatures due to climate change in the Northwest Territories (IPCC 2014) has and will continue to pose challenges for the transportation system (TAC 2010). Climate change has impacted fall freeze-up and spring thawing, causing delays and reduced operations of highways.

Construction is carried out only during the winter season for ease in moving fill materials and to minimize environmental impact. Typical 'cut and fill' techniques employed in the southern areas of the Northwest Territories are not used in this project to protect the permafrost terrain along the highway alignment (EIRB 2011). There are uncertainties related to the mechanical behaviour of embankments that were initially compacted with frozen fill and then experienced natural thawing and settlements during the summer following construction. The fill material of the ITH embankment is dominated by fine till that may include high content of ground ice. Fills are very difficult to compact at sub-zero temperatures when ice is present, but are relatively strong while they remain frozen. They become soft and compressible upon thawing.

Embankment performance is affected by the presence of culverts. Culverts are structural elements installed across road embankments to maintain natural drainage conditions and minimize hydrological impacts, but these culverts also pose thermal and mechanical concerns on embankment performance. Because frozen soil is difficult to compact and an optimum density cannot be achieved (De Guzman et. al, 2018), thawing around the culvert will translate to settlements and cracking at the ground surface and slopes. Figure 2 shows some of these issues along the highway after the first thawing in the summer following winter construction.

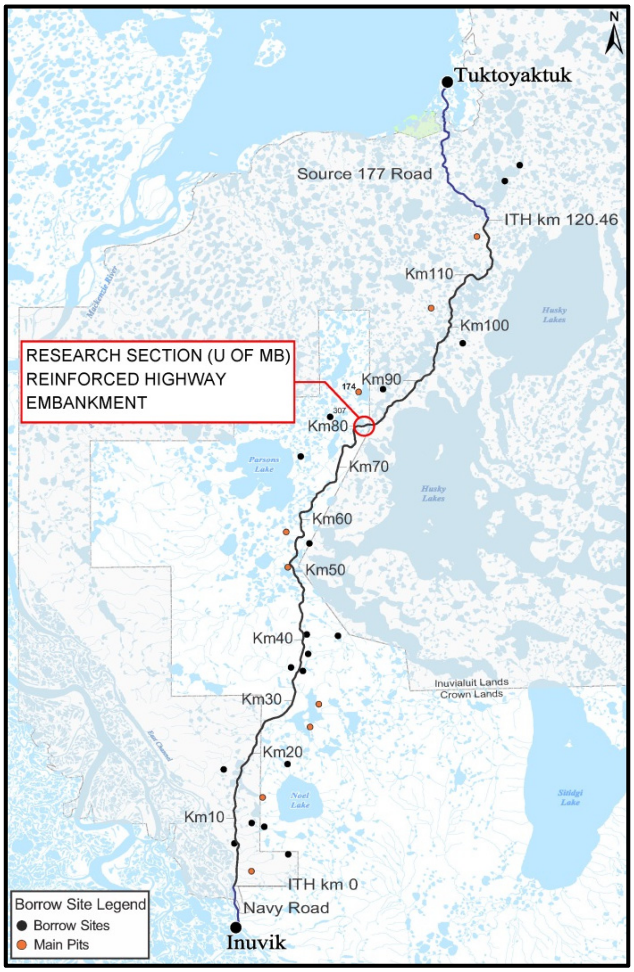
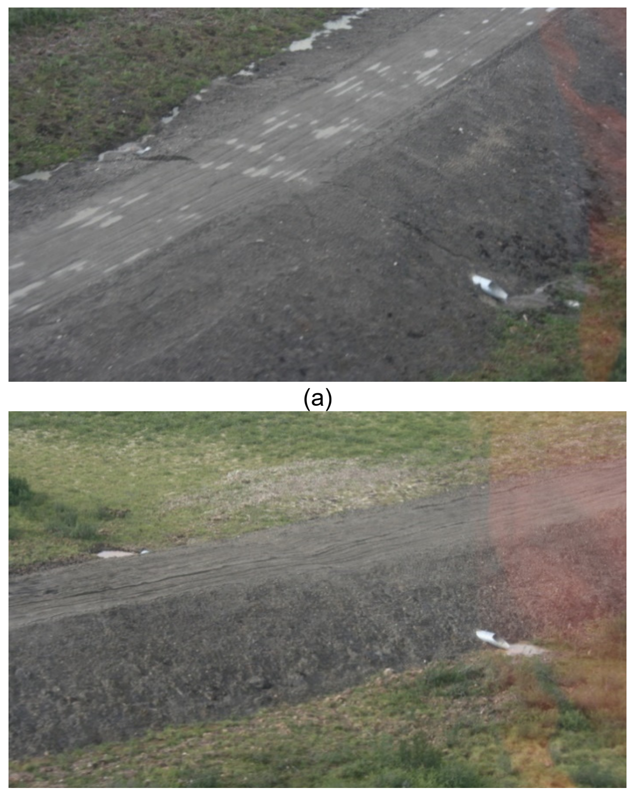


