Thermal performance of sloped thermosyphons installed at the Dry Creek Highway section, Yukon, Canada

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ABSTRACT

A total of 58 sloped thermosyphons were installed to arrest permafrost thaw beneath a section of the Alaska Highway at Dry Creek, Yukon, Canada. The highway foundation consists of warm (> -0.5 °C) permafrost with massive ground ice that is locally in excess of 9 m thick. In the fall of 2019, construction commenced with minimal vegetation clearing within the right-of-way and shallow excavation along the east tow of the highway embankment. Thermosyphons were installed in cased boreholes drilled beneath the embankment at an 11° incline, approximately every 7 m on centre. Each thermosyphon unit consisted of a single 19.5 m^2 radiator attached to an approximately 35 m long, 76 mm diameter schedule 80 evaporator pipe. The thermosyphons have increased winter heat loss from the foundation since completion of installation in 2020. Permafrost temperature has decreased by several degrees and the permafrost table has vertically aggraded up to 2.5 m above its pre-construction position. The greatest ground cooling has occurred beneath the thickest section of embankment fill which acts to reduce heat gain during the thawing season. The thermosyphons are expected to continue to contribute to permafrost stabilization over the 30-year design life. This project contributes to evaluation of techniques for the adaptation of highway infrastructure to climate change in permafrost environments.

1 INTRODUCTION

The Alaska Highway in the Yukon between Burwash Landing and the international border with Alaska extents across extensive discontinuous, warm (> -1 °C), permafrost that is commonly ice-rich (Calmels et al. 2016). Permafrost degradation resulting in thaw-settlement of the highway embankment has caused the need for frequent and costly maintenance and remediation.

The Dry Creek highway section (kilometre 1841) of Alaska Highway is approximately 400 m in length (Figures 1 and 2). This section of highway was built across a glaciofluvial deposit consisting of ice-rich permafrost with massive ground bodies of ice up to 9 m thick. In 2017, Yukon Highways and Public Works (YHPW) initiated a study to stabilize the permafrost foundation at the site due to the potential risk of embankment failure.

A solution was developed based on the installation of sloped thermosyphons to increase heat extraction from the foundation and arrest permafrost thaw. Realignment of the highway was not considered a viable option due to the presence of ice-rich permafrost within the surrounding terrain.

In this paper, we describe design and initial thermal performance of the sloped thermosyphons that have been used to stabilize permafrost at the Dry Creek highway section. Thermal performance of the design is important to determine its effectiveness and the need for improvement to similar designs in permafrost environments.

Figure 1. Location of Dry Creek highway section of the Alaska Highway, Yukon, Canada.

2 DRY CREEK HIGHWAY SECTION

The Dry Creek highway section extends across a well-drained glaciofluvial deposit (Rampton 1979; Figure 2).

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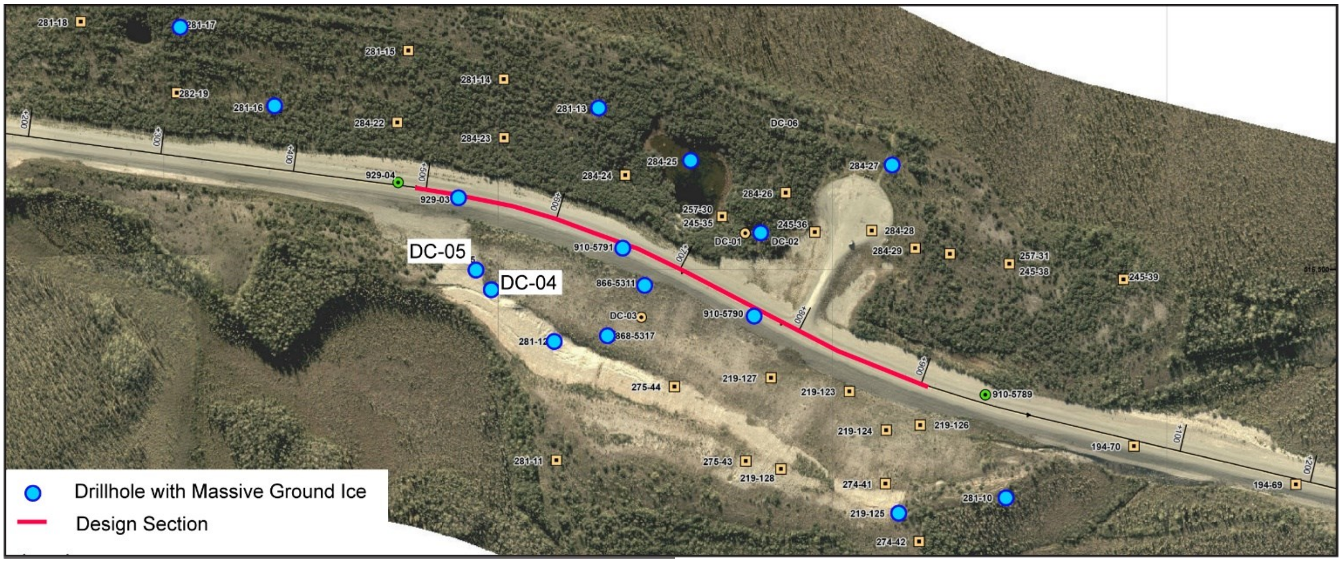

Figure 2. Aerial photograph of the Dry Creek highway section showing the design section (red line) and drillholes intercepting massive ground ice (solid blue circles).

