NWT Highway 3 Test Sections near Yellowknife

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ABSTRACT
Highway 3 is the only all-weather road connecting southern Canada to the City of Yellowknife. The last 100 km of the highway is located in an area of extensive discontinuous permafrost in the Great Slave Lowlands. Ground temperatures are typically warmer than -1°C and extensive permafrost degradation has been noted in recent years. Originally constructed as a gravel road in the mid-1960’s, the highway was straightened and reconstructed between 1999 and 2006. Since reconstruction, sections of the highway have experienced significant sagging in soil-covered areas and considerable maintenance is required to maintain safe driving conditions. In 2012, four test sections were constructed to evaluate potential mitigation techniques for road embankments on permafrost foundations. The test sections involved different levels of embankment reconstruction, from dressing the existing side slopes, to partial and full replacement of the road embankment fills. Thermistors were installed in the test sections and bi-annual inspections carried out to monitor the thermal and structural behaviour of the embankment. This paper presents data and findings from the first 2.5 years of monitoring.

RÉSUMÉ

1 INTRODUCTION

1.1 Background

The Yellowknife Highway (NWT No. 3) travels from the Mackenzie Highway (NWT No. 1), near Fort Providence, to Yellowknife, a distance of about 340 km, and is the only all-weather road access to Yellowknife from southern Canada. The highway was originally constructed in the mid-1960’s as a clay road embankment with a gravel surface. The original route wound around frequent granite rock outcrops and driving conditions were extremely poor when the road surface got wet, e.g., after spring freshet. Between 1999 and 2006, the final 100 kilometres of Highway 3, from Behchokǫ̀ to Yellowknife, was re-aligned to be much straighter and to maximize the length built on rock to provide a stable base for the road embankment. Coarse blast rock was used as the main construction material for the embankment fill. Road deformations became apparent within a few years after reconstruction, which necessitated frequent re-grading and chip-sealing of the road surface to keep the road in a comfortable and safe driving condition.

1.2 Roads on Permafrost – Issues and Challenges

Permafrost is a thermal condition that is typically in a quasi-stable state, and can be affected by changing climate, surface disturbance (e.g., removal of forest canopy or vegetation cover), convective heating from surface and ground water flows, and heat sinks such as water bodies or heated on-grade structures. In an arctic permafrost environment, exposed near-surface soils and rock thaw to a certain depth each summer due to heat gained from the ground surface, predominantly from warm ambient air temperatures and the absorption of radiant heat from near-24 hour sunlight. This depth of seasonal thaw is termed the “active layer” and a deepening of the active layer in a given year may cause the permafrost to thaw. If the permafrost is thaw-unstable, i.e., contains excess ground ice that would settle when melted, this can result in roadway deformations including pavement settlement, pavement cracking, embankment spreading, shoulder rotation, formation of thermokarst, and slope instability in cuts (Esch, 1996).

Embankments in permafrost regions are typically designed to minimize the risk of permafrost degradation along the embankment slope by allowing minimal, partial, or complete protection of the permafrost foundation. Provision of minimal protection is applicable when the
permafrost is insensitive to thaw – e.g., thaw stable sandy gravel or bedrock with low ice content – or when protection would be too costly from a capital cost perspective. In the latter case, the infrastructure usually requires frequent maintenance and is limited to light traffic or low/moderate speeds. Partial protection is the approach most commonly adopted, and involves controlling permafrost degradation to an acceptable rate and depth that would minimize damage to the road embankment and limit the amount of annual maintenance work required (TAC, 2010). Complete protection is more applicable to roads in continuous permafrost regions, where the permafrost is cold. Conventional design practice for complete protection of the permafrost is to size the embankment sufficiently thick and wide such that the top of the permafrost (the permafrost table) is raised to within the embankment and the permafrost foundation is always frozen.

The reconstruction of Highway 3 was designed to balance capital costs against the risks that permafrost degradation posed on long-term performance (McGregor et al., 2008). As such, the strategy used was a risk-based design in which more innovative embankment configurations would be adopted to mitigate the effects of permafrost thaw that could not be managed using conventional design principles.

