Long-term evaluation of mitigation techniques used for permafrost thermal stabilization at the Beaver Creek (YT) experimental road site

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Abstract

In northern environments, the construction of transportation infrastructures on permafrost, in combination with climate change, can have a significant impact on the thermal equilibrium of the ground. To ensure the safety of remote communities and maintain serviceability of roads, adapted embankment design methods may be needed to avoid thawing of permafrost during construction and throughout the service life. The conventional design and construction methods used in non-permafrost areas have not been adequate to prevent thermal degradation in northern Canada, resulting in considerable losses in the functional and structural capacity of some sections of roads. In order to optimize and assess the effectiveness of mitigation solutions, 12 instrumented test sections were implemented on the Alaska Highway near Beaver Creek, Yukon, Canada, in 2008. These test sections were designed to evaluate different thermal stabilization methods, such as heat drain, air convection embankments, snow and sun sheds, grass-covered embankments, and longitudinal culverts, to name a few. The main objective of this research is to evaluate the long-term effectiveness of the mitigation methods used to maintain the thermal stability of permafrost in the context of transportation infrastructures using an approach based on the temperature differential in the soil.

1 Introduction

In recent decades, increasing global warming has triggered drastic changes in Canada's northern ecosystems and geosystems. The effects of climate change in these areas have created several significant challenges, particularly with respect to soil and infrastructure stability. Over the last decades, Yukon authorities have witnessed an alarming phenomenon: previously stable structures are now showing signs of distress, posing a serious threat to the safety and sustainability of local communities, as well as a high maintenance cost of existing infrastructure (Malenfant-Lepage, 2016).

The consequences of permafrost degradation are of particular concern for transportation infrastructure in northern environments. Thawing of the underlying thaw sensitive permafrost is causing significant structural damage, such as differential settlement and embankment shoulder degradation which makes driving more difficult and increases the risk of accidents. Degradation could as well result from slope instability, creep of frozen soil under thick embankment, thermokarst and thermal erosion causing drainage issues. The temperature of the backfill and natural soil layers is influenced by various climatic and heat transfer factors, adding complexity to the challenge of thermal stabilization (Dumais and Doré 2016; Hall 2017). Landslides are also becoming more common as permafrost thaws, blocking roads, and causing significant damage to linear infrastructure. This results in significant maintenance costs and a drastic reduction in the service life of roads and embankments (Hjort et al. 2022; Cheng 2005; Reimchen et al. 2009).

To address this issue, a large-scale research initiative has been undertaken to study various techniques to mitigate permafrost warming underneath an in-service road. A test section has been constructed on the Alaska Highway near Beaver Creek in 2008, including several 50-meter-long embankment thermal stabilization experiments using innovative approaches to limit heat intake or maximize heat extraction. The techniques considered include heat drains, air convection embankment (ACE), light-colored aggregates, and snow/sun shed to limit the insulating effects of snow in the winter and to reduce heat intake from solar radiation in the summer. In addition, an extensive network of thermistors has been installed in deep boreholes, at the center and in the slope of the embankment as well as in natural ground near the toe of the slope, in each section to monitor dynamic thermal changes in the permafrost over time.

A short-term evaluation of the effectiveness of the mitigation techniques was previously done (Malenfant-Lepage et al. 2012). The study concluded that mitigation techniques showing the best short-term performance were the ACE uncovered, ACE full embankment, longitudinal culverts, snow/sun shed, and light-colored aggregates. These options provide effective solutions for reducing ground warming for infrastructure projects in permafrost areas. The assessment of their long-term effectiveness is still required to assess their economic viability. Therefore, this paper is focused on evaluating the long-term effectiveness of mitigation methods for maintaining permafrost thermal stability. To achieve this goal, temperature records of the Beaver Creek Experimental Road Site, for a 10-year period (2009–2019) were analyzed and the long-term permafrost thermal regime, and its evolution were evaluated. In addition, a comprehensive analysis of the long-term effectiveness of thermal equilibrium-based methods (Doré et al., 2016) was conducted by comparing temperature data over time. An adaptation of the thermal equilibrium principle is proposed to improve its applicability and effectiveness.