The north-south trending deposit is surrounded by relatively low-lying terrain characterized by wetlands with organics and sparely populated stunted black spruce.

2.1 Site History

The northern portion of the Alaska Highway that includes the Dry Creek highway section was rebuilt between 1992 and 2005 (YES 1996). During this time, the glaciofluvial sand and gravel immediately surrounding the current alignment was excavated and used for construction material. Massive ground ice was exposed during development of the borrow material which subsequently required placement of backfill to arrest immediate thaw.

The Dry Creek highway section was reconstructed in 2014, which included raising, straitening, and widening of the alignment to improve traffic flow and safety (Government of Yukon 2024). In some locations, near surface ground ice was excavated and replaced with structural fill.

2.2 Climate

The site is characterized by continental climate with warm, dry summers and relatively long cold winters. Baseline climate data for the region is reported for Beaver Creek A, located approximately 26 km to the north of Dry Creek due to continuity and longevity of the station record.

The mean annual air temperature recorded at Beaver Creek is -4.9 °C for the most recent climate normals (1981–2010; ECCC 2023). Figure 3A shows the average monthly air temperature for the period of 1981 to 2010. Average annual air temperature recorded at Dry Creek from 2019 to 2022 ranged from -3.8 to -4.0 °C.

The Beaver Creek climate normals indicate mean annual precipitation is 416.3 mm, with 295.7 mm falling as rain and 123.1 cm falling as snow (ECCC 2023). On the ground snow depth has been measured to range from 54 to 84 cm in late winter for areas of natural ground located adjacent to the highway (Lepage 2016). The average annual windspeed recorded at the Beaver Creek highway test section, located approximate 20 km north of Dry Creek was 1.1 m s^{-1} from 2008 to 2016. Winter windspeed was 0.9 m s^{-1} from October to April with the dominant wind direction from the southwest. Average winter windspeed was measured at Dry Creek to be 0.7 m s from 2019 to 2022.

Historical air temperature measured at Beaver Creek indicates an increase of 0.45 °C per decade for the period of 1969 to 2022 (Figure 3B). Climate change model projections from the Sixth Assessment Report (AR6) Shared Socio-economic Pathways (SSPs) SSP1-2.6, SSP2-4.5, and SSP5-8.5 estimate an increase in air temperature of 0.41 °C per decade, 0.47 °C per decade and 0.53 °C per decade, respectively. The project mean annual air temperature is -2.6 °C for SSP5-8.5 and -3.0 °C for SSP1-2.6 at the end of the 30-year design life (Figure 3B).

2.3 Background Ground Temperature

The ground thermal regime prior to installation of the sloped thermosyphons was based on measurements from two ground temperature cables installed by the Northern Climate ExChange at Yukon College, referred to as DC-04 and DC-05 (Calmels et al. 2016). These sites are located outside of direct influence from the highway embankment (approximately 60 m from the embankment) within the area of historic surface disturbance caused by excavation of borrow material.

At DC-04 and DC-05, permafrost temperature measured at approximately 12 m below ground surface (bgs) is -0.9 °C and -0.7 °C, respectively. At DC-04, the active layer depth was 2.2 m in 2015 and 2.9 m in 2016. Additional baseline ground temperature measurements for the highway foundation are discussed in Section 6.1.

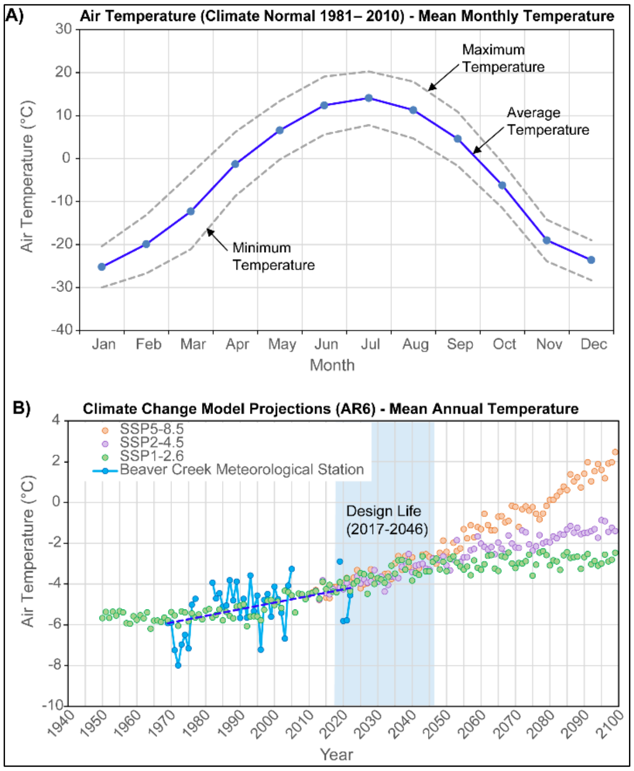

Figure 3. A) Average monthly air temperature measured at Beaver Creek, Yukon from 1981 to 2010 and B) future climate change model projections of mean annual air temperature for Dry Creek, Yukon.

