Inuvik to Tuktoyaktuk Highway Road Embankment Constructed on Ice-Rich Permafrost Terrain

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ABSTRACT

The Inuvik to Tuktoyaktuk Highway (ITH) crosses delicate tundra and continuous ice-rich permafrost terrain along the 137-km length of the two-lane gravel surfaced road. To protect the permafrost, a fill-only embankment design approach was employed, and construction took place during winter months when frozen soils from local borrow sources were placed on the frozen tundra to preserve the underlying permafrost. Pre-design geothermal evaluations were conducted to support the road embankment design. The design basis was to limit the annual thaw into the original ground beneath the core of the embankment and promote permafrost aggradation into the original active layer. After highway construction was substantially completed, ground temperature cables were installed at predetermined locations along the alignment for long term monitoring. This paper presents an overview of the ITH embankment design and construction approach addressing the challenging permafrost conditions along the highway alignment, and presents some post-construction ground temperature data collected in 2017.

RÉSUMÉ

L'autoroute Inuvik-Tuktoyaktuk (ITH) traverse une toundra délicate et un terrain de pergélisol continu et riche en glace le long des 137 km de la route en gravier à deux voies. Pour protéger le pergélisol, on a utilisé une méthode de remblai seulement et les travaux de construction se sont déroulés durant les mois d'hiver, lorsque des sols gelés provenant de sources locales ont été placés dans la toundra gelée pour préserver le pergélisol sous-jacent. Des évaluations géothermiques préconçues ont été effectuées pour appuyer la conception du remblai routier. La base de conception consistait à limiter le dégel annuel dans le sol d'origine sous le noyau du remblai et à favoriser l'aggradation du pergélisol dans la couche active d'origine. Une fois la construction de la route terminée, des câbles de température au sol ont été installés à des emplacements prédéterminés le long de l'alignement pour une surveillance à long terme. Cet article présente une vue d'ensemble de la conception et de la construction d'un remblai d'ITH en réponse aux conditions difficiles du pergélisol le long de l'alignement, et présente quelques données sur la température au sol après construction recueillies en 2017.

1 INTRODUCTION

The Inuvik to Tuktoyaktuk Highway (ITH) is the first Canadian highway constructed entirely on sensitive, ice-rich, continuous permafrost terrain. The 137-km two-lane, gravel surface road connects the communities of Inuvik and Tuktoyaktuk, Northwest Territories (Figure 1).

Maintaining the existing permafrost condition was a key element in the design and construction of the highway. If the underlying, ice-rich soils were to thaw, the road embankment and subgrade could become unstable through loss of soil strength and thaw-settlement.

The design approach was to construct a fill-only embankment that would insulate the underlying permafrost, thus creating a stable, frozen foundation. Aggrading (raising) the permafrost into the original active layer, limited the risk associated with an unfrozen or thawing subgrade. Pre-design geothermal evaluations were conducted to assist with the embankment design.

The owner, the Government of the Northwest Territories (GNWT), required the highway to be resilient, cost-effective and constructible, with foreseeable maintenance costs to meet its 75-year design life. Other key objectives included that construction maximized using local resources, workforce, and equipment.

In March 2017, the GNWT procured the installation of ground temperature instrumentation at specific locations along the highway alignment for long term temperature monitoring.

This paper presents an overview of the ITH embankment design and construction approach, and presents some post-construction ground temperature data collected in 2017.

2 BACKGROUND

The Inuvik Tuktoyaktuk Highway was opened to the public on November 15, 2017. It is the first public highway in Canada connecting the southern Canadian highway network to the Arctic Ocean. This historic project fulfills a strategic mandate the Government of the Northwest Territories and the Government of Canada have held since the 1960s. The project involved placing about 4.8 million cubic metres of embankment material, constructing 8 bridges, and installing over 300 culverts.

