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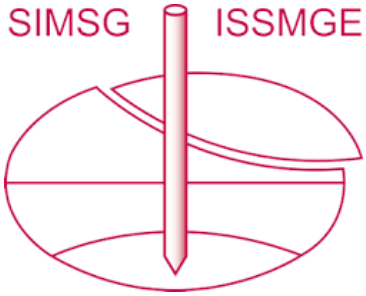

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Field performance and numerical simulation of embankments in the Arctic

Performances sur le terrain et simulation numérique des remblais dans l'Arctique

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ABSTRACT: Embankment test sections were constructed and instrumented with temperature and displacement sensors along the Inuvik-Tuktoyaktuk Highway in the Northwest Territories, Canada to assess the thermal and mechanical performance of frozen fill embankments constructed under winter conditions in a continuous permafrost region. One of the test sections was reinforced with layers of wicking woven geotextiles at its side slopes, while the other serves as a control section. Four years of continuous monitored data are presented. Significant lateral displacements occurred in the summer following end-of-construction, with the reinforced section showing reduced lateral movements. Temperatures in the embankment and permafrost foundation have also been increasing due to warming air temperatures. Numerical modelling was carried out using commercially-available finite element software ABAQUS to simulate the thermal and mechanical behaviour of both embankments. Models developed were calibrated with recorded field data and showed reasonable agreement. The results presented in this paper will help improve the development of existing design guidelines for highway embankments in Arctic regions.

RÉSUMÉ : Des sections d'essai de remblai ont été construites et instrumentées avec des capteurs de température et de déplacement le long de la route Inuvik-Tuktoyaktuk dans les Territoires du Nord-Ouest, au Canada, pour évaluer la performance thermique et mécanique des remblais de remblais gelés construits en conditions hivernales dans une région de pergélisol continu. L'une des sections d'essai a été renforcée avec des couches de géotextiles tissés à effet de mèche sur ses pentes latérales, tandis que l'autre sert de section de contrôle. Cinq années de données surveillées en continu sont présentées. Des déplacements latéraux importants se sont produits au cours de l'été suivant la fin de la construction, la section renforcée montrant des mouvements latéraux réduits. Les températures dans le remblai et les fondations du pergélisol ont également augmenté en raison du réchauffement de la température de l'air. La modélisation numérique a été réalisée à l'aide du logiciel d'éléments finis ABAQUS disponible dans le commerce pour simuler le comportement thermique et mécanique des deux remblais. Les modèles développés ont été étalonnés avec des données de terrain enregistrées et ont montré une concordance raisonnable. Les résultats présentés dans cet article aideront à améliorer l'élaboration des lignes directrices de conception existantes pour les remblais routiers dans les régions arctiques.

KEYWORDS: Highway embankments, winter construction, permafrost, frozen fill compaction, reinforced slopes.

1 INTRODUCTION

The completion of the Inuvik to Tuktoyaktuk Highway (ITH) in the Northwest Territories, Canada, has been a long standing goal of the Town of Inuvik, the Hamlet of Tuktoyaktuk, and the residents of the Inuvialuit Settlement Region. The highway was identified as a priority development by the Government of Canada and the Government of the Northwest Territories (GNWT). The ITH, which extends the Dempster Highway past the community of Inuvik to the Arctic Coast, is an all-weather transportation link and completes Canada's road network from the Pacific, to Atlantic, and to Arctic coasts.

Embankments are constructed during the winter months to preserve the permafrost foundation and minimize environmental impacts. Non-frost-susceptible materials (e.g., gravel) suitable for embankment construction are not always available in construction sites in the Arctic (Berg and Esch 1983; Saboundjian 2008). Construction is done in the winter with locally-available frozen soil from nearby borrow sources. Frozen soil when used as fill material is very difficult to compact at sub-zero temperatures. They are relatively strong while they remain frozen but become soft and compressible upon thawing. In addition to the potential for development of settlements once the soil thaws there is also a significant reduction in shear strength (De Guzman et al. 2018a). Thermal disturbance of the permafrost foundation may lead to instabilities in the road embankment, ranging from longitudinal cracks at the embankment surface to lateral spreading of the side slopes (McGregor et al. 2010). Settlements and lateral spreading can lead to serviceability problems impacting overall highway performance which may lead to embankment failure (Saboundjian, 2008) and ultimately affect economic productivity and safety (Regehr et al., 2013). Five years of monitored temperature and displacement data along test sections in ITH were used to develop numerical models to investigate the operating mechanisms causing instabilities and deformations of these embankments and contribute in improving overall embankment performance.