2.4 Foundation Conditions

The Dry Creek highway section foundation consists of well and poorly sorted sand (SW-SP) and gravel (GW-GP) which is underlain by silt (ML). The glaciofluvial sand and gravel is variable in thickness, in part due excavation. The thickness of the lowermost glaciolacustrine silt is unknown due to drillholes terminating prior to reaching bedrock. Embankment thickness is anticipated to 2.0 to 2.5 m thick.

Ground ice was originally observed during auger drilling and excavation of borrow material in the mid-1990s (Figure 4). Additional geotechnical programs were completed between 2011 and 2018. Massive ground ice (ICE) based on the Standard Practice for Description of Frozen Soils (ASTM D4083-89) has been identified to be in excess of 9 m thick and spatially discontinuous across the site (Figure 2).

Historic auger drilling completed during development of borrow material identified massive ground ice in 8 of 33 historical boreholes, with massive ice ranging from 0.6 to 4.0 m thick. The historic depth to the top of massive ground ice prior to removal of surface material was recorded to be from 4.7 to 11.6 m bgs. In 2015, two sonic drillholes were completed and confirmed 3 to 4.6 m of poorly and well graded gravel underlain by 3 to 5 m of massive ground ice (ICE). Material below the massive ground ice is characterized by silt, silty sand, and gravel. Ground ice in intervals of silt is described as being stratified lenses (Vs) and randomly oriented ice lenses (Vr). Three additional sonic drillholes were completed in March of 2017. Two of the three drillholes indicates massive ground ice extends from 5.8 mbgs to 10.3 mbgs and from 6 m bgs to 15 m bgs. Drilling completed in 2018 confirmed the top of massive ice was approximately 7 m below the embankment which corresponded to the top of ice-bonded (frozen) permafrost.

Figure 4. Massive ground ice exposed during excavation of borrow material in 1995.

3 DESIGN

3.1 Overview

A 30-year design life (2017-2046) for the permafrost stabilization was defined by YHPW. Thermal performance of the design was evaluated over this 30-year period with consideration of climate change.

Preliminary designs for the Dry Creek highway section considered two options: i) construction of an air convection embankment (ACE) using coarse crushed rock and ii) installation of sloped thermosyphons beneath the existing highway embankment (SRK 2017).

Ground thermal modeling completed for the site showed that both ACE and sloped thermosyphons could be used to reduce ground temperature and limit permafrost thaw beneath the highway embankment. However, the thermosyphon-based design was determined to provide more immediate and dependable heat loss to stabilize permafrost at the site and minimal earthwork activity. In comparison to the ACE design that would require full excavation of the existing embankment, relatively high cost of rock development and transport, and greater uncertainty in thermal performance immediately following construction.

3.2 Sloped Thermosyphons

The sloped thermosyphon design accepted by the YHPW specified a total of 58 thermosyphon evaporator pipes (76.2 mm diameter, schedule 80 pipe), approximately 34 m in length, installed in a cased borehole drilled 7 m on centre at an ~11° incline beneath the highway embankment (Figure 5A, B). A vertical riser pipe, with a 19.5 m^2 thermosyphon radiator was installed at a minimum height of one meter above the design grade (Figure 5B).