This research is intended to contribute to scientific knowledge of permafrost engineering, and to provide information for the design and implementation of effective mitigation measures based on large-scale and long-term reliable data from an experimental test site. The results will

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not only benefit the local communities that depend on transportation infrastructure but will also contribute to the development of more resilient and sustainable construction strategies in the context of climate change and permafrost degradation.

2 Description of the Test Site

The Alaska Highway, a major transportation route connecting Alaska with the rest of North America, has experienced recurring problems related to thaw settlement and longitudinal cracking, particularly in the section from Destruction Bay to the Canada-USA border. Although some sections of this highway were reconstructed about a decade ago, the degrading permafrost foundation and resulting differential settlement problems are affecting the quality and safety of travel to this day.

To address these challenges and improve road quality, Yukon Highways and Public Works partnered with the US Federal Highways Administration, Transport Canada, University of Alaska Transportation Center, Université Laval and Université de Montréal. A world class experimental site was then built to study the effectiveness of mitigation techniques used to prevent permafrost degradation underneath transportation infrastructures. The site is located near Beaver Creek, Yukon, 30 km south of the Canada-USA border at 62°22′59″N and 140°52′29″W.

This section of the Alaska Highway is in a transition zone between sporadic discontinuous permafrost and extensive discontinuous permafrost (Malenfant-Lepage, 2016). The stratigraphy of the region is characterized by a diamicton covered by a silty soil.

The test site was constructed in summer 2008. The 600-m-long road section is divided into 12 test segments (Figure 1c), each one being 50-m-long and 40-m-wide. Eleven different mitigation methods were applied to mitigate permafrost thaw and its negative impact on road infrastructure stability. One section was constructed using normal construction practice to be used as a reference section.

It is important to note that, although there is a total of 11 mitigation techniques available, only six of them are discussed in this document (Table 1). Since the original reference section is in bad condition, it was decided to use the grass-covered slope embankment as the reference section for this analysis. Some techniques were rejected due to design or construction issues noticed after construction (e.g., heat drains). The description of the techniques studied are in Table 2.

Each of the sections is equipped with thermistors strings installed in boreholes on the west-side of the road, allowing continuous monitoring of the thermal regime throughout the project under the center of the slope (Figure 1a). For some sections, thermistor strings are also positioned at the center of the road. The positioning of thermistor strings was carefully chosen to assess the thermal behavior in the zone of influence of the mitigation techniques (center and/or slope).

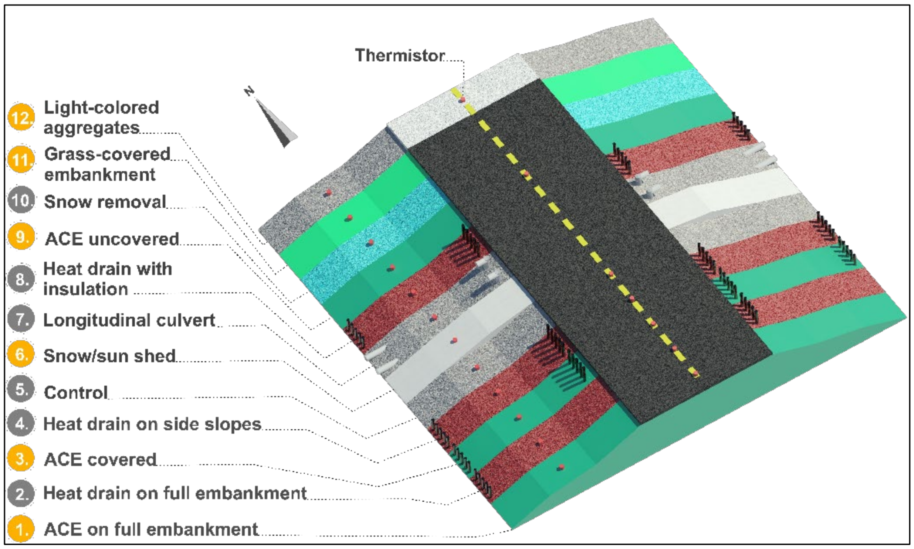
Table 1. Mitigation techniques considered in this study.