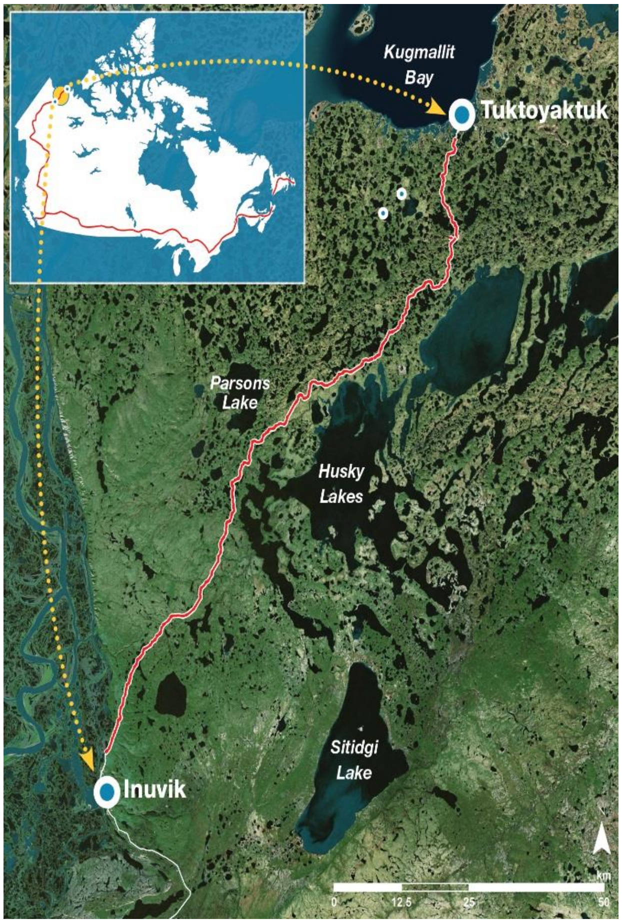

Figure 1. Inuvik to Tuktoyaktuk Highway Location.

3 SITE CONDITIONS

3.1 Permafrost

The ITH corridor is located entirely within the zone of continuous permafrost (NRC 1995). Ground temperatures at depth are within the range of -2˚C to -5˚C. Permafrost is defined as ground (soil or rock and included ice or organic material) that remains at or below 0°C for at least two consecutive years (IPA, 2018). The two-year minimum excludes from the definition the overlying ground surface layer which freezes every winter and thaws every summer (called the "active layer" or "seasonal frost"). The thickness of the active layer in the project area is typically between 0.6 m and 1.5 m for ground with an organic cover, but can be more than 2.0 m on exposed, organic-free ground, and south facing slopes. Below the active layer the ground is continuously frozen. The permafrost is typically a few hundred metres thick, but depends on many factors including proximity to lakes, stratigraphy, and site-specific slope and aspect conditions.

Permafrost is reflected in well-developed patterned ground. The native mineral soils in the region generally have high ice content, greater than 20% by volume of visible ice (NRC 1995), and are sensitive to disturbances. In this condition there are several forms of ground ice that can occur. Excess ice is described as ice-rich, where the amount of water contained in the soil matrix in a frozen state is higher than could be retained in the soil in an unfrozen state after thaw. The excess ice can be found mixed (disseminated, non-visible) within the soil matrix, or can be in the form of pure ice lenses, and discrete ice inclusions. Permafrost and particularly ice-rich soils limit the infiltration of water and promote the accumulation of organic material on surface.

3.2 Surficial and Bedrock Geology

Rampton (1987) presents the surficial geology of the Tuktoyaktuk Peninsula and general project area. The highway alignment crosses two distinct physiographic regions between Inuvik and Tuktoyaktuk.

The southern third of the alignment (from Inuvik to south of Husky Lakes) crosses the eastern extension of the Caribou Hills on the edge of the Anderson Plain, and consists of mainly moraine and unconsolidated sediments comprising glaciofluvial, lacustrine, and organics, with varying quantities of ground ice. Topographic relief along this section reflects the bedrock surface, but bedrock is rarely exposed. Overburden is <50 m thick. The northern two-thirds of the alignment crosses the Coastal Plain and is littered with lakes. Unconsolidated sediments include ground moraines, ice-contact tills, and glaciofluvial and glaciolacustrine deposits—all containing ground ice and massive ice lenses.