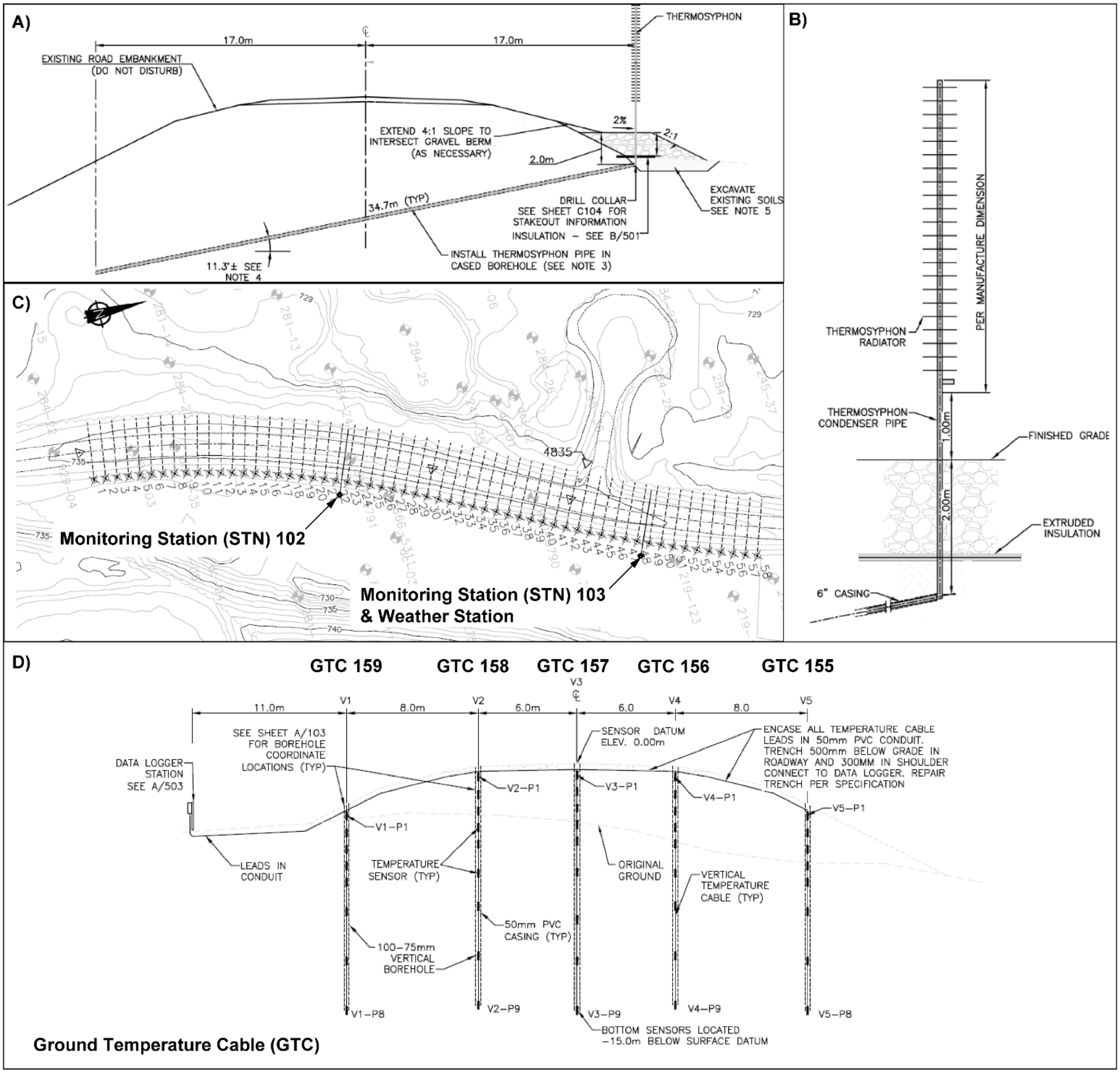

Figure 5. Design showing A) cross-sectional view with slope thermosyphon evaporator pipe beneath existing highway embankment, B) thermosyphon riser and radiator, C) plan view evaporator pipe layout, and D) cross-section of vertical ground temperature cables (GTCs) installed at monitoring stations STN 102. Ground temperature cable installed along inclined evaporator pipe not shown.

Thermosyphon units installed at Dry Creek were manufactured and installed by Arctic Foundations of Canada (AFC). Each thermosyphon unit consists of a pressurized sealed pipe, charged with a two-phase working gas that vaporizes and condenses to move heat without the need of a mechanical pump. The passive thermosyphons include an evaporator pipe buried in the ground that is connected to a vertical riser pipe and surface radiator (Figure 5A). The radiator section is manufactured with horizontal fins attached to the radiator pipe to enhance heat transfer with the atmosphere.

Thermosyphon heat transfer is a function of composition and physical properties of the working gas, radiator and evaporator design, temperature difference between the upper and lower sections of pipe, ground thermal properties, and exposure of the radiators to advective cooling from the wind, among other things.

Numerical thermal modeling was completed to predict thermal performance of the sloped thermosyphon design. Model simulations were completed for the 30-year design life. Thermal performance was evaluated with the objective of maintaining the top of the massive ice below -2 °C over the 30-year period, with consideration of climate change. The warmest location in the ground between two thermosyphon evaporator pipes were used to evaluate the predicted performance.

A thermosyphon radiator surface area (size) of 19.5 m^2 with a maximum evaporator pipe separation of 7 m was estimated to meet the thermal design criteria. Several years were predicted to have a maximum ground temperature greater than 0 °C at the uppermost surface of the massive ground ice, and therefore could be subject to seasonal thaw. A greater level of confidence in short and long-term performance of the thermal design was predicted for model cases with a decrease in evaporator pipe separation.