Mitigation technique		Section number
Air convection embankment (ACE)	ACE full embankment	1
	ACE slopes covered with vegetation	3
	ACE slopes uncovered (Fig. 1b)	9
Snow/sun shed (installed in 2009)		6
Grass-covered slope		11
Light-colored aggregates bituminous surface treatment (BST)		12

Table 2. Description of the techniques studied.

Section	Design description and cooling system
1 3 9 ACE	Constructed with porous granular material with particles size ranging between 15 and 30 cm, allowing for natural air convection to occur inside the embankment. During winter, the air cooling in the upper part of the convective material is moving downward into the embankment, causing the warm air to rise and exit from the embankment. No convection is occurring during summer and the ACE is acting as a thermal shield by keeping warm air near the surface and cool air at the base of the embankment. Also, the small contact areas between the crushed rocks and the low thermal conductivity of the air hinder heat transfer to the permafrost.
6 Shed	These structures were designed to provide permafrost protection year-round. In the summer, they reduce heat transfer to the ground by shading the surface. In the winter, they allow cold air to circulate under the structure and counteract the insulating effect of the snow cover to facilitate the evacuation of heat from the ground to the atmosphere.
11 Grass-covered	The embankment slope was seeded with a native grass seeds mix creating a suitable grass cover. Organic soils have low thermal conductivity in summer, which minimizes heat absorption on slopes. In winter, thermal conductivity increases, which accelerates the soil cooling process. This section will be used as the reference section.
12 BST	A standard bituminous surface treatment (BST) using clear aggregates was used on this section. Light-colored aggregates reflect more solar radiation, thus reducing surface temperature and heat absorption into the embankment.

a)



b)

c)

Figure 1. a) Schematic illustration (not to scale) of the mitigation techniques tested at the Beaver Creek Experimental Road Site, the yellow numbers indicate the sections analyzed in this paper; b) construction of the ACE uncovered section, 2008; c) view of the site (looking south), 2009 (before the installation of the snow/sun shed).

The different configurations of ACE designed and used at the Beaver Creek Experimental Road Site are shown in Figure 2.

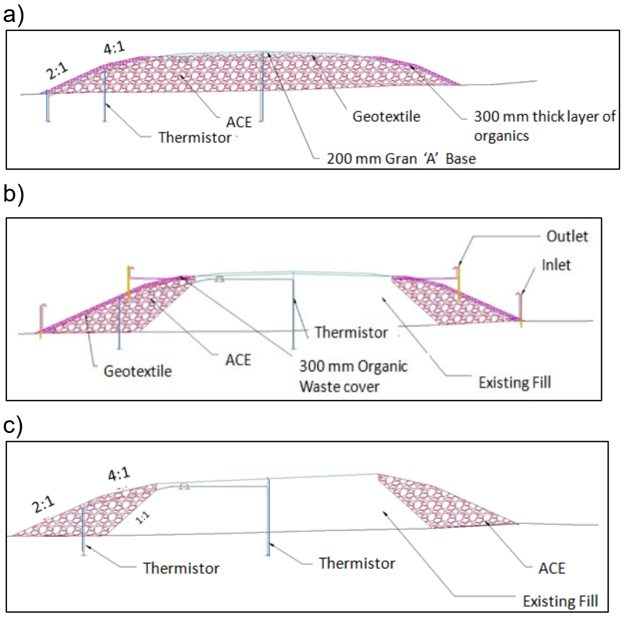


Figure 2. Schematic of a) ACE full (section 1), b) ACE on slope covered with vegetation, with ventilation pipes to improve heat evacuation (section 3); and c) ACE on slopes uncovered (section 9; Malenfant-Lepage 2012).

2.1 Instrumentation

Two or three thermistor strings were installed in each borehole to ensure that monitoring would continue even if one of the strings was damaged. These thermistor strings play a critical role in the thermal data collection approach.