Figure 1. Alignment of the Inuvik-Tuktoyaktuk Highway and the University of Manitoba's research section

Culverts are conservatively designed to satisfy hydraulic requirements along highway embankments (Lingnau 1985, TAC 2010). Water flow and temperature impact embankment temperatures, where heat transfer underneath the culvert is more affected by water temperature compared to water flow (Perier et. al, 2015). The thermal capacity and conductivity of water is significantly greater than that of air and contributes to the thermal regime of the embankment, particularly ponding water at the toe and large flows which may accelerate thawing and impact the depth of the permafrost table (Esch 1988, TAC 2010, Bouchard and Guimond 2012). The effect of water on the thermal performance of the underlying foundation embankment has been studied extensively in literature. However, the air inside the culvert is cooler than the ambient air temperature during the summer months but provide passive cooling in the winter months if the culvert is large enough for the culvert ends not to be covered in snow. Most culverts installed along the ITH however are 800 mm in diameter which get covered in snow during the winter months. The snow is either deposited naturally or due to snow road clearing operations. To determine the temperature changes inside a culvert shortly before and during the winter months, a thermistor string was installed along the culvert at the research sections of the University of Manitoba along the ITH (De Guzman et. al, 2017). This paper presents the results of the temperature monitoring program along the culvert from September 2017 to April 2018. The measured temperatures will be used as boundary conditions for thermal and mechanical modeling that will be carried out to investigate the effects of culverts on overall embankment performance.



(a)

(b)

Figure 2. Some issues around culverts: (a) lateral cracking and (b) differential settlements

2 CULVERT INSTALLATION AND FIELD OBSERVATIONS

Figure 3 shows the University of Manitoba's research site along the ITH. Zones A and B are 5.3 m in height and 20 m in length. Zone A has its side slopes reinforced with wicking geotextiles. Zone B is the unreinforced section.