4 CONSTRUCTION

4.1 Construction Timeline

Construction began in the fall of 2018 and extend to the early summer of 2020 (Figure 6). The major construction events included:

- October 2018 – Installation of monitoring system; ground temperature cables and weather station to established pre-construction baseline conditions.
- Fall 2019 – Vegetation clearing, excavation along the embankment toe and start of inclined drilling for installation of casing and evaporator pipes (Figure 6A).
- Early winter 2020 – Completion of drillholes, installation of casing, and evaporator pipes.
- Early winter 2020 – Temporary installation of sloped thermosyphon radiators charged with working fluid (Figure 6B).
- Early summer 2020 – Permanent installation of thermosyphon radiators in vertical orientation, placement of backfill and final grading at riser pipes (Figure 6C).

4.2 Drilling and Installation

A hammer drill was used to advance inclined boreholes and casing (Figure 6A). The holes were cased to ensure integrity of the borehole wall prior to evaporator pipe installation. Drill site requirements limited use of drill fluids to minimize thermal disturbance of the foundation. At the time of construction, it was discovered that the casing strength (schedule 40) was not sufficient to advance during drilling. This required shipment of additional schedule 80 casing to the site before proceeding with the construction which consequently delayed completion of the project. As a result, the thermosyphon radiators were temporarily installed horizontally to allow for removal of heat induced by the drilling method used on-site (Figure 6B). The horizontally aligned radiators were removed during the next construction season to allow for vertical installation of the riser components and continuation of civil works, including installation of insulation within the toe berm and compaction of fill material (Figure 5A). The system was commissioned in the summer of 2020 (Figure 6C).

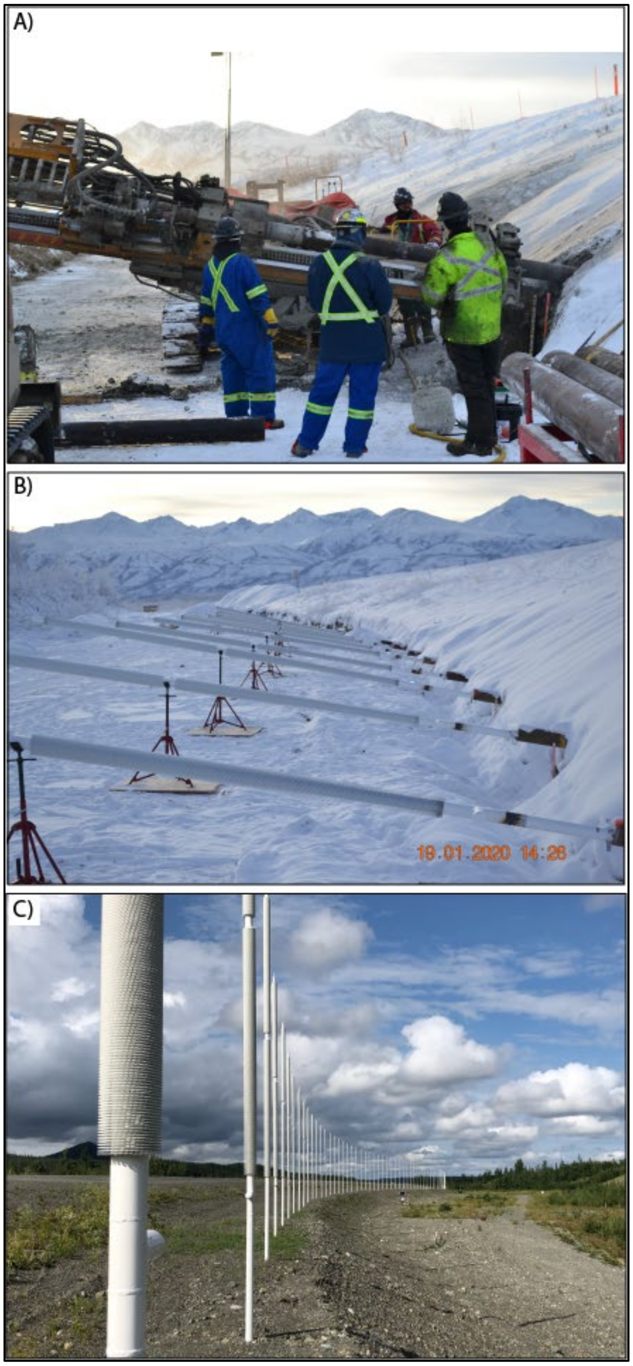

Figure 6. Construction photographs showing A) horizontal directional drilling beneath the highway embankment,
B) temporary installation of surface radiators, and
C) completed vertical installation of surface radiators and graded backfill along east toe of the embankment.

5 MONITORING SYSTEM

A long-term monitoring system was developed to verify the ground thermal performance and function of the thermosyphon units and to provide information that supports future sloped thermosyphon designs. The system includes two monitoring sections referred to as STN102 and STN103 (Figure 5C). This paper presents data collected at STN102 where massive ground ice was confirmed with drilling. Massive ground ice was not confirmed at STN 103 and provides contrasting ground conditions for future evaluation of thermosyphon performance.