Specifically, the thermistor configuration in each borehole, located on the slope and under the centerline of the embankment, was structured as follows: the first string, located just below the road surface, consists of a single thermistor. The second string is particularly important because it contains a total of 13 thermistors, spaced between 0.3 m and 1 m apart. This arrangement allows the string to reach a total depth of 15 m below the surface. The third string has 2 thermistors spaced 0.2 m apart on both sides of the interface between the embankment and the natural ground.

A total of 300 thermistors have been carefully distributed throughout the site. Each of these thermistors is strategically placed at specific depths, allowing for thorough and detailed monitoring of thermal changes throughout the project site. This extensive deployment of temperature measurement sensors ensures that comprehensive and accurate data on the ground thermal regime is available for the analysis.

Thermal data logging began in October 2008 and since then, temperatures have been recorded six times a day. These data are transmitted via satellite every four hours to the Government of Yukon SCADA (Supervisory Control and Data Acquisition) server in Whitehorse, YT. Campbell Scientific CR1000 loggers have been used for data logging in conjunction with thermistors cables supplied by EBA Engineering Consultants Ltd. These thermistors operate over a range of -50 °C to +30 °C, with an accuracy of 0.1 °C over the -10 °C to +10 °C range and 0.2 °C over the rest of the operating range. The quality of thermal data was verified by checking the consistency of the data point in time series and in space series. Afterwards, the collected thermal data have been thoroughly analyzed to extract valuable information. Temperature evolution with depth and time are studied using computer tools such as Microsoft Excel and Golden Software Grapher.

3 METHODOLOGY

The results presented in this paper are based on the analysis of the thermal data from the six sections selected, as discussed in section 2 of this paper. These raw data were provided by Yukon Highways and Public Works (YHPW) and have been subjected to an analysis process to extract relevant information, focusing on the evolution of temperature as a function of depth and time.

To characterize the effectiveness of the sections studied, temperature data from 2009 to 2019 have been used. The choice of this analysis period allows to minimize the effect thermal disturbance by construction activities during the first year and to minimize problems related to aging test sections and monitoring equipment after 2019. It is important to note that only a five-year analysis has been done for section 12 (Light-colored aggregates) due to the rehabilitation of the section with a dark BST surface at that period.

Since the sensors in the control section have shown a change in thermal behavior starting in 2014, Rioux (2017) performed an analysis of the air-ground temperature relationship in the three sections where no mitigation techniques were applied (sections 5, 11, and 12), to select the most suitable section to use as a benchmark to compare the thermal regime of another section. The results indicated that section 12 showed a more natural behavior. However, in this paper, sections 5 (control) and 12 (light-colored BST) were discarded because of an abnormal thermal behavior during the period analyzed. Therefore, section 11 (grass-covered embankment) was chosen as the new reference section in the following analysis, as its thermal behavior was considered the most representative of natural conditions for a conventional design of embankment built on permafrost.

In each of the test sections, several thermistor strings have been installed and positioned specifically to monitor the thermal performance of the different techniques used. To assess the thermal behavior in the zone of influence of the mitigation techniques, the appropriate thermistor strings were selected for the analysis depending on where in the embankment the technique is expected to influence the thermal regime (center and/or slope). For example, the ground temperatures recorded under the center of the embankment were used to analyze the light-colored BST and the ACE full embankment, while the temperature under the slope were used for the techniques installed in the slope (snow/sun shed, grass-covered slope, ACE slopes covered with vegetation, ACE slopes uncovered). The temperatures under the slope were also used for the ACE full section considering that this technique has an effect on the entire embankment.

The annual period chosen begins in October and ends in September of the following year to include both entire winter and summer in each year analyzed. The first year, referred to as 2010, begins in October 2009 and continues through September 2010, and so on for each subsequent year. This approach provided a clearer and more relevant picture of the impact and effectiveness of the mitigation technique in each of the years studied.