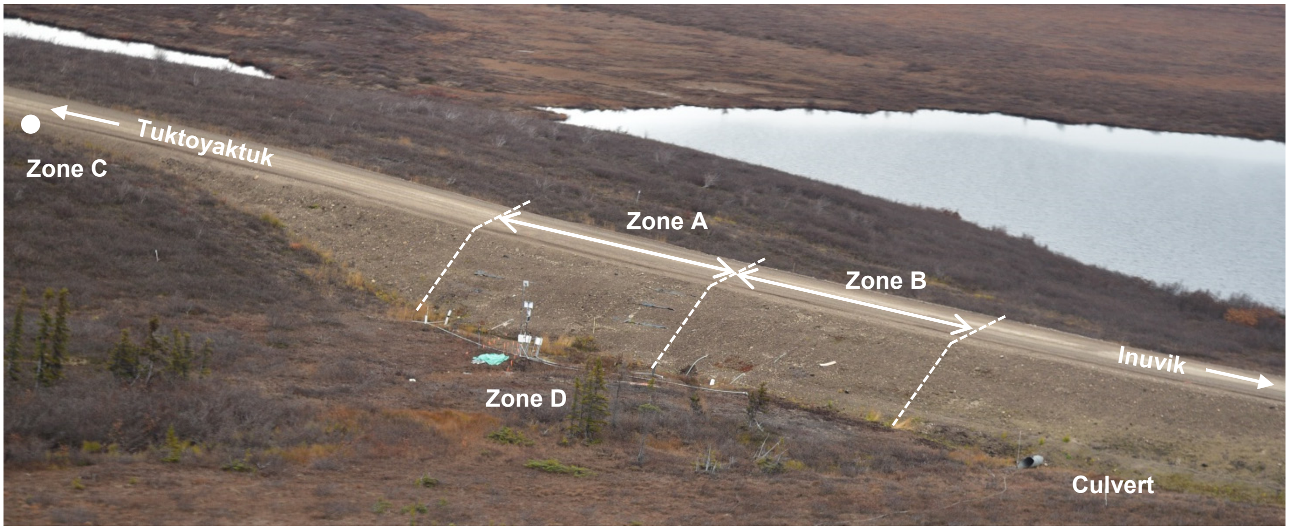


Figure 3. Aerial view of the University of Manitoba research site along ITH

Both sections are instrumented with sensors to measure temperatures and displacements. Zone C is instrumented with temperature sensors to compare the thermal regime of high-fill sections (such as Zone A and Zone B) with low-fill sections. Zone C has an embankment height of 1.83 m. All sensors are connected in Zone D and accessed remotely via a satellite system.

The culvert being investigated is located at KM 82+375 of ITH from Inuvik (Figure 3). The culvert was installed prior to the construction of the University of Manitoba test sections in April 2015. An initial lift was placed above the culvert until the desired height was reached.

Figure 4 shows frozen chunks of soil were dumped above the culvert for compaction once the embankment was being constructed in stages. Unlike the other culverts along the highway which have diameters larger than 800 mm, no rock riprap material was added around the perimeter of this culvert. The culverts for ITH were constructed at positive camber to account for differential settlements. Success of this technique was observed along the Dempster Highway to reduce sagging and that ponding of water (Lingnau, 1985).

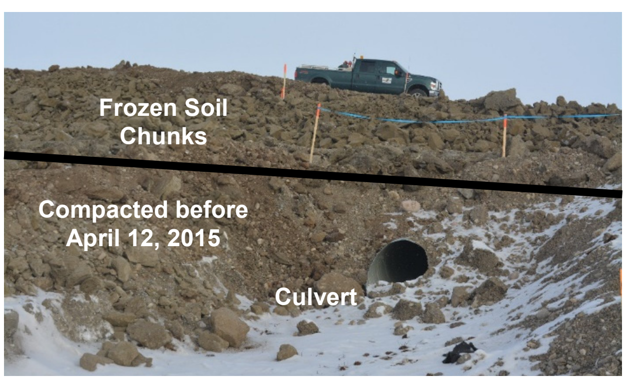


Figure 4. Construction of highway fill embankment above the culvert at the research section of the University of Manitoba

The culvert was found clogged on May 18, 2016 (Figure 5) and was remediated 6 days after. One of the key issues with the clogged culvert was that the water ponded at the toe of the embankment which may lead to two concerns: (1) accelerated thawing of the frozen foundation soil and (2) water seeping into the embankment towards the frozen core of the embankment. The actual number of days when the culvert was clogged and depth of standing water are unknown.

Embankment slopes above culverts were also observed to develop cracks which are significantly larger and wider compared to embankment sections along the highway where there are no culverts installed. In Figure 6, a silt fence was installed to prevent the embankment soil from flowing through the crown as this can lead to clogging of the culvert. Compaction density of frozen chunks during winter is significantly lower in comparison to unfrozen soil (De Guzman et. al, 2018). Compaction is even lower around culverts.

Culverts act as heat conduits, which thaws the embankment and foundation soils. This was prominent during site visits before the final surfacing was added as passing through sections with culverts felt like road ‘humps’ and undulations.