Figure 5D shows the general arrangement of ground temperature cables and the cable naming convention for monitoring station STN102. Five thermistors of the six cables are vertically installed to measure embankment fill and permafrost foundation temperature. An additional thermistor cable was installed on the sloped thermosyphon evaporator pipe. Ground temperature cables were calibrated to ± 0.1 °C prior to installation. One meteorological station was installed at the location of STN103 to measure hourly ambient air temperature, windspeed, and humidity.

6 THERMAL PERFORMANCE

6.1 Baseline Period

Baseline ground temperature prior to construction was measured from the five vertically installed ground temperature cables at monitoring station STN102 (Figure 5D). The measurements have been summarised on the basis of a thermal year extending from October 1 to September 30. The thermal year approach was used to avoid combining values measured across two different winter seasons that are within the same calendar year.

The average annual temperature at the top of permafrost prior to construction was -0.2 °C (Figure 8A). At a depth of 12 m bgs, the permafrost temperature ranged from -0.4 °C to -0.5 °C. The active layer was measured to be 7 m bgs for STN102 GTC 157, located beneath the highway centerline (Figure 7A). Seasonal thaw at this location corresponds to the top of massive ground ice, as confirmed by drilling. Seasonal freezeback to this depth is facilitated by snow clearing from the driving surface which promotes heat loss from the ground.

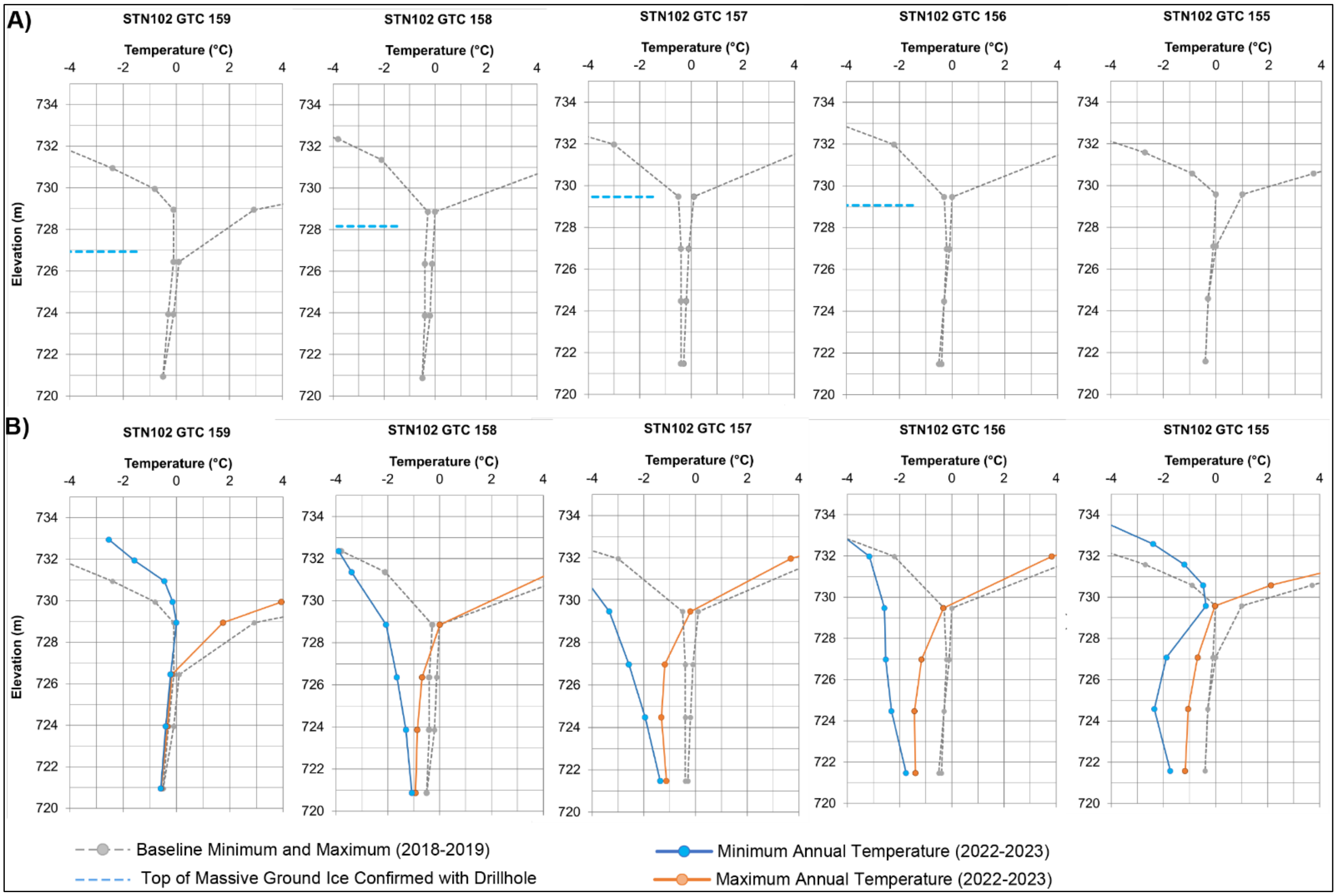

Figure 7. Minimum and maximum annual ground temperature at Monitoring Station STN 102: A) prior to construction during baseline period (2018–2019) and B) post-construction (2022–2023) compared to baseline period.