Bedrock in the Mackenzie Delta is sedimentary, comprised of Tertiary shale and sandstone. Preglacial, glacial and postglacial deposits overlie the bedrock. Depth to bedrock in the Delta ranges from about 50 m near Inuvik to greater than 150 m near the seaward limit.

3.3 Terrain

Terrain types common along the route vary from relatively dry upland and hummocky conditions, to wet, ice-rich lacustrine and thick organic conditions (Kiggiak-EBA, 2010). Initial routing focused on traversing the most favorable terrain within a study corridor while being aware of overall length and avoiding unfavorable thick organic and ice-rich polygonal terrain where possible.

Diverse types of surficial materials occur along the ITH. The corridor contains many seasonal watercourses, lowlands, peatlands and lakes, many of which are remnants of glacial outwash channels. The surficial geology along route was generalized into five distinctive landforms (terrain types): morainal, glaciofluvial outwash, lacustrine, alluvial/colluvial, and organic deposits.

Through the remainder of the Holocene Period, periglacial processes resulted in the mechanical breakdown of materials and contributed to gravity transport of both glacial soils and products of periglacial grinding. Thin alluvial soil deposits formed along watercourses, and pond (lacustrine) deposits have accumulated in shallow depressions. Thicker organic deposits have formed on poorly drained floodplains and low, flat areas.

4 KEY GEOTECHNICAL ISSUES

4.1 Ice-Rich Permafrost

Melting of permafrost can seriously affect all infrastructure, particularly when the permafrost is ice-rich (Figure 2). Ice-rich soils are highly sensitive to thermal disturbances, which can result in substantial thaw settlement, loss of soil strength, and instability when thawed.

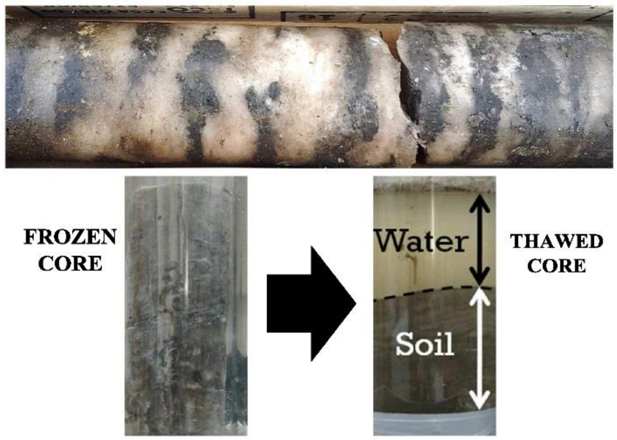

Figure 2. Thawed ice-rich permafrost.

4.2 Sensitive Terrain

A major routing design consideration was to avoid problematic sensitive terrain, where possible. Common permafrost-related features in the project area include ice-rich polygonal ground, retrogressive thaw-flow slides, thermokarst terrain, thick organics, and pingos. These areas have been avoided where practically possible. The likelihood of a retrogressive thaw slide impacting the Highway was reduced by purposely routing away from existing slides and steeper slopes that could be susceptible to failure. Pingos are cultural and heritage resources that have been avoided entirely, and provide scenic views near Tuktoyaktuk.

5 GEOTECHNICAL INVESTIGATION

A geotechnical investigation program was completed between March and April 2013 at selected locations along the proposed highway alignment. The program included drilling geotechnical boreholes and installing ground temperature cables (GTC) at six alignment sites and thirteen stream crossing sites. The purpose of the drill program was to carry out logging and sampling to characterize soil and ground ice conditions at representative sections along the highway alignment, and to install GTCs to monitor ground temperatures.

The program for the six alignment sites included drilling 18 boreholes and installing a GTC in one borehole at each alignment site to collect ground temperature data for use in the design of the road embankment. Measured ground temperatures generally became colder from south to north; however, warmer temperatures were recorded at specific locations affected by flowing water and those near large water bodies.

Geotechnical investigation programs were also completed in 2012 and 2013 to identify suitable borrow sources considered for construction and operation of the ITH. The investigation assessed the quality, quantity and extent of suitable borrow materials available within each potential source to construct and operate the highway.