Figure 5. Clogged upstream side of the culvert in May 2016

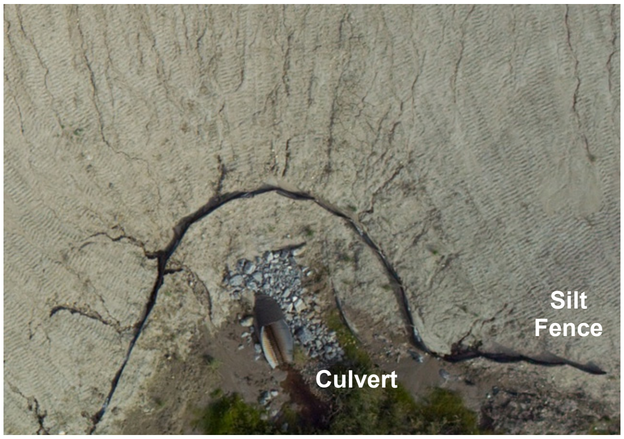


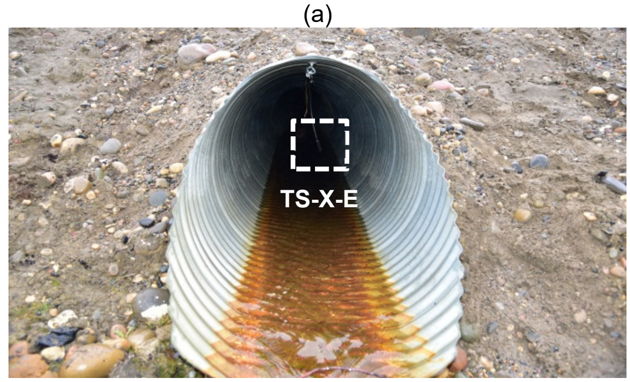
Figure 6. Aerial shot of slope cracking above culverts

3 THERMISTOR INSTALLATION

A 5-noded thermistor string was installed on August 12, 2017 along the culvert. The thermistor nodes have a spacing of 13.5 m. One of the issues encountered on site was tensioning of the cable where the thermistor string was attached. The weight of the thermistor string led to a significant sag which had the middle thermistor barely above the water level at the culvert. The tension cable was replaced on September 28, 2017 with a higher strength cable and was attached to a winch system to adjust the tension and minimize sagging of the thermistor string. The cable was tensioned to have the thermistor string approximately 75 mm below the crown of the culvert. This ensured that the thermistor node was not in contact with the cable and the culvert. The thermistor node in the upstream side (TS-X-A) was left outside the culvert to measure the ambient air temperature. This also measures the temperature just outside the crown when it is buried in snow. The thermistor node in the downstream side (TS-X-E) is 100 mm from the edge of the crown and left to hang 250 mm at the connection point. This was done to provide comparison of air temperature just at the exit of the culvert. Figure 7 shows the upstream (Figure 7a) and downstream (Figure 7b) thermistor nodes. The thermistor string is connected to a data acquisition system of the University of Manitoba test sections (De Guzman et al., 2017) which can remotely be accessed via satellite.

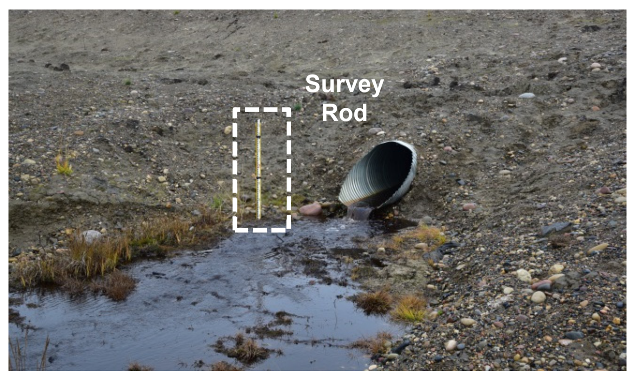
A survey rod was also installed in front of the culvert on the downstream side to measure the snow depth during the winter season (Figure 8a). Figure 8b shows the same survey rod on December 11, 2017 which clearly displays that the culvert ends are buried in snow. Approximately 900 mm of snow was recorded on the downstream side of culvert. A camera trap was installed on this side of the culvert to monitor how snow is accumulating at the toe. As mentioned earlier, culverts are structural conduits which can passively cool or exacerbate heating in the embankment and foundation soils. With the ends of the culvert buried in snow during the winter months, the temperature inside the culvert is warmer compared to the ambient temperature as will be discussed in the following section.

