Experimentation of mitigation techniques to reduce the effects of permafrost degradation on transportation infrastructures at Beaver Creek experimental road site (Alaska Highway, Yukon)

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ABSTRACT
In order to better understand permafrost degradation on transport infrastructures, 12 experimental sections have been constructed on the Alaskan Highway near Beaver Creek. These sections experiment one or several combined methods of thermal stabilization such as convection air embankment, heat drains, grass-covered embankment, reflecting surfaces and snow clearing on embankment slopes. To rigorously monitor the temperature evolution for the next years and to determine the efficiency of theses text sections, thermistor cables have been installed into the shoulder and at the center of the embankment.

RÉSUMÉ
Afin de trouver des solutions pour contrer les problèmes engendrées par la dégradation du pergélisol sur les infrastructures routières, 12 sections d'essais ont été construites sur l'Alaska Highway près de Beaver Creek. Ces différentes sections d'essais expérimentent des techniques de stabilisation thermique utilisées seules ou combinées, telles que le drain thermique, le remblai à convection d'air, le remblai couvert de matière organique, la surface réfléchissante ainsi que la protection contre les effets isolants de la neige. Afin d'effectuer un suivi rigoureux de l'évolution du pergélisol durant les prochaines années pour ainsi déterminer l'efficacité des sections, des chapelets de thermistances ont été installés dans l'épaulement du remblai ainsi que sous le centre de la route.

1 INTRODUCTION

Global warming in the past ten years has lead to important present day repercussions in soil stability in the Canadian Far North. Permafrost is now melting at an incredible speed and losing bearing capacity because it dynamic is directly related to climate change. In Yukon, transport infrastructures that were always stable until today now show some signs of weakness. This is creating major risks of instability as well as important costs of maintenance for the existing civil infrastructures. In order to better understand the phenomenon, 12 experimental sections have been implemented on the Alaskan Highway near Beaver Creek. The main objective of this project is to analyze the thermal regime of the ground for each of the 12 sections during their first year in service to determine the thermal impact of the construction and their short term effectiveness.

2 PROBLEMS STATEMENT

During transport infrastructure construction on ice-rich soil, the thermal regime is highly affected and may cause rapid thawing of permafrost as well as longitudinal cracking along the road (figure 1).

Figure 1 : Longitudinal cracking observed along Alaska Highway (2009)

This phenomenon causes an important loss of the functional and structural capacities of the road. The establishment of these different sections has the purpose of preventing permafrost from thawing by extracting heat present in the ground under the highways, by increasing the quantity of cold air that sinks into the embankment during the winter or by reducing adsorbed sun rays by the surface. These methods will allow the diminution of the active layer thickness and limit the apparition of differential settlements when the thawing occurs. The active layer has an average thickness of 40 cm in Yukon discontinuous permafrost zone. However, as the road construction is one of the main factors causing permafrost degradation, the active layer thickness can easily go up to 3 or 4 meters locally under these infrastructures.

3 METHODOLOGY

The analysis presented in this paper is based on the analysis of thermal data collected in each one of the test sections. Temperature monitoring in each of the test sections was done using thermistor strings. As a minimum, a vertical thermistor string has been installed in the middle of the section at mid-slope (south side) to a depth of 15 m from the surface. Sections including protection systems extending across the embankment also included a thermistor string positioned at the center of the cross section of the embankment. Finally, a few sections included an additional thermistor string located at the toe of the embankment slope (south side). These sections are the reference section as well as the air-convection embankment and the heat drain applied across the full embankment width.

Thermal data are recorded 6 times a day since October 2008 and are made available to researchers by Yukon Highways and Public Works (YHPW). The raw data has been analysed to extract useful information including evolution of temperature with depth and time, thermal regimes at specific times and thermal gradients using EXCEL and SURFER softwares.

4 MITIGATION TECHNIQUES TESTED

4.1 Control section

The control section has been constructed using the standard construction practices on the Alaska Highway. The thermal regime in the section has been monitored since 1995 by YHPW. This section is used as a reference to be able to compare the thermal regime of the other test sections with its own thermal regime. It will in this way be possible to assess the relative effectiveness of the mitigation techniques.