Ground temperature measured at STN102 GTCs 155 and 159 beneath the embankment toe indicate thaw exceeded seasonal freezeback during the baseline period and a suprapermafrost talik was present (Figure 7A). Minimum heat loss from foundation was measured beneath the embankment toe due in part to the suprapermafrost talik that remains perennially unfrozen. At STN GTC 159, the top of massive ground ice was confirmed with drilling to correspond to the permafrost table (Figure 7A).

The positive ground thermal gradient of permafrost (i.e., the increase in the ground temperature with depth) measured at each of the five locations and the presence of suprapermafrost talik indicates permafrost degradation has occurred beneath and adjacent to the embankment prior to construction.

6.2 Post-Construction Period

The thermosyphons installed at Dry Creek have been designed to passively extract heat from the ground without the need of a mechanical pump. Figure 8 shows the evaporator pipe temperature compared to air temperature for the first three years since installation. Activation of the thermosyphons has taken place each winter in early-to-mid October when the air temperature is less than the ground temperature. The thermosyphon units become inactive in early-to-mid April when the air temperature is warmer than the ground temperature. The current duration of thermosyphon function at the site each year is approximately 183 days. The average winter ground temperature at the evaporator pipe has been -8 °C to date, with a minimum temperature of -17.5 °C. Baseline ground temperature prior to installation of the thermosyphons was significantly warmer (winter minimum of -0.4 °C) and characterized by minimum winter heat loss from the ground.

Figure 7B shows the ground temperature at the warmest location between two evaporator pipes for the most recent thermal year and the baseline period. Both the minimum and maximum annual ground temperature has decreased (Figure 7B). The greatest ground cooling has taken place beneath the thickest embankment fill and/or the deepest installation depth of the sloped thermosyphon. These locations include the centreline of the highway embankment STN102 GTC 157 beneath the thickest section of fill and STN102 GTCs 156 and 155 where the evaporate pipe is effectively deeper in the ground.

Figure 9 shows the relative change in the permafrost table. The permafrost table immediately beneath the highway embankment has aggraded upwards by approximately 20 cm over the first three years. The greatest upward aggradation of permafrost has been at STN 102 GTC 155, representing the former location of a suprapermafrost talik observed beneath the embankment toe. The permafrost table at this location has aggraded upwards by approximately 2.5 m. The talik has completely frozen back with the uppermost ground subjected to seasonal thaw during development of the active layer. This location is represented by the deepest installation depth of the evaporator pipe. At the opposing embankment toe beneath the surface radiator, the placement of insulation in the toe berm has above STN 102 GTC 159 has maintained the permafrost table at a higher elevation (Figure 9A). While the insulation installed in the toe berm reduces heat gain to the ground, there is limited heat loss from the thermosyphon evaporator pipe at this location (Figure 9C). This location is particularly sensitive to future thaw.

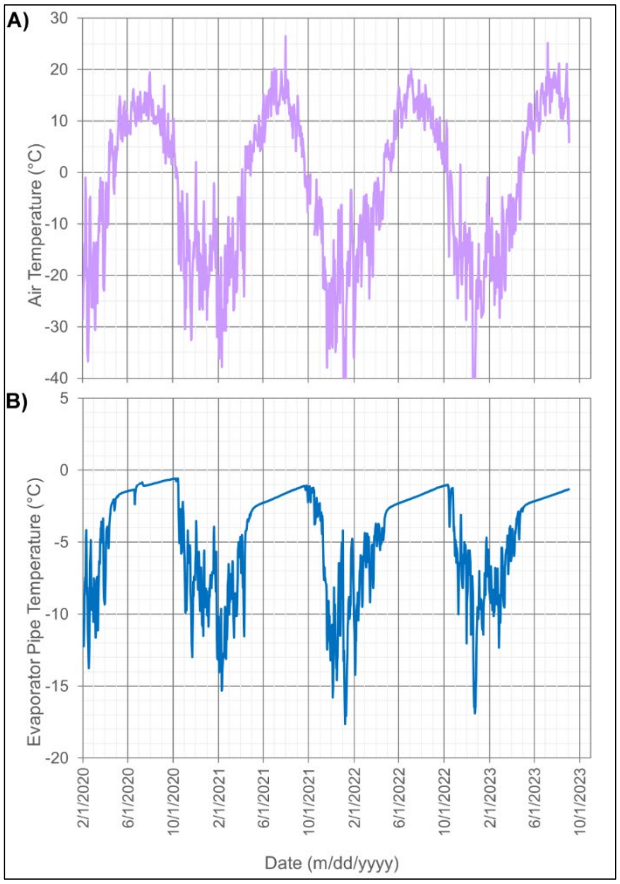

Figure 8. A) Air temperature and B) thermosyphon evaporator pipe temperature.