To carry out a rigorous analysis, a thermal gradient analysis has been ruled out, since many movements have been observed on the road and it is not possible to confirm if the thermistor depths from the interface, have changed over the analysis period. The analysis was made using two reference depths in the systems. First, the temperatures closest to the interface of the natural ground with the embankment, in each of the sections, is considered (Tinterface, T_I), as shown in Figure 3. This measurement point is located at different depths depending on the thickness of the embankment analyzed, as shown in Table 3. An interpolation of the temperature recorded by the thermistance above and below the interface depth, has been made. The second reference depth in the system is the deepest measurement points (Tpermafrost, T_P) assumed to be close to the depth of null annual temperature variation and therefore used to quantify permafrost temperature. The difference between annual average Tinterface and annual average Tpermafrost referred to as the “temperature difference”, or ΔT, was used as an indicator of thermal performance and was therefore calculated for each year of the analysis period.

Table 3. Depth of the embankment/soil interface and of the deepest measurement point.

	SLOPE		CENTER	
	Interface (m)	Deep (m)	Interface (m)	Deep (m)
ACE full	4.3	15.3	5.2	15.8
ACE slope covered	4.1	15.4	5.5	15.5
ACE slope uncovered	4.0	15.7	6.0	15.4
Snow/sun shed	4.6	15.3	-	-
Grass covered	3.9	15.9	-	-
Light-colored BST	-	-	4.3	15.1

It is believed that this approach will allow to effectively evaluate the relative thermal performance of each of the mitigation methods studied. Average annual thermal gradient has been used by many authors (e.g., Malenfant-Lepage 2012, 2016; Kong 2019) to assess permafrost stability. Null or negative gradients are considered to be representative of stable thermal conditions in permafrost, while positive thermal gradients are representative of unstable conditions. In this study, the difference in temperature is used without considering the difference in depth. Therefore, a null or negative ΔT indicates thermal stability of permafrost over time, providing valuable information on the effectiveness of the techniques implemented. In addition, as it is expected that T_P will have evolved very slightly in comparison with T_I, a decrease in ΔT should indicate cooling over time and increase effectiveness of the mitigation technique with time, while an increase in ΔT should be an indication of warming of the soil and reduced effectiveness with time.

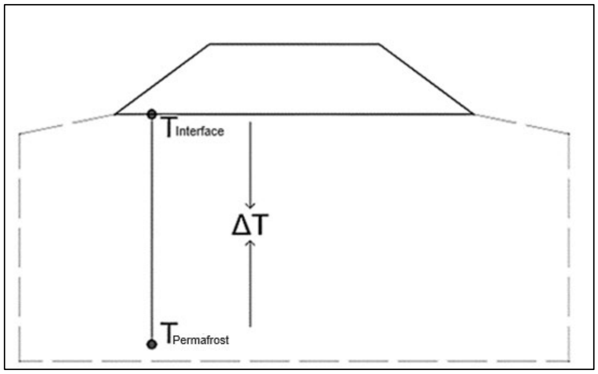


Figure 3. Schematic illustration of temperature difference ΔT, between the temperature at the embankment/soil interface (T_I) and the temperature of permafrost (T_P).

To calculate the temperature difference, the following equation will be used:

$$\Delta T = T_I - T_P \quad (1)$$

Where:

ΔT: Represents the difference in temperatures (°C)

T_I: Interface temperature (°C)

T_P: Permafrost temperature (°C)

This equation was used to analyze the effectiveness of the techniques installed for permafrost conservation at the study site. To perform the analysis, annual averages for the thermistors considered, and depth were calculated. Afterwards, Equation1 was used to assess the ΔT values and compare the evolution over time of each of the test sections considered.

4 Results and Discussion

Using the mean annual soil temperature at the selected depth, located under the slope or under the centerline of the road, allows us to obtain representative values covering a wider range of thermal conditions throughout the year. These mean annual temperatures (T_I and T_P) were used in Equation 1 to calculate the temperature differences in each of the cases analyzed.

Figure 4 and Figure 5 show the mean annual temperatures of the soil at the interface of the embankment with the natural ground (T_I), at the depth of permafrost temperature (T_P), and the difference of those two temperatures, between October 2009 and September 2019 for each technique studied, except for section 12 (light-colored aggregates BST) whose analyses stops in 2014 as previously explained. To visualize the results more easily, the analyzed mitigation methods are presented according to their zone of influence: under the slope (Figure 4) and under the center of the road (Figure 5).

