Compendium of Permafrost Reports: Northern Transportation Adaptation Initiative (NTAI) 2011-2021

(Transport Canada: NTAI Compendium)

Inuvik, NT
Dempster Highway
September 2020

Foreword

The following compendium provides a comprehensive overview of permafrost research projects supported by the Northern Transportation Adaptation Initiative (NTAI) program from 2011 to 2021. A collection of 61 reports have been adroitly summarized and organized to provide convenient access to permafrost knowledge gained over the last decade. The compendium can be used as a reference document by the scientific and engineering communities, governments, industries, policy makers, students, and general public. Most reports and accompanying publications can be accessed online through their associated URL or DOI. Report themes and key terms are compiled in an index at the end.

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Contents

Glossary

ACCVI	Arctic Climate Change Vulnerability Index
ACE	Air Convection Embankments
ANPF	Arctic and Northern Policy Framework
BST	Bituminous Surface Treatment
CR-EVm	Climate Risk and Economic value model
CRHM	Cold Regions Hydrological Model
CSM	Cohesive Strength Meter
DEM	Digital Elevation Models
DOT	Department of Transportation (GNWT)
DSC	Differential Scanning Calorimetry
DTS	Distributed Temperature Sensing
EO	Earth Observation
ERT	Electrical Resistivity Tomography
ETVP	Elastic-thermo-viscoplastic
FTP	File Transfer Protocol
GIN	Groundwater Information Network
GIS	Geographic Information System
GNWT	Government of the Northwest Territories
GPR	Ground Penetrating Radar
GRS	Geotextile Reinforced Structure
GSC	Geological Survey of Canada
IGP	Information Gathering Plan
InSAR	Interferometric Synthetic-Aperture Radar
ITH	Inuvik-Tuktoyaktuk Highway
IWS	Instrumented Wheelset
LiDAR	Light Detection and Ranging
MAAT	Mean Annual Air Temperature
MOU	Memorandum of Understanding
MTQ	Ministère de Transports du Québec
NCE	Northern Climate Exchange
NRC	National Research Council Canada
NSERC	Natural Sciences and Engineering Research Council
NTGS	Northwest Territories Geological Survey
NPP	Navigation Protection Program
PCM	Phase Change Materials
PIEVC	Public Infrastructure Engineering Vulnerability Committee
PIN	Permafrost Information Network
PSMAA	Permafrost and Surficial Material Active Archive
QRA	Quantitative Risk Analysis

RTS	Retrogressive Thaw Slump
SPCSP	Structural Plate Corrugated Steel Pipe
TC	Transport Canada
TDR	Time-Domain Reflectometry
TEB	Transportation Engineering Branch (Yukon Government)
TM-DSC	Temperature Modulated Differential Scanning Calorimetry
TRACS	Transportation Risk in the Arctic to Climate Sensitivity
TRAILS	Transportation Resilience in the Arctic Informed by Landscape Systems
TRS-Shed	Thermo-reflective Snow-sun Shed
UQAT	Université du Québec en Abitibi-Témiscamingue

Introduction to the Compendium

Chris Burn, Carleton University

The *Northern Transportation Adaptation Initiative* (NTAI) is a federal program designed to increase the capacity of northerners to adapt northern transportation infrastructure to anticipated climate change. The program has had two themes, one concerned with marine infrastructure and the other with infrastructure built on permafrost. Since 2011, NTAI has supported a wide range of research projects associated with highways and airports in northern Canada. The compendium contains summaries of 61 reports submitted to Transport Canada concerning the permafrost environment. The majority of the reports may be found in full at their associated URL. Some projects supported by the NTAI are not included in this compendium because reports were not required as part of the project, or the work was still underway when the compendium was developed[1].

Climate change is a significant national issue, whose importance is enhanced in Canada by the presence of permafrost over large parts of the country. Permafrost terrain is sensitive to climate change, particularly where the ground is ice rich. Subsidence and loss of bearing capacity are two principal effects anticipated for permafrost terrain as a result of climate warming. Other effects are associated with changes to the precipitation regime. In each case, changes to soil conditions may affect the integrity of infrastructure built with foundations in permafrost.

Climate change follows from increases in the atmospheric concentration of greenhouse gases (GHGs) such as carbon dioxide and methane. The concentration of these gases in the atmosphere was about 280 parts per million (ppm) before the Industrial Revolution and rose to 315 ppm by 1958. The value is now 418 ppm. There is no prospect of this concentration declining in the next 1,000 years, and it may well increase substantially before it stabilizes. In practical terms, the climate change we are experiencing is irreversible.

The western Arctic is the Canadian epicentre for climate change. Mean annual air temperatures at Inuvik, NT, climbed from -9.7 °C in 1961–70 to -6.1 °C in 2011–20. The rates of change in southern Canada are lower, but just as definitive. For example, at Ottawa, ON, the mean annual air temperatures for 1961–70 and 2011–20 were 5.5 °C and 6.5 °C, respectively. Changes to the precipitation regime have also begun to be noticed. It takes time for increases in GHGs to become apparent in the climate, the lag being about 20 years due to the response time of the oceans to a new atmospheric regime. The time now required by the oceans to reach equilibrium with the atmosphere in terms of carbon concentrations is at minimum 200 years. It is likely about 1000 years because dissolution of carbon in the oceans slows down as water temperature rises. We should not assume that the climate is close to stability. It will take several decades to establish a carbon-neutral economy. Effective adaptation is going to be important if we are to maintain functioning overland transportation infrastructure, especially in permafrost regions.

The summary reports that follow this introduction concern a number of key themes. Page numbers of some reports that illustrate these themes are given in parentheses. The reports have been grouped together in the compendium by the contributing agencies.

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[1] Examples of some projects funded but not included in this compendium: Mitigating pavement cracking during thaw by controlling roadbed moisture with wicking geosynthetics on low volume roads in the Yukon (FPInnovations); Development of field-based numerical heat transfer models for the Beaver Creek test site, Yukon (Université de Montéal); Annual monitoring by airborne remote sensing of permafrost degradation and of destabilization of transport infrastructure (Université de Montréal); Considering uncertainty from climate change impacts in transportation investment decisions: Modelling framework and application to the Slave Geological Province (University of Alberta); Impact of surface material type on thermal conductivity of roads in permafrost regions (University of Waterloo); Prioritizing standardized guidance needs for resilient northern transportation infrastructure (Standards Council of Canada); Literature review on induced thaw techniques to improve frozen soils in permafrost regions (SRK Consulting); Improving accuracy of future climate change scenarios for permafrost in Nunavut to effectively integrate into decision-making and infrastructure design (Government of Nunavut)

Planning

First and foremost, we will not be able to manage the transitions that are being forced upon us without planning for the inevitable consequences of climate change. This is a primary responsibility of governments with respect to public infrastructure. Not every infrastructure component will be affected by climate change in the same way. Considerable effort has been made to conduct vulnerability assessments, particularly at principal northern airports (p. 10-12, 43), in order to identify infrastructure elements that must be actively monitored to ensure adequate performance during continuing climate change. Following these assessments, significant steps have been taken in standards development for maintenance and construction to address risks to northern airports (p. 18). Similar considerations have been examined with respect to highways at specific locations (p. 5-8, 21), with the most detail provided for the Dempster Highway in Yukon (p. 30).

Innovation in construction

Research projects on highways have tested innovations in construction techniques, for example, the use of geotextiles to minimize deformation during thaw settlement (p. 22), the installation of air convection embankments (ACE) and thermosyphons to preserve permafrost beneath the highway embankment (p. 40), and use of light-coloured asphalt (p. 62). Some novel applications, for example, of phase change materials to minimize thawing (p. 41) and geotextiles to interrupt capillary rise and thereby dry embankment soils (p. 31), have been examined. Test sites were built on NWT Highway 3 near Yellowknife to examine the efficacy of various construction methods and materials to reduce settlement beneath the driving surface (p. 23). These are critical tests to determine viability of rehabilitation techniques for sites where differential subsidence reduces the service standard of the highway. The Beaver Creek test site on the Alaska Highway is Canada's largest experimental highway embankment above permafrost. Its performance was reviewed after several years: a key result is the importance of managing groundwater flow beneath the embankment because subsidence continues due to thawing induced by heat carried by the seepage (p. 14).

Several projects assisted design, construction, and maintenance planning for the Inuvik-Tuktoyaktuk Highway (ITH). This is the first public road built in Canadian permafrost terrain using winter construction techniques. Managing thaw subsidence of the frozen embankment after construction was a major known challenge of the design (p. 22). Management of snow cover on embankment side slopes was also examined through NTAI support (p. 6). Maintenance and repair standards were provided, with some assessment of how these may be affected by climate change (p. 8).

Innovation in maintenance

Innovations in maintenance practice have concentrated on snow management to promote freezing of embankment side slopes and at the toe. Much of the work has been by modelling, suggesting clearing of snow in early winter (November or December) may be most effective at reducing embankment temperature (p. 6). Measurements of snow-bank surface gradients at the north end of the Inuvik-Tuktoyaktuk Highway were between 1:5 and 1:7, indicating side-slope angles for minimization of snow accumulation (p. 15), as constructed in northern Quebec. The performance of snow sheds in reducing embankment temperatures has been successfully examined at the Beaver Creek test site (p. 48). These structures lift the snow cover of the ground and allow the embankment surface to cool efficiently in winter. The sheds shade the ground in summer.

Innovation in monitoring

The NTAI also supported innovations in monitoring practices that are designed to reduce risk of infrastructure failure by alerting staff to necessary maintenance (p. 64). The most sophisticated approach uses fibre-optic cables to monitor ground temperature and soil deformation along the Salluit Airport access road (p. 13, 51). Baseline monitoring stations were established to determine the condition of permafrost and detect changes in temperature over time. There are over 130 locations in NWT (p. 25) and a smaller number at strategically selected locations in Yukon (p. 21, 27). Remote sensing tools for monitoring embankment integrity were assessed for their potential use in remote landscapes (p. 9).

Innovation in investigation

An integrated multi-disciplinary assessment of the physical setting of infrastructure and the sensitivity of permafrost and ground ice to thaw has been conducted at Iqaluit Airport. The intention of the assessment was to locate specific components of the terrain under runways and taxiways that are susceptible to subsidence and may lead to unacceptable departure of the surface from horizontal alignment. The assessment combined drainage management, thaw prediction, delineation of ground ice bodies, and subsidence potential with critical components of the infrastructure (p. 26, 55). The wide-ranging nature of the assessment is a novel characteristic for research, which is characteristically reductionist, with most investigations of permafrost conditions focussing on only a few components of the Earth system. A quantitative risk analysis of the airport was also conducted to consider damages to infrastructure that may occur either gradually or suddenly (p. 54).

Critical components

Drainage management is a key element of embankment design and maintenance. It is necessary to facilitate drainage where an embankment impedes a water course. Management is essential because ponding normally leads to permafrost degradation (p. 58). Embankment design characteristically draws up permafrost into the fill, raising the level of the frozen ground and blocking streams and groundwater seepage. Most drainage management structures are culverts. Culverts introduce warm air into the embankment in summer and may become blocked with icing in winter. They become locations of maintenance and management stress along a highway. The NTAI supported research on installation and performance of insulated culverts (p. 63), on modelling the thermal disturbance of culverts to embankment temperatures (p. 56), and on open-bottom arches (p. 24). Both projects advanced design of robust culverts for installation above permafrost and minimization of permafrost thaw.