(a)



(b)

Figure 7. Culvert at KM 82+375: (a) upstream and (b) downstream sides



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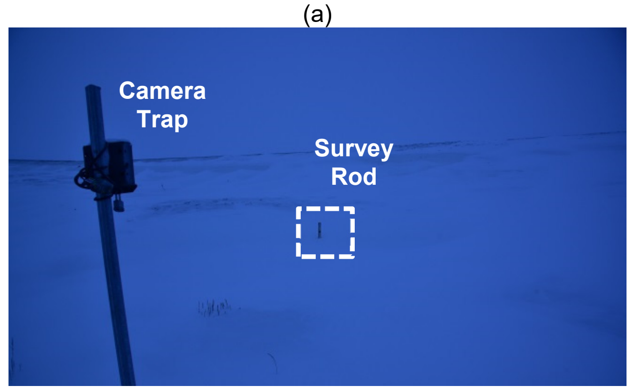


(b)

Figure 8. Culvert section on the east side of the embankment: (a) September 2017 after installation of thermistor string and (b) December 2017 during winter conditions

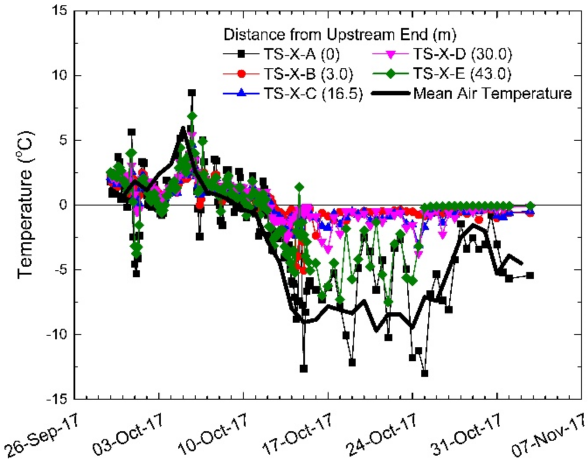
4 MONITORED RESULTS

Figure 9 shows plots of temperature with time for the thermistor string along the culvert. The mean air temperature from the site was obtained from Environment Canada at a weather station in Tuktoyaktuk. In Figure 9a, it can be seen that the readings recorded by TS-X-A (upstream thermistor node) corresponds to the trend of the mean air temperature for this period. Temperature readings of the thermistor nodes before October 13 showed the same pattern, although the thermistor nodes inside the culvert are slightly cooler than the ones at the end. After October 13, the mean air temperature significantly dropped; however, TS-X-B, TS-X-C, and TS-X-D were recording temperature readings between 0°C and -5°C. The batteries powering up the thermistor string and satellite connection were depleted during the period of November, December, and January at the height of the winter season. The batteries were replaced on February 16, 2018 which resumed reading of the thermistor nodes. Figure 9b shows the readings recorded from resumption of power supply until the writing of this paper. The mean air temperature was significantly colder than the temperature inside the culvert. The readings recorded by TS-X-A and TS-X-E further support the discussion regarding Figure 8b where the ends of the culvert are covered in snow. Snow is a good insulator and thus prevents considerable heat transfer between the mean air temperature penetrating the snow and the temperature inside the culvert.