6 PRE-DESIGN GEOTHERMAL EVALUATION

6.1 Geothermal Analysis Introduction

The ice-rich soils, and highly variable soil conditions along the ITH alignment required careful consideration when designing the embankment. Preservation of the natural permafrost soils supporting the embankment was critical in minimizing the risk of thermal degradation and associated thaw-settlement, creep deformation, and slope instability. A road embankment of minimum thickness was the primary design variable for enhancing stability of the permafrost soils underlying the embankment.

Geothermal analyses were conducted in support of the ITH geometric embankment design. After calibrating the thermal model with measured ground temperatures from the pre-design site investigation, one-dimensional (1D) geothermal analyses were conducted to estimate the maximum thaw depth into the road embankment under various ground and climatic conditions. Two-dimensional (2D) analyses were then performed to evaluate the ground temperature distributions with space and time for selected road embankment geometries.

6.2 Analysis Model

Geothermal analysis was carried out using Tetra Tech's proprietary two-dimensional finite element computer model, GEOTHERM. The model simulates transient, 1D and 2D (or three dimensional axisymmetric) heat conduction with phase change for a variety of boundary conditions. The heat exchange at the ground surface is modelled with an energy balance equation considering air temperature, wind speed, snow density and thickness, solar radiation, and evaporation. GEOTHERM also accounts for progressive latent heat release during freezing and thawing in both fine-grained and saline soils.

GEOTHERM results are checked with closed form solutions and field observations. The software has been used successfully for thermal design and evaluations of many projects in the arctic and subarctic.

6.3 Climate Regions

Known variations in climate and ground temperatures along the ITH alignment did not permit the use of a single set of input data for the geothermal analyses. There is also a considerable geographical difference between the weather stations at Inuvik and Tuktoyaktuk, and between the GTC sites installed in 2013. So, to undertake the geothermal analysis, the route was divided into two generalized regions to account for the known climate and ground temperature differences: North Section (ITH km 0 to km 60); and South Section (ITH km 60 to km 137). Each region represents approximately half of the entire highway with the South Section having warmer conditions than the North Section.

6.4 Climatic Conditions

Climate data required for the geothermal analyses included air temperature, wind speed, snow depth, and solar radiation. The closest Environment Canada meteorological stations for the project are located at Inuvik and Tuktoyaktuk. Both stations have historical climate data including air temperature, wind speed, snow depth and solar radiation. The climatic input data used in the analysis were interpolated using the data from the Inuvik and Tuktoyaktuk weather stations.

The air temperature data for 10 years (2001 to 2010) from Inuvik and Tuktoyaktuk were proportioned for each of the two climate regions and used as mean air temperatures for the 1D embankment geothermal analyses. Similarly, the air temperatures for a 1 in 10 return warm year were estimated based on long-term air temperatures at Inuvik and Tuktoyaktuk and were proportioned for each region.

The climate change projections for a moderate green-house gas emission scenario (A1B) in CSA (2010) were adopted in preliminary geothermal analyses. The analysis results suggested that the predicted maximum annual thaw depth for the air temperatures considering 50 years of the projected climate change is approximately 0.2 m deeper than that for the mean air temperatures (2001 to 2010).

6.5 Soil Profiles and Properties

Three soil profiles were evaluated for the 1D geothermal analyses: Profile A (organic soil over sand and clay with low excess ice), Profile B (organic soil over ice and icy clay) and Profile C (thick peat over ice and silt). Soil profiles were developed based on borehole data from the winter 2013 investigations.

Thermal properties of the materials in the analyses were mainly determined indirectly from well-established correlations with soil index properties (Farouki 1986; Johnston 1981). Soil index properties were based on laboratory test results, available geotechnical information, experience, and engineering judgement.

Embankment materials were sourced from borrow areas along the highway alignment, so for the geothermal analysis typical embankment material properties were selected based on information collected from the borrow source investigations. Embankment construction was planned to occur during winter and the embankment materials were excavated, hauled, and placed in frozen state at typically above optimum moisture contents and low dry densities. In the summer following winter placement, the frozen embankment materials underwent thaw-settlement. The amount of settlement associated with the embankment thawing in the summer was analyzed and incorporated into design with an embankment overbuild, average 450 mm. As the material consolidates, the moisture contents decrease and the dry density increases; these changes in material properties were considered in the geothermal analysis. However, the geometry (or fill thickness) of the modelled embankment was not changed for analyses because the overbuild applied to construction resulted in the post-thaw road embankment being close to its modelled thickness.