Vulnerability mapping

The Geological Survey of Canada (GSC) has traditionally undertaken programs addressing national issues in geoscience, and commonly leading to publication of maps. The Northern Canada Division has six research scientists who focus on terrain hazards in permafrost environments. These members of staff contributed maps of terrain vulnerability to thaw, especially near Highway 3 in the Yellowknife area (p. 37), and for the Dempster-ITH corridor (p. 38). The GSC has also played a key role in creation of databases for permafrost information from northern Canada (p. 25, 39).

Economic aspects

Sound economic analysis must underlie all potential adaptation initiatives for public infrastructure. A life-cycle analysis examines the cost-effectiveness of frequent rehabilitation with conventional techniques against higher investment in capital costs required for innovative methods. Similarly, a principal conclusion of the research at the Beaver Creek test site was the need for a fuller economic assessment of the application of various new techniques (p. 14).

Conventional highway construction and rehabilitation techniques involve fill applied repetitively over the lifetime of the infrastructure. This is likely cheaper for areas, such as much of glaciated northwest Canada, where there are abundant gravel and aggregate resources. Nevertheless, there will be some places, such as at Dry Creek on the north Alaska Highway, where the risk of infrastructure failure is not acceptable and significant capital investment is required, in this case approximately $8M per km for installation of thermosyphons (p. 32, 40).

Urgent needs

Finally, development of a retrogressive thaw slump in Takhini River valley, about 40 km west of Whitehorse, poses a significant threat to the Alaska Highway. Without remediation, the headwall of the slump may reach the highway in 2024 or 2025. The growth of the feature and permafrost conditions, especially temperature and ground ice, have been examined in preparation for engineering works to stabilize the site (p. 65).

Publications

The compendium concludes with a list of many publications derived from NTAI permafrost projects.

Project Reports

Report title: Northern Transportation Infrastructure: Improving Maintenance Procedures for Highways in Permafrost Regions

Project lead: N/A

Affiliation: AMEC Foster Wheeler Environment & Infrastructure

Dates: 2014/2015; 2015/2016

Themes: Maintenance; Guidelines; Roads; Snow; Drainage;

Key terms: ITH; Climate Change; Embankment; Ponding; Repairs; Bridges; Culverts; Inspection; Remediation; Active Layer; Surveys;

Objectives: (1) Develop maintenance protocols for the ITH; (2) Determine personnel and equipment requirements for application of protocols; (3) Assess potential influence of climate change on road stability and maintenance.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Northern%20Transportation%20Infrastructure-Improving%20Maintenance%20Procedures%20for%20Highways%20in%20Permafrost%20Regions.pdf

Summary:

Surveys of road maintenance companies and agencies were conducted to obtain information about protocols, equipment and personnel involved in snow removal, drainage improvement, and road repairs. Geothermal models (1) estimated the influence of snow on freezing of embankment slopes and established optimal dates of snow removal to achieve fastest freezing rates; and (2) estimated the thermal influence of ponded water on active-layer thickness. Protocols for snow removal, drainage management and road repairs for the ITH were established to provide standards on inspection frequencies, recommended equipment, and maintenance methods.

Models demonstrated snow removal from embankment slopes is beneficial for the southern ITH. Embankment slopes in continuous permafrost completely freeze with snow removal in November and in discontinuous permafrost with snow removal in December. Ponded water had little influence on active layer thickness, but influence was greatest in continuous permafrost.

Climate change influences on ITH snow management include more slippery sections, increased requirements for sand/gravel, and potential for embankment snow removal on northern sections. Increases in equipment and labor are also expected to maintain drainage as required by protocol. Embankment stability concerns due to climate change include increased slumps and slides, increased longitudinal cracking, reduced frost cracking, and more locations with thaw settlement.

Methods/ Approaches: (1) Survey of existing road maintenance companies and agencies; (2) Geothermal modelling; (3) Development of maintenance protocols; (4) Assessment of climate change influence on ITH maintenance.

Key findings/ suggestions: (1) Snow removal from embankment slope is beneficial for the southern ITH; (2) Maintenance efforts should focus on removal of ponded water from northern locations; (3) Climate warming will influence road stability and maintenance protocols; (4) Future studies should focus on influence of snow removal and compaction, and the influence of pavement color and reflection to embankment height design, culvert protection against early freezing, and snow density effects on embankment slopes.

Additional information/ links: Full descriptions of snow, drainage, and road distress protocols are available in:

'Interim Report: Improvement Maintenance Procedures for Highways in Permafrost Regions Volumes I, II, and III'.

Report title: Interim Report: Improved Maintenance Procedures for Highways in Permafrost Regions Volume I – Snow Accumulation

Project lead: Alexandre Tchekhovski

Affiliation: AMEC Foster Wheeler Environment & Infrastructure

Dates: 2014/2015; 2015/2016

Themes: Roads; Guidelines; Maintenance; Snow; Modelling;

Key terms: ITH; Surveys; Risk Assessment; Active Layer; Embankment; Snow Management; Freeze-up; Resource Allocations; Climate Change;

Objectives: (1) Develop maintenance protocols related to snow accumulation for the ITH; (2) Assess potential climate change impacts.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Northern%20Transportation%20Infrastructure-Improving%20Maintenance%20Procedures%20for%20Highways%20in%20Permafrost%20Regions.pdf

Summary:

Weather station data across northern Canada was compiled to better understand the climate along the ITH and similar northern roads. Stations were divided into four zones based on the duration of winter and average freezing degree days. The zones represent average conditions in a discontinuous permafrost region, a continuous permafrost region south of the ITH, the southern half of the ITH, and the northern half of the ITH.

Climatic conditions for each zone were input to a geothermal model to project the temperature of a road embankment under a variety of snow management scenarios. Results suggest the removal of embankment snow early in the winter reduces freeze-up time by one month but has minimal effect further north. This was most prominent in the lower half of the embankment, which freezes before the upper half. Therefore, early winter snow removal is recommended in areas prone to thaw subsidence in the southern ITH region to improve stability.

Eight northern road maintenance companies were surveyed to establish further context for protocol development. Responses indicated the snow removal period to be dependent on traffic conditions and road sections at risk of snow-related hazards. Snow fencing and trenching are recommended to reduce drifting, while gravelling is recommended in slippery sections. Climate warming is anticipated to increase maintenance costs by increasing slippery sections and the frequency of extreme precipitation events and reducing roadway stability. By 2050-2055, the climate of northern zones is likely to resemble those of more southerly zones.

Methods/ Approaches: (1) Identification of climate parameters and zones; (2) Survey results and published sources; (3) Geothermal modelling; (4) Provide inspection standards.

Key findings/ suggestions: (1) Time required for snow removal depends on the level of priority and volumes of traffic on the roadway; (2) Snow drifts occur most frequently along road cut sections and in manmade landscapes, and snow fences or trenches are recommended for mitigation; (3) Modelling suggests removal of embankment snow in October will significantly reduce freeze-up times; (4) The undisturbed lower half of the embankment freezes quickly in northern climate zones, therefore snow removal has little effect; (5) Conditions in each climate zone will likely resemble those in more southerly climate zones by 2050-2055.

Additional information/ links: N/A

Report title: Interim Report: Improved Maintenance Procedures for Highways in Permafrost Regions Volume II – Drainage

Project lead: Alexandre Tchekhovski

Affiliation: AMEC Foster Wheeler Environment & Infrastructure

Dates: 2014/2015; 2015/2016

Themes: Drainage; Modelling; Roads; Maintenance; Guidelines;

Key terms: Culverts; Bridges; Active layer; Embankment; ITH; Boundary layer; Ponding; Climate Change; Inspection; Remediation;

Objectives: (1) Determine the influence of surface water in relation to highway stability; (2) Assess potential climate change impacts.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Northern%20Transportation%20Infrastructure-Improving%20Maintenance%20Procedures%20for%20Highways%20in%20Permafrost%20Regions.pdf

Summary:

Geothermal modeling of highway embankments was carried out to assess the influence of ponded water on permafrost temperatures and active layer thicknesses across several climatic zones of north-western Canada. Finite element models examined the effect of various water depths (0.2 m and 0.4 m) on soil profiles composed of ice-rich peat underlain by ice-rich clay. Models showed the depth of ponded water to have little influence on active layer thickness across the climatic zones, but a greater effect on permafrost temperatures further north.

Therefore, more effort should be spent on removing water from and around highways in more northern locations (i.e., ITH), with a focus on areas experiencing damage associated with permafrost degradation. Areas with ongoing deterioration which facilitate ponding, should consider fill as a permanent solution to direct water towards culverts, transitional sections, bridges, and terrain drainage. This report provides standards for drainage inspection including performance ratings and remediation options, and maintenance cost considerations including cleaning equipment, water removal, repairs, and personnel. An anticipated rise in mean annual air temperature and precipitation by 2050-2055 will likely result in increased maintenance in northern locations where deepening permafrost levels may cause topographic flattening and depressions, which could encourage ponding. However, if the extent and duration of frozen soil decreases, drainage conditions will be improved due to seepage of surface water into deepening active layers and newly formed taliks.

Methods/ Approaches: (1) Identification of climate parameters and zones; (2) Survey results and published sources; (3) Geothermal modelling; (4) Provide inspection standards.

Key findings/ suggestions: (1) Ponded water depth has little influence on active layer thickness, but a greater effect on permafrost temperatures further north; (2) Maintenance efforts should focus on removing ponded water; (3) Additional equipment and labor will be required along the ITH due to extreme precipitation in the future; (4) Due to climate warming, ponded water may have less effect on warmer soils; (5) Drainage conditions will be improved where frozen soil is reduced, due to seepage of surface water into deepening active layers and newly formed taliks; (6) Ponding may be encouraged where deepening permafrost levels cause topographic flattening and depressions.

Additional information/ links: See Volume I – Snow Accumulation for physical and mathematical modeling.

Report title: Interim Report: Improved Maintenance Procedures for Highways in Permafrost Region, Volume III – Road Distress

Project lead: Alexandre Tchekhovski

Affiliation: AMEC Foster Wheeler Environment & Infrastructure

Dates: 2014/2015; 2015/2016

Themes: Maintenance; Roads; Guidelines; Mitigation;

Key terms: ITH; Climate Change; Repairs; Geotextiles; Remediation; Inspection; Sinkholes; Thaw Settlement; Embankment;

Objectives: (1) Describe common deficiencies influencing road conditions; (2) Provide standards to maintain road surface distresses; (3) Assess potential influence of climate change on road maintenance.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Northern%20Transportation%20Infrastructure-Improving%20Maintenance%20Procedures%20for%20Highways%20in%20Permafrost%20Regions.pdf

Summary:

Information from eight survey reports and road surface maintenance documents were consulted in preparation for the development of the road maintenance protocol. Survey results demonstrated typical road deficiencies and defects including, longitudinal cracks and sinkholes, embankment slumps, settling, heaving, and erosion. These deficiencies resulted from thawing of the subgrade or embankment material. Road repairs were generally conducted during warm air temperature seasons unless urgent repairs were required.