1.3 Literature review of other test sections

Since the 1960’s, there has been, and continue to be, considerable research efforts aimed at developing effective and economical road embankment configurations designed to prevent or minimize roadway instability, particularly in light of the potential impacts of future climate warming. Linear transportation infrastructures such as roads, railways, and airfields have been built on thaw-sensitive permafrost across the arctic and in the high-altitude Qinghai-Tibet region of China. Research has focused on numerical analyses, laboratory testing, and field scale demonstration tests. Numerous protection measures have been proposed and experimented to mitigate against the impacts of permafrost degradation.

Protection measures range from minimizing the heat intake through the road embankment by insulating the embankment, replacing the dark road surface with a light-coloured or reflective surface, and clearing snow from embankment slopes to maximize frost penetration; extracting heat from the embankment through natural convection using heat drains, thermosyphons or open-graded rockfill; and reinforcing the embankment with geosynthetics to minimize differential settlement as the permafrost thaws (see Esch, 1996; Doré and Zubeck, 2009). None of these methods have been widely adopted as “proven technology” for a variety of reasons, including costs, safety, maintenance, and other practical considerations. Even today, variances of technologies initiated over 40 years ago continue to be tested and evaluated. In recent years, test sections have been constructed along the Alaska Highway near Beaver Creek, Yukon (e.g., see Malenfant-Lepage et al., 2012), Provincial Road (PR) 391 near Thomson, Manitoba (Flynn et al., 2015), and the Qinghai-Tibet highway (e.g., Ma et al., 2009).

2 SITE DESCRIPTION

The test sections are located along a segment of Highway 3 approximately 30 to 40 km west of the City of Yellowknife, NWT (62°27’N/114°21’W). The highway corridor traverses generally flat terrain, with elevations predominantly between 160 metres above sea level (m asl) increasing to just over 200 m asl at the eastern portion of the highway. The landscape consists of numerous rock hills and ridges rising abruptly in the order of 2 to 8 metres in height (Mollard, 1995) interspersed with bogs, wetlands and ponds in low-lying areas (Wolfe et al., 2015). Approximately 48 percent of the highway is routed along outcropping bedrock, 48 percent of the route on overburden, and 4 percent crossing water bodies. Additionally, the new highway crosses several small sections of the old gravel highway. Vegetation in the area is typical of the Taiga Shield ecozone, consisting of open forests of low-growing Black Spruce and Jack Pine. Figure 1 shows an overview of the Highway 3 route.

Figure 1. Overview of Highway 3 terrain (Landsat image).

2.1 Climate

Given the relatively level regional topography and continental climate, Environment Canada’s meteorological station at Yellowknife Airport (WMO ID: 71936; 62°27’N/114°26’W; 206 m asl), located at the far east end of the highway, is considered representative of the climate across the Highway 3 test section area. Yellowknife has a semi-arid subarctic climate with a mean annual air temperature of -4.3°C (average from the normal period of 1981-2010) and receives approximately 300 mm of precipitation annually. Summers are short and cool and winters are long and cold with mean annual air freezing and thawing indices of 3250 and 1720 degree-days, respectively, for the 1981-2010 climate normal period (the “normal”). Snow typically accumulates from late-October to early-May. During highway reconstruction (1999-2006), Yellowknife was, on average, relatively warm compared to the normal, particularly during the winter, with a mean freezing index of 3030°C-days and a mean thawing index of 1700°C-days. Since construction of the test sections in 2012, annual average air temperatures have been slightly
colder than normal and annual rainfall and snowfall have been approximately 25% lower than normal.