7 CONCLUSIONS

The Dry Creek highway section is characterized by glaciofluvial sand and gravel underlain by glaciolacustrine silt and clay. The presence of warm permafrost (> -0.5 °C) and massive ground ice in excess of 9 m thick necessitated stabilization of the site to reduce ongoing thaw settlement and risk of embankment failure.

The sloped thermosyphons design was developed to maintain integrity of the existing embankment without disruption of highway traffic. Thermosyphons have performed as expected during the initial three full years following construction, with notable decrease in the minimum and maximum annual ground temperature. The greatest ground cooling has occurred beneath the thickest section of embankment fill which acts to reduce heat gain during the thawing season. At locations of reduced embankment fill or where the evaporator pipe is installed at a shallower depth, the ground temperature is warmer due to the seasonal heat gain to the ground that is not directly addressed by the design implemented at the site. Additional measures could be taken to reduce heat gain to the ground, such as installation of insulation within the embankment fill above the position of the evaporator pipes.

Change in the ground thermal regime has decreased permafrost temperature and aggraded the permafrost table upward beneath the highway embankment. Suprapermafrost taliks located beneath the embankment toe have also frozen back to arrest permafrost degradation. The thermosyphons are expected to continue to contribute to permafrost stabilization over the 30-year design life.

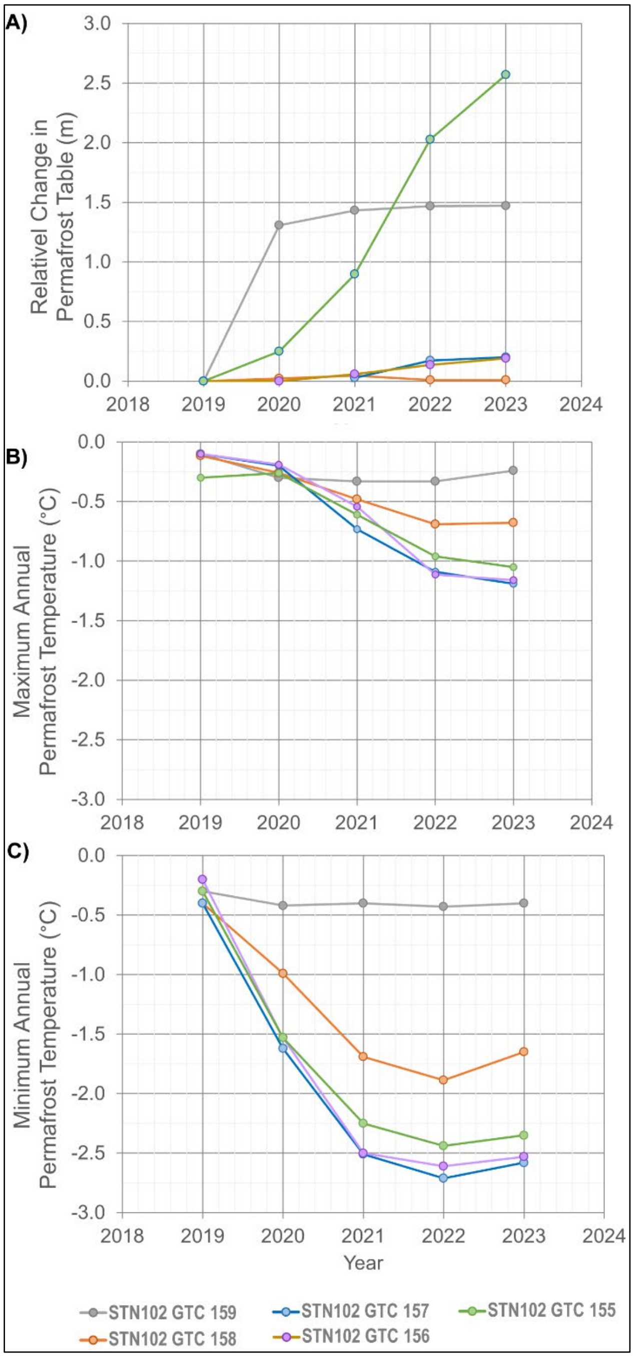

Figure 9. A) Relative change in permafrost table compared to baseline period, B) change in maximum annual and C) minimum annual permafrost temperature at 9.5 m bgs.

The Dry Creek Permafrost Stabilization project contributes to evaluation of techniques for the climate change adaptation of highway infrastructure in permafrost environments. Information obtained from the site can be used to support similar designs.

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