This report provides maintenance and repair standards to ensure safe road conditions. Protocols for road repair inspections include monthly routine and major biannual (spring and fall). Key mitigation activities for the ITH include road surface re-grading, reparation of settling, heaving, and cracking spots, excavating, and backfilling collapsed sections, and installation of geotextiles and insulation. Mitigation activities for road surface distresses are classified as Level 1, 2, and 3 with a timeframe for each activity. Level 1 work can be undertaken by maintenance contractors, while Level 2 and 3 require engineering inspection and design. Recommendations are provided for equipment and personnel to ensure protocol requirements.

Climate warming is anticipated to increase the frequency of embankment instabilities, longitudinal cracking, and thaw settlement on roads, and decrease frost cracking. Therefore, road surface maintenance should focus on embankment slopes and avoid disturbance of permafrost along the embankment toe.

Methods/ Approaches: (1) Identification of climate parameters and zones; (2) Survey results and published sources; (3) Provide road repair standards; (4) Assessment of road distress due to climate change.

Key findings/ suggestions: (1) Road deficiencies mainly occur due to thawing of subgrade or embankment material; (2) Maintenance companies should have offices and garages in Inuvik and Tuktoyaktuk, and a mechanical shop in Inuvik; (3) Materials required include clean sand, gravel, riprap, geotextile, and rigid insulation; (4) Future efforts should focus on maintenance of embankment slopes and prevent disturbance of permafrost along the embankment toe.

Additional information/ links: N/A

Report title: Remote Sensing and Northern Transportation Infrastructure Literature Review

Project lead: Lukas Arenson (larenson@bgcengineering.ca)

Affiliation: BCG Engineering Inc.

Dates: 2012/2013

Themes: Remote Sensing; Infrastructure; Airports; Roads; Monitoring;

Key terms: Literature Review; Remote Monitoring; Satellites; Terrain Mapping; Geohazards; Embankment;

Objective: Identify state-of-the-art remote sensing technologies that are applicable to transportation infrastructure related tasks in northern permafrost environments

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Remote%20Sensing%20and%20Northern%20Transportation%20Infrastructure%20Literature%20Review.PDF

Summary:

Several reoccurring problems are associated with northern transportation infrastructure constructed on thermally unstable permafrost including destabilized road subgrade and embankments, warped road surfaces, potholes, cracks, sideslope sloughing, culvert failure, and shoulder sinking. Identifying local climate and terrain conditions can inform design and maintenance decisions by helping to estimate the site-specific risk of these problems occurring. Remote sensing techniques offer a means of quickly obtaining this information over broad regions. The potential benefits and limitations of satellite, airborne and terrestrial sensing are discussed in this report.

Satellite remote sensing includes active microwave sensing which utilizes SAR, multispectral, and passive microwave imagery. These techniques are typically characterized by broad spatial coverage and spatial resolution comparable to terrestrial or airborne imagery but can be limited by lower temporal resolution or distorted by atmospheric conditions. Airborne remote sensing includes active microwave and electro-optimal imagery, LiDAR, and airborne electromagnetic mapping. These techniques typically allow for higher temporal resolution than satellite imagery and have the potential for higher spatial resolution but are limited by a narrow spatial coverage. Terrestrial remote sensing includes terrestrial laser scanning, remote logging of in-situ devices, and electrical resistivity testing. These techniques allow for highly accurate measurements and can determine a wide range of subsurface properties but are limited by their low spatial coverage. Multispectral sensors combined with photogrammetry are identified as widely applicable for usage on northern infrastructure, while photon counting LiDAR and solutions for seasonality in SAR based monitoring should be investigated further.

Methods/ Approaches: Identify and compare the potential utility of remote sensing for usage on northern transportation infrastructure.

Key findings/ suggestions: (1) Multispectral sensors are widely applicable due to their ability to evaluate changes in the surface energy balance; (2) Photon counting LiDAR and solutions for seasonality in SAR based monitoring should be investigated further; (3) Advances in UAV technology are expected to be useful for northern remote sensing; (4) remote sensing can complement but not replace site investigation, instrumentation, and inspections.

Additional information/ links: Appendix A of the project report summarizes the benefits, limitations and uses for each technology.

Report title: PIEVC Climate Change Vulnerability Assessment: Inuvik Airport

Project lead: Lukas Arenson (larenson@bgcengineering.ca)

Affiliation: BGC Engineering Inc.

Dates: 2015/2016

Themes: Airports; Climate Change; Adaptation; Mitigation; Maintenance;

Key terms: Inuvik; Risk Assessment; Drainage; Thaw Settlement; Repairs; Monitoring; Design; Performance Response; Workshop;

Objectives: (1) Identify likely effects of climate change and their impacts on defined airport infrastructure; (2) Complete consultations with interested parties; (3) Provide recommendations to address vulnerable engineering features.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-07/Northern%20Airport%20Vulnerability%20Assessment%20%28PIEVC%20for%20Inuvik%20Airport%29%20-%20Mike%20Zubko%20Inuvik%20Airport%20Climate%20Change%20Vulnerability%20Assessment.PDF

Summary:

Inuvik Mike Zubko Airport, located 12 km southeast of Inuvik off the Dempster Highway, is the regional hub for commercial and military air traffic. The airport contains a single paved runway (Runway 06/24) 1,830 m long and 45 m wide with a proposed eastward extension of 914 m. Permafrost is around 90 m deep and continuous with high ground ice contents (>20%) within 20 m of the surface. Subsidence and settlement of the pavement surfaces have occurred where antecedent drainage processes were blocked. Due to cost constraints during initial construction, the embankment thickness is not sufficient to prevent permafrost thaw.

Historic climate data (1985-2014) indicates a decrease in precipitation of 16 mm per decade and increasing mean annual air temperature (MAAT) of 0.8 °C per decade, mainly in fall and winter. Climate models forecast 3 °C rise in MAAT and 5-20% more precipitation by 2045 (relative to 1986-2005). Maintenance records suggest increased frost events on pavement surfaces. The PIEVC Protocol identified over 800 climate-infrastructure element pairs with 465 selected for risk assessments. The results identified 56 (12%) medium-low risk and 9 (2%) medium-high risk pairs. No high-risk pairs were identified since these require hazardous conditions with loss of an infrastructure element in response to climate change. Higher risks were associated with the drainage network, data availability, and visibility. The runway, foundations, winter maintenance, and snow clearing were listed as high consequence (i.e., risk is low, but failures would be highly unfavourable). Four of the pairs were classed as high priority due to a lack of data. No immediate action is required, but collection of additional baseline data is necessary.

Methods/ Approaches: (1) PIEVC protocol; (2) Analysis of historic climate data and climate models; (3) Risk assessment; (4) Engineering analysis.

Key findings/ suggestions: (1) The majority (86%) of climate-infrastructure pairs were low risk and none were high risk; (2) The drainage system and winter/summer flights are the infrastructure elements most vulnerable to climate change; (3) Frost on the runway and visibility are the two main climate events of concern; (4) Improve collection and monitoring of frost, visibility, and snow data; (5) Evaluate the drainage system; (6) Systematically document maintenance and repair efforts; (7) Re-assess climate change vulnerability in 5 years with interested parties.

Additional information/ links: N/A

Report title: PIEVC Climate Change Vulnerability Assessment: Cambridge Bay Airport

Project lead: Lukas Arenson (larenson@bgcengineering.ca)

Affiliation: BGC Engineering Inc.

Dates: 2015/2016

Themes: Airports; Climate Change; Modeling; Adaptation; Mitigation; Maintenance

Key terms: Cambridge Bay; Nunavut; Victoria Island; Risk Assessment; Repairs; Monitoring; Design; Performance Response; InSAR; Workshop;

Objectives: (1) Identify likely effects of climate change and their impacts on defined airport infrastructure; (2) Identify possible infrastructure-climate event interactions; (3) Provide recommendations for future studies.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-07/Northern%20Airport%20Vulnerability%20Assessment%20-%20%28PIEVC%20for%20Cambridge%20Bay%20Airport%29%20-%20Cambridge%20Bay%20Airport%20-%20Climate%20Change%20Vulnerability%20Assessment.PDF

Summary:

Cambridge Bay Airport, Nunavut's third busiest gateway airport, features a single gravel-surfaced runway 1,524 m long and 46 m wide. It is located within the continuous permafrost zone in southeastern Victoria Island, 2.6 km west of the hamlet of Cambridge Bay. It is Canada's only gravel runway serviced by jet aircraft (as of 2010) and is the Medevac base for the Kitikmeot Region. Due to increasing passenger and cargo demand, annual aircraft movements are expected to increase from 4,600 in 2015 to 8,100 in 2030.

Historic climate data (1986-2015) shows an increase in mean annual air temperature (MAAT) of 0.6 °C per decade (mainly in fall and winter), a decrease in freezing degree-days of 212 per decade, and an increase in thawing degree-days of 42 per decade, an increase in annual precipitation of 5.4 mm per decade (mainly in July and August), and a later occurrence of first snow days. Depending on the emissions scenario, climate models forecast 3-5 °C rise in MAAT and 10-40% more precipitation by 2045 (relative to 1986-2005).

Following the PIEVC Protocol for Climate Change Vulnerability Assessment, 32 climate and 24 airport infrastructure elements (totalling 768 climate-infrastructure combinations) were identified to undergo risk assessments. Unfortunately, a risk assessment workshop was not completed, therefore detailed engineering analyses could not be performed. Climate events deemed critically important to airport infrastructure include, climate variability, rainfall, visibility, ground thawing index, and frost. Current data have insufficient detail to accurately assess future trends, so systematic monitoring and collection of baseline data is required. No immediate action is required, but climate change will likely cause more frequent maintenance and repair.

Methods/ Approaches: (1) PIEVC protocol; (2) Analysis of historic climate data and climate models; (3) Risk assessment.

Key findings/ suggestions: (1) Systematic collection and monitoring of baseline climate; (2) Future engineering considerations associated with a changing climate include drainage, mechanical erosion, ponding, poor visibility, warming ground temperatures, active layer thickening, differential settlement, and sinkholes; (3) Complete a climate change vulnerability assessment every 5 years with interested parties.

Additional information/ links: N/A

Report title: PIEVC Climate Change Vulnerability Assessment: Churchill Airport

Project lead: Lukas Arenson (larenson@bgcengineering.ca)

Affiliation: BGC Engineering Inc.

Dates: 2015/2016

Themes: Airports; Climate Change; Modeling; Adaptation; Mitigation; Maintenance

Key terms: Churchill; Manitoba; Hudson Bay; Risk Assessment; Thaw Settlement; Repairs; Monitoring; Design; Performance Response; Workshop;

Objectives: (1) Identify likely effects of climate change and their impacts on defined airport infrastructure; (2) Complete consultations with interested parties; (3) Provide recommendations to address vulnerable engineering features.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Churchill%20Airport-Climate%20Change%20Vulnerability%20Assessment%20PIEVC.pdf

Summary:

Churchill Airport is located 6.5 km southeast of the community of Churchill, MB, on the southwestern shore of Hudson Bay. The airport includes two runways, one gravel (Runway 07/25, 1,219 m long) and one paved (Runway 15/33, 2,803 m long). Permafrost is continuous and about 80 m thick with an active layer thickness of 3 m. In 2007, massive ice underlying one of the taxiways was identified. Permafrost degradation has resulted in thaw settlements up to 150 mm and depressions on the taxiway and apron surfaces.