6.6 1D Analyses and Results

1D geothermal analyses were carried out to evaluate the maximum thaw depths below the centerline of the road embankment for three soil profiles in the two climate regions. The geothermal analyses assumed that negligible snow will exist on the top of the road surface due to normal road traffic and wind clearing. Table 1 summarizes the predicted maximum thaw depth for various cases in 1D geothermal analyses.

Table 1: Summary of 1D Geothermal Analysis Results

Embankment Fill Thickness (m)	Air Temperature Conditions	Predicted Maximum Thaw Depth below Road Surface (m)
1.7 (North Climate Region)	Mean (2001 to 2010)	1.55 (Soil Profile A)
	1 in 10 Return Warm Year	1.62 (Soil Profile A)
1.8 (North Climate Region)	Mean (2001 to 2010)	1.58 – 1.72 (Soil Profiles B and C)
	1 in 10 Return Warm Year	1.70 – 1.79 (Soil Profiles B and C)
2.0 (South Climate Region)	Mean (2001 to 2010)	1.74 – 1.88 (Soil Profiles A, B and C)
	1 in 10 Return Warm Year	1.81 – 1.98 (Soil Profiles A, B and C)

6.7 2D Analyses and Results

2D geothermal analyses were performed to evaluate the ground temperature distributions with space and time for selected road embankment geometries. 2D analyses was also completed for a special road embankment case which included a layer of insulation. 2D thermal analysis results were presented in figures including ground temperature 2D distributions, isotherms with time and space, and trumpet curves at selected locations in road embankments. The 2D analyses and results are not presented due to paper length limitations.

7 GEOTECHNICAL ROAD DESIGN

The design basis was to limit the annual thaw into the original ground beneath the core of the embankment and promote permafrost aggradation into the original active layer. The established design criteria included minimum embankment height objectives for four general terrain types representative of the ITH route, which are presented on Table 2 (EGT Northwind, et al. 2013). Minimum total road heights were adopted based on the geothermal analysis results and engineering judgement.

Table 3 presents the minimum total road height by the terrain type and climatic region. Figure 3 shows a typical road design section.

Table 2: Terrain Type and Description

Terrain Type	Terrain Description
1	Ground moraine deposits, medium-ice with possible massive ice. Upland till and glaciofluvial deposits, overlain by a developed vegetative cover (Soil Profile A)
2/3	Ice-medium and ice-rich till & glaciofluvial deposits (wet terrain, with some expression of ice-rich permafrost overlain by moderately thick vegetative/organic cover); Ice-rich silts & clays (lacustrine deposits with distinct expressions of ice-rich permafrost, overlain by well-defined, thick vegetative/organic cover) (Soil Profile B)
4	Thick peat, organic peatlands ice-rich terrain, including polygonal terrain. Sections of polygonal terrain requiring enhanced (insulated) embankment (Soil Profile C)

Table 3: Minimum Embankment Height by Terrain Type Adopted for Design

Terrain Type	Minimum Road Embankment Heights by Terrain Type Adopted for Design	
	South Region (0 km to ~60 km)	North Region (~60 km to 137 km)
1	1.9 m	1.7 m
2/3	1.9 m	1.7 m
4	2.0 m	2.0 m

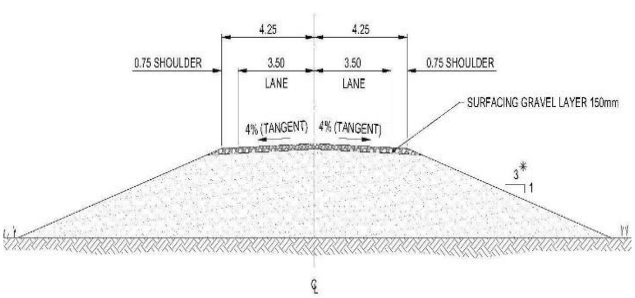

Figure 3. Typical embankment design section.

