Performance of instrumented sections along a highway in the Canadian arctic

Performance des sections instrumentées le long d'une route dans l'Arctique Canadien

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ABSTRACT: Highway embankments in the Canadian arctic are often built in permafrost terrain and on thaw-sensitive foundations. Higher embankment fill heights are sometimes required to comply with vertical road geometry requirements. Such design cause side-slope sloughing and embankment cracking due to rising of the permafrost table in the fill and lowering of the permafrost table below the toe of the embankment. A reinforced test section was built along a newly-constructed highway with layers of wicking geotextiles on its side slopes to provide reinforcement and drainage path for the water during the thawing season. An unreinforced section was also constructed beside the reinforced section. Both sections were instrumented to monitor temperatures and deformations. The geotextile reinforcement has been additionally instrumented with strain gauges to measure tensile forces. Field observations indicate that placement of the wicking geotextiles reduced lateral displacements in the reinforced embankment. This paper presents the analysis and synthesis of the two-year performance of the embankment test sections.

RÉSUMÉ : Remblais routiers dans l'Arctique Canadien sont souvent construits dans un terrain de pergélisol et sur sol sensibles à la décongélation. Une augmentation des hauteurs de remplissage des remblais sont parfois nécessaires pour se conformer aux exigences de la géométrie routière verticale. Cette conception provoque des glissades côté-pente et fissurations dons le remblais due à la montée de la table du pergélisol dans le remplissage et l'abaissement de la table du pergélisol en dessous du pied du remplissage. Une section d'essai renforcé a été construit le long d'une route nouvellement construite avec des géotextiles sur ses pentes latérales pour introduire un renforcement et un chemin de drainage pour l'eau pendant la décongélation. Une section non renforcée a également été construit à côté de la section renforcée. Les deux sections ont été instrumentés pour surveiller les températures et les déformations. Le renforcement avec le géotextile a été instrumenté aussi avec des jauges de contrainte pour mesurer des forces de tension. Les observations de terrain indiquent que les géotextiles réduit les déplacements latéraux dans le remblai renforcé. Ce papier présente l'analyse et la synthèse de la performance des sections de remblai d'essai de deux ans.

KEYWORDS: highway embankments, permafrost, frozen soil, geotextiles, full-scale field tests, reinforced slopes, instrumentation.

1 INTRODUCTION

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

Detailed road alignment, environmental data gathering, and engineering design were conducted in the 1960's and 70's and has been continuously revised to address the concerns of local communities and other stakeholders during an extensive environmental review process, leading to the development of the route alignment alternatives in 2009. The highway has been identified as a priority development by the Government of Canada and Government of the Northwest Territories (GNWT). The ITH, which extends the Dempster Highway past the community of Inuvik to the Arctic Coast, will be an all-weather transportation link and will complete Canada's road network from the Pacific, to Atlantic, and to Arctic coasts. Figure 1 shows the designed alignment of the highway.

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

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

In order to comply with vertical road geometry constraints, the embankment fill height can exceed five meters. Higher fills cause problems of side-slope sloughing and spreading, resulting in longitudinal embankment cracking due to thawing of frozen fill material. Side-slope sloughing and fill cracking can also be related to localized thaw-settlements under the shoulders and side slopes of the embankment created by the rising of the permafrost table into the embankment fill in combination with depression of the permafrost table at the toe of the embankment.

Knowledge gaps exist on the behaviour of high fills compacted under Arctic winter construction conditions. Therefore, research is needed to (1) investigate the operating mechanisms causing instabilities and deformations of the embankment; and (2) develop efficient mitigation strategies. A partnership was developed between the University of Manitoba, Université Laval, and the Department of Transportation of the Government of Northwest Territories to construct two 20 m-long test sections side-by-side along the ITH to address these research needs. The test site location along the ITH, which was completed in April 2015, is shown in Figure 1. The two-year performance of the highway is presented in this paper.

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

2 EMBANKMENT CONSTRUCTION

Two 20 m-long test sections were constructed along ITH. The first 20 m (STA 82+380 to STA 82+400), referenced hereto as Section A, was constructed and instrumented to serve as the control section for the research program. The second 20 m (STA 82+400 to STA 420), referenced hereto as Section B, was an instrumented embankment similar to Section A, but its side slopes are reinforced with woven geotextiles. Non-woven geotextiles 6 m in length were placed at the toe of the embankment towards the centerline as a separator between the natural ground and the fill material for both test sections.

The woven geotextiles installed at the side slopes of Section B have drainage capabilities in addition to their reinforcement function. It is assumed they provide drainage paths for the water during spring and summer seasons when the embankment undergoes thawing. The ultimate tensile strength in both machine and cross directions is 78.8 kN/m. This type of geotextile has been successfully used in the Dalton Highway Beaver Slide Area in Alaska to act as a capillary barrier 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 occurance of frost heaves along the highway (Sikkema and Carpita 2016). For these studies the wicking fabric only utilized its drainage function. The geotextile has an overhang of 0.5 m (Figure 2) to allow water to flow out of the embankment and dissipate the potential build-up of pore water pressure during thawing. The length of the geotextile installed was conceptualized to intercept the failure surface when the embankment thaws and if sloughing occurs. The geotextiles were spaced at every 0.9 m of elevation, starting at Elevation 22.45 m on the west side of the embankment. Both embankment sections are 5.3 m high.

Figure 2. Geotextiles exposed on the side slopes of the embankment

3 MONITORING RESULTS

Installation of instrumentations commenced on April 14, 2015 and was completed on April 20, 2015. Section A and Section B are both instrumented with thermistors for temperature readings, ShapeAccelArrays (SAAs) for the vertical and horizontal deformations, vibrating wire piezometers for pore water pressures, and thermal conductivity sensors for matric suctions. Strain gauges were also installed in the geotextile reinforcements for Section B. Only the results of deformation and temperature readings from end-of-construction (April 20, 2015) to September 15, 2016 are presented in this paper. The locations as to where the piezometers and suctions sensors are in the embankment are still frozen as of December 21, 2016.

3.1 *Deformation measurements*

Figure 3 shows the locations of the geotextile layers for Section B and the SAAs for both test sections. The vertical SAAs are recording lateral movements closest to the ground surface. The lateral displacements recorded in the reinforced section (Figure 4b) are less than that of the control section (Figure 4a). Maximum lateral deformation of the Section A at a point near the slope surface is approximately 40 mm greater than that of Section B for the first year of thawing on September 02, 2015. On the same date the following year, additional lateral deformations were observed equal to 55 mm for both test sections. Interestingly, the depth of zero-movement (2 m below the slope surface) coincides with the first layer of geotextile at Elevation 22.45. This indicates that the soil is still frozen as will be discussed later in temperature results.

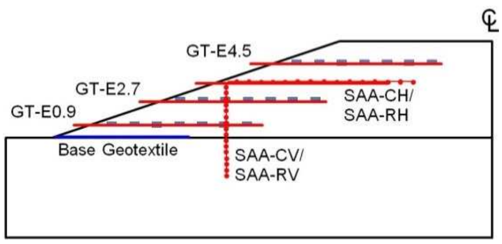

Figure 3. Schematic representation of the locations of the SAAs and geotextiles.

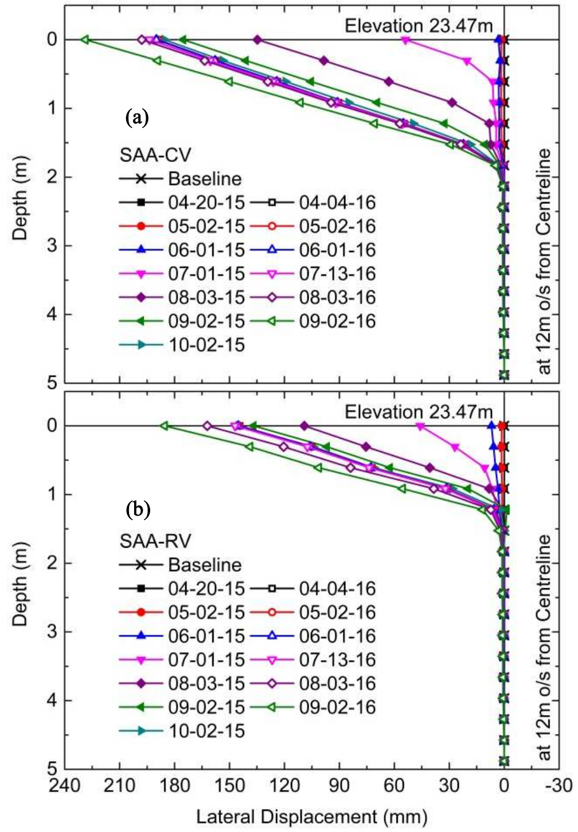

Figure 4. Lateral deformations at 12m o/s from centerline in (a) control and (b) reinforced sections

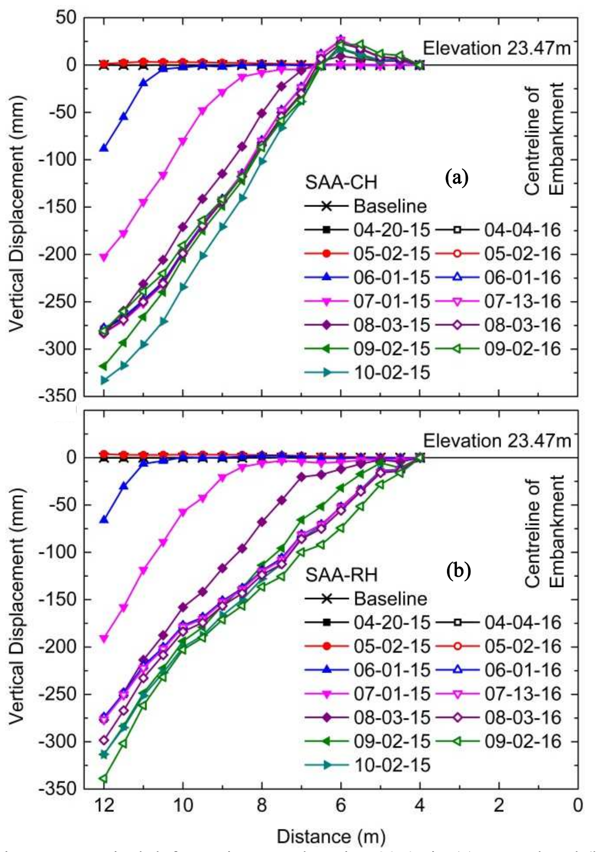

Figure 5. Vertical deformations at Elevation 23.47 in (a) control and (b) reinforced sections

The horizontal SAAs (Figure 5) show that the settlements at the slope for both sections are the same at 350 mm as of September 02, 2016. The small heaving at the control section is currently being investigated as this behaviour was not observed in the reinforced section. Both vertical and horizontal SAAs show little to no movement at all during the winter months. The progression of movement is also slower during the second year of thawing. Figure 6 shows the two test sections along the highway, with cracks noticeable in the unreinforced sections.

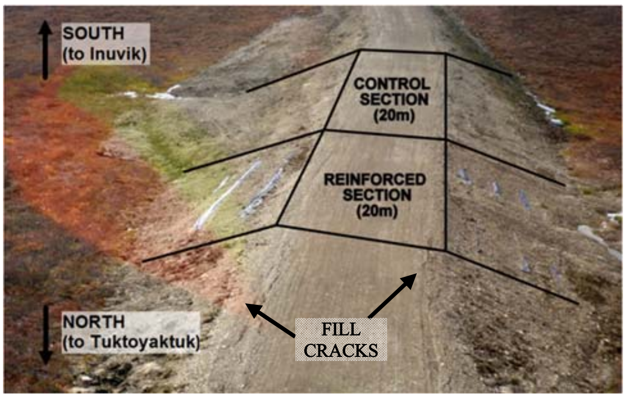

Figure 6. Reinforced and control sections along the ITH (09-16-2015)

3.2 *Strain gauge measurements*

Strain gauges were installed on the woven geotextile to measure the development of strains as the embankment deforms. They determine the effectiveness of the geotextiles as reinforcement and how it can reduce the lateral displacement of the slope. The strain gauges were attached to the geotextiles following the recommendations by Warren et al. (2010). The results of the geotextile close to the road surface (GT-E4.5 in Figure 3) is shown in Figure 7. The strains (loads) are generally mobilized during the thawing season after construction but the rate of straining in the winter months is minimal. Readings after Febuary 2016 are still currently being evaluated.

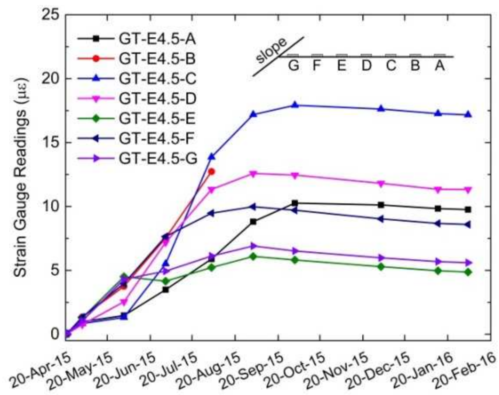

Figure 7. Strain gauge readings at GT-E4.5

3.3 *Temperature measurements*

Recorded readings indicate that the thermistors closest to the ground surface are responding quickly to the warming air temperatures. Figure 8 shows the thermal profile of the embankments on September 02, 2016. There is little to no difference between the recorded readings of the two test sections. It is noted that the depth of penetration at the toe is about 1.5 m, with the zero temperature line at 2.5 m above the native ground at the centreline. As mentioned earlier, the SAA nodes below a depth of 2 m from the slope surface is within the zero temperature line. Temperature plots with time for select nodes (refer to Figure 8) are also shown in Figure 9.

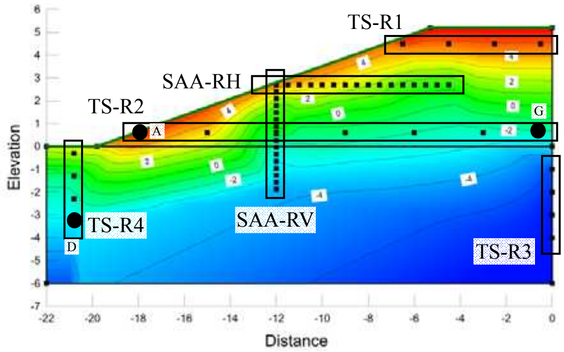

Figure 8. Thermal profile of the embankment on September 02, 2016

4 PRELIMINARY THERMAL MODELLING

A preliminary thermal model in TEMP/W (Geo-Slope International Ltd. 2007) was developed to observe the change in temperature within the embankment. Thermal properties of the embankment fill material, peat layer, and foundation soil were taken from the thermal analysis reports for the highway. Climate data used in modelling was obtained from a weather station in Tuktoyaktuk. Climate data was converted to an empirical temperature function (sinusoidal function) with thermal ground modifiers (n-factors) as the thermal boundary condition and was applied at the ground surface. The thermistor readings on April 20, 2015 were used to anchor the initial readings for the analysis.

Figure 9 shows a comparison of the modelled results against the measured values from select thermistor nodes (Figure 8) in the embankment. It can be seen that there is small difference between the measured and modelled values although the behaviour of the temperature with time is well replicated. Further calibration of the n-factors and conducting tests to determine the thermal properties of the soil obtained from the field will improve the results of the numerical modelling. The effect of the reinforcement and wicking of the geotextile fabric in Section B was not considered in the analysis. In addition, the computer programs do not have the capability to fully couple thermal (TEMP/W) and mechanical (SIGMA/W and SEEP/W) behaviour. The consolidation of the embankment during the thawing season will change the stresses internally and thus will change the thermal properties of the soil.

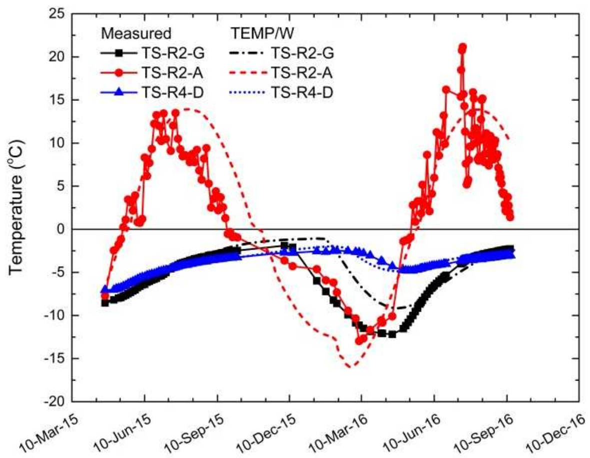

Figure 9. Measured vs. modelled temperature values for select thermistor nodes

5 SUMMARY

Instrumentation were installed along the ITH embankment to monitor its performance. The initial results from these test sections that were constructed to study the effects of winter construction on highway embankment performance in Arctic regions are presented here. A wicking geotextile reinforcement was used to reinforce (and provide drainage) in one test section and after two years of monitored performance, results indicate that there are less lateral movements when reinforcements are installed. Laboratory testing is currently being conducted on the soil samples obtained from the site to determine its mechanical, hydraulic, and thermal properties. Pullout and tensile capacities of the wicking geotextile are also being tested at different temperatures and environmental conditions. These properties will ultimately be used in numerical modelling to assess the stability of the embankments. A fully coupled thermal-mechanical model is currently being developed to further investigate the operating mechanisms in the field. The time-dependent behaviour (creep) of the embankment considering the effects of climate change is being evaluated using both advanced finite element and finite difference solutions. The results of this on-going study will help develop improved design, construction, and maintenance of embankments constructed in Arctic regions.

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