Historic climate data (1986-2015) show an increase in mean annual air temperature (MAAT) of 0.6 °C per decade (mainly in fall and winter), a decrease in freezing degree-days of 172 per decade, a decrease in annual precipitation of 33 mm per decade, and a later occurrence of first snow days. Depending on the emission scenario, climate models forecast 3-4 °C rise in MAAT and 5-10% more precipitation by 2045 (relative to 1986-2005).

The PIEVC Protocol identified over 1,000 climate-infrastructure element combinations with 639 undergoing detailed risk assessments. The results identified 64 (10%) medium-low and 8 (1%) medium-high risk pairs. Higher risks were associated with climate data availability, emergency procedures, and winter flight operations. Visibility is the main climate factor which may cause issues due to climate change. Despite low risks, runways, terminals, and access roads were deemed high consequence (i.e., failures would be highly detrimental). Six pairs were classed as high priority, requiring future management action and monitoring. No immediate action is required, but a more detailed monitoring system is necessary.

Methods/ Approaches: (1) PIEVC protocol; (2) Analysis of historic climate data and climate models; (3) Risk assessment; (4) Engineering analysis.

Key findings/ suggestions: (1) The majority (89%) of climate-infrastructure pairs were low risk and none were high risk; (2) The infrastructure element most vulnerable to climate change is the heterogeneity of permafrost (causing differential thaw settlement); (3) Visibility is expected to become more problematic with climate change; (4) Recommend the immediate deployment of a systematic monitoring system and database to combine infrastructure performance, air traffic operations and climate events; (5) Re-assess climate change vulnerability every 5 years with interested parties; (6) Use LiDAR or photogrammetry to monitor differential thaw settlements.

Additional information/ links: N/A

Report title:	Climate Change Impacts and Adaptation for Transport Networks and Nodes: Case Study 1 (Canada): All-Season Roads in Northern Canada and Implications of Climate Change
Project lead:	Lukas Arenson (larenson@bgcengineering.ca)
Affiliation:	BGC Engineering Inc.
Dates:	2018/2019
Themes:	Adaptation; Mitigation; Roads; Maintenance; Drainage; Monitoring;
Key terms:	Alaska Highway; Dry Creek; Beaver Creek; Salluit Airport; Climate change; Embankment; Fibre Optics; Thermosyphons; Culverts; Risk Assessment;
Objectives:	Discuss the implications of climate change on all-season roads in Northern Canada.
Link:	https://unece.org/DAM/trans/doc/2020/wp5/ECE-TRANS-283e.pdf

Summary:

The northernmost Canadian section of the Alaska Highway, YT, is constructed on sporadic and extensive discontinuous permafrost and identified as having high and moderate vulnerability to climate change. At the Beaver Creek Test Section, Laval University and others assessed different methods to increase heat extraction or limit heat input, studied thaw settlement vulnerability, and mapped thaw sensitive areas. At Dry Creek, the Yukon Government piloted thermosyphons to mitigate thaw of buried massive ice.

The Salluit Airport access road, Nunavik, QC, is constructed on ice-rich sloping terrain. It is experiencing permafrost degradation and road embankment damage in the form of significant differential settlement, active layer detachment slides at the embankment toe, and culvert damage. The Ministère de Transports du Québec (MTQ) and Laval University modified the embankment, improved water drainage, installed heat drains to stabilize vulnerable sections, and installed monitoring instrumentation (i.e., fibre optic technology). This information is expected to inform design criteria for transport infrastructures built on sensitive permafrost.

Methods/ Approaches:	(1) Assess infrastructure adaptation methods; (2) Install monitoring equipment; (3) Assess construction costs in permafrost and non-permafrost areas.
Key findings/ suggestions:	Permafrost sections along the Alaska Highway cost $22k to $36k more per year per km than non-permafrost regions.
Additional information/ links:	N/A

Report title: Five Year Review of the Beaver Creek Permafrost Test Site

Project lead: N/A

Affiliation: Brannoc Engineering

Dates: 2013/2014

Themes: Adaptation; Mitigation; Roads; Maintenance; Thaw;

Key terms: Beaver Creek; Embankment; Design; Thaw Settlement; Thermal Regime; Drilling; Construction; Air Convection Embankments; Active Layer; Groundwater;

Objectives: Research mitigation of highway distresses resulting from thawing permafrost.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Five%20Year%20Review%20of%20the%20Beaver%20Creek%20Permafrost%20Test%20Site_2.PDF

Summary:

Since 2008, research on the mitigation of highway distresses resulting from thawing permafrost has been completed near Beaver Creek on the Alaska Highway. Test mitigation techniques include air convection embankments (ACE); heat drains with ventilation pipes and geo-composite; longitudinal air convection ducts; snow/sun sheds; high albedo road surfacing; grass-covered side slopes; and side-slope snow removal.

The research is summarized into (1) effectiveness of the mitigation techniques; (2) effects of groundwater on the thermal regime; (3) detailed characterization of the test site geo-system; and (4) constructability and cost of mitigation techniques. Some of the techniques appear to be effective at lowering ground temperatures and stabilizing permafrost; however, there is still significant settlement of the embankment core due to the influence of groundwater flow. It would be premature to implement these techniques as part of a highway rehabilitation program unless groundwater effects are also addressed and there is greater certainty that rehabilitation would stabilize the embankment.

Each mitigation technique was ranked in order of their anticipated cost of construction, considering their expected lifespan and projected efficiency of scale over several kilometres of highway. However, better cost data are needed in order to facilitate decision making on highway rehabilitation strategies based on reliable life cycle analysis.

Methods/ Approaches: (1) Construct a road embankment test site; (2) Install monitoring equipment; (3) Assess the effectiveness of thaw mitigation techniques; (4) Characterize the test-site geo-system; (5) Estimate constructability and cost of mitigation techniques.

Key findings/ suggestions: (1) Mitigation techniques effective at lowering ground temperatures and stabilizing permafrost include, full ACE embankments, covered and uncovered ACE side slope treatments, snow/sun sheds, and longitudinal air convection ducts; (2) Less effective mitigation techniques include, side slope heat-drain treatments, light coloured BST surface treatments, full embankment heat drains, side-slope heat drains with insulation, side-slope snow plowing and grass covered side slopes; (3) Even effective techniques show significant embankment core settlement due to groundwater flow underneath.

Additional information/ links: Sixty-one published reports, articles and conference papers directly related to the Beaver Creek test site are provided in Appendix 1 and 2 of the project report.

Report title:	Scoping Study for a Proposal to Examine Highway Embankment Vulnerability to Snow Accumulation in Ice-rich Permafrost Terrain, Inuvik-Tuktoyaktuk Highway, NWT
Project lead:	Christopher Burn (christopher.burn@carleton.ca)
Affiliation:	Carleton University
Dates:	2012/2013
Themes:	Roads; Snow; Field survey;
Key terms:	Monitoring; ITH; Embankment; Design; Construction; Inuvik; Tuktoyaktuk; Treeline; Richards Island;
Objectives:	(1) Measure the effect of a road embankment on snow depth; (2) Measure the slope of the snowbank beside the road to assist design of embankment slopes.
Link:	https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Scoping%20study%20for%20a%20proposal%20to%20examine%20highway%20embankment%20vulnerability%20to%20snow%20accumulation%20in%20ice-rich%20permafrost%20terrain%2C%20%20Inuvik-Tuktoyaktuk%20Highway%2C%20NWT.pdf

Summary:

Snow conditions along the proposed route of the ITH were surveyed in March 2013. Snow depth was measured at 5 km intervals along the northern half of the route and across the tree line to the south. The source 177 haul road was surveyed to determine the slope of the snow surface beside the road and the snow depth at the embankment toe. Snow depth was measured at a site with a long-term record on Richards Island to establish the long-term temporal context of measurements. Along the sides of the embankment the snow surface elevation was determined by optical level in relation to the top of the side slope. Snow depth was measured at each point that was levelled.

Snow on the sides of the haul road embankment had slopes between 1:5 and 1:7. Snowbanks 1 m deep were located at the embankment toe. The thinnest snow covers were in uplands but in the lowlands the snow was up to 1 m deep. Mean snow depths were greater than 40 cm along the northern section. In the south, depths increased across tree line from 40 cm in the tundra to over 1 m in the willows. The survey on Richards Island placed data close to mean values in 17 years of surveys since 1997. Data collected in 2013 are likely representative of normal conditions.

Methods/ Approaches:	(1) Field survey; (2) Comparison of conditions north and south of tree line; (3) Comparison with long-term records.
Key findings/ suggestions:	(1) Snow over 1 m deep was common near the toe of the haul road embankment; (2) Snow surface slopes beside the embankment were between 1:5 and 1:7 at sites aligned north-south and were less on an east-west trending alignment; (3) Snow depths in undisturbed terrain were 40 cm or greater. Snow depths in flat terrain were influenced by vegetation, especially near creeks; (4) Snow up to 1 m deep was measured at the base of slopes; (5) In the south, snow depths increased from 40 to 90 cm with vegetation size and density; (6) Deepest snow was measured within 15 km of Inuvik. Snow management will be critical in this region as local accumulation may be compounded by the embankment.
Additional information/ links:	N/A

Report title:	NSERC PermafrostNet Data Workshop 2020: Transport Canada Engagement Report
Project lead:	Nicholas Brown (nick.brown@carleton.ca)
Affiliation:	NSERC PermafrostNet
Dates:	2020/2021
Themes:	Data; Standards;
Key terms:	Data Quality; Data Management; Data Accessibility; Workshop;
Objectives:	Build on previous workshops that highlighted the need for accessible permafrost data and greater support throughout the data creation process by (1) adding specificity and context to established data needs and (2) outline next steps.
Link:	N/A

Summary:

The NSERC PermafrostNet virtual workshop on permafrost data took place May 27-29, 2020, with a total of 81 participants from five provinces, three territories and five different countries (Canada, USA, Switzerland, China, and Japan). The workshop made use of several collaboration platforms including Zoom (for videoconferencing), Mural (to display digital flipcharts and sticky-notes), ThoughtExchange (for collecting and ranking survey information), and Google Docs (for collaborative writing).

A pre-workshop survey and two sessions identified the needs, challenges, and solutions in sharing permafrost data. PermafrostNet's data policy was also explored, specifically the adoption of a data quality management plan and the issue of open data release. Three sessions were dedicated to the topic of permafrost data interoperability such as prioritizing data types for interoperability, adopting vocabularies and semantics for sharing permafrost data, and adopting shared standards and specifications for efficient data sharing. Finally, two sessions focused on developing a long-term strategy for a permafrost data management system.

The main theme emerging from the workshop was a lack of available resources to put towards data gathering, cleaning, and disseminating at all levels of the data management process. A remaining challenge is ensuring access to standardized data, and the discoverability of data. Other themes included the importance of using existing tools and solutions to conserve resources, avoid the duplication of effort and ensure long-term sustainability, and the need for continued communication so data systems do not develop in isolation from one another.