8 ROAD CONSTRUCTION AND PROJECT INNOVATION

Building a road on sensitive permafrost terrain in a remote location posed unique challenges. Construction activities occurred in winter and at times in darkness, with temperatures often below –30°C. Construction equipment was restricted from working on the tundra in the summer when the active layer was thawed.

The highway was designed and constructed as fill-only embankment by placing frozen materials on the frozen tundra. These materials were excavated (Figure 4), hauled, placed and compacted in a frozen state on the frozen tundra during the winter months (Figure 5). The organic cover overlying the ice-rich soils, was left in place to act as a separator and a protective insulating layer. No ditch cuts were made along the highway.

Because frozen soils cannot be compacted to the same density as unfrozen soils, specifications for material selection, placement and compaction were developed by establishing gradation specifications, maximum ice content, unfrozen moisture content and minimum compaction requirements. The embankment settlement, resulting from the compacted frozen soils thawing in the summer months, was estimated and incorporated into the design as an embankment overbuild.

Schedule and cost were continuously tracked against a preapproved capital cost ceiling of $300 million. Due to this budget constraint, it was necessary to reduce project costs during construction. The most significant cost-reduction option was to reduce embankment quantities. However, reducing the minimum embankment thicknesses changed the original design approach of maintaining a continuously frozen subgrade under the embankment.

To address this challenge, additional field reconnaissance, terrain mapping, engineering design and judgment was required to identify specific sections of the alignment where the effect of a thinner embankment could be managed with acceptable risk. The modified design required segments of the road to be redesigned in a tight timeframe before resuming next season's winter construction.

Granular materials used for embankment fill were relatively scarce along the alignment. Surficial geology mapping identified potential borrow sites, then approximately 700 boreholes delineated and characterized the materials. The materials were categorized as silty sand with trace gravel. These varied gradations and above optimum moisture contents would not have been considered under conventional circumstances.

A non-woven geotextile was placed beneath the embankment side slopes to separate the embankment fill from the underlying tundra, and to provide reinforcement to reduce the potential for lateral embankment spreading.

Efforts were taken to avoid the concentration of surface water flow and ponded water along the road embankment. Culverts were installed at all low points along the embankment to minimize ponding, and drainage ditches were not excavated.

Figure 4. Winter construction activities in borrow source.

Figure 5. Winter construction along ITH alignment.

9 POST-CONSTRUCTION GROUND TEMPERATURE CABLE INSTALLATION

A geotechnical drilling and ground temperature cable installation program was completed along the ITH in March 2017 (Kiggiak-EBA 2017). Fourteen (14) vertical boreholes were drilled 2 m into the original ground beneath the embankment at predetermined locations along the highway. Ground Temperature Cables (GTC) were installed vertically through the embankment and then horizontally to the shoulder of the embankment. The geotechnical boreholes were logged and samples retained for index testing. A typical section showing the GTC installation is shown in Figure 6. Two readings per day are being collected from the GTCs using automated acquisition data loggers.

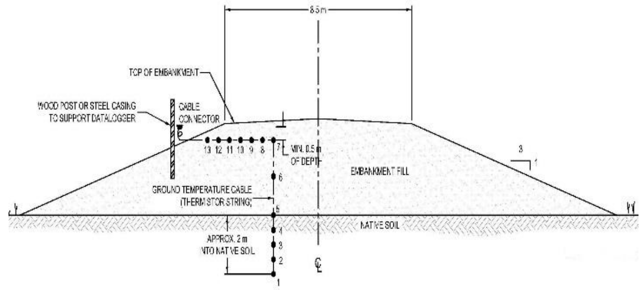

Figure 6. Typical section for ground temperature cable installation in ITH embankment.

The sites ranged from km 23.0 to km 71.6 (ITH-01 to ITH-14) along the alignment (Figure 7). Auger drilling was completed using a track mounted Prospector P1 Multipower RC drill. Undisturbed frozen auger coring and sampling was attempted, using a CRREL (Cold Regions Research & Engineering Laboratory) core barrel at preselected boreholes.