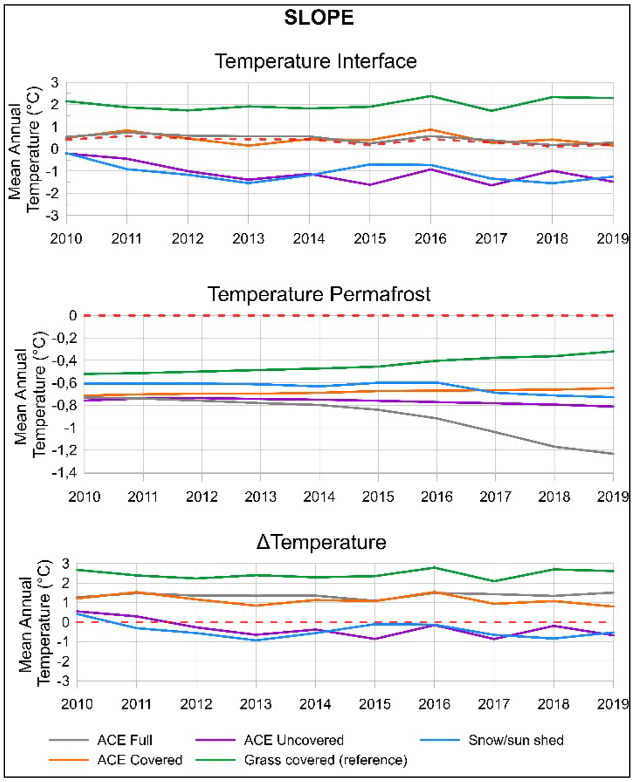


Figure 4. Soil temperatures (T_I, T_P, ΔT) under the slope of the embankment for the reference section grass covered, the snow/sun shed and three configurations of the ACE technique: ACE slope uncovered, ACE slope covered and ACE full. The red dashed line indicates 0 °C.

In Figure 4, the interface temperature under the slope reveals that the grass covered technique stands out as the warmest compared to the other four during the period analyzed. The ACE full and ACE covered methods show fluctuations between 0 and 1 °C over time, stabilizing in 2018 close to 0 °C. In contrast, the snow/sun shed and ACE uncovered techniques have the coldest temperatures, ranging between 0 and -2 °C throughout the analysis period. Both techniques show a decrease of temperature in the first few years, followed by some variations and a tendency to decrease again at the end of the period analyzed.

The permafrost temperature (T_P) is stable in the early years for all techniques. Then, from 2015, T_P of the grass covered area (reference section) begins to warm consistently from -0.5 °C to -0.3 °C in 2020 indicating a slow warming of the permafrost, thus a deepening of the permafrost table. On the other hand, T_P of the ACE full shows a decrease through time, reaching around 0.5 °C of cooling in six years from 2014 to 2020.

The difference of temperature shows that the ACE full, ACE covered and grass covered techniques are above 0 °C during the entire period analyzed showing limited capacity to induce a decrease of interface temperatures and maintaining thermal stability underneath the slope over time, although the difference does not exceed 3 °C. In contrast, the ACE uncovered and snow/sun shed techniques maintain their temperature differences below 0 °C, as soon as two years after the installation (shed), demonstrating effectiveness in maintaining thermal stability and cooling the soil under the slope.

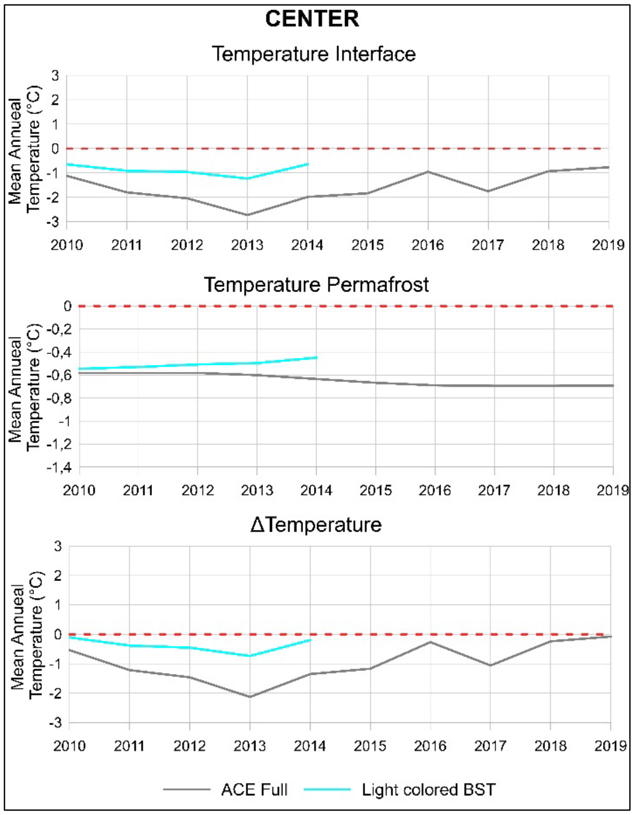


Figure 5. Soil temperatures (T_I, T_P, ΔT) under the centerline of the embankment for the BST with light-colored aggregates and the ACE full embankment. The red dashed line indicates 0 °C.

In Figure 5, the two techniques analyzed in the centre of the embankment, ACE full and BST with light-colored aggregates, are shown. Both methods show similar trend in temperature at the interface, being always colder than 0 °C, with BST section being up to approximately 1.5 °C warmer than the ACE full section. For the ACE full, it can be observed that after an initial decrease of the temperatures from 2010 to 2013 (-1.2 °C to -2.8 °C), a general increasing trend is noticed up to 2019. Other factors will be analyzed to understand this behavior, like contamination of the ACE material by fines particles, or groundwater flow.

No significant variation of the permafrost temperature over time is observed, indicating a stability in the permafrost thermal conditions maintained just under 0 °C and supporting the effectiveness of the mitigation techniques applied.

Finally, when evaluating the difference in temperatures, both techniques remain below zero during the entire period showing thermal stability of the ground, as in general the interface temperatures are slightly colder than the permafrost temperatures. For both techniques, the ΔT follow the interface temperature tendency which decreased rapidly after construction, indicating a cooling of the system, and then starting to increase in 2013 with a stabilization just under 0 °C in 2018 for the ACE full.

Moreover, the air temperature will be analyzed throughout the studied period to better understand the ground temperatures differences, especially considering that T_P does not vary significantly over the monitoring period. This means that the interface temperature, located at a depth varying from 3.9 to 4.6 m from the surface of the embankment (slope) and 4.3 to 6 m from the surface of the road (center), would have a greater effect on the ΔT variations. Also, field observations over the period might indicates other factors influencing temperature difference, like vegetation growing on the embankment surface and water flow under the embankment.

5 Conclusions

The analysis of temperature data at the Beaver Creek Experimental Road Site provides valuable insights into the long-term performance of permafrost mitigation techniques. Over a decade of observation, promising performance in some slope protection techniques is observed, such as the ACE uncovered (section 9) and the snow/sun shed (section 6). Indeed, these two sections have shown the best embankment conditions after 15 years, during a site visit in 2023 (Figure 6).

The light-colored embankment was effective in maintaining thermal stability of the permafrost under the center of the embankment, as well as the ACE full which stands out for its ability to maintain lower temperatures in the center than in the slope of the embankment, although this technique is applied to the entire width of the embankment. However, work remains to be completed to understand some performance issues that could explain trends and observations in some sections where the permafrost continued to warm following the construction in 2008. This emphasizes the need to continue thermal analysis using different thermistor depths and calculation approach to better quantify the performance of the test sections while evaluating the durability and economics of long-term maintenance of these techniques. Ultimately, these findings will provide scientists and stakeholders with a solid basis for making informed decisions and developing effective permafrost mitigation strategies in this vulnerable environment, especially in a context where climate change is adding stress on the systems.

a)

b)

Figure 6. The snow/sun shed (a) and ACE uncovered (b) sections in 2023.

6 Acknowledgements

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