Four-year monitoring of a geotextile-reinforced fill slope along a highway to Canada's Arctic Coast

E.M.B. De Guzman, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada
S.W. Kaluzny, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada
D.M.J. Stafford, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada
M.C. Alfaro, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada
L.U. Arenson, BGC Engineering Inc., Vancouver, Canada
G. Doré, Département de génie civil et de génie des eaux, Université Laval, Québec, Canada

ABSTRACT
A reinforced highway embankment test section was constructed along the Inuvik-Tuktoyaktuk Highway in Northwest Territories, Canada. The embankment was constructed under frozen conditions for logistical and environmental reasons. There is limited understanding on the mechanical behaviour of embankments that are initially compacted with frozen fill and then experience natural thawing during subsequent summer seasons. Side-slope sloughing and fill cracking occur due to localized thaw-settlements under the shoulders and side-slopes of the embankment in combination with the depression of the permafrost table at the toe of the embankment. In order to minimize these issues, layers of wicking geotextiles were installed to provide reinforcement at the slopes and drainage path for the water during the thawing season. Strain gauges were installed along the geotextiles to measure its elongation, while ShapeAccelArrays were installed mid-slope and mid-height of the embankment to measure lateral and vertical displacements, respectively. Thermistor strings were also installed at different locations in the embankment fill and foundation soil to monitor soil temperatures. A control test section (unreinforced) with the same instrumentation was also constructed beside the reinforced test section to evaluate the benefit of using wicking geotextiles in Arctic environment. This paper presents four years of monitored performance of both control and reinforced test sections.

1. INTRODUCTION

Highway embankments in the Arctic are usually constructed during winter conditions to preserve the permafrost foundation and minimize environmental impacts. However, there is limited understanding on the mechanical behaviour of embankments that are initially compacted with frozen fill and experienced natural thawing and settlements during the spring and summer seasons following winter construction. Frozen fill is very difficult to compact at sub-zero temperatures. They are relatively strong while they remain frozen but they become soft and compressible after thawing. Side-slope sloughing and fill cracking are caused by localized thaw-settlements under the shoulders and side-slopes of the embankment created in combination with the depression of the permafrost table at the toe of the embankment.

Two sections along a newly constructed Inuvik-Tuktoyaktuk Highway was instrumented to monitor temperatures and displacements. One section is reinforced with layers of wicking geotextiles to minimize side slope movements. The other section is unreinforced. Wicking geotextiles have been recently introduced in the market where the geotextile provides in-plane drainage (wicking) when water infiltrates through the soil (Zhang et al. 2014). The wicking function of the geotextile allows for wicking of the water even in unsaturated soil conditions (Han et al. 2016). The wicking geotextile has been successfully used in the Dalton Highway Beaver Slide Area in Alaska to act as a capillary barrier to mitigate effects of frost heave and prevent the occurrence of frost boils (Zhang et al. 2014). A similar successful application was used in the Pioneer Scenic Byway in Montana to prevent the occurrence of frost heaves along the highway (Sikkema and Carpita 2016). Both application focused on moisture management and drainage applications, with the reinforcement function secondary. The test sections are monitored for temperatures in the embankment fill and foundation soil, and vertical and lateral displacements at their mid-slopes. Strain gauges were also installed along the length of the geotextile at different levels of the reinforced embankment to monitor mobilized reinforcement tensile forces. Four years of monitored data have been recorded and results are presented in this paper. The temperature sensors have shown that there is a warming trend in the embankment fill and foundation soil. The central and bottom part of the embankment fill has remained frozen in the three-year monitoring period, but has reduced in size since end-of-construction. Largest lateral displacements were recorded in the summer following construction, which is attributed to the thawing of side slopes.

2. SITE CONSTRUCTION AND INSTRUMENTATION

Installation of instrumentation commenced on April 14, 2015 and was completed on April 20, 2015. The temperature on site during construction ranged from -35°C to -2°C, with an average temperature of -18°C during fill material dumping and compaction. Construction was halted when air temperatures were above -10°C. The road surface became wet closer to -5°C with ruts developing due to truck traffic. Prior to construction of the test sections and installation of instrumentation, an initial lift of 600 mm was placed on the research site. Only snow along the road right-of-way was removed during construction and at the toe of the embankment where the data acquisition system was installed. Great care was taken to avoid stripping of the natural ground surface to protect the underlying permafrost. The control and reinforced embankment test sections are both instrumented with thermistor strings for temperature monitoring and ShapeAccelArrays (SAAs) to measure lateral displacements and settlements as shown in Figure 1. These instrumentation were connected to a data acquisition system at an offset from the toe of the embankment (Figure 2) which can be remotely accessed through satellite connection. Results of the temperature, displacement, and strain gauge readings from end-of-construction to April 20, 2019 (four-year monitoring period) are discussed in the subsequent sections.