Figure 7. Location map for ground temperature cable installations along the ITH alignment.

9.1 Subsurface Conditions

The embankment fill varied from sand with some gravel and trace silt, to a silty sand with trace gravel, and trace cobbles were occasionally present. The embankment material was frozen with no visible ice. Measured moisture contents at the borehole locations ranged from 5% to 33%, and increased with depth below grade.

The native soils underlying the embankment varied significantly from clay till, to sand and gravel, to ice, and lacustrine silt and clay. Organics were observed in several boreholes within the native soils. Moisture contents were also appreciably greater in the original ground. Based on the borehole logs, the underlying materials were generally more clayey from km 23 to km 34.7 and siltier from km 42.6 to km 71.6.

All native materials encountered in the boreholes were frozen. Ice descriptions ranged from Vx (ice crystals) to Vs (stratified ice) up to 200 mm thick and ice contents were generally high in all borehole locations. Peat was encountered in boreholes ITH-09, ITH-10, and ITH-12 ranging in thickness from 0.3 m to 0.5 m.

10 GROUND TEMPERATURE DATA COLLECTED IN 2017

For the preparation of this paper, useable readings were available from 11 of the 14 GTCs installed in March 2017 (data from late March to early December 2017). The readings were processed to approximate the maximum thaw depth below the road surface in 2017. Figures 8 and 9 present the measured ground profiles for ITH-08 (km 46.8) and ITH-14 (km 71.6).

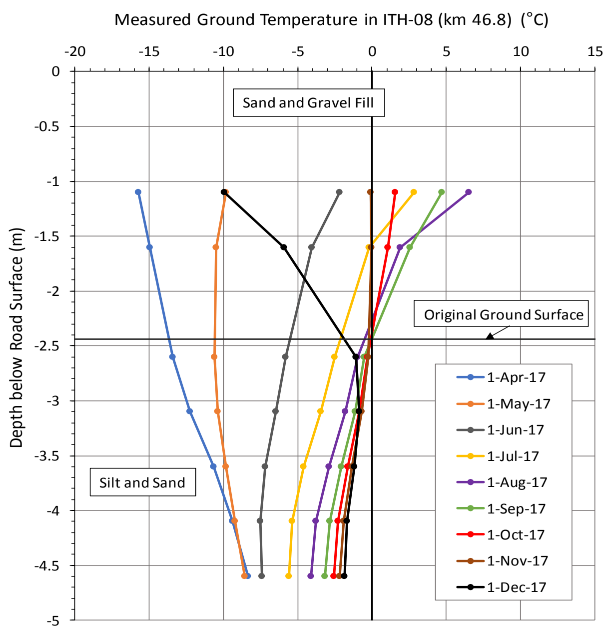

Figure 8. ITH-08 measured ground temperature profiles.

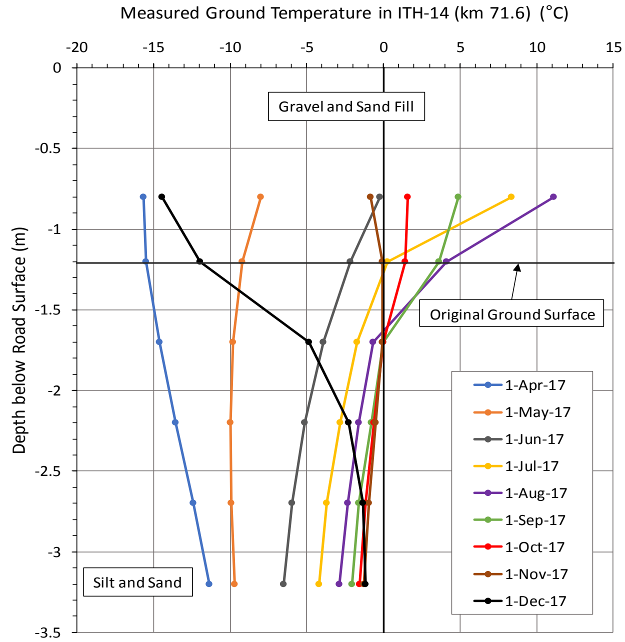

Figure 9. ITH-14 measured ground temperature profiles.