The kriging interpolation graph shown in figure 2 has been created using the daily mean temperature data from October 5th 2008 to October 31st 2009. These temperature readings vary between -14.8°C and 25.3°C. The dashed line located at a depth of 0 meter illustrates the limit between the embankment and the natural ground. The positive depth values then represent the embankment while the negative values characterize the natural soil. The dark solid line corresponds to the 0°C isotherm. The grey-coloured region represents a critical temperature zone where the soil has temperatures values between -1°C and 0°C. On this figure, the 0°C isotherm reaches the natural soil / embankment contact around mid-July. It is also possible to notice that a significant perturbation of the cooling process occurs in January as a result of a temperature warming event during that period. In October 2008 and October 2009, 0°C isotherm is at the same depth of 1.4 meters.

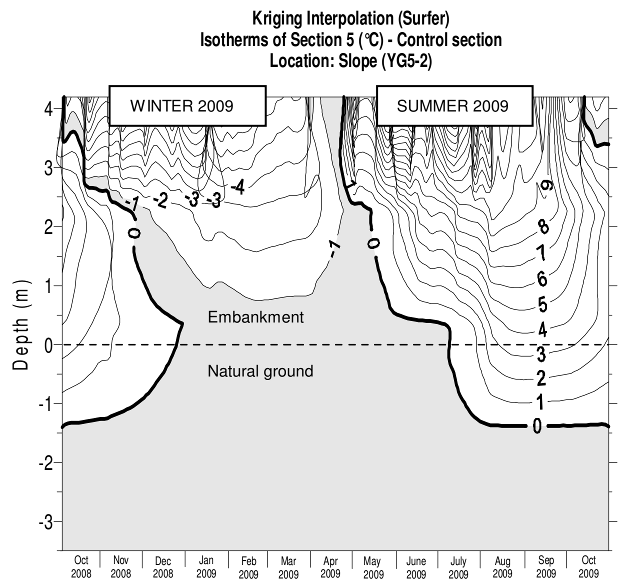

Figure 2: Kriging interpolation of the control section thermal regime

4.2 Sections protected with air convection embankment

The air convection embankment (ACE) is a permafrost protection technique developed by D.J. Goering at the University Alaska Fairbanks. This thermal stabilization method is based on the substitution of normal embankment materials by a porous stone layer consisting of particles ranging from 150 to 300 millimeters in diameter. Air convection embankment is a protection technique designed to extract heat from the embankment. During the winter period, ACE material allows for the formation of convection cells in the interconnected pores of rock material (figure 3). As pore air near the top of the embankment cools down with the surface of the embankment, it tends to go down through the pores as a result of its density being higher than warm air. In turn, warm moves upwards replacing the cold pore air and transporting heat toward the embankment surface. The air convection movement increases thus considerably the effectiveness of the heat transfer process between permafrost and air during winter. In addition, during summer, the convective flow stops because warm air stays at the surface of the porous layer which then act as an insulation layer.

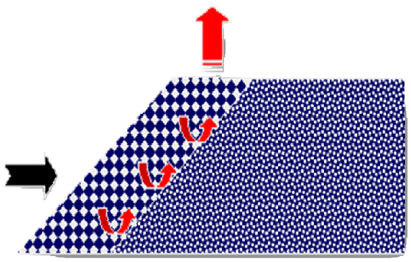

Figure 3: Air ascension in air convection embankment

Three of the sections are using ACE layers. Section 1 is characterized by the presence of a convective layer across the full width of the embankment. The embankment's slopes are also covered by an organic layer to impede heat intake and reduce warming of the ACE material during summer. Section 3 differs from section 1 by the fact that the application of ACE material was limited to the shoulder of the embankment. The slope of the section is also protected by a granular layer. In an attempt to maximize the effectiveness of the convective system, two ventilation pipes have been placed at the base and at the top of the convective layer: the first one is one meter away from the traffic lane and the second one is located at the toe of the embankment slope. For each pipe section, five 150-mm-diameter inlets and outlets of have been placed at even spacing along the road. Theses pipes are in contact with the ACE material and are designed to improve the circulation of cold air in the embankment during winter. Finally, section 9 (figure 4) is similar to section 3 with the exception that the ACE material is exposed at the surface.