2.2 Surficial Geology

This segment of the highway lies within the Canadian Shield uplands and is underlain by several intrusive granite and granodiorite, Archean-aged rock masses (Henderson, 1985). The most recent period of glaciations reached its maximum approximately 20 thousand years ago, during the late Wisconsinan, when most of Canada was covered by the Laurentide Ice Sheet. This period of glaciation was predominantly erosive in this area and left much of the bedrock exposed. Near the end of the last glaciations, about 10 thousand years ago, Glacial Lake McConnell, a large ice marginal lake, formed along the western margin of the retreating ice, up to an elevation of 280 m asl. Great Slave Lake reached its present level of 157 m asl. about 8,500 years ago. Above the limit of inundation, there was widespread washing of till and bedrock by meltwater, which likely occurred during the easterly retreat of the ice front. However, fine-grained glaciolacustrine silts and clays remain in the low-lying areas between bedrock outcrops. Organic deposits may overlie the glaciolacustrine sediments.

2.3 Permafrost

This segment of the highway is underlain by extensive discontinuous permafrost (Wolfe et al., 2015). Locally, the presence and temperature of permafrost varies depending on a variety of factors, including soil type and thickness, vegetation cover, proximity to and depth of water bodies, slope aspect, and snow cover. Where it is present, permafrost is found to be generally warm (-1°C or warmer) and frequently contains excess ground ice. Permafrost is typically found beneath spruce and deciduous forests and peatlands, and is absent in bedrock and wetlands. Taliks are generally found beneath streams, creeks, and ponds (Wolfe et al., 2011). Permafrost that may have been present prior to construction of the original gravel highway may have since degraded (warmed and/or melted).

3 SITE ASSESSMENT

Since reconstruction of the highway, the state and distribution of permafrost along the highway corridor have changed due to changes to surface cover (removal of vegetation) and snow distribution, disruption to surface and ground water hydrology, as well as recent climate factors.

3.1 Site Investigation

Starting in 2010, a two-phase site investigation was carried out. The first phase was to characterize the general site conditions and evaluate the types and severity of road instability. Test pit excavations, active layer probing, vegetation surveys, terrain analysis and ground surface temperature datalogger installations were carried out to gain an understanding of the current state of permafrost in the vicinity of the road. Generally, the top of the permafrost was found at a depth of 1.0 to 1.5 m below the ground surface within 12 to 15 m of the embankment toe. Closer to the embankment toe, the active layer became deeper. Further away from the embankment toe, the active layer was 0.7 m or less, mainly controlled by the vegetation cover and surface water. However, the distribution and depth to the top of the permafrost varied across the highway.

In the second phase of the site characterization, eight sites with severe differential settlement of the road surface were examined in detail to assess their suitability as potential test sections. Electro Resistivity Tomography (ERT) was used to map subsurface features such as bedrock, ice-rich permafrost and thawed zones along the road. Jet-wash drilling, solid stem auger boreholes and cone penetration tests were carried out to help interpret the geophysical surveys. Boreholes located adjacent to the road embankment were drilled to refusal on bedrock (typically less than 10 m) and instrumented with thermistor strings connected to dataloggers to monitor ground temperatures. Permafrost temperatures were found to vary (-0.2°C to -2.2°C) depending on vegetation, proximity to water bodies and bogs, and distance from the embankment.

3.2 Assessment of the Problem

Based on findings from the geotechnical investigations, the majority of the road instabilities were attributed to three main locations: i) transition zones; ii) stream crossings; and iii) where the new highway crossed over or runs adjacent to the old highway embankment.

3.2.1 Transition Zones

Transition zones are sections of the road where the route transitions from either bedrock to ice-rich permafrost soils, or from ice-rich permafrost soils to non-permafrost soils. As the permafrost warms and degrades, the road embankment undergoes differential settlement. In particular, settlement has been abrupt in transition zones from rock to ice-rich glaciolacustrine silts and clays.

Some sections of the highway were routed over existing ponds because it was believed that the foundation soils were already in an unfrozen condition, which would minimize future settlement due to permafrost thaw degradation. Although true, this has led to uneven settlements along the road at the interface of these transitions areas.

3.2.2 Stream Crossings and Culverts

At stream crossings and culverts, permafrost degradation caused by convective heat transfer from flowing water have resulted in differential settlements of the embankment base and undulations in the road surface. Factors inducing thermal disturbances include uncontrolled water flow through the embankment, water flow through culverts, stagnant water in the culvert and or ponding at the culvert inlet and outlets, and thermal
disturbances introduced during the construction of the culvert itself. Due to the poorly-drained condition and level terrain, standing water has developed at various locations in the ditches and against the road embankment. In many areas, the flow gradients over the majority of the year have been much smaller than the culverts were designed for, resulting in a reduction in the culvert’s flow capacity and contributing to ponding at the inlet and through the embankment, i.e. connecting standing water bodies under the highway. During spring freshet, water has been observed to flow through the embankment in some areas because of the permeable nature of the embankment rock fill. This can lead to warming of the permafrost subgrade and migration of fines through the rock fill. Small sinkholes have been noted in several areas along the road surface and in the embankment side slopes.

3.2.3 Highway Crossings

Substantial differential settlement was also observed in areas where the new highway crosses over the old highway, or runs adjacent to the old highway. This is believed to be due to permafrost degradation that had developed along the old highway embankment and its right-of-way, such as thaw bulbs that developed under the old highway ditches, prior to the construction of the new road. Thaw consolidation, water accumulation and ongoing permafrost degradation in these former ditch locations can result in differential settlements on the realigned highway where the old and new highway cross each other. One-sided shoulder rotation can occur if the two alignments are parallel and the new shoulder is situated on the old ditch, i.e. the existing thaw bulb.

4 TEST SECTIONS

Following the phase 2 site characterization, four areas were selected for constructing test sections.

4.1 Design Intent

In the fall of 2012, four test sections ranging in length from 10 to 60 m were constructed by replacing parts or all of the existing highway embankment. The test sections used one or more of the following techniques to target failure mechanisms identified during the site assessment:

- Geosynthetic-reinforced fill to bridge transition sections and distribute road surface settlements over a longer distance, minimizing abrupt differential settlements.
- Foamed cellular concrete to provide some structural rigidity over transition sections and some thermal insulation to the embankment base.
- Replacing the shoulder of the embankment with cobbles to promote natural convective cooling, i.e. to maintain the existing permafrost foundation and minimize further thaw settlements.
- Using open bottom arch culverts to replace existing pipe culverts and French drains.

Given the warm permafrost conditions along the highway and projected air temperature increase, it is impractical to completely halt permafrost degradation and restore the pre-construction ground conditions. The primary intent of these mitigation techniques was therefore not to aggrade nor completely preserve the permafrost, but rather to improve road safety and reduce maintenance costs by minimizing abrupt differential settlements. However, mitigation measures that can preserve permafrost under current conditions may also increase the design life, thereby reducing future maintenance costs.

To assess the thermal conditions of the test sections, thermistor cables were installed within the road embankment during construction. Each thermistor cable was typically buried horizontally across the road embankment at depths ranging from 0.7 m to 4.7 m below the driving surface. Each thermistor cable was housed in flexible PVC hose to protect the cables during construction. The cable leads were extended out from the embankment toe and connected to data loggers for continuous automated measurements.

4.2 Test Section Construction

4.2.1 Test Section 1

At Test Section 1, the road transitions off a bedrock outcrop and traverses alongside a large pond before transitioning back on to bedrock. The length of the section between the bedrock outcrops is approximately 80 m. The embankment height ranges from very shallow over the rock cut to approximately 5 m at the midpoint. Stagnant water was observed along the shoulder. An 800 mm diameter culvert located approximately 10 m east of the bedrock outcrop appeared to sit outside of the natural drainage path. Both ends of the culvert were projected upwards, suggesting the culvert may have collapsed beneath the road crest. Road instabilities at this location include an abrupt dip, which coincided with the culvert alignment, and several smaller dips extending eastward.

Guardrail deformations were indicative of differential settlement along the embankment crest and rotation of the shoulder (see Figure 2). The section had been repeatedly re-graded since it was constructed in 2005-06. Based on the number of layers of chip seal observed during excavation of the road for test section construction, it was inferred that this section of the highway experienced up to one metre of vertical settlement (more than 15 cm per year, on average). Road deformations at the section were attributed to transitioning off bedrock to ice-rich permafrost soils that degraded due to thermal disturbances from uncontrolled water flow through and around the toe of the embankment.
Construction at Test Section 1 involved relocating and replacing the culvert with an open-arch culvert and geosynthetic-reinforced fill. The road was excavated up to a depth of 5 m and the open-arch culvert (3.1 m x 1.6 m x 21.7 m long) was placed directly on a prepared fill base on top of the native foundation soils. The embankment was rebuilt with layers of geotextile reinforcement vertically spaced at 0.25 m intervals over a longitudinal distance of 60 m. Each layer of geotextile was folded over compacted 40 mm minus rock fill and overlapped with the next lift of geotextile and fill, encapsulating the fill and preventing lateral spread. Thermistor cables were installed at distances of 0.5 m to 45 m from the culvert wall at various depths.

4.2.2 Test Section 2

At Test Section 2 (Figure 4) there was an abrupt settlement at the north end of the section where the road transitions off shallow bedrock, and rotation and settlement of the guardrail along both sides of the shoulder. These instabilities are attributed to the transition off stable bedrock on to melting, ice-rich clay. Embankment heights range from shallow over rock to approximately 4 m. There is ponded water on the south side of the embankment and seasonally wet terrain on the north side. Instrumented boreholes along the toe of the embankment on either side of the highway indicate that the permafrost is marginally frozen (-0.2°C to -0.3°C). Outside the right-of-way (~25 m) ground temperatures are as cold as -2.0°C.

4.2.3 Test Section 3

At Test Section 3, the road surface had several dips, cracks and potholes (Figure 5). At the east end of the test section, the road is routed over bedrock. At the far west end of this section, the highway crosses over the old highway alignment. Instabilities are attributed to the transition off bedrock on to ice-rich permafrost soils and to the thermal disturbances caused by water bodies forming on both sides of the embankment. On the south side, the embankment subsides into a large pond. On the north side, there is an undrained, low area that impounds stagnant water during most of the year. Dead black spruce trees on the north side of the embankment indicate that the ponded water likely formed after the new highway embankment was built and was not present prior to the road construction. Ground temperatures range from unfrozen (in the low-lying area to the north) to just below freezing (-0.2°C) in boreholes located along the edge on the embankment to the south.
Remediation strategies at Test Section 3 focused on stabilizing the road embankment as it transitions from frozen to unfrozen clay and from frozen clay to bedrock. At the bedrock transition, the upper portion of the road embankment was partially-excavated and a 0.4 m thick layer of cellular concrete was installed directly beneath the base course across a 40 m section. Adjacent to this section, another 40 m section was partially excavated and replaced with two, 0.5 m layers of geogrid-reinforced 40 mm minus rock fill. Both sections are intended to provide structural rigidity to the embankment and limit abrupt differential settlements. Thermistors were placed beneath the cellular concrete and the geogrid (as a reference section) to assess the insulating effects of the cellular concrete.

4.3 Test Section 4

At Test Section 4 (Figure 6), the existing road surface had an abrupt dip beneath the west bound lane. The length of the dip coincided with the alignment of the existing rock drain. Although the embankment height is shallow (approximately 2 m), it was inferred during excavation of the embankment during test section construction that this area had settled up to 0.5 m since construction in 2006. Remedial work at this site involved replacing the rock drain with a small open-arch culvert (1.5 m x 0.8 m x 19 m long) and geotextile-reinforced fill (Figure 7).

4.4 Monitoring and Assessment

Performance assessment of the test sections over the past 2.5 years has been done through semi-annual site visits (one in the spring and one in the fall), that include visual inspection of the road surfaces and embankments.

4.4.1 Embankment Temperature Monitoring

Figures 8 through 10 show embankment temperatures at Test Sections 1 to 3. The data spans a 2.5 year period since test section construction was completed in October 2012. Daily air temperatures from Environment Canada’s meteorological station at Yellowknife Airport are shown for reference.

The measured embankment temperatures around the open-arch culvert at Test Section 1 show that air temperatures within the culvert influence internal fill temperatures within an approximately 5 m radius of the culvert. Embankment temperatures immediately adjacent to the culvert (0.5 m) closely follow air temperature fluctuations. At a distance of 3 m from the culvert wall, the air temperature influence is attenuated and there is a lag of approximately one month from the thermistor at 0.5 m radius when the thermistor begins to freeze or thaw during the winter and summer, respectively. At a distance of 3 m from the culvert, temperatures ranged from -13°C to 12°C over the monitored period. At a distance of 5 m, embankment temperatures ranged from -9°C to 8°C, with no appreciable change at a distance of 25 m. From May through August, air temperatures within the culvert (measured with a miniature temperature data logger) were approximately 2°C cooler at the culvert wall and 6°C cooler at the culvert floor than those measured at Yellowknife Airport.

Compared to the reference embankment section, temperatures within the ventilated shoulder are colder. Temperatures in the ventilated shoulder at Test Section 2 were approximately 5°C colder in the early part of winter (November through January), practically the same temperature later in the winter (February through April), and 4°C cooler in the summer compared to the reference section for a depth of 1.2 m. Temperatures at the embankment base of the ventilated shoulder were even colder, ranging from -20°C to 7°C.

Measured temperatures beneath the cellular concrete at Test Section 3 were warmer, by as much as 11°C, from...
October through April and subsequently cooler, by approximately 6°C, from May through August compared to the adjacent reference section constructed with granular fill. The temperature data show the influence of thermal insulation provided by the cellular concrete, with the mean annual temperature at 1.3 m depth (0.3 m depth beneath the base of the cellular concrete) being, on average, 1°C warmer than at the same depth in the reference section. The overall thermal effect of the insulation is a warming and not a cooling because less heat can be extracted from the ground through the snow cleared road surface during winter compared to the section without cellular concrete.

At Test Section 4 (data not shown), embankment temperatures were predominately influenced by their close proximity to the road surface. Temperatures within the embankment were generally warmer than the air temperatures throughout the year, by about 4°C to 5°C. Thermistors located close to the culvert wall and near the embankment base were slightly cooler in the summer and warmer in the winter than those located farther from the culvert. Unlike in the culvert of Test Section 1, where culvert air temperatures during the summer of 2014 were somewhat cooler than air temperatures at Yellowknife Airport, internal culvert temperatures at Test Section TS4 were essentially identical to the ambient air temperatures. The smaller culvert size and stagnant water in the culvert are likely the reason for this.

Figure 8. Measured embankment temperatures at various radial distances from the open-arch culvert wall at Test Section 1. Air temperatures from Environment Canada weather station at Yellowknife Airport.

Figure 9. Measured temperatures beneath the embankment side slopes at the ventilated shoulder and adjacent reference section at Test Section 2. Air temperatures from Environment Canada weather station at Yellowknife Airport.

Figure 10. Measured embankment temperatures at a depth of 1.3 m below the driving surface at the cellular concrete section and in the embankment fill at the reference section at Test Section 3. Air temperatures from Environment Canada weather station at Yellowknife Airport.
5 CONCLUSIONS

In September 2012, four test sections were constructed on Highway 3 near Yellowknife, NWT, to evaluate techniques that help reduce maintenance efforts and maintain safe driving conditions along sections of the road where abrupt differential settlements have occurred. To date, the key observations from the initial monitoring are:

- The large open-arch culvert (3.1 m x 1.6 m x 21.7 m long) is effective in cooling the embankment and passing the flow. Measured air temperatures at the culvert floor and wall were approximately 6°C and 2°C colder, respectively, than Yellowknife Airport air temperatures during the summer.

- The small open-arch culvert (1.5 m x 0.8 m x 19 m long) is not successful in passing water; stagnant water forms, connecting ponds on both side of the road. The small open-arch culvert causes warming of the embankment fill.

- The ventilated shoulder cools the embankment shoulder on average by approximately 4°C compared to the reference section.

- Mean embankment temperatures immediately beneath the cellular concrete are warmer than the reference section, indicating that the insulating layer reduces the net heat extraction of the embankment base as it insulates the embankment from cold winter temperatures more so than from warm summer temperatures.

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