Table 4 summarizes the estimated maximum thaw depths below the initial road surface in 2017, together with other relevant information. The accuracy of the estimated thaw depths is expected to be around ±0.1 m.

Table 4. Estimated maximum thaw depths in 2017 and relevant information

Borehole Number	Kilometer Location along the ITH	Total Embankment Fill Thickness (m)	Estimated Maximum Thaw Depth Below Initial Road Surface in 2017 (m)
ITH-01	km 23.0	2.4	2.8
ITH-02	km 28.2	0.9	1.6
ITH-05	km 34.7	1.7	1.9
ITH-06	km 42.6	2.1	2.6
ITH-07	km 43.6	2.1	2.4
ITH-08	km 46.8	2.4	2.4
ITH-09	km 50.8	1.5	2.5
ITH-10	km 57.2	4.3	3.2
ITH-12	km 64.7	2.7	2.7
ITH-13	km 68.9	0.9	1.7
ITH-14	km 71.6	1.2	1.7

Table 4 indicates that the estimated maximum thaw depth in 2017 for a road embankment with an initial fill thickness of less than 2.5 m is generally greater than the fill thickness, which shows that the thawing front reached the original ground below the bottom of the road fill. The results also suggest that the estimated thaw depths in 2017 are generally greater than those predicted from the pre-design geothermal analyses under different climatic conditions for different soil profiles.

Warmer air temperatures along the ITH in 2017 were one of the major reasons for the deeper thaw depths observed in 2017. Table 5 compares the Inuvik freezing and thawing indices in 2017 with those in Inuvik for the climatic conditions adopted in the pre-design geothermal analyses. The Inuvik thawing index in 2017 is equivalent to that for a 1 in 30 return warm year (based on historic mean air temperatures from 1960 to 2011), while the Inuvik freezing index in 2017 corresponds to that for a 1 in 100 return warm year (based on historic mean air temperatures from 1960 to 2011).

Table 5. Comparison of mean annual air temperatures and thawing/freezing indices in Inuvik

Climatic Conditions	Mean Annual Air Temperature (°C)	Freezing Index (based on calendar year) (°C.days)	Thawing Index (°C.days)
Mean Air Temperatures (2001 to 2010)	-7.4	3919	1247
Air Temperatures for a 1 in 10 Return Warm Year	-6.4	3750	1439
Air Temperatures in 2017	-4.8	3239	1521

Other factors may also contribute to the observed deeper thaw depths in 2017 when compared to those from the pre-design geothermal analyses, including:

- The road fill thickness and the depths to the thermistor beads were measured in winter. After the 2017 summer thaw settlement, the actual road fill thickness and depths to the beads (thus, actual thaw depths below the road surface) were probably reduced.
- Seepage water though road embankment would significantly increase the thaw depth. The thermal effects due to seepage under the embankment were not considered in the geothermal analyses.
- The geothermal analyses may under-predict the thaw depths due to unconservative input data assumptions, such as the assumed road fill moisture contents being higher than some of the actual values for the sand and gravel fill.

11 SUMMARY

This paper presents an overview of the ITH embankment design and construction approach presenting the challenging permafrost conditions along the alignment, and some post-construction ground temperature data collected in 2017.

To protect the permafrost, a 'fill-only' embankment design was employed, and construction took place during the winter months, placing frozen granular materials on the frozen tundra. Preserving the existing permafrost condition was critical in minimizing the risk of thermal degradation and associated thaw-settlement and instability of the embankment.

Pre-design geothermal evaluations were conducted to support the embankment design. The design basis was to limit the annual thaw into the original ground beneath the core of the embankment and promote permafrost aggradation into the original active layer.

Ground temperature cables were installed at 14 locations along the alignment for long term monitoring. The maximum thaw depths in 2017 were estimated from the measured ground temperatures. The data suggest that the estimated maximum thaw depth below the initial pre-thaw road surface in 2017 is typically greater than the total fill thickness for a road embankment with an initial fill thickness of less than 2.5 m. Warmer air temperatures in 2017 within ITH region were one of several major reasons for the deeper thaw depths.

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