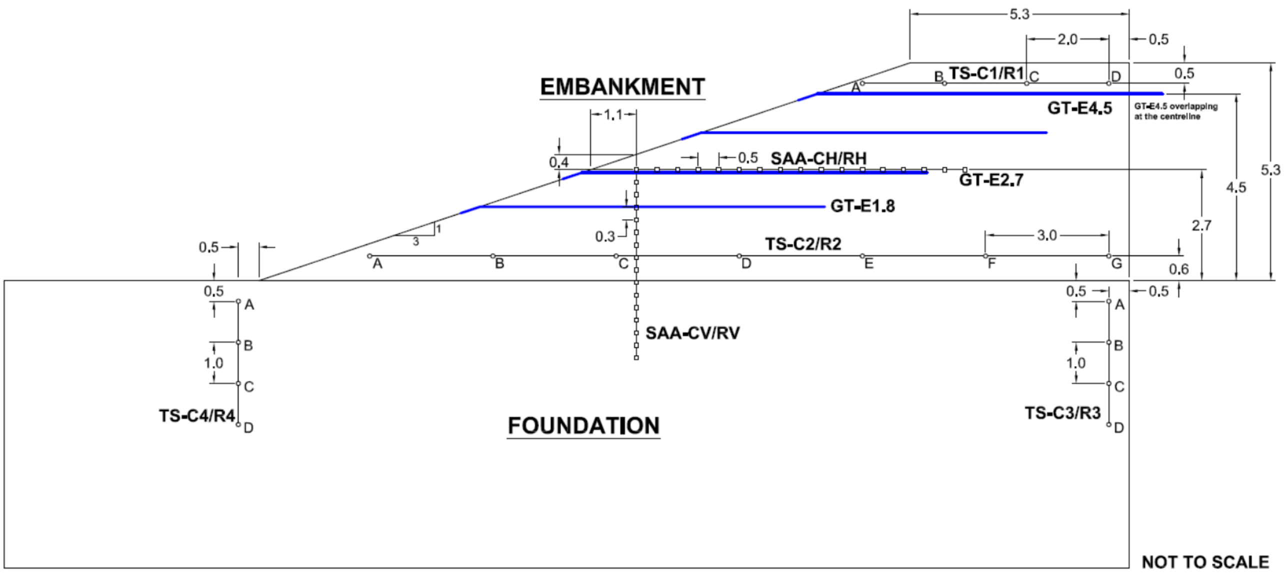


Figure 1. Cross-section of high-fill section with wicking geotextiles, thermistor strings and SAAs. All units in metres.

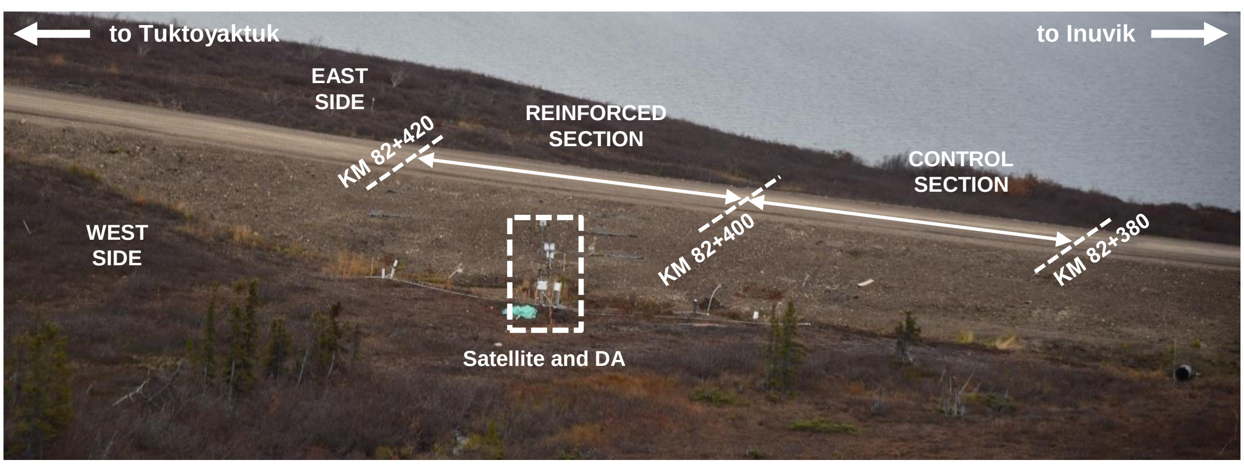


Figure 2. Aerial view of the completed test sections along the highway.

2.1 Geotextile Installation

The woven geotextiles installed at the side slopes of the reinforced section have drainage capabilities (wicking) in addition to their reinforcement function. It was conceptualized they will provide drainage paths for the water when the embankment undergoes thawing during spring and summer seasons. The wicking geotextiles were laid out on the side slopes during construction as shown in Figure 3a to provide reinforcement. These geotextiles have an overhang of 0.5 m (Figure 3b) dissipate the potential build-up of pore water pressure during thawing and to allow water to flow out of the embankment. The length of the geotextile installed in the embankment is 8.4 m to intercept the potential failure surface when the embankment thaws and if sloughing occurs. The geotextiles were spaced at every 900 mm of elevation, starting at El. 22.564 m on the west side of the embankment. In the authors' knowledge, this is the first application of using a wicking geotextile fabric with reinforcement as the primary function and in-plane drainage as secondary, and using geotextiles as slope reinforcement for embankments in cold regions environment.