Methods/ Approaches:	(1) Three-day online workshop; (2) Pre-workshop survey.
Key findings/ suggestions:	(1) Participants highlighted a lack of resources for gathering, cleaning, and disseminating permafrost data, therefore capacity-building is needed at all levels; (2) Using existing tools and solutions is important to conserve resources, avoid the duplication of effort and ensure long-term sustainability; (3) Access to standardized data by technical users and discoverability of data by non-technical users remains a challenge; (4) Continued communication will be essential to ensure data systems do not develop in isolation.
Additional information/ links:	Brown, N., *et al.* (2020). Permafrost Data Workshop Final Report. *NSERC PermafrostNet*, Ottawa, ON. DOI: 10.22215/pn/10120001.

Report title: Contributions of Earth Observation Technologies to Transport Canada Priorities

Project lead: Paul Adlakha (paul.adlakha@c-core.ca)

Affiliation: C-CORE (LOOKNorth)

Dates: 2014/2015

Themes: Remote Sensing; Monitoring; Project Development;

Key terms: Earth Observation; Satellites; Aircraft; Coastal Erosion; Marine; Railways; Airports; Collaboration; Resource Allocations; Interview;

Objectives: (1) Collect geo-information requirements of Transport Canada to develop a plan for identifying, engaging, and consulting interested parties; (2) Link EO capabilities with information needs to identify where EO is present, not present, and/or may be integrated within transportation projects.

Link: N/A

Summary:

Canada's transportation system faces increasing challenges from climate change effects and extreme weather, reduced Arctic ice cover, and aging infrastructure, resulting in increased pressure on Transport Canada and its resources to effectively perform its mandate. Existing and emerging Earth Observation (EO) technologies provide opportunities to manage the increased workload more efficiently and investigate new projects.

Using an Information Gathering Plan (IGP), C-CORE interviewed interested parties and identified thirteen projects currently utilizing EO or deemed technically feasible for EO: (1) Airport assessment infrastructure; (2) Vessel detection and identification; (3) Vessel risk assessment; (4) Ice crystals in clouds; (5) Ship routing support; (6) Railway route rock slides; (7) Bridge monitoring; (8) Site monitoring for emergency responders; (9) Zone/date guidelines audit; (10) Climate change impacts on ice roads; (11) Coastline erosion monitoring; (12) Iceberg deterioration; and (13) EO data for Navigation Protection Program (NPP) compliance monitoring support. Further analysis and preliminary outlines were created for several projects where EO techniques could be further developed.

Methods/ Approaches: (1) C-CORE Information Gathering Plan (IGP); (2) Interviews with interested parties; (3) Assessment of EO capabilities and needs; (4) Development of preliminary project outlines.

Key findings/ suggestions: (1) Identify additional projects where EO may be applied; (2) Identify potential end-users for consultations on project development; (3) Implement a remote sensing resource group within Transport Canada to better support end-users; (4) Research and develop EO capabilities for monitoring ice roads, cloud ice crystals, and iceberg deterioration; (5) Further develop pilot project definitions.

Additional information/ links: N/A

Report title:	Towards a Guideline for Assessing Climate Change Vulnerabilities of Northern Airports
Project lead:	Andy Kwong (andy.kwong@csagroup.org)
Affiliation:	CSA Group
Prepared by:	Heather Brooks, BGC Engineering Inc. (hbrooks@bgcengineering.ca)
Dates:	2019/2020; 2020/2021
Themes:	Airports; Climate Change; Policy; Protocol Standardization; Adaptation;
Key terms:	Risk Assessment; Vulnerability Assessment; Data Accessibility; Literature Review; Interview; Design; Collaboration;
Objectives:	(1) Compile information on existing climate risk and vulnerability assessments; (2) Identify components to be included within and to improve future assessments.
Link:	https://www.csagroup.org/wp-content/uploads/CSA-Group-Research-Climate-Change-Vulnerabilities-Northern-Airports-1.pdf

Summary:

Transportation networks connect northern communities with southern Canada. Air travel is important for northern communities which would otherwise be isolated. In total, 202 Canadian airports are in northern regions of which 156 are within or near permafrost regions. The term “northern” here refers to environments “controlled by extended periods of freezing temperatures and associated terrain conditions [commonly associated with permafrost]” which differs from more common definitions of “The North”. Despite being critical infrastructure components, insufficient attention has been paid to northern airports by national policymakers. In the context of climate change, which is amplified in northern regions, development of a set of guidelines and best practices for climate change vulnerability assessments of northern airports is crucial.

A review of relevant literature identified key climate trends, and methodologies used in previous vulnerability assessments (e.g., PIEVC). However, where assessments were undertaken, they were often not standardized, not repeated, and resulted in few adaptations. An online questionnaire and interviews with twenty-seven respondents from interested parties (engineering firms, government agencies, air service operators, etc.) were performed to better understand the nature of previous assessments and future requirements. The responses suggested that (1) operational and maintenance activities are difficult to include in existing methodologies; (2) there is often little action taken upon completion of the assessments; and (3) there is moderate interest in the standardization of assessments. Therefore, a standard protocol for performing climate change risk and vulnerability assessments for northern airports should be developed.

Methods/ Approaches:	(1) Literature review; (2) Stakeholder questionnaire and interviews.
Key findings/ suggestions:	(1) Previously-completed risk and vulnerability assessments contain many inconsistencies and often lack influence on decision-making; (2) Standardize guidelines for assessments including consistent methodology and terminology, assessments of uncertainty, inclusions of climate and climate change parameters, and applications to decision-making; (3) Future assessments should holistically include infrastructure components, and operations and maintenance activities; (4) The PIEVC protocol could act as a framework for the new standards.
Additional information/ links:	N/A

Report title: Scoping Study of Climate Data and Infrastructure for Specific Northern Labrador Communities

Project lead: Jamee DeSimone (jdesimone@dillon.ca)

Affiliation: Dillon Consulting Ltd.

Dates: 2020/2021

Themes: Climate Change; Adaptation; Infrastructure; Community; Data;

Key terms: Labrador; Transportation; Maintenance; Risk Assessment; Data Accessibility; Database; Interview;

Objectives: (1) Describe existing transportation infrastructure and operations among six remote Northern Labrador communities; (2) Identify climate risk information needed for an assessment of present and future infrastructure.

Link: N/A

Summary:

This project aims to assess the availability of transportation data for infrastructure and operations in six remote Northern Labrador communities (Hopedale, Makkovik, Nain, Natuashish, Postville, and Rigolet), and to also assess the availability and quality of climate data for this area. Potential climate change induced challenges include surface warming up to three times the global average and altered storm and sea ice characteristics. These factors can undermine the structural stability of coastlines and coastal infrastructure, particularly where regional transportation infrastructure is limited.

To better inform future decision making about these challenges, this study will identify existing transportation infrastructure and operations within the six communities, compile existing climate data, and offer practical solutions to missing data deemed necessary for a complete risk assessment. Infrastructure information will be obtained through a literature review and interviews with provincial government representatives and a number of transportation operators. Climate data will be obtained through a combination of weather stations and previous regional research efforts. Once the data has been compiled, gaps in the data preventing an informed risk assessment will be identified and practical solutions will be recommended.

Methods/ Approaches: (1) Literature review and survey of regional infrastructure; (2) Identify relevant climate variables; (3) Compile climate data; (4) Identify data gaps and offer solutions.

Key findings/ suggestions: Determined upon project completion.

Additional information/ links: N/A

Report title: Draft Summary: Adapting Northern Airport Infrastructure to Climate Change

Project lead: Pascal Garand

Affiliation: Englobe Corp.

Dates: 2015/2016

Themes: Airports; Climate Change; Adaptation; Mitigation; Maintenance;

Key terms: Kuujjuaq; Nunavik; Albedo; Active Layer; Sub-surface Water Flow; Cracking; Embankment; Pavements;

Objectives: (1) Summarize and evaluate reports produced for the TC research project on climate change mitigation for Runway 07/25 at Kuujjuaq Airport; (2) Identify key findings and recommendations for adaptation and mitigation of climate change.

Link: N/A

Summary:

Transport Canada (TC) initiated a study program in 2006 to assess permafrost conditions under Runway 07/25 at Kuujjuaq Airport in Nunavik, QC in anticipation of climate change effects. Several subjects were identified for mitigation measures including, (1) runway surface albedo to minimize heat transfer and reduce permafrost thaw; (2) runway texture to maintain safe friction levels in a changing climate; and (3) management of ground and surface water to combat increases in precipitation and freeze-thaw cycles. Further adaptation studies were performed from 2011 and Englobe was tasked with summarizing and evaluating six reports (listed therein, p.6).

Ground thermal regime studies suggested differences in albedo between the runway and embankment promoted a horizontal ground temperature gradient, warming of embankments and enhanced groundwater flow. Abrasion from mechanical sweepers has increased macro-texture and decreased micro-texture of the runway surface. Consequently, the runway friction number has fallen towards the minimum safety threshold. Pavement cracking and deeper active layers below the runway have increased water infiltration, occasionally reaching the pavement surface after significant precipitation.

Methods/ Approaches: Review and summarize six reports to address the state of knowledge and identify key findings and recommendations.

Key findings/ suggestions: (1) Research satisfies the majority of TC objectives; (2) The albedo of Runway 07/25 caused a horizontal temperature gradient and warming of embankments; (3) Increased pavement cracking and active layer depths enhanced water infiltration and collection below the runway creating surface deformations; (4) Mechanical sweepers and aircraft tires altered the runway texture, decreasing friction levels toward the minimum safety threshold; (5) An ESG-10 type asphalt mix should be used for resurfacing; (6) Conduct annual in situ runway surface measurements and perform simulations of sub-surface water flow.

Additional information/ links: N/A

Report title: Climate Change Vulnerability Assessment Dempster Highway, YT/NT

Project lead: N/A

Affiliation: Government of Northwest Territories (GNWT)

Prepared by: Richard Trimble, Tetra Tech EBA Inc. (richard.trimble@tetratech.com)

Dates: 2013/2014; 2014/2015

Themes: Climate Change; Adaptation; Mitigation; Maintenance; Roads;

Key terms: Dempster Highway; Monitoring; Data Management; Ground Temperature; Culverts; Thermokarst; Ground Ice; Thaw Settlement; Construction; Bridges;

Objectives: (1) Determine if there is sufficient information to conduct a PIEVC assessment of the highway; (2) Determine feasibility and scope for a systematic vulnerability assessment for improving highway management; (3) Develop a scope for future maintenance management to climate change impacts along the highway.

Link: N/A

Summary:

This report outlines the first phase in a study to assess the vulnerability of the Dempster Highway to the potential impacts of current and future climate warming. During a 2013 field examination, Tetra Tech EBA, Carleton University, and the Governments of NWT and Yukon gathered information about maintenance requirements related to climate change. A summary workshop was held after the field work to present and discuss the information obtained. To improve the feasibility of a PIEVC assessment on linear infrastructure, the route was divided into seven terrain segments with identified maintenance priorities linked to climate change effects.