2 EMBANKMENT CONSTRUCTION

The embankment test section is located between KM 82+380 and 82+420 along the ITH in the Northwest Territories, Canada (Figure 1). Construction of the test section began in April 2015 for a two-week period. An initial fill of 600 mm was laid out along the stretch of the test section in March 2015 for continued construction operations before the instrumentation were installed. Thermistor strings for temperature measurements and ShapeAccelArrays (SAAs) for displacement and temperature measurements were installed at different locations in the embankment fill and foundation soil. The thermistor strings were installed at the top (TS-C1), base (TS-C2), centreline (TS-C3), and toe (TS-C4). The SAAs were installed midslope (SAA-CV) and midheight (SAA-CH) of the embankment. These instrumentation were connected to a data acquisition system at an offset from the toe of the embankment, which can be remotely accessed through satellite connection. After construction, the embankment height at the test section is 5.3 m.

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 during spring and summer seasons when the embankment undergoes thawing. The geotextiles were laid out on the side slopes during construction as shown in Figure 2a to provide reinforcement. These geotextiles have an overhang of 0.5 m (Figure 2b) to allow water to flow out of the embankment. The geotextiles were spaced at every 900 mm of elevation.

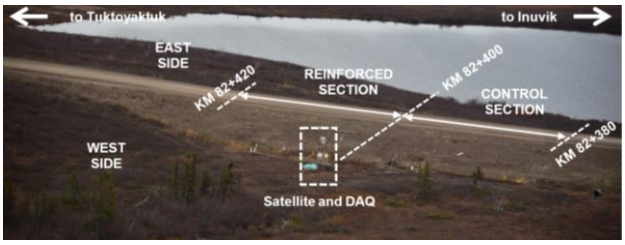
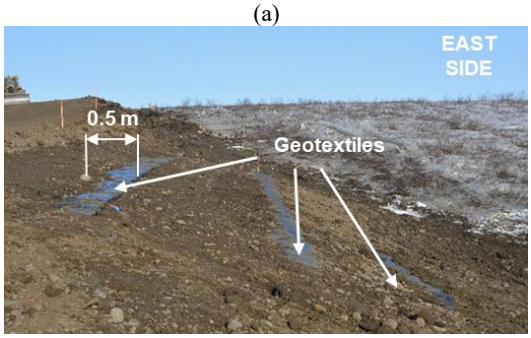


Figure 1. Aerial view of the completed test sections along the highway.

(a)



(b)

Figure 2. Wicking geotextiles in the reinforced embankment section: (a) installation of wicking geotextile and (b) geotextile overhang for wicking function.

3 FIELD MONITORED RESULTS

3.1 *Temperatures*

The temperature readings recorded by the thermistor strings for both control and reinforced sections were similar; therefore, only the recorded readings from the control section are presented. Figure 3 shows the temperature readings from the horizontally-laid thermistor strings at the top (Figure 3a) and base (Figure 3b) as well as the vertically-laid thermistor strings at foundation centreline (Figure 3c) and toe (Figure 3d) of the embankment. They are plotted at different times during the summer (August) and winter (December) seasons. The top thermistor (TS-C1) shows that there is uniform warming and cooling across the road surface in response to the ambient air temperatures. The base thermistor (TS-C2) 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. The estimated thickness of the frozen core based on available temperature data is 2.5m from the base of the embankment. Thermal numerical models by De Guzman et al. (2021a) reflected the same thickness of the frozen core. They also found that the slope of the frozen core inside the embankment fill is parallel to the side slope of the embankment.

The temperature readings (TS-C3) show that the foundation at the centreline remained below -2.5°C for the five-year monitoring period. The month of December for each year was when TS-C3 recorded the warmest temperatures due to seasonal lag. Warming in the foundation was observed in December but the thickness of the fill material for the test sections provided adequate insulation preventing permafrost thaw from the centreline to the shoulder. The thermistor string at the toe (TS-C4) recorded the same warming trend for the months of August. It should be noted that the seasonal thaw depth at the toe is ranging between 0.5 and 1.5 m from the natural ground surface and not where the line crosses the 0°C ordinate. 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. This warm temperature at the toe during the winter months may be attributed to the reduced extraction of heat as snow accumulated near the toe. It was observed during installation of an additional sensor at the test site in late August 2017, that the frozen ground across the toe of the embankment was approximately at 0.53 m below ground surface.

The warming trends observed in the temperature nodes (thermistors) in the embankment fill and foundation soil are attributed to two factors: (a) warmer and longer summer months recorded led to deeper thaw penetration in the slopes and foundation soil, and (b) heat extraction during the winter months was attenuated because of the snow accumulation at the embankment slopes. Wu and Niu (2013) had similar observations indicating that there is an overlapping influence of warming air temperatures and thermal disturbance on the permafrost underneath the embankment.

The frozen core of the embankment is by definition permafrost as the soil has remained continuously below 0°C for at least 2 years. It should be pointed out that the embankment is an engineered structure using frozen soil. The environment (winter conditions) when the embankment was constructed with frozen soil means the thermal regime was below 0°C. Under these conditions, the permafrost table aggraded into the embankment fill. The frozen core of the embankment, however, has been shrinking since completion of the test sections based on the measured ground temperatures (De Guzman et al. 2021b)

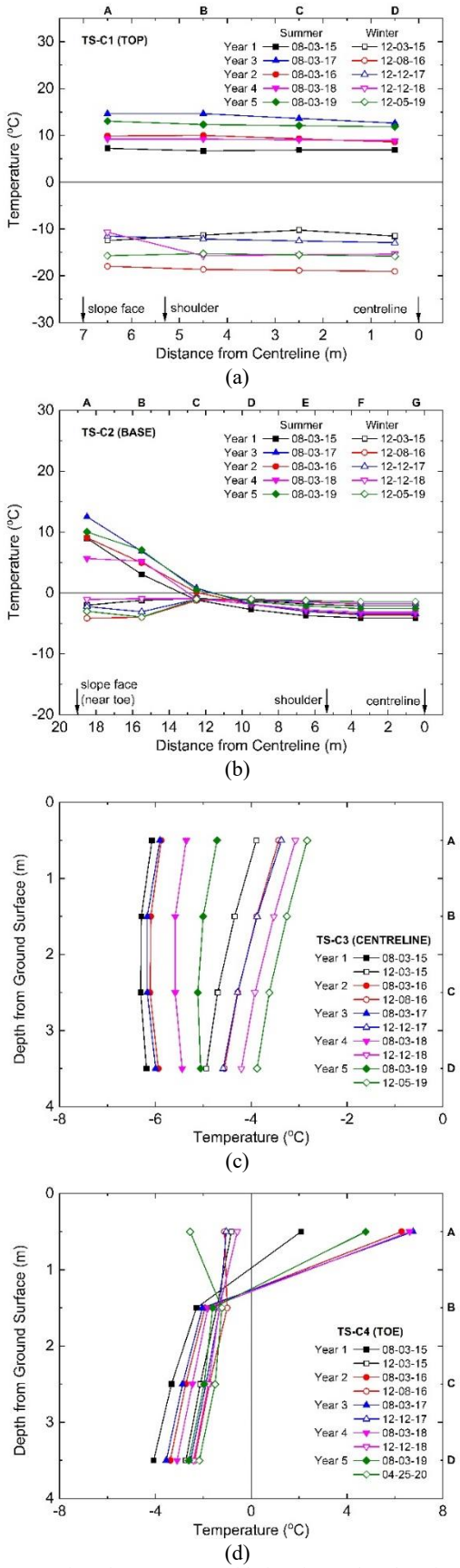


Figure 3. Monitored temperatures with time from select thermistor nodes at different locations in the test section: (a) TS-C1 along the top of embankment, (b) TS-C2 along the base of embankment, (c) TS-C3 through the foundation at embankment centerline, and (d) TS-C4 through the foundation at embankment toe.

3.2 *Displacements*

Recorded lateral displacements for both control and reinforced sections are shown in Figure 4. The lateral displacements recorded in the reinforced section (Figure 4b) are less than that of the control section (Figure 4a). The largest displacements occurred at the SAA node closest to the slope surface during the first thawing season after construction. Frozen soil provides anchor support to the vertical SAAs. 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 as expected. 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. De Guzman et al. (2018a) observed in their large-scale direct shear tests of compacted frozen soils from the test site that there is a significant reduction in shear strength and shear stiffness after the first cycle of thawing (e.g., thawing following embankment construction) and thus leading to lateral displacements. Since end-of-construction of the test sections, the embankment was able to consolidate for three thawing seasons before the highway was officially opened to traffic in November 2017.

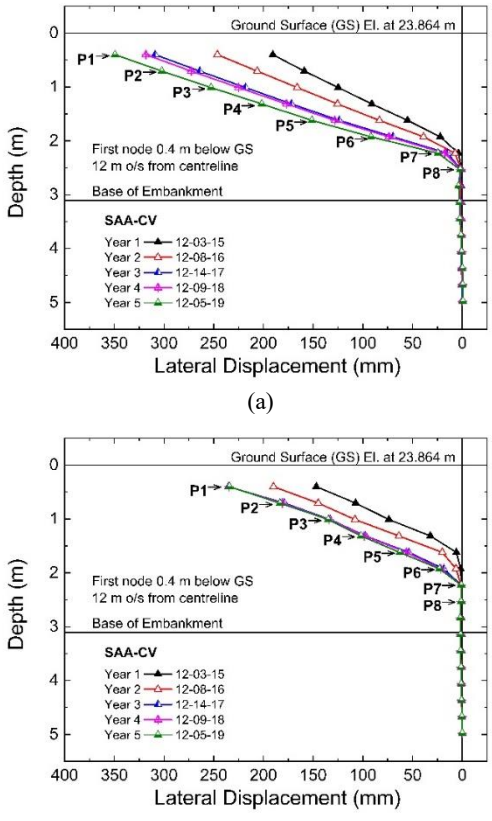


Figure 4. Lateral displacements at different time steps at midslope of embankment: (a) control and (b) reinforced sections. P#s are point numbers starting from the top of the SAA.

Although these displacements are increasing due to thawing at the slopes, the cumulative displacements of the reinforced section at different elevations are considerably less than that of the control section, confirming that the geotextiles are providing reinforcement to the high fill section. From summer site visits conducted by the first author, there are other high fill sections along the ITH that have shown distress in the form of side slope sloughing and shoulder cracking. Different design configurations

(slope inclination, reinforcement length, reinforcement spacing) are being investigated using numerical modelling as part of this on-going study to use geotextiles as slope reinforcement in Arctic regions.

Based on these observations, there are two possible scenarios on displacement trends: (1) the development of lateral displacements will eventually decrease over time, or (2) the development of these lateral displacements will increase over time due to the effects of warming where previously compacted frozen soil begins to thaw in the embankment and possible loss of toe support as the seasonal thaw depth in foundation soil increases. The deformation of the embankment is closely related to the thermal changes in the embankment fill and foundation soil. The embankment fill affects the thermal behaviour of the foundation, and any increase in the foundation temperature can lead to compression of the native soil, which affects embankment stability. Proactive maintenance operations (e.g., snow clearing during the winter months) should be planned accordingly to reduce the heat trapped in the winter.

4 NUMERICAL MODELLING

4.1 *Modelling Approach*

The monitored results are used to calibrate numerical models to further understand the behaviour of these embankments. The model cross-section in ABAQUS is shown in Figure 5. The geotextile reinforcements are shown in red (Figure 5a). The cross-section was cut at multiple locations where nodal results will be saved for comparison with field data. The cross-section has a thickness of 3 m in the y-direction. The global datum is established at the interface of the embankment fill and foundation soil. Only half of the embankment was modelled due to assumed symmetry.

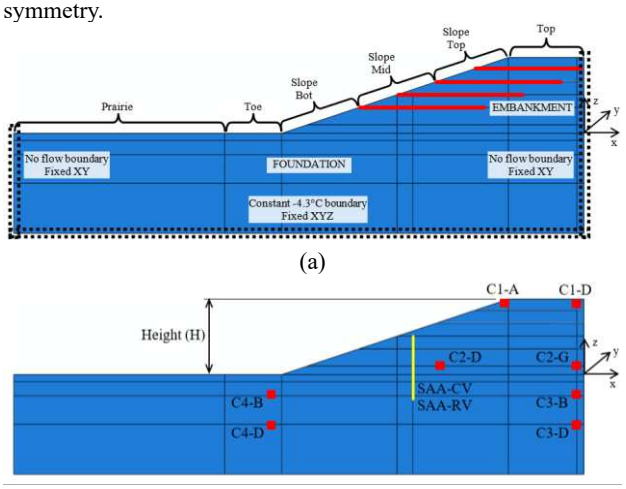


Figure 5. Model cross-section in ABAQUS: (a) temperature and displacement boundary conditions and (b) select observation locations in the test section. The geotextiles (in red) were removed in (b) for clarity

For the stress-deformation part of analysis, the left-vertical and right-vertical sections of the model were restrained in the x- and y- directions. The base of the model was restrained in all directions, while the x-z plane was restrained in the y-direction. A zero pore pressure boundary condition was also assigned at the natural ground surface, slope faces, and top of the embankment to allow seepage across these surfaces. The geotextile layers were also restrained in the y-direction. For the heat transfer part of the analysis, the surfaces of the embankment fill and foundation soil interacting with the ambient air temperature were subdivided accordingly. The road surface is labelled as Top, while the slope is divided into three regions because of the different snow depths that can accumulate in these regions. The surface on the foundation soil immediately at the base of the embankment is labelled as Toe, and outside this the foundation surface is labelled as Prairie. The rightmost and leftmost boundaries are no flow boundaries, while a constant temperature of -4.3°C was applied at the base of the foundation soil based on temperature readings nearby the research site. The corresponding freezing ($n_{freezing}$) and thawing ($n_{thawing}$) n-factors were applied to these boundary conditions at the ground surface. The n-factor is defined as the ratio of the of the ground surface freezing or thawing indices to the air freezing or thawing indices, respectively. Table 1 summarizes the thermal modifiers used in the numerical model. The values in the specific locations where they were applied are typical of literature values and were adjusted accordingly to best match the results from the field. Figure 6 shows a comparison of the actual and average sinusoidal ambient air temperatures used in the models. The meshing applied to the foundation soil is finer at the interface closer to the embankment fill and increases to a coarser size towards the base and outside the embankment footprint. All geotextile layers in the reinforced embankment have a mesh size of 0.2 m.

Table 1. Summary of thermal modifiers used on embankment and foundation surfaces

Location	$n_{freezing}$	$n_{thawing}$
Top	0.95	1.00
Slope Top	0.92	1.00
Slope Middle	0.83	1.00
Slope Bottom	0.55	1.00
Toe	0.20	0.55
Prairie	0.20	0.45

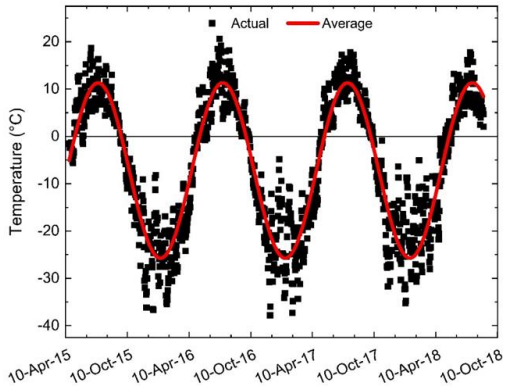


Figure 6. Comparison of actual and average sinusoidal air temperatures at the research site

The control (unreinforced) section was modelled using a fully-coupled (CP) approach where the heat transfer (thermal) and stress and deformation (mechanical) occurring on the soil elements are solved simultaneously in a single analysis. Because there is no direct coupling between shell (geotextile) and solid surfaces in ABAQUS that would satisfy the degrees of freedom for both types of elements (e.g. pore pressure), a sequentially-coupled approach (SQ) was employed for the reinforced section. In this approach, a heat transfer analysis is first conducted for the same analysis duration as the expected duration of the deformation analysis. The temperature field for each time step in the heat transfer analysis is referenced in the deformation analysis to invoke the corresponding material properties dependent on that temperature.

The thermal properties for the embankment fill and foundation soil are summarized in Table 2. Mechanical and hydraulic properties for the embankment fill and foundation soil are summarized in Table 3. The shear strength of the fill material was obtained from De Guzman et al. (2018a) from large-scale direct shear tests subjected to different environmental conditions (frozen, thawed, cyclic freeze-thaw). The shear strength

properties obtained by De Guzman and Alfaro (2018b) for amorphous peat above 0°C were used for the foundation soil. The Modified Drucker-Prager/Cap plasticity model was selected to define the inelastic behaviour of the fill material and foundation soil as it has been widely used in geotechnical engineering and considers the effect of stress history, dilatancy, and the effect of intermediate principal stresses (Helwany 2007). The hydraulic conductivities in unfrozen condition were estimated from typical values available in the literature supported by several modelling iterations to obtain a best fit with the field results and were made dependent on void ratios once the temperatures reach 0°C.

Table 2. Summary of thermal properties for the embankment fill and foundation soil (De Guzman et al. 2021)

Property	Units	T (°C)	Foundation	T (°C)	Fill
Thermal conductivity	J/days·m·°C	-0.5	120000	-1	163948
		0	45000	0	122500
Specific heat	J/kg·°C	-0.5	2756	-0.5	890
		0	5086	0	1160
Latent heat	J/kg	Solidus: -0.5 Liquidus: 1	334000	Solidus: -2 Liquidus: 0	21850
Density	kg/m^3	---	1039.8	---	1625.9

Table 3. Summary of mechanical properties for the embankment fill and foundation soil

Property	Units	T (°C)	Foundation	T (°C)	Fill
Material cohesion (d)	Pa	-1	25000	-1	21764.4
		0	7294.1	0	7115.4
Angle of friction (β)	°	-1	51.2	-1	49.4
		0	39.5	0	37.3
Elastic modulus (E)	Pa	-1	100000000	-1	214000000
		0	130000	0	150000
Poisson's ratio (ν)	---	-1	0.25	-1	0.25
		0	0.3	0	0.3
Lambda (λ)	---	-1	0.006	-1	0.006
		0	1.6	0	0.9
Kappa (κ)	---	-1	0.0008	-1	0.0008
		0	0.2	0	0.02
Hydraulic conductivity (k)	m/day	-1	1E-8	-1	1E-8
		0	0.00226 (e_o = 5.0)	0	0.001 (e_o = 0.64)
			0.00076 (e_o = 0.1)		0.005 (e_o = 0.72)
Density	kg/m^3	---	1039.8	---	1625.9

The interface strength properties between the wicking geotextile and the soil used in the reinforced embankment models are summarized in Table 4 based on the results obtained by De Guzman (2020). The interface friction angle between the soil and the geotextile were translated as contact properties in ABAQUS. A high interface friction angle was assumed when the temperature field in the embankment was below 0°C to simulate the behaviour that no sliding is occurring during the winter months as very small horizontal displacements were observed from the vertical SAA (SAA-RV). In addition to the interface friction, a thermal conductance property was added at the top and bottom of the geotextile layers to ensure thermal flow between the soil layers above and below these geotextiles. The geotextiles were assumed to have the same thermal conductivity as the embankment fill.

4.2 *Modelled Displacements*

Figure 7 shows a comparison of the measured horizontal displacements from the vertical SAA (SAA-CV) with the model results at midslope of the embankment using the CP approach. The model results show reasonable agreement with the displacement trend where the increasing thaw depths led to additional displacements. The displacements at the top node of the SAA are slightly underestimated for August 2015, 2016, and 2017, but this difference reduced with time. The model results of the underlying nodes follow the same trend of the field data. The model displacements 1 m above the natural ground surface are slightly larger compared to the monitored values. SAA-CV indicates that there is no movement 0.6 m above the natural ground surface where the ground might still be frozen, whereas the model results show that the frozen soil is only 0.4 m above the natural ground surface. As expected, there were little to no movements occurring during the winter months while displacements occur when the slope experiences positive temperatures. The overall magnitude and trend of the model results reasonably achieved the same results with the recorded field data especially during the first summer thawing were significant displacements occurred. This provides confidence that the modelling approach is satisfactory to assess the thermal and mechanical performance of different embankment configurations.

Table 4. Summary of mechanical and interface properties for wicking and non-wicking geotextiles

Type of Geotextile	Elastic Modulus (Pa)	Interface Properties (°)		
		Both conditions	At 2% strain	At EOT
		Frozen (at -1°C)	Thawed (at 0°C)	Thawed (at 0°C)
Wicking	150000000	50 (1.1918)	5.8 (0.1016)	7.7 (0.1352)
Non-wicking	150000000	50 (1.1918)	4.3 (0.0752)	6.3 (0.1104)

Note: Numbers in parentheses are the equivalent values of the interface property as $\tan\phi$.

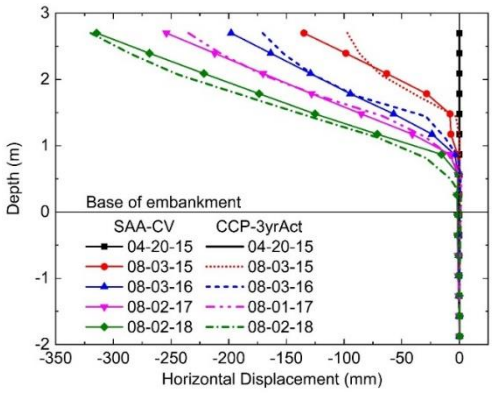


Figure 7. Comparison of horizontal displacements between measured field values and model results for the control section using CP approach

Figure 8 shows the horizontal displacements from the RSQ model compared to recorded field data of SAA-RV. There is a noticeable difference between the recorded and simulated results. The horizontal displacement of the soil between Layer 1 (GL1, 1.8 m) and Layer 2 (GL2, 2.7 m) from SAA-RV shows a linear variation of displacement with depth accumulating over time. The RSQ model displacements on the other hand show this to be curved, with the top node of the layer observed to be less than the recorded one. With respect to depth, the horizontal displacements just above GL1 from August 2015 to August 2017 show that it is slightly overestimated by 5 to 10 mm, but this difference increased to 50 mm in August 2018. These displacements are related to temperatures modelled in a pure heat transfer analysis, which were used to determine the properties to be activated in the model. In addition, a basic friction model was used to simulate the interface sliding between the geotextile reinforcement and the soil. The underestimated displacements below GL2 is offset by the overestimation in displacements

above L1. Further studies are recommended to apply more sophisticated interface models (e.g. Duncan and Chang model) between the geotextile and the soil, which may improve the numerical results presented.

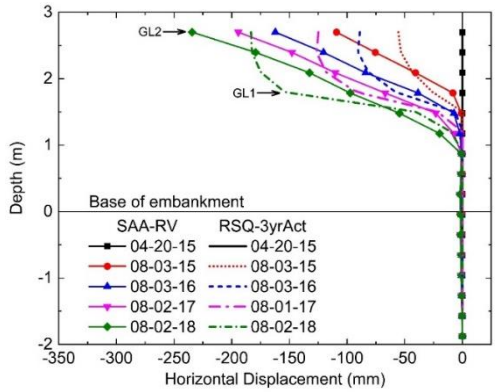


Figure 8. Comparison of horizontal displacements between measured field values and model results for reinforced section using SQ approach.

5 CONCLUSIONS

Two fully-instrumented test sections were constructed along the ITH to monitor the performance of a highway embankment constructed during winter. The recorded field data from the thermistor strings and SAAs were used to calibrate numerical models. The following conclusions are made:

- The seasonal thaw depth at the slopes have gone deeper due to warmer air temperatures in the region. It is recognized that there is an overlapping influence of warming air temperatures and thermal disturbance on the permafrost underneath the embankment due to embankment construction. It is expected that with climate warming the frozen core will continuously shrink and exacerbate displacements.
- The modelling approach provided reasonably accurate results when calibrated against the recorded field data on temperatures and displacements using the actual air temperatures during the monitoring period. Similar to the recorded field data, the largest displacements occurred during the summer following winter construction. Thawing of the previously compacted frozen soil may lead to reduction in shear strength available to resist traffic loading and development of larger lateral displacements and settlements. The increasing seasonal thaw depth at the toe might also lead to loss of support and cause instability in the embankment slopes.
- The reinforced model results slightly underestimated the horizontal displacements at the midslope. A comparable unreinforced section showed that the geotextile layers installed reduced the horizontal displacements by as much as 40%. The large displacements occurring during the summer following winter construction was reduced by 31% using wicking geotextiles. Similar to the recorded field data, the largest incremental displacements occurred during the summer following winter construction.

6 ACKNOWLEDGEMENTS

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