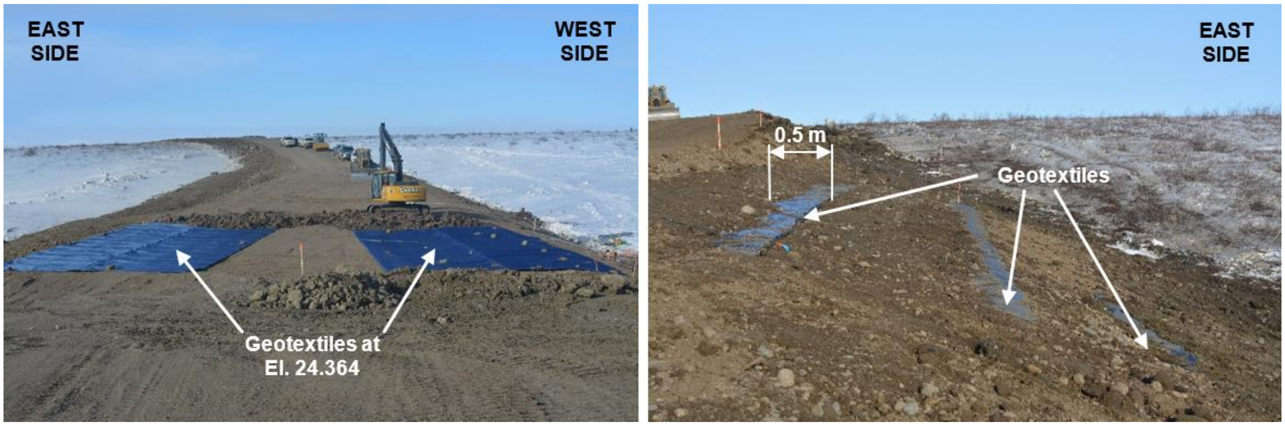


Figure 3. Wicking geotextiles in the reinforced embankment section: (a) installation of wicking geotextile and (b) geotextile overhang for wicking function.

2.2 Thermistor Strings

Thermistor strings were installed at different locations in the two embankments and underlying foundation soil. Two thermistor strings were laid out horizontally at the top (TS-C1, TS-R1) and along the base (TS-C2, TS-R2) of the embankments, and another two vertically installed through the foundation at the centreline (TS-C3, TS-R3) and at the toe (TS-C4, TS-R4) for each test section. A schematic diagram showing the locations of these thermistor strings and their nodes are shown in Figure 1. The base thermistor is 600 mm above the natural ground surface, while the top thermistor is 500 mm below the road surface.

2.3 ShapeAccelArrays

Vertical and horizontal ShapeAccelArrays (SAAs) were installed at mid-slopes of both test sections to monitor lateral displacements and settlements, respectively, as shown in Figure *1*. The vertical SAAs (SAA-CV, SAA-RV) are located at an offset of 12 m from the embankment centreline, with its first node 400 mm below the slope ground surface. The vertical SAAs were anchored at the frozen foundation soil. Similarly, the horizontal SAA (SAA-CH, SAA-RH) were anchored inside the embankment either sitting on top of compacted frozen soil at the core of the embankment or below the 0°C isotherm. The outer end of the horizontal SAAs are 12 m away from the embankment centreline. The first nodes of the horizontal SAAs are also 400 mm below the slope surface. In addition to displacements, the SAA nodes also provide additional temperature measurements to supplement the thermistor readings.

2.4 Strain Gauges

Strain gauges were installed on geotextile strips 4.2 m in width parallel to the direction of wicking to measure the development of strains as the embankment deforms. As part of an on-going study, the strain gauges can provide an insight to the effectiveness of the geotextiles in terms of reducing lateral displacements of the slope. The strain gauges were attached to the geotextiles following the recommendations by Warren et al. (2010). Han and Jiang (2013) presented a review on the application of geotextiles in cold regions and provided a summary of their expected behaviour. Their review showed that geosynthetics at low temperature have higher tensile strength and stiffness, lower creep rate, and lower elongation at failure.

The wicking geotextile layers were laid out horizontally at every 900 mm from initial placement of fill material on both sides of the embankment. Only half of the embankment is instrumented with strain gauges and the instrumented geotextile layers installed at Els. 22.564 m, 23.464 m, and 25.264 m as shown in Figure 1. A total of nine (9) strain gauges were installed per geotextile layer: seven (7) at the top and (2) at the bottom. The strain gauges at the top of the fabric were installed every 1.0 m with the first strain gauge installed 1.5 m away from the edge of the slope. The strain gauges at the bottom of the fabric were spaced by 3.0 m with the first strain gauge installed 3.5 m away from the edge of the slope. The two strain gauges at the bottom of the fabric were installed directly underneath the strain gauges at the top of the fabric to account for possible bending of the geotextile fabric.

3. RESULTS AND DISCUSSION

3.1 Temperature Readings

The results of the monitored temperatures readings from the thermistor strings are shown in Figures 4 to 7 for both test sections labelled as (a) for control and (b) for reinforced. Figures 4 and 5 show the temperature at the top and base of the embankment plotted against distance from the centreline of the embankment, respectively. Figures 6 and 7 show the temperature at the foundation centreline and toe plotted against depth, respectively. The top thermistor (TS-C1, TS-R1) shows that the road surface is responding quickly to the ambient air temperatures. The warmest temperatures recorded by the top thermistors were between the months of July and August. It can be seen that the temperatures for August 2017 were warmer than the first and second years of monitoring. The base thermistor (TS-C2, TS-R2) shows that from the embankment centreline to about 11.5 m towards the toe, the core of the embankment has remained frozen since end-of-construction, while beyond this distance the seasonal temperature fluctuations occur on the embankment slopes. At the location of thermistor TS-C2-C, the temperature was below 0°C in August 2015, but has since been experiencing warming. This means the horizontal extent of the frozen core was decreasing.

The foundation centreline thermistor (TS-C3, TS-R3) shows that the thermistor remained below -3°C for the four-year monitoring period. The month of December for each year was when TS-C3 recorded the warmest temperatures due to seasonal lag. Throughout its depth the thermistor string has showed warming for the month of December. Although warming has been observed, the thickness of the fill material for the research sections is providing enough insulation to prevent permafrost thaw at the embankment centreline and underneath the shoulders.

The toe thermistor (TS-C4, TS-R4) shows the same warming trend for the months of August in the monitoring period. TS-C4-A and TS-C4-B are 1.0 m apart which only provides temperature at these depths and not in between the nodes. The seasonal thaw depth at the toe is ranging between 0.5 to 0.7 m from the natural ground surface based on previous site visits, not where the line crosses the 0°C ordinate. This warm temperature at the toe may be trapped during the winter months due to the snow cover and the peat's insulating effects and accelerate thawing.

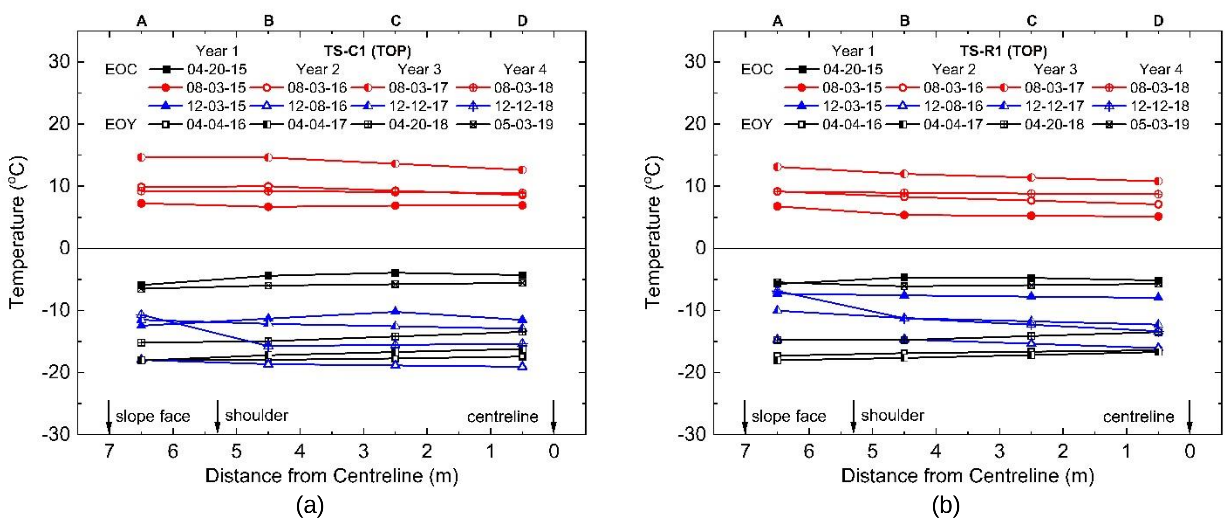


Figure 4. Temperature readings at different time steps at the top of the embankment: (a) control section and (b) reinforced section.

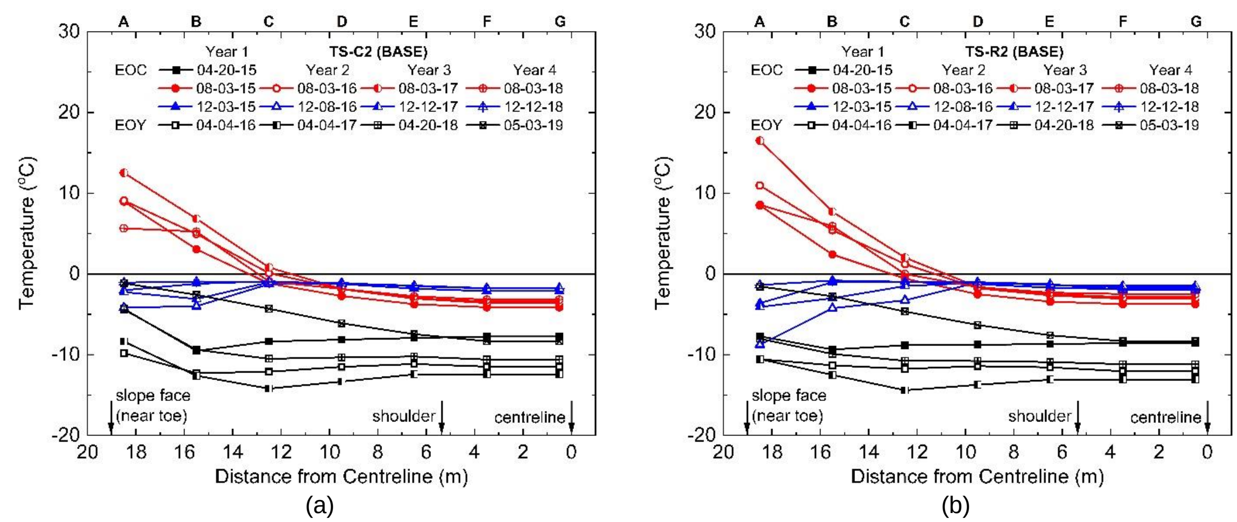


Figure 5. Temperature readings at the base of the embankment: (a) control section and (b) reinforced section.

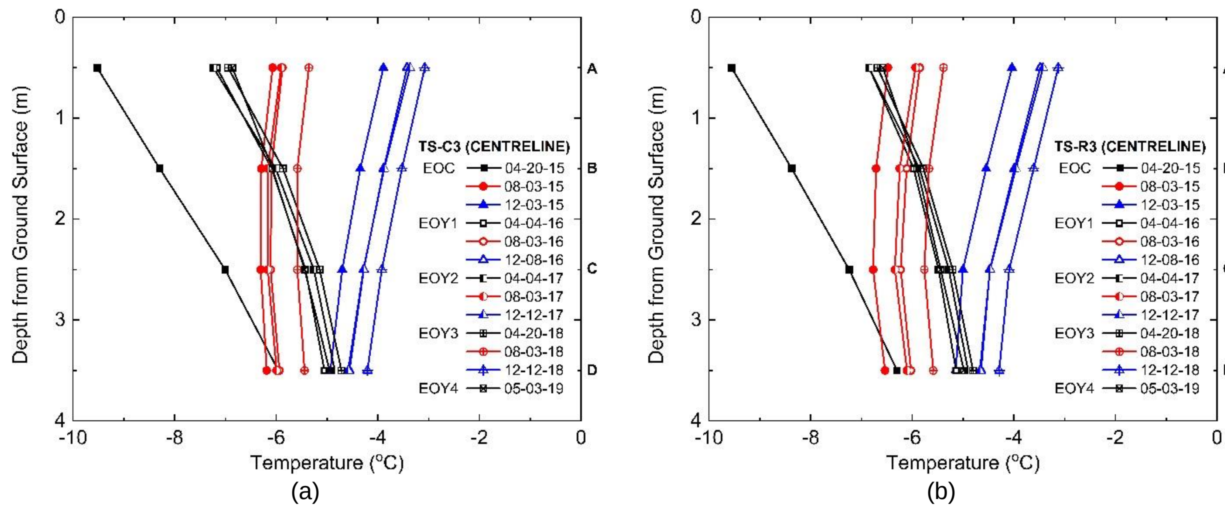


Figure 6. Temperature readings at the foundation centreline: (a) control section and (b) reinforced section.

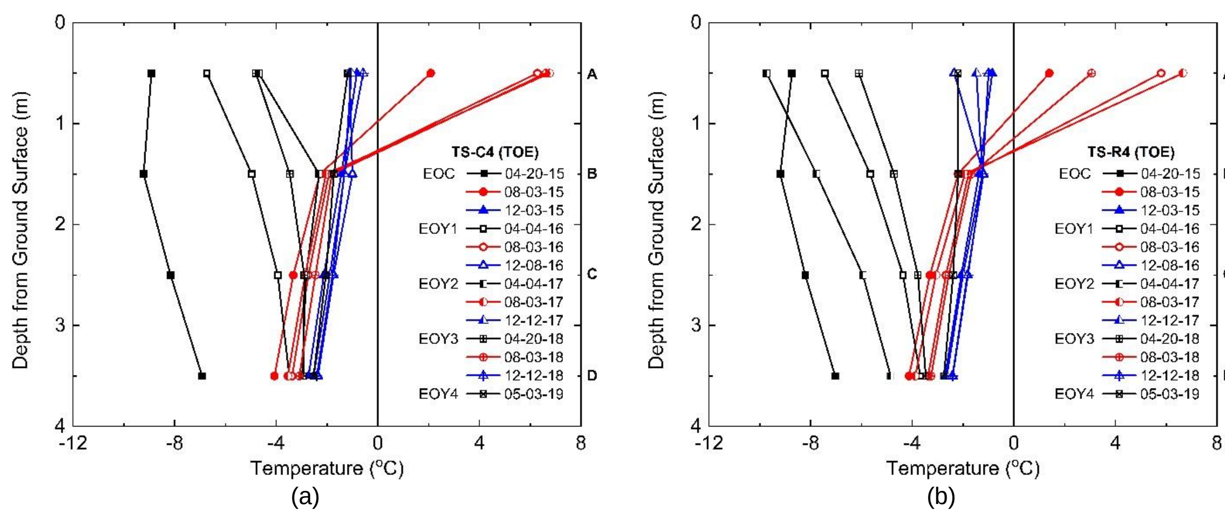
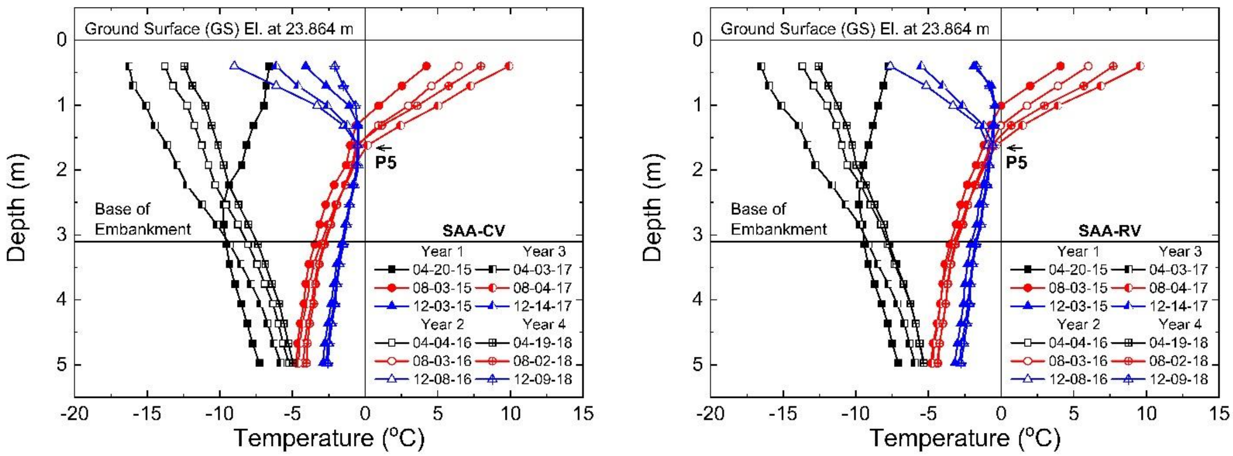


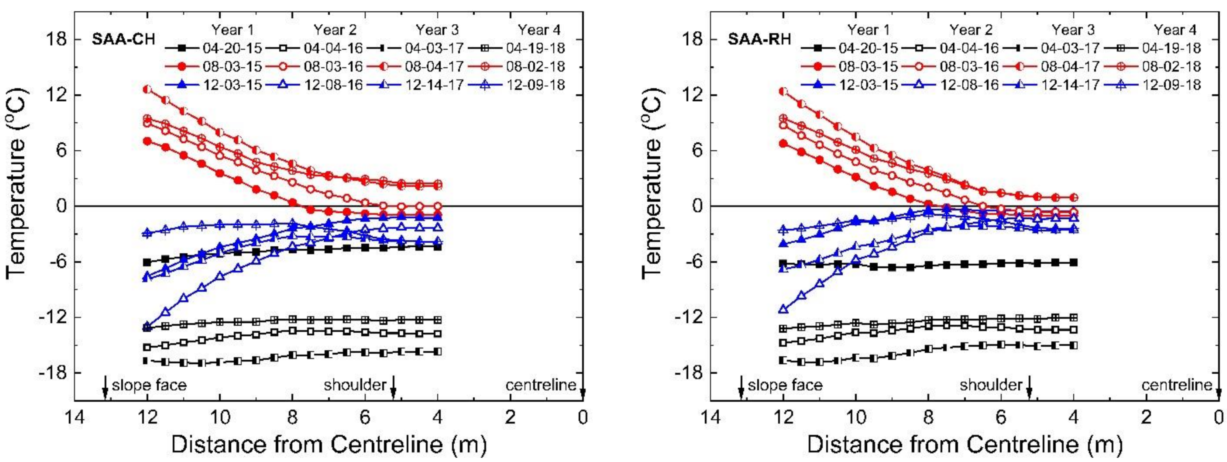
Figure 7. Temperature readings at the toe of the embankment: (a) control section and (b) reinforced section.

Figures 8 and 9 show the temperature readings from the vertically-laid and horizontally-laid SAAs installed at mid-slope and mid-height of the test sections, respectively. The readings are consistent with those from thermistor strings. Similar to thermistor readings from TS-C1 and TS-C2, the SAAs recorded the warmest temperatures close to the slope surface in August of each year. The seasonal temperature fluctuation has gone as deep as 1.7 m for SAA-CV from the slope ground surface in August 2017, compared to the 1.2 m depth in August 2015. The temperatures recorded by the vertically-laid SAA-CV confirm that the foundation soil is still frozen at this offset from the embankment centreline. In Figure 9a, the horizontally-laid SAA-CH showed that until October 2016 the core of the embankment fill has remained frozen up to a height of 2.7 m from the base of the embankment and 5.0 m away from its centreline towards the slope. For the third and fourth years, the nodes that used to be below 0°C have experienced warming as high as 2.5°C in August 2017. This resulted to the decrease in height and lateral extent of the frozen core as was also observed with the temperature readings from thermistor strings TS-C2.



(a) (b)

Figure 8. Temperature readings from vertical SAAs: (a) control section and (b) reinforced section.



(a) (b)

Figure 9. Temperature readings from horizontal SAAs: (a) control section and (b) reinforced section.

The warming trends observed in the temperature nodes (thermistors, SAAs) in the embankment fill and foundation soil can be attributed to two factors: (a) warmer and longer summer months leads to deeper thaw penetration in the slopes and foundation soil, and (b) heat extraction during the winter months is attenuated because of the presence of snow at the slope and toe of the embankment.

3.2 Lateral and Vertical Displacements

Recorded lateral displacements for both control and reinforced sections are shown in Figure 10. The lateral displacements recorded in the reinforced section (Figure 10b) are less than that of the control section (Figure 10a). The largest displacements occurred at the SAA node closest to the slope surface during the first thawing season after construction. The temperature readings from the vertical SAAs confirm this observation. The lateral displacements in the reinforced section are consistently less than that of the control section. The mobilization of tensile forces in the geotextile reinforcements reduced the lateral movements of the embankment slope. Although the temperature of the SAA nodes P6 and P7 were recorded to be between -1°C and 0°C (Figure 8a), there have been movements observed in the four-year monitoring period, particularly larger for the control section. The thickness of the soil from the base of the embankment that has not moved in the control section is approximately 0.62 m and 0.75 m for the reinforced section based on the SAA readings where the temperatures are less than -2°C. Thawing of previously compacted frozen soil means a reduction in shear strength (De Guzman et al. 2018) especially at the first thawing season and thus leading to mobilization of displacements.

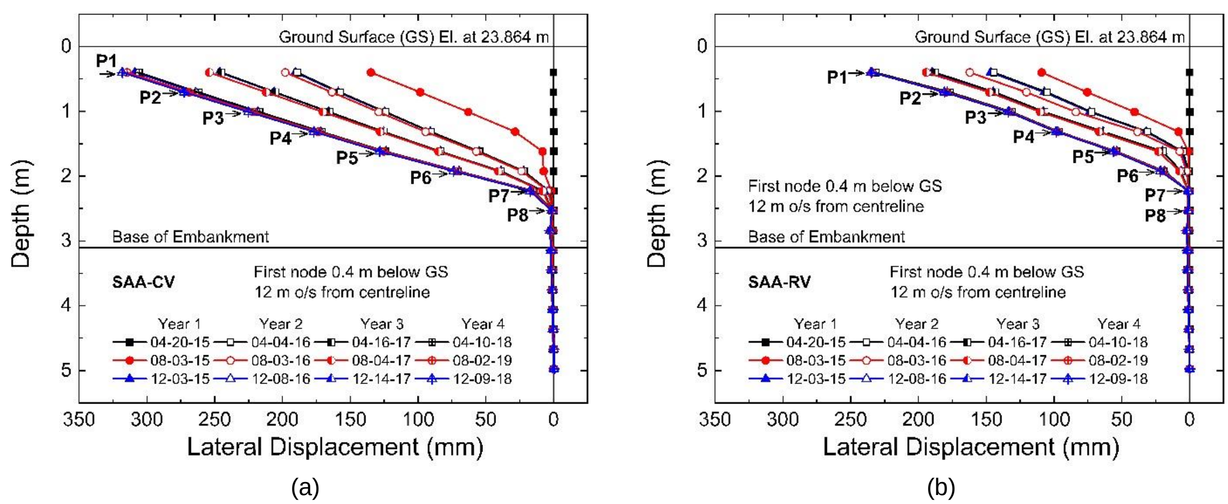


Figure 10. Lateral displacements at midslope: (a) control and (b) reinforced sections.

Figure 11 shows the vertical settlements of the control (Figure 11a) and reinforced (Figure 11b) sections. Most of the settlements occurred during the first year of thawing. At the end of the first year of monitoring, both horizontal SAAs at the outermost node recorded 275 mm of vertical settlement. The difference in settlements in the third year of monitoring is between 225 and 325 mm in the control section and between 275 mm and 325 mm in the reinforced section. Unfortunately, the temperature recorded at the anchor point (SAA-CH-P17, SAA-RH-P17) has experienced above 0°C temperatures (Figure 9a,b) which could have affected the settlement readings. The University of Manitoba is currently using Unmanned Air Vehicles (UAV) and Terrestrial Laser Scanning (TLS) technologies to monitor surficial slope displacements and compliment the recorded lateral displacements of the vertical SAAs (SAA-CV, SAA-RV) and numerical modelling.

3.3 Strain Gauges

Figure 12 shows the strain gauge readings for the three layers of geotextile at Els. 22.564 m (GT-E1.8, Fig. 16a), 23.464 m (GT-E2.7, Fig. 16b), and 25.264 m (GT-E4.5, Fig. 16c). All wire connections of the strain gauges on GT-E1.8 stopped working after February 2016 as they were damaged due to accidental snow clearing. Similar to the observations with the vertical SAAs, the largest strains (mobilization of forces) in the reinforcements occurred during the first thawing season. There were also minimal to no straining occurring during the winter months. From the latest recorded readings (April 20, 2019), the strain gauges recorded between 0.0005 to 0.0023% elongation. Although these are not significant strains, these plots confirm the relative mobilization of tensile forces that reduced lateral displacements at the slopes. As indicated earlier, the design of the embankment was not modified for the reinforced section. The slopes were graded (3H:1V) to minimize the potential of slope instabilities and provide adequate thermal insulation to the permafrost foundation. The use of geotextiles can provide reinforcement to build steeper slopes and minimize required fill material to construct future highway embankments.

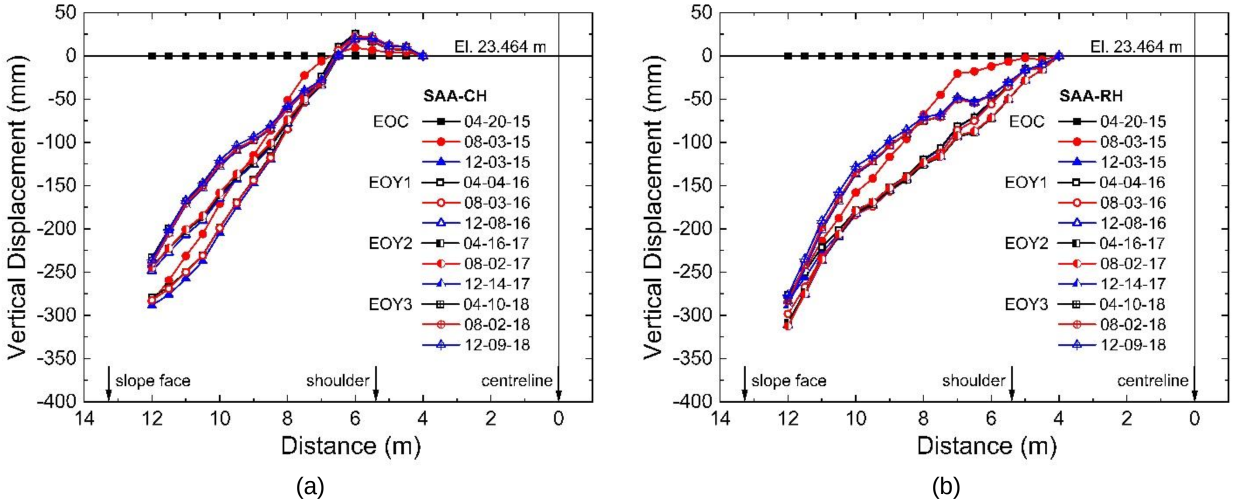


Figure 11. Vertical displacements at midslope: (a) control and (b) reinforced sections. EOC: end-of-construction and EOY: end-of-year.

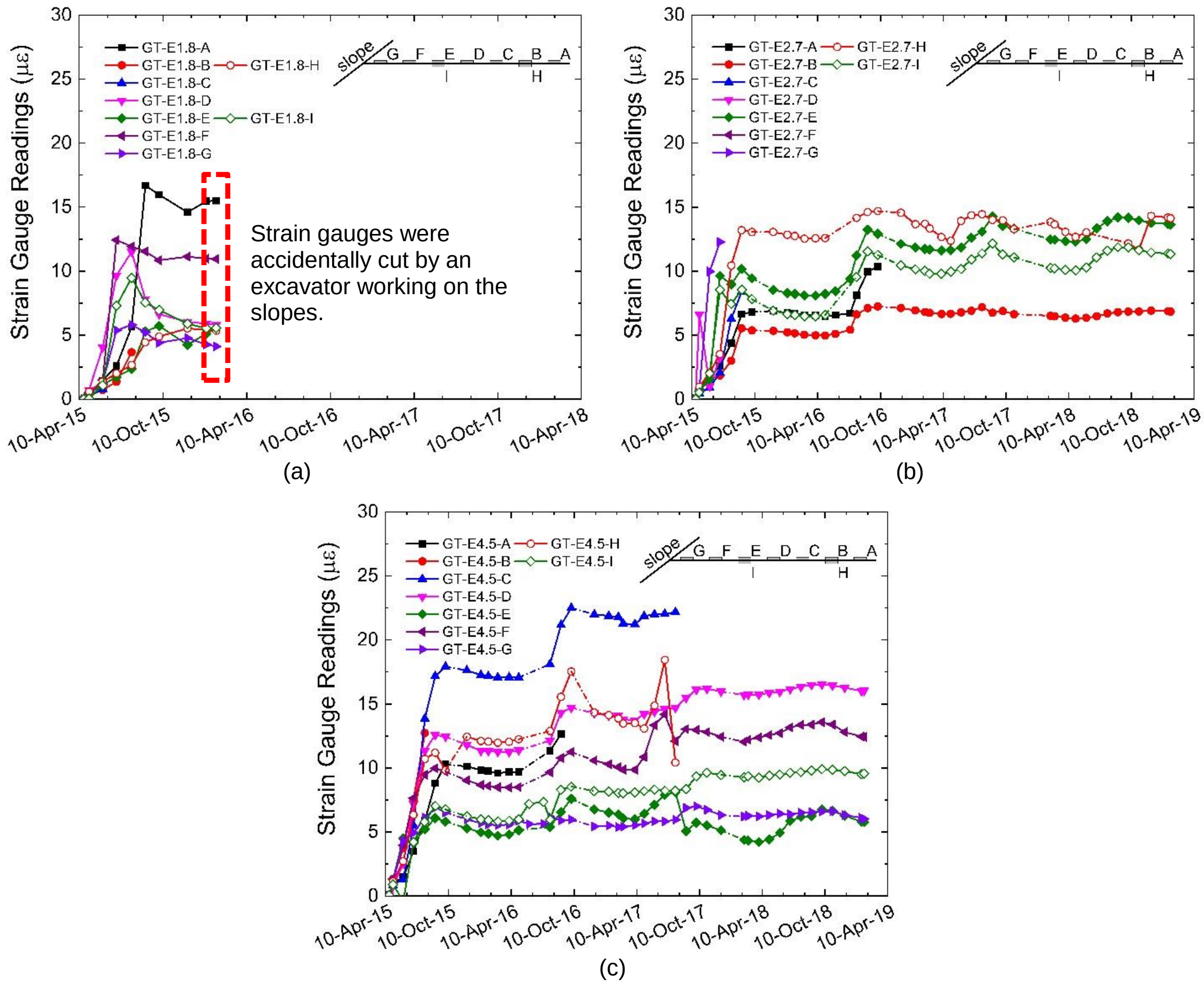


Figure 12. Strain gauge readings with time at different locations: (a) 1.8 m, (b) 2.7 m, and (c) 4.5 m from embankment base.

4. SUMMARY

Two fully-instrumented test sections were constructed along the ITH to monitor the performance of the highway. One of the test sections was reinforced with wicking woven geotextiles at its side slopes. The temperature sensors have shown that there is a warming trend in the embankment fill and foundation soil. This is attributed to warming air temperatures and the heat trapped in the embankment during the winter months when the embankment slopes are covered in snow. The core of the embankment has remained frozen in the four-year monitoring period, but has reduced in size since end-of-construction. The thaw-depth at the embankment toes have also increased during this period. The thawing of frozen soil will lead to reduction in shear strength available to resist traffic loading and development of larger lateral displacements and settlements.

Largest lateral displacements were recorded in the summer following construction of the embankments and attributed to the thawing of the frozen soil at the slopes. Although lateral displacements which occurred on the second and third year of thawing were less than that at end-of-construction, the seasonal thaw depth at the slopes have gone deeper and led to additional displacements. The addition of the wicking woven geotextiles has reduced the lateral displacements in the reinforced section. The control section remains stable even without slope reinforcement but development of longitudinal cracks and settlements will eventually lead to serviceability issues.

The monitored field results, together with the results of the laboratory tests conducted on the soil and the geotextile, will be used to calibrate a coupled thermal-mechanical model to investigate the operating mechanisms contributing to the short-term and long-term performance of the embankment test sections. Continuous monitoring of the site is on-going to establish long-term trends with improved confidence. The results of this on-going study will help develop improved guidelines for the design, construction, and maintenance operations of highway embankments and use of geosynthetics in Arctic regions.

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