Due to a lack of geotechnical and environmental data within the segments an instrumentation and monitoring program was initiated along the entire route. The greatest hazards for highway safety and maintenance are thawing fine-grained permafrost foundation soils with significant ground ice and more extreme weather events. These should be addressed in future upgrades to operating and maintenance procedures.

Methods/ Approaches: (1) Collect existing data; (2) Multi-collaborative meetings and field trips between engineers and scientists (3) Workshop.

Key findings/ suggestions: (1) Document locations vulnerable to permafrost thaw; (2) Identify and monitor thermokarst features threatening embankment integrity; (3) Review functionality of culverts; (4) Document sinkhole formation to identify a probable cause and mitigation procedures; (5) Identify locations where embankment side slopes are progressively failing to evaluate the risk of overall rapid slope failure and adopt a proactive mitigation procedure to protect the road from sudden collapse.

Additional information/ links:

(1) Burn, C.R., Moore, J.L., O'Neill, H.B., Hayley, D.W., Trimble, J.R., Calmels, F., Orban, S.N., and Idrees, M. (2015). Permafrost characterization of the Dempster Highway, Yukon and Northwest Territories. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 705.

(2) O'Neill, H.B., and Burn, C.R. (2017). Impacts of variations in snow cover on permafrost stability, including simulated snow management, Dempster Highway, Peel Plateau, Northwest Territories. *Arctic Science*, 3(2), 150-178. DOI: 10.1139/as-2016-0036.

Report title: Inuvik to Tuktoyaktuk Highway Permafrost Research and Development Project, Phase 1 (2015/2016 Progress Report)

Project lead: N/A

Affiliation: Government of Northwest Territories (GNWT)

Dates: 2013/2014; 2014/15; 2015/2016

Themes: Roads; Adaptation; Maintenance; Monitoring; Drainage;

Key terms: Construction; ITH; Collaboration; Design; Embankment; Geotextiles; Thermal Regime; Engineering; Stream Crossings;

Objectives: (1) Test and evaluate innovative highway construction techniques; (2) Compare geotextiles and unreinforced highway sections; (3) Test the applicability of alternate stream crossing structures;

Links: N/A

Summary:

Construction of the ITH provided an opportunity to test and evaluate innovative highway construction techniques aimed at mitigating long-term maintenance liabilities related to permafrost degradation. The Government of Canada and the Department of Transportation (DOT) Government of Northwest Territories (GNWT) collaborated on two research projects associated with Phase 1 of the ITH from 2014-2016. The first project, "Monitoring of the structural stability of highway embankments along the ITH corridor", compared the use of geotextiles as a method of minimizing embankment movements with an unreinforced section. To achieve this, DOT contracted the University of Manitoba to construct and monitor two test sections. The second project, "Innovative watercourse crossings along the ITH", tested the applicability of alternate means of constructing stream crossings to reduce the potential disruption to the thermal regime, and manage impacts to the highway. DOT contracted Terratech Consulting Ltd. to design and monitor crossing structures at km 22.2 of the ITH.

Methods/ Approaches: (1) Construct and monitor highway test sections; (2) Construct and monitor crossing structures; (3) Multi-collaboration.

Key findings/ suggestions: Determined upon project completion.

Additional information/ links:

(1) De Guzman, E.M.B, Alfaro, M., Doré, G., Arenson, L.U., and Piamsalee, A. (2021). Performance of highway embankments in the Arctic corridor constructed under winter conditions. *Canadian Geotechnical Journal*, 53 p. DOI: 10.1139/cgj-2019-0121.

(2) Ensom, T., Kokelj, S.V., and Marsh, P. (2019). Thermal regime of stream channels in continuous permafrost, western Canadian Arctic. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 254-262. DOI:10.1061/9780784482599.030.

(3) Ensom, T., Makarieva, O., Morse, P., Kane, D., Alekseev, V., and Marsh, P. (2020). The distribution and dynamics of aufeis in permafrost regions. *Permafrost and Periglacial Processes*, 31(3), 383-395. DOI: 10.1002/ppp.2051.

Report title: Monitoring Study: Yellowknife Highway #3 Construction Test Sections (2015/ 2016 Final Report)

Project lead: N/A

Affiliation: Government of Northwest Territories (GNWT)

Dates: 2013/2014; 2014/2015; 2015/2016

Themes: Roads; Thaw; Climate Change; Adaptation;

Key terms: NWT Highway 3; Yellowknife; Embankment; Construction; Design; Cracking; Repairs; Thermal Regime; Culverts; Maintenance;

Objective: Develop rehabilitation techniques for roads constructed on warm, ice-rich permafrost

Link: N/A

Summary:

As part of a program to investigate road instability along the final 100km of NWT Highway 3, four test sections were constructed to develop rehabilitation techniques for roads built on warm, ice-rich permafrost. The goals were to (1) evaluate and compare two reinforcement techniques for limiting differential settlement over transition areas; (2) evaluate a new construction technique for installing culverts in permafrost areas; (3) reduce the potential for water flow through the embankment; (5) assess the thermal and structural benefits of using foamed cellular concrete for roads constructed over permafrost; and (6) assess the thermal benefits of a ventilated shoulder. Each section was inspected in May and September for three years following construction. Test section 1 experienced 7 cm of thaw settlement, however techniques used during construction were not specified. No deformation or settlement was observed at the other sections.

Methods/ Approaches: (1) Design and construct highway test sections; (2) Install thermistor cables within the embankment; (3) Inspect each section biannually for three years.

Key findings/ suggestions: (1) A ventilated embankment shoulder recorded consistently cooler temperatures than the standard construction embankment section; (2) Cellular concrete installed beneath the road base resulted in warmer winter temperatures and cooler summer temperatures relative to the standard embankment.

Additional information/ links:

(1) Stirling, J.L., Seto, J., Arenson, L.U., and Abu Bakar, M. (2015). NWT Highway 3 test sections near Yellowknife. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 343.

(2) Wolfe, S.A., Morse, P.D., Hoeve, T.E., Sladen, W.E., Kokelj, S.V., and Arenson, L.U. (2015). Disequilibrium permafrost conditions on NWT Highway 3. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 115.

Report title: Northwest Territories (NWT) Transportation Monitoring Program (Final Report)

Project lead: N/A

Affiliation: Government of Northwest Territories (GNWT)

Dates: 2016/2017; 2017/2018

Themes: Roads; Adaptation; Maintenance; Monitoring; Drainage;

Key terms: Construction; ITH; Collaboration; Design; Embankment; Geotextiles; Thermal Regime; Engineering; Stream Crossings;

Objectives: (1) Understand lateral spreading operating mechanisms; (2) Compare the performance of highway test sections; (3) Understand winter water flow and performance of culverts; (4) Assess the applicability of alternate stream crossing structures; (5) Determine suitable rehabilitation techniques for warm permafrost.

Links: N/A

Summary:

The program comprised four projects, (1) ITH embankment test sections; (2) Installation of twenty-four additional thermistors and other instrumentation along the ITH with on-going monitoring; (3) Examination of alternate watercourse crossing structures (ITH and Mackenzie Valley Winter Road); and (4) Highway 3 construction test sections. Project 1 aimed to understand the operating mechanisms of lateral spreading and compare the performance of test sections with other highway sections. Overall, it offered a better understanding of the performance of northern highway embankments and an evaluation of the effectiveness of wicking geosynthetic reinforcements to improve structural stability of high embankment fills.

Project 2 monitored temperature fluctuations in the roadbed, embankment, right of way and riparian areas. The latter monitored upstream of problematic or experimental culverts to understand winter water flow and inform performance. Altogether, this information provided baseline data from three sections representing a steep climate and ecological gradient. Project 3 assessed the applicability of innovative alternate stream crossing structure designs at three locations to reduce thermal regime disruption and manage its impact on the highway. Strawberry Creek and 4 Mile Creek included two open bottom arch structures (GRS arches) with geotextile. Crossings at ITH site 15 included conventional structural plate corrugated steel pipe (SPCSP), plastic culverts, and an embedded SPCSP. Project 4 utilized existing test sections to determine rehabilitation techniques for roads constructed on warm discontinuous/sporadic permafrost.

Methods/ Approaches: (1) Monitor highway test sections; (2) Monitor temperatures in the road and right of way; (3) Monitor crossing structures.

Key findings/ suggestions: *Project 1:* (1) Reinforced section performs better than control section after one winter; (2) Less lateral movement and surficial cracking in the reinforced section; (3) Longer term analysis is required for continued monitoring to allow for a sustainable and more easily maintained highway. *Project 2:* (1) Created a research corridor which has received national and international attention. *Project 3:* (1) Designs need to consider thermal stresses due to expansion of the metal arch, fixed foundation conditions and post construction settlement, water management; (2) LiDAR scans to assess structural movement. *Project 4:* (1) Roads designed to preserve ice-rich warm permafrost are uneconomic.

Additional information/ links: See additional information/links in ‘Inuvik to Tuktoyaktuk Highway Permafrost Research and Development Project, Phase 1 (2015/2016 Progress Report)’ and ‘Monitoring Study: Yellowknife Highway #3 Construction Test Sections (2015/ 2016 Final Report)’.

Report title:	A Permafrost Data Management and Analytical System for the Dempster and Inuvik to Tuktoyaktuk Highways
Project lead:	Ashley Rudy (Ashley_Rudy@gov.nt.ca)
Affiliation:	Government of Northwest Territories (GNWT)
Dates:	2018/2019; 2019/2020; 2020/2021
Themes:	Infrastructure; Data Management; Remote Sensing; Monitoring; Roads;
Key terms:	Dempster Highway; ITH; Collaboration; Database; Remotely Piloted Aircraft System (RPAS); Ground Temperature; Geotechnical; Guidelines; Workshop;
Objectives:	(1) Develop an NWT Permafrost Database for the Dempster Highway and ITH; (2) Support the analysis and synthesis of permafrost data and relevant project information conducted along the corridor; (3) Support the completion of existing test section research and development on the ITH.
Link:	N/A

Summary:

Significant resources have been invested in the collection of permafrost and geotechnical information for infrastructure design and maintenance purposes in the NWT, and a growing instrumentation network has been deployed to monitor permafrost-road dynamics. In collaboration with the Department of Infrastructure (INF), over 130 ground temperature monitoring sites are maintained along the corridor. The development of an NWT Permafrost Database will allow the GNWT and its partners to realize the potential of this information and address a critical climate change issue facing Canada's transportation infrastructure.

Geotechnical and ground temperature templates have been developed to standardize data collection and facilitate data management and access. Contractors, academic partners, and research collaborators will be required to use templates. The NTGS is also developing permafrost monitoring templates in collaboration with the Aurora Research Institute (ARI) and Inuvialuit Land Administration (ILA) in Inuvik. Existing ground temperature and geotechnical datasets have been formatted and published as NTGS Open Reports. The NTGS is working with Canadian partners to ensure interoperability between permafrost database systems.