Figure 4 : Air convection embankment uncovered

Some difficulties have been experiences during the construction of these sections. First of all, a very good material transportation logistic was needed due to a 130 km hauling distance. Some zones of this experimental section have been excavated down to one meter above the natural ground and left unprotected for few days due to the difficulties of transporting the quantities ACE material needed. Ideally, backfilling should have been done immediately after excavation. Considering the logistic involved in the transportation and the storage of the material on the site, the backfilling was completed in several days. This problem is likely to have caused thermal degradation underneath the section likely to affect the performance evaluation of these sections during the first winter.

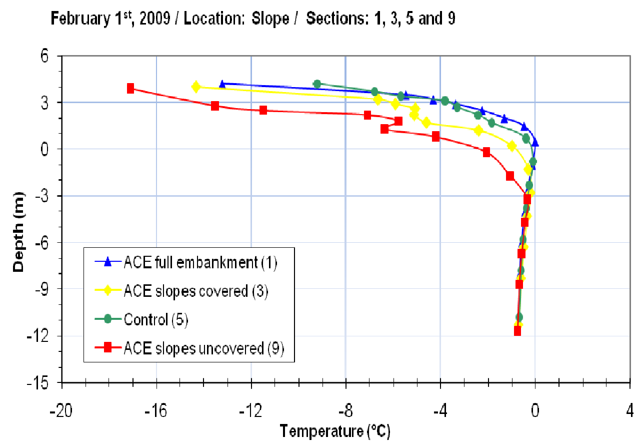

Figure 5: Thermal regimes in air convection embankment sections compared with the control section (February 1st, 2009)

These permafrost protection systems have shown so far a good potential during their first winter in service. As it has been anticipated, the full road excavation of section 1 has lead to a more important warming of the underlying soil compared with sections 3 and 9 only excavated for their embankment slopes. However, this section succeeds to slow down the heat waves propagation in the natural ground under the embankment. It is mainly for sections 3 and 9 that it is possible to observe a good cooling improvement of the embankment at the end of the winter (Figure 5).

For the best performing section (section 9), a kriging interpolation graph has been produced (figure 6). This graph shows daily mean temperature values varying between -22°C and 23°C. The temperature isotherm of -1°C has risen by at least 0.6 m to reach the interface between the embankment and natural soil during the first winter of service.

In less than a year, this mitigation technique has succeeded to significantly cool the embankment, but the active layer so far has remained the same thickness. On the other hand it will be interesting to monitor the effect of warm summers on unprotected ACE slopes as experimental results have shown that faster warming can occur during summer on these systems (Beaulac and Doré, 2007).

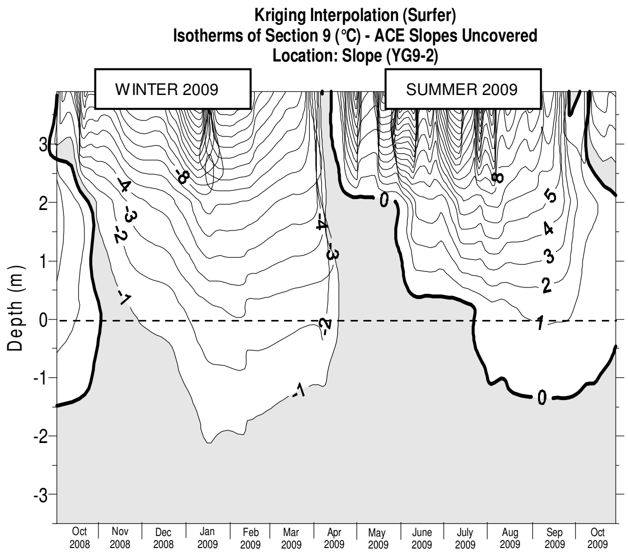

Figure 6 : Kriging interpolation thermal regime of the most efficient air convection embankment (section 9)

4.3 Sections protected with heat drains

The heat drain is an innovative technique proposed by the Pavement engineering research group of Laval University (GRINCH). This protection technique is based on the use of a highly permeable geocomposite made of a corrugated plastic core covered on both sides by geotextile. The 25 mm-thick geocomposite is placed approximately 1 m above the natural ground level and extends towards the embankment surface to facilitate heat drainage (figure 7). The heat drain can be used across the full width of the embankment or in the embankment shoulder.

Figure 7: Placement of the heat drain across the full width of the embankment (section 2)

In order to make the heat drain system functional, the geocomposite needs to be connected to 100 mm drains pipes located at the base and at the top of the drainage layer. These drains are connected to inlet and outlet pipes to allow free air circulation in the system. As indicated in figure 8, one side of the geocomposite drainage layer needs to be placed at a steep angle to generate upward circulation of warm air towards the outlets. The warm air is then replaced by cold air entering the system through the inlets contributing thus to embankment cooling. After installation, the geocomposite was backfilled with 40 cm lift of 20 mm aggregate, followed by the existing embankment material and the ventilation pipes have been fixed to wooden posts.

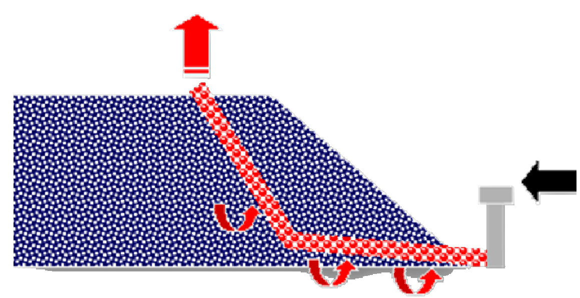

Figure 8: Conduction and convection air movements in the geocomposite

Some problems were also encountered during the construction of the heat-drain sections. These problems include the labour intensive assemblage of the drain with the ventilation system. This problem has later led to the improvement of the design of the ventilation system. Another problem that occurred during construction was the relatively long period during which the drainage layer was left exposed to solar radiation during construction. This problem might have induced thermal degradation likely to affect the results obtained during the first year of monitoring of the thermal performance of these systems.

There are three different tests sections using this heat drain technique. First, section 2 was constructed using a heat drain extending across the full width of the embankment (figure 7). Section 4 uses also the heat drain but limited to the embankment shoulders. Figure 9 illustrates the ventilation system of the shoulder application of the heat drain in section 4. Finally, section 8 is also based on the heat drain mitigation method similar to the one described for test section 4. In addition, the system used in section 8 involves the use of an insulation layer above the heat drain. The insulation layer is constituted of 50-mm-thick polystyrene boards placed uniformly 40 centimetres under the surface along the slope of the experimental section.

Figure 9: Heat drains on side slopes (section 4)

It has been observed that the construction of these test sections has caused a more important thermal degradation than for the placement of other mitigation technique. The degradation can be observed between levels +2 and -2 m on figure 10. However it seems that the degradation is slightly less important for section 8. This difference might be explained by the use of polystyrene insulation that has been added after placing the geocomposite. According to the light-color of this insulate, this has an effect of reflecting sun rays instead of absorbing them as the black geotextile does. Section 8 appear to be the best performing heat drain section during the first winter of service with a slight cooling effect compared to the control section (figure 10). It is expected that the effect of thermal degradation will be reduced and that the other heat drain sections will be more effective during the subsequent winters.

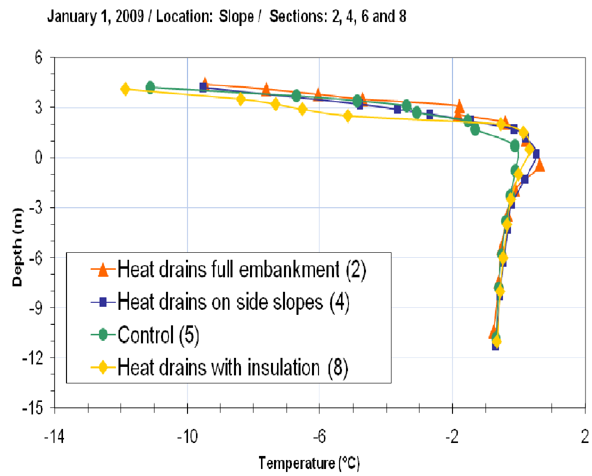

Figure 10: Thermal regimes of the heat drain sections compared with the control section (January 1st, 2009)

4.4 Longitudinal culverts

Longitudinal culverts are also an air convection method involving the use of three 750 mm-diameter culvert sections. The first section contains three 6 m-long culvert sections placed in the embankment shoulder parallel to the road for a total length of 18 meters. All the joints have been carefully sealed with an impervious membrane. The main culvert section is connected at one end to another horizontal section placed perpendicularly to the road alignment between the longitudinal section and the toe of the embankment slope where an air inlet valve has been installed. The third culvert section is composed of a vertical culvert segment connected at the other end of the longitudinal pipe and exceeding by about two meters the embankment surface. An air outlet valve has been installed at the top of the vertical culvert section (figure 11). After installation slightly above the natural ground level in the embankment shoulder, the culverts were backfilled with granular materials. It is expected that cold air will be introduced in the culvert through the inlet valve during winter and flow along the longitudinal section before being evacuated through the vertical outlet. This cold air flow should allow soil cooling during winter. During summer, the valves of the system will be closed to avoid the inverse effect, such as warming of the embankment. The experimental section includes 4 ventilation systems; two on each side of the road. It is important to keep in mind that they are not interconnected together, so they operate individually.

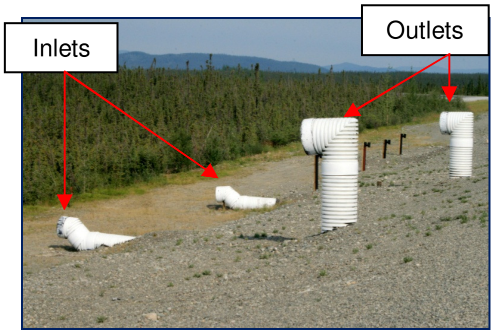

Figure 11 : Inlets and outlets of the longitudinal culvert system (section 7).

Test section 7 shows temperatures variations with time and depth ranging between mean daily ground temperatures of -21℃ and 22℃ (figure 12). This test section is one of the three showing effective cooling down to the natural soil level during winter. Even thought thaw penetrates rather deeply into the natural ground in summer 2009, it is nevertheless significantly reduced compared to summer 2008. There is already a decrease in active layer thickness only one year after the section has been in service. At this rate, it might be possible in summer 2010 to keep the natural soil under the embankment above 0℃. This fast improvement of the thermal regime might be explained by the relatively limited impact of construction operations for the installation of the longitudinal culverts. Finally, water accumulation has been observed in summer 2009 inside the culvert and around the test section. The effect of this water accumulation on the performance of the section is unknown at this time.

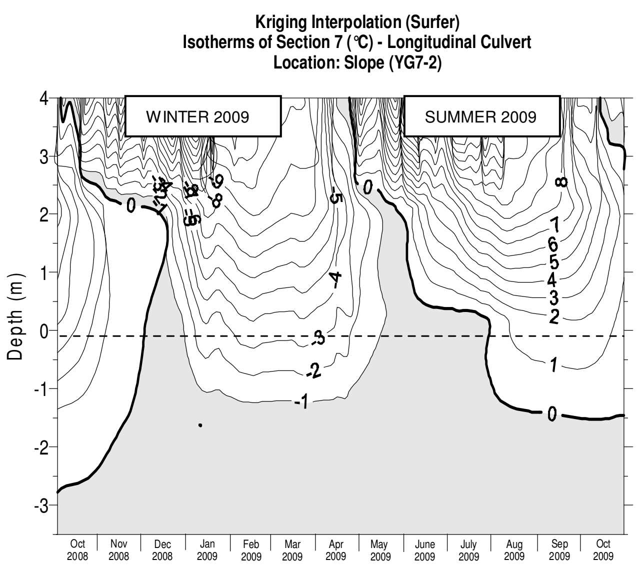

Figure 12: Thermal regime of section 7

4.5 Snow clearing

The objective of this technique is to reduce the negative effect of snow accumulation on the embankment. Snow removal reduces its insulation effects during winter season allowing heat to be removed more effectively during winter. The main advantage is that no specific construction is required for this mitigation technique else than to design a slope that can accommodate snow clearing equipment. However, maintenance operations have to be reliable over the life of the embankment to avoid snow accumulation for long periods during winter in order to obtain the maximal cooling of the test section.

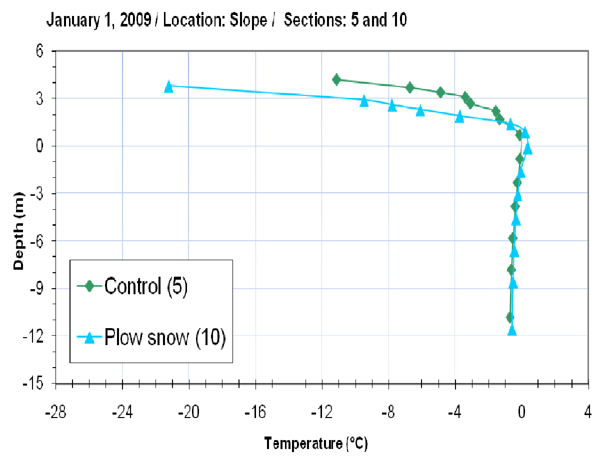

Figure 13: Thermal regimes of section 10 compared with the control section (January 1st, 2009)

Test section 10 shows daily mean temperature values variation with depth and time ranging between -19℃ and 24℃. This temperature variation range is in fact similar to the variation observed in the control section. The only difference can be seen during winter. Temperatures significantly cooler than in the control section have been observed to a depth of approximately 3 m in the embankment shoulder. This effect is obviously related to snow clearance on the embankment slope (figure 13). However, the cooling effect doesn't seem to have significant cooling effect at lower levels so far. It is expected that the effect will eventually influence temperature regimes at greater depths.

4.6 Grass covered embankment

This test section is mainly characterized by the addition of a layer of approximately 300 millimeters thickness of organic material on the slopes of the pre-existing slopes embankment. Vegetation is a good natural insulator and allows the presence of permafrost where it would be normally absent. Thermal conductivity of organic soils is weak during summer contributing thus to a reduction of heat penetration in the embankment. Moreover, the presence of a vegetation cover is likely to reduce solar radiation at the ground surface during summer. The main advantage of this thermal protection method is that the costs of implementation are very low. However, a few difficulties appeared in this project when trying to find good organic material in the area of the experimental site. The only good quality organic material has been found more than 80 kilometers away from the site. One year after construction, it was possible to observe that grass has a very low density on the slope of the test section. It was then recommended to add native grass seed mixture to help the development of a proper grass cover. A longer observation period is required to assess the benefit of this technique.

Figure 14: Grass covered on the slopes of the embankment (summer 2009)

4.7 Light-grey coloured Bituminous Surface Treatment

This section is a bituminous surface treatment using light-colored aggregates in order to reduce heat absorption from solar radiation at the road surface (figure 15). The main advantage of this mitigation technique is that the application of the BST and the equipment used are following the exact same process than that of a normal BST surfacing. The main constraint is that a source of light color aggregate has to be available near the construction site. In the case of the Beaver Creek project, granular material had to be hauled over more than 80 km. However, the quantity needed was not very important considering the size of the section. Since the effect of a light colored surface is limited to the center of the embankment, the performance of this section will be assessed using the thermistor string located at the center of the embankment. A technical problem occurred in the first year of monitoring at this section making the thermal regimes unreliable for a short term assessment of the performance of the section.

Figure 15: Light-grey coloured BST

5 THERMAL GRADIENTS

Figure 16 show thermal gradients (°C/m) that have been calculated on a 2 meter section located in the embankment just above the natural soil for the air convection embankment sections from October 2008 to October 2009. For material with similar thermal conductivities, the thermal gradient is directly proportional to the heat flux across a section of soil. According to the results of this analysis, steeper thermal gradients are observed during winter in sections 1, 3 and 9 compared with the control section (figure 16). However, sections 3 and 9 exhibit higher positive gradients during the following summer compared to the reference section. The early occurrence of a steep positive gradient in the section 3 is difficult to explain at this point and further investigation on the thermal behavior of this section will be required to fully assess the performance of this protection method.

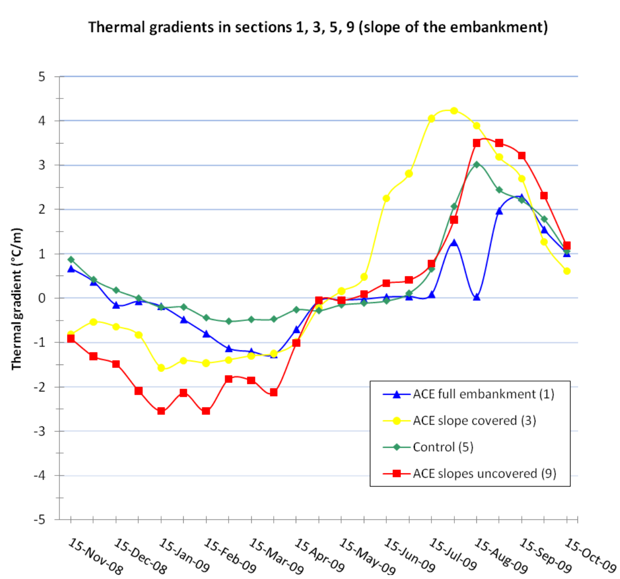

Figure 16: Thermal gradients (°C/m) calculated in the slopes of the air convection embankment sections

6 CONCLUSION

This early analysis of the temperature data from the Beaver Creek experimental site has led to preliminary conclusions on the thermal performance of permafrost mitigation techniques. First, the construction of the test sections involving full or partial excavation of embankment material has caused a more important thermal degradation in the subgrade soils compared to the sections where excavation was minimal or not required. Thermal degradation appear to be higher in heat drains sections 2, 4 and 8. This was possibly caused by the dark geocomposite material left exposed to solar radiations during construction. Thermal degradation appear to have affected the thermal performance of several sections for the first winter of operation.

Some permafrost protection systems have shown so far a good potential during their first winter in service. This is the case for sections 1, 3 and 9 (air convection embankments), section 7 (longitudinal culverts) and section 10 (snow removal on slope). As it has been anticipated, the full road excavation of section 1 has lead to a more important warming of the underlying soil compared with sections 3 and 9 where excavation was done only in the embankment shoulder. However, this section has successfully reduced thaw penetration in the natural soil under the embankment. Sections 3 and 9 show a good cooling performance in the embankment shoulder at the end of the winter. Temperature isotherm -1°C has been raised above the natural ground in section 9. Section 7 has also shown a promising performance during the first winter.

At this point, it is premature to assess the effectiveness of sections 11 and 12 considering late installation of these systems and technical problems that occurred during the first year of monitoring.

To conclude, it is still too early to make final conclusions on the thermal regime of these 12 test sections. It is necessary to continue the thermal analysis over the course of a few years. The durability of these sections as well as their long-term economical potential must be also be assessed.

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