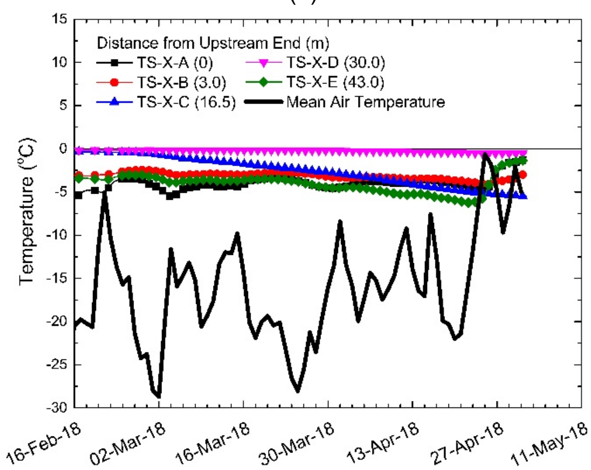
In Figure 9b, the nodes closest to the end of the culvert (TS-X-A, TS-X-B, TS-X-E) have similar behaviour until April 24, 2018 when TS-X-A and TS-X-E started to go on a warming phase. TS-X-B similarly showed the same pattern of warming by April 26, 2018. Temperatures recorded by TS-X-C has been linearly decreasing since February 23, 2018 and is suspected that this will start to warm up once both ends of the culvert are partially exposed to the ambient air temperature. Of all the thermistor nodes, TS-X-D has remained at the threshold of 0.2°C below freezing point since February 16, 2018, with a slight cooling trend beginning March 30, 2018. The temperature of this node is currently at -0.5°C.

Figure 10 shows the temperature along the culvert at specific time steps since its installation. October 1 shows that while the ambient temperature already dropped below 0°C, the temperature inside the culvert has remained above the 0°C. From the period of November 2017 to March 2018, TS-X-C and TS-X-D are within the range of 1°C from each time steps; however, TS-X-C significantly dropped after March 2018 (see Figure 9) while TS-X-D has remained relatively the same. Figure 10 confirms that although the ends of the culvert are covered in snow, there is change in temperature month to month.

Figure 11 shows the change in temperature along the culvert every 3 hours on October 14, 2017 (Figure 11a) and April 22, 2018 (Figure 11b). During the transition phase from summer to winter season, Figure 11a confirms that the temperature inside the culvert is fluctuating with the ambient air temperature. When the culvert ends were covered in snow, there is almost no change in temperature for the 3-hour reading cycle. In Figure 11b, TS-X-D is significantly warmer than the other thermistor nodes.



(a)



(b)

Figure 9. Temperature readings along the culvert with time: (a) September to November 2017 and (b) February to April 2018.

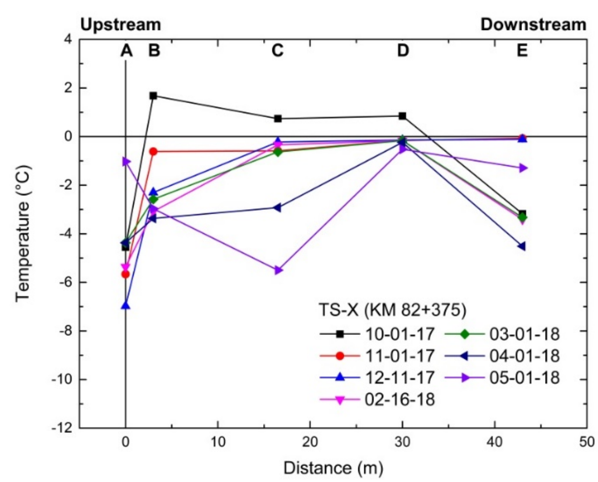


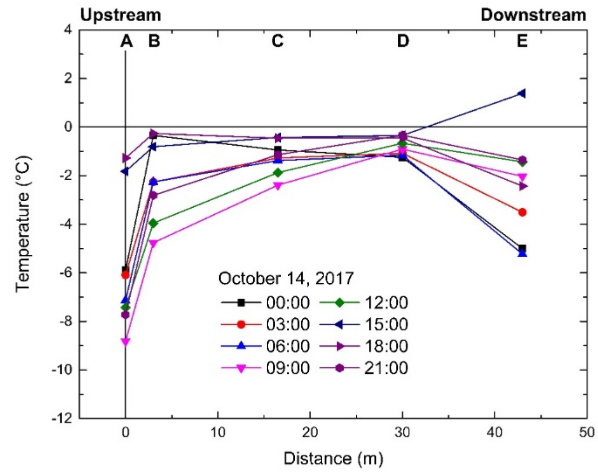
Figure 10. Temperature along the culvert at different time steps