In collaboration with the GNWT Centre for Geomatics, the NTGS is collecting spatial data along the corridor to examine landscape, hydrological and infrastructure-related changes using Remotely Piloted Aircraft (RPAS) surveys, including a retrogressive thaw slump which threatens the Dempster Highway. The GNWT's capacity to manage and analyze the geotechnical, ground temperature, and geohazard data along important infrastructure corridors is critical for evidence-based decision-making, and to inform maintenance and mitigation of road infrastructure in a changing climate. Knowledge gained from this work will result in a more secure and resilient infrastructure corridor.

Methods/ Approaches:	(1) Collect and summarize permafrost data; (2) Consult partners; (3) Organize meetings and workshops; (4) Disseminate knowledge.
Key findings/ suggestions:	Determined upon project completion.
Additional information/ links:	Over 30 reports and conference presentations listed therein. GNWT Open Reports can be found at: https://webapps.nwtgeoscience.ca/WebAppsV2/Searching/ReferenceSearch.aspx.

Report title: Understanding Permafrost Processes under the Iqaluit Airport: Final Report

Project lead: Art Stewart

Affiliation: Government of Nunavut

Prepared by: Valérie Mathon-Dufour, Université Laval

Dates: 2012/2013; 2013/2014; 2014/2015

Themes: Airports; Climate Change; Modelling; Ground Ice;

Key terms: Iqaluit; Nunavut; Baffin Island; Remote Sensing; Drilling; Thermal Regime; Cracking; Thaw Settlement; Drainage; Mapping;

Objectives: Acquire and synthesize information on permafrost processes and characteristics below the Iqaluit Airport to compensate for knowledge gaps.

Link: N/A

Summary:

Iqaluit International Airport, situated in southeast Baffin Island, hosts the longest runway (3 km) in Nunavut. Active layer thicknesses at the airport were 1.24 m in natural ground and 2.94 m below paved surfaces for 2010-2015. Mean annual air temperatures (MAAT) at Iqaluit are expected to increase 2.5 °C by 2050. Several techniques were used to characterize permafrost below the airport. Maintenance records indicated issues with pavement cracking, subsidence, and drainage issues. InSAR measurements indicated annual cycles of winter heave and summer subsidence, especially in the central runway. GPR and permafrost drilling indicated ice-rich ground and ice wedges underlying much of the runway. Pavement cracking was also common in the southern half of the runway.

Thermal regime modelling was performed for three climate scenarios between 2015 and 2050, (1) stabilization of 2000-2014 temperatures; (2) 2.5 °C increase in MAAT; and (3) occurrence of five consecutive warm years. In scenario 1, ground thermal profiles quickly stabilized and remained so until 2050. Scenario 2 showed increased near-surface ground temperatures and active layer depths from 2025. Scenario 3 simulated a 'burst' of climate warming, resulting in steady ground warming over the 5-year period with active layer thicknesses increasing in the first year and stabilizing thereafter.

Methods/ Approaches: (1) Historic photo interpretation; (2) Surface geology and ground displacement (InSAR) mapping; (3) Permafrost drilling and core analysis; (4) Geophysical surveys (GPR); (5) Analysis of historic climate data; (6) Geothermal modelling.

Key findings/ suggestions: (1) Subsidence and heave of the central runway section result from a perched water table; (2) Ice wedges exist extensively under the runway and near-surface ground ice is common under southern runway sections; (3) Thermal regimes below the pavement are shifting more rapidly with climate change than undisturbed ground with future consequences for thaw settlement; (4) Develop a system to monitor infrastructure performance to avoid repetition of problems.

Additional information/ links: (1) Mathon-Dufour, V., Allard, M., and Leblanc, A-M. (2015). Assessment of permafrost conditions in support of the rehabilitation and adaptation to climate change of the Iqaluit airport, Nunavut, Canada. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 146.

Report title: Establishment of Baseline Data Collection Sites and Assessment of Permafrost Response to Climate Warming for Transportation Infrastructure in Yukon and NWT

Project lead: Paul Murchison (Paul.Murchison@yukon.ca)

Affiliation: Government of Yukon

Dates: 2013/2014; 2014//2015; 2015/2016

Themes: Infrastructure; Monitoring; Modelling; Climate Change;

Key terms: Thermal Regime; Dempster Highway; Transportation; Boreholes; Embankment; Database; Thaw Settlement; Weather Stations;

Objectives: (1) Determine the thermal regime in permafrost at strategic sites along the Yukon and NWT transportation networks; (2) Model the sensitivity of permafrost to climate warming at a selected site; (3) Determine the time frame for permafrost degradation that may have significant effects on highway embankments.

Link: N/A

Summary:

Much of the transportation network in northwestern Canada has been constructed over permafrost, some of which is ice-rich and sensitive to disturbance. The objective of the project was to establish baseline permafrost conditions throughout the network, estimate the sensitivity of permafrost to future warming, and determine its impact on highway embankments.

The project proposed the installation of thermistors underneath and adjacent to the embankment at several sites deemed vulnerable to the impacts of permafrost degradation in order to monitor the ground thermal regime. As well as local site conditions such as air temperature, wind speed and direction, snow depths, and drill logs to determine the stratigraphy at each site.

The intended project outcomes include a numerical simulation of the ground thermal regime underlying and adjacent to at least one section of road, with a second section being added if timing and budget permit. Following calibration of the model, potential climate changes can be simulated using a variety of scenarios from Environment Canada. The total thermal effect of climate warming will then be simulated on the highway embankment.

Methods/ Approaches: (1) Install thermistor cables at six to nine transportation infrastructure sites; (2) Characterize site conditions using fieldwork and borehole data; (3) Data compilation; (4) Data analysis and simulation; (5) Numerical modelling.

Key findings/ suggestions: Determined upon project completion.

Additional information/ links:

(1) Burn, C.R., Moore, J.L., O'Neill, H.B., Hayley, D.W., Trimble, J.R., Calmels, F., Orban, S.N., and Idrees, M. (2015). Permafrost characterization of the Dempster Highway, Yukon and Northwest Territories. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 705.

(2) O'Neill, H.B., and Burn, C.R. (2015). Permafrost degradation adjacent to snow fences along the Dempster Highway, Peel Plateau, NWT. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 7 p. Paper 219.

Report title: Sensitivity of Dempster Highway Hydrological Response to Climate Warming: Final Report

Project lead: J. Richard Janowicz (deceased)

Affiliation: Government of Yukon

Dates: 2013/2014; 2014/2015; 2015/2016

Themes: Hydrology; Mapping; Modelling; Data; Climate Change

Key terms: Dempster Highway; Database; Hydrotechnical; Weather Stations; Risk Assessment; Terrain Mapping; Hydraulic Conductivity; Active Layer;

Objectives: (1) Quantify the timing, magnitude, and interaction of water balance components along the Dempster Highway; (2) Assess the sensitivity of hydrologic response to climate warming and associated permafrost thaw.

Link: N/A

Summary:

Climate change has altered hydrological cycles in northern regions, resulting in greater flood risk and negative impacts on infrastructure. A hydrological assessment of the Dempster Highway corridor was performed to quantify current water balance components and assess the effects of climate change. The corridor was divided into ten ecoregions, and a database of physical, hydrological, and meteorological characteristics of a selected representative watershed from each region was developed. Data was gathered from existing meteorological and hydrometric stations. Two new stations were constructed where data was unavailable.

The data was input to the Cold Regions Hydrological Model (CRHM), a physically based hydrological model incorporating global radiation, shortwave and longwave radiation, albedo, net radiation, blowing snow and sublimation, evapotranspiration, runoff routing, soil moisture, canopy interception, frost table thaw, snow accumulation and melt, and soil infiltration. After the model was calibrated to local conditions, forty-one different climate change scenarios were assessed. The model simulated a 1 °C to 5 °C increase in mean annual temperature, 5% to 30% more precipitation in the summer and 10% to 60% in the winter. The response to these climate scenarios varied significantly between ecoregions. Some locations experienced a compensation effect between increasing temperature and precipitation, likely due to warmer temperatures decreasing the proportion of precipitation falling as snow and consequently snowpack depth. Additionally, greater evaporation losses are expected due to increased temperatures.

Methods/ Approaches: (1) Divide the Dempster Highway corridor into ecoregions; (2) Compile available climatological data; (3) Install weather stations; (4) Hydrological Modelling in CRHM; (5) Test climate change scenarios.

Key findings/ suggestions: (1) Response to increases in temperature and precipitation vary considerably between ecoregions; (2) Greater return periods are usually associated with a greater increase in annual peak flow; (3) Some ecoregions show compensation between increasing temperature and precipitation, which limits the potential impact of climate change over annual peak flows.

Additional information/ links: Janowicz, J.R., Pomeroy, J.W., Carey, S., Williams, T., and Krogh, S. (2014). Sensitivity of Dempster Highway hydrological response to climate warming. [Conference Presentation], *2nd Annual General Meeting of the Changing Cold Regions Network (CCRN)*, 20-22 October 2014, Waterloo, ON.

Report title: Yukon Infrastructure Remote Sensing Feasibility Study – Final Report - DRAFT

Project lead: Muhammad Idrees (Muhammad.Idrees@gov.yk.ca)

Affiliation: Government of Yukon

Prepared by: Jerry English, C-CORE (LOOKNorth)

Dates: 2014/2015; 2015/2016

Themes: Remote Sensing; Roads; Airports; Ground Movement; Climate Change;

Key terms: Active Layer; Subsidence; Heave; InSAR; Alaska Highway; Dempster Highway; Klondike Highway; Mayo; Linear Infrastructure;

Objectives: (1) Evaluate the cost effectiveness and viability of remote monitoring of ground movement; (2) Identify seasonal ground movement at five sites and longer-term movement at Beaver Creek North; (3) Evaluate radar coherence of imagery.

Link: N/A

Summary:

Significant ground subsidence associated with active layer thickening and near-surface ground ice melt may occur with climate warming, causing maintenance issues for transportation infrastructure. Following a feasibility assessment in a previous project phase, five sites were selected for remote monitoring of subsidence including, Beaver Creek North and South (Alaska Highway kms 1832-1865 and 1707-1770, respectively), Flat Creek (Klondike Highway kms 650-674), Two Moose Lake to Chapman Lake (Dempster Highway kms 70-130), and Mayo Airport. The Interferometric Synthetic Aperture Radar (InSAR) technique was used in association with RADARSAT-2 imagery and digital elevation models (DEM).

Radar coherence was assessed at each site and areas with > 40% coherence were selected for InSAR analysis. Only seasonal changes by active layer movement were observed due to the short temporal scale of the imagery. Commonly, surface heave occurred from November to March due to surface soil freezing, whereas subsidence occurred in summer due to surface soil thaw. A longer-term analysis at Beaver Creek North showed 5 mm/yr of settlement with seasonal ground movement being inversely related to air temperature. Following identification of atmospheric errors in the imagery, a cumulative ground displacement of 100 mm was associated with permafrost degradation.

Methods/ Approaches: (1) Identify sites where remote monitoring is feasible; (2) Obtain relevant satellite imagery; (3) Assess radar coherence of satellite imagery; (4) Perform InSAR analyses with satellite imagery and DEM data.

Key findings/ suggestions: (1) Trade-off between high resolution data covering a smaller area, and medium resolution data covering a much larger area; (2) Radar coherence depended on look direction at topographically complex sites; (3) November to March heave was associated with surface soil freezing, while summer subsidence was associated with surface soil thawing; (4) Long-term subsidence at Beaver Creek North was possibly due to permafrost degradation; (5) Perform long-term analyses at other sites.