This warm temperature inside the culvert is of interest in this research since this can affect the thermal regime of the soil around the culvert. The embankment was constructed using frozen soil and this could have thawed already due to warm temperatures inside the culvert in the summer months, thus resulting to settlements and cracks at the road embankment surface. Unfortunately, no thermistor strings were attached around the culvert that is contact with soil. The closest thermistor in the embankment soil is 25 m away at the base of the unreinforced embankment section (Zone B in Figure 3). Figure 12 shows a comparison of the soil temperature recorded at this location with the thermistor node inside the culver at TS-X-C. The temperature recorded inside the culvert was warmer than the one recorded for the embankment soil. Once the culvert ends have been cleared off from the snow cover, air was able to flow though again and hence the fluctuation in temperature at TS-X-C while the temperature of the soil is adjusting to the new thermal boundary in the spring season. A 3D numerical model is currently being developed using the monitored results as boundary conditions to establish the thermal regime of the embankment and foundation soils around the culvert and will be the subject of further analyses under climate change conditions. The size and configurations (circular and rectangular) of the culvert, spacing between culverts, and overburden height are some of the parameters that will be looked into in assessing the effect of culverts on the stability of embankments constructed under winter conditions as well as optimizing construction practices and embankment performance.

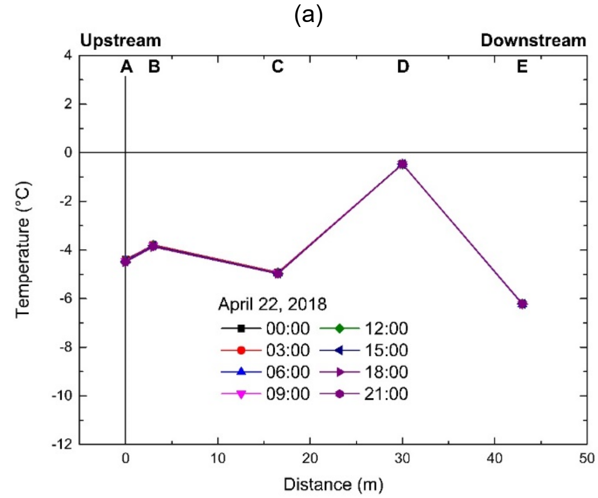
5 SUMMARY

Culverts are structural elements installed across road embankments to maintain natural drainage conditions and minimize hydrological impacts. Optimal layout of these culverts prevents ponding of water at the toe of the embankment which can accelerate thawing of underlying permafrost foundation and embankment fill and thus affect embankment stability. Culverts act as heat conduits during the summer months but can trap heat during the winter months when both ends of the culvert are covered in snow.

From the monitored temperature results presented in this study, it was found that at the transition phase from summer to winter season the temperature inside the culvert during the summer is cooler compared to the air temperature but in the winter months the temperature inside the culvert is warmer. The air inside the culvert is remnant of the air before the ends of the culvert were covered in snow. The temperature inside the culvert when both of its ends are covered is an additional boundary condition that should be taken into account in numerical modelling. By doing so, more accurate thermal regimes can be obtained that will improve the design and performance of embankments with culverts.



(a)



(b)

Figure 11. Hourly temperature development along the culvert: (a) October 2017 and (b) April 2018

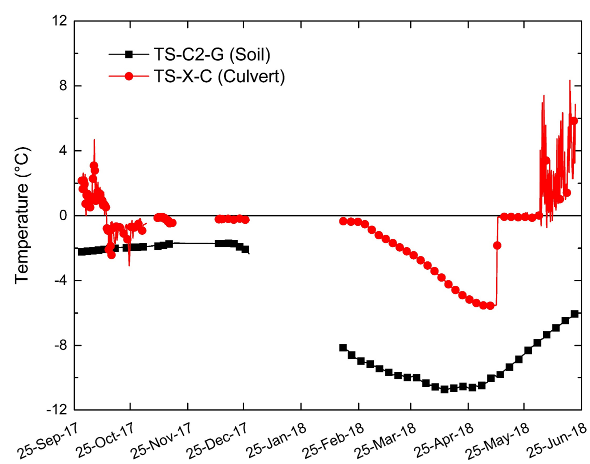


Figure 12. Comparison of embankment fill (Zone B) and culvert temperatures

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