Additional information/ links: N/A

Report title: Dempster Highway Functional Plan, Highway #45, km 0.0 to km 465.0 Yukon, 2016-17 – Draft Report

Project lead: Paul Murchison (Paul.Murchison@yukon.ca)

Affiliation: Government of Yukon

Prepared by: Matthew Bowen, Associated Engineering

Dates: 2016/2017; 2017/2018

Themes: Guidelines; Roads; Maintenance; Climate Change;

Key terms: Dempster Highway; Design; Geotechnical; Hydrotechnical; Construction; Culverts; Bridges; Surface Restoration; Sinkholes;

Objectives: (1) Develop a functional plan to guide investments and identify and prioritize potential improvements along the Dempster Highway over a 20-year period.

Link: N/A

Summary:

The Government of Yukon retained Associated Engineering to develop a Functional Plan for the Yukon section of the Dempster Highway, from km 0 to 465. Phase 1 of the plan assessed the existing conditions of the highway to establish current and future needs along the corridor associated with climate change. Phase 2 involved the development of potential options, and conceptual designs for costing and planning purposes, evaluation and prioritization, as well as completing an implementation strategy for a 20-year planning horizon. This information will be used by the Government of Yukon to guide investment and budget requirements.

The report identified sites with the potential to impact the highway, and determined the respective priority, cost estimate, and timeframe. Other recommendations on culvert replacements, surface restoration, sinkholes, highway maintenance, and signage are included in the functional plan. The implementation strategy also highlights material requirements for the corridor such as additional gravel pit development and production for surfacing material and rip rap.

Methods/ Approaches: (1) Existing conditions assessment; (2) Hydrotechnical assessment; (3) Geotechnical assessment; (3) Prepare a basis for design; (4) Collaborate with Yukon University; (5) Environmental and archeological assessment; (6) Prepare an implementation strategy with funding requirements.

Key findings/ suggestions: (1) Thirty-three culverts should be replaced annually; (2) Sinkholes often develop from km 72-102 and km 372-465, thus warning signs should be installed and a highway patrol program implemented; (3) Surface conditions and aggregate quality are poor, thus a gravel structure with 150 mm of base course and 150 mm of surfacing aggregate should be used in deficient areas; (4) Surface restoration should be completed with drainage culvert replacement; (5) Re-gravelling is required every 7 years, with 53.2 km re-graveled annually; (6) Work packages should be developed to use mobilized equipment and contractors; (7) Routine maintenance requirements include, ditch and culvert maintenance, brushing, available mobile equipment, acquisition of a portable bridge, investigation into the application of snow fences along Hurricane Alley.

Additional information/ links: Bowen, M. *et al.* (2018). 'Functional plan for the Dempster Highway considers changing climate to protect this critical transportation link'. *AE Today*, 28 October 2018.

Report title: Incorporating a New Wicking Geotextile in Northern, Low Volume Highways to Mitigate Pavement Edge Cracking

Project lead: Paul Murchison (Paul.Murchison@yukon.ca)

Affiliation: Government of Yukon

Prepared by: Allan Bradley, FPInnovations (allan.bradley@fpinnovations.ca)

Dates: 2016/2017; 2017/2018

Themes: Adaptation; Mitigation; Engineering; Roads;

Key terms: Watson Lake; Geotextiles; Pavements; Design; Campbell Highway

Objectives: Evaluate the ability of geosynthetics to drain the road and prevent edge cracking.

Link: https://trid.trb.org/view/1511345 and https://www.tac-atc.ca/sites/default/files/conf_papers/bradleyah_-_incorporating_a_new_wicking_geotextile_in_northern_low_volume_highways_to_mitigate_pave.pdf

Summary:

The Government of Yukon partnered with FPInnovations and TenCate in 2015 and 2016 to construct two thin instrumented pavement test sites on the Campbell Highway near Watson Lake, Yukon. The aim was to prevent edge cracking in low volume pavements. The test pavements were reinforced with a new geosynthetic product and instrumented above and below the geotextile to monitor roadbed moisture content and temperature. Mirafi® H_2R*i* is a high strength woven geotextile with hygroscopic, hydrophilic and wicking properties that promote rapid drainage. Geotextile is expected to prevent edge cracking by interrupting capillary rise from the subgrade, draining excess moisture from thawing layers, providing additional structural support, and confining road edge materials. Additional benefits may include the mitigation of rutting, cracking and potholes associated with excess roadbed moisture. In 2015, site construction and monitoring of moisture and temperature trends was undertaken.

The shoulders of the test pavement sections were consistently wetter than near centerline before and after paving. The geotextile, installed at the subbase-subgrade interface, reduced moisture in the subbase of both test pavements by up to 3%. However, a difference in moisture level between the road running surface and the road shoulder is potentially not the main reason for edge cracking. Results suggest the geosynthetic wicking and draining properties to be working well. Roadbed moisture was well controlled through the geotextile. Despite reducing roadbed moisture levels, the geosynthetic might not be sufficient to prevent edge cracking. During spring 2016, some minor edge cracking was observed on the treated shoulders of two sites. However, more severe edge cracking was found in nearby untreated road sections. It is premature to state the ability of Mirafi® H_2R*i* to eliminate or reduce edge cracking. In 2016, evaluation of roadbed moisture controlled by the geosynthetic continued and an assessment of the new pavement design on edge cracking and other distresses began.

Methods/ Approaches: (1) Install Mirafi® H_2R*i* geotextile at two test sites; (2) Analyze moisture and temperature data; (3) Monitor surface distress.

Key findings/ suggestions: (1) The geosynthetic drained moisture effectively; (2) Minor edge cracking appeared in spring 2016 at both test sites; (3) Preliminary observations showed reduced cracking at the test sites compared to the untreated sites; (4) It was not clear if the geosynthetic reduced the severity of cracking.

Additional information/ links: Thiam, P-M., Bradley, A.H., Laprade, R., Idrees, M., Drummond, S., and Murchison, P. (2018). Mitigating pavement shoulder cracking in northern, low volume highways by incorporating Tencate Mirafi® H2Ri wicking geotextile. *Proceedings of the 71st Canadian Geotechnical Conference and 13th Joint CGS/IAH-CNC Groundwater Conference*, 23-26 September 2018, Edmonton, AB. 8 p. Paper 329.

Report title: Supply and Installation of Thermosyphons and Monitoring Stations at km 1841 (Dry Creek) of the Alaska Highway, Yukon.

Project lead: Muhammad Idrees (Muhammad.Idrees@yukon.ca)

Affiliation: Government of Yukon

Dates: 2018/2019; 2019/2020; 2020/2021

Themes: Roads; Engineering; Climate Change; Mitigation; Monitoring;

Key terms: Embankment; Dry Creek; Thermosyphons; Drilling; Alaska Highway; Thermal Regime; Design; Construction; Database;

Objectives: (1) Test the usage of thermosyphons on a large scale to mitigate the effect of permafrost thaw on a high-risk section of the Alaska Highway; (2) Evaluate the resulting thermal performance.

Link: N/A

Summary:

This progress report highlights activities and outputs for a project to install and monitor fifty-eight thermosyphons along the Alaska Highway at Dry Creek. All thermosyphons were installed, as well as two additional instrumentation stations at strategic sites to monitor the performance of the thermosyphons. Each instrumentation station includes five thermistor cables, a data logger, and a transmitter to upload data remotely. The backfill could not be completed in January 2020 and was rescheduled for the spring. Once the backfill is completed, radiators and riser pipes will be installed alongside the thermosyphons. Despite delays, data collection from the thermosyphons is ongoing and will be reviewed and analyzed at a later date.

Methods/ Approaches: (1) Purchase and install monitoring stations and thermosyphons; (2) Complete installation of casings, grouting and other earthwork; (4) Install riser pipes and radiators; (5) Review and analyze collected data.

Key findings/ suggestions: Determined upon project completion.

Additional information/ links:

(1) Calmels, F., Doré, G., Kong, X., Roy, L-P., Lemieux, C., Horton, B. (2016). Vulnerability of the north Alaska Highway to permafrost thaw: Design options and climate change adaptation. Northern Climate ExChange, Yukon Research Centre, *Yukon College*, 130 p.

(2) Stevens, C. (2019). Thermal design of the Dry Creek permafrost stabilization project. [Conference Presentation], *18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, 18-22 August 2019, Quebec City, QC.

Report title: Climate Change Impacts and Adaptations for Canadian Highways Built on Permafrost (2019 Mid-project Conference Report – Whitehorse, YT)

Project lead: Paul Murchison (Paul.Murchison@yukon.ca);
Christopher Burn (christopherburn@cunet.carleton.ca)

Affiliation: Government of Yukon; Carleton University

Dates: 2017/2018; 2018/2019; 2019/2020; 2020/2021

Themes: Adaptation; Climate Change; Roads; Infrastructure; Hydrology;

Key terms: Remote Sensing; Snow Management; Groundwater; Data Management; Ground Temperature; Geohazards;

Objectives: Implement innovative management strategies for risks to infrastructure in permafrost terrain posed by warming and thawing of the ground and changes to the precipitation regime.

Summary:

In 2018, Transport Canada approved a proposal by Yukon Transportation Engineering Branch (TEB), with support from the Government of Northwest Territories, to conduct research along the Dempster-ITH corridor on a range of climate-related geohazards that pose risks to the integrity of the highways. Common issues have emerged, especially regarding management of water in winter, organization of data on permafrost, and application of new technologies for sensing changes in the state of terrain. The proposal also undertook a mid-project workshop held in Whitehorse from 19-21 February 2019. Attendees included managerial, engineering, research, and maintenance staff from the two territories, several universities, Transport Canada, the Geological Survey of Canada, and the private sector. The workshop program was organized to allow presentation and discussion of various topics under consideration by the project. The primary themes are permafrost degradation and embankment stability; cost implications of degradation for infrastructure serviceability; snow management; winter water flow and icings; summer hydrologic events; development of permafrost information systems; and airborne systems for monitoring infrastructure integrity. Summary reports on these themes, and presentations are included in the mid-project conference report.

Methods/ Approaches: (1) Project overviews from the Governments of Yukon and Northwest Territories;

Key findings/ suggestions: N/A

Additional information/ links: Burn, C.R. (ed.) 2019. *Climate Change Impacts and Adaptations for Canadian Highways Built on Permafrost.* Proceedings of the mid-project conference, 19-21 February 2019, Whitehorse, YT. Northern Transportation Adaptation Initiative, Government of Yukon and Transport Canada. 61 p.

Report title: Climate Simulations and Thresholds for Nunavut

Project lead: Laxmi Sushama (laxmi.sushama@mcgill.ca)

Affiliation: McGill University

Dates: 2019/2020; 2020/2021

Themes: Climate Change; Policy; Infrastructure; Adaptation; Engineering;

Key terms: Iqaluit; Kivalliq Corridor; Slave Geological-Grays Bay Corridor; Modelling; Transportation; Framework;

Objectives: (1) Advance the shared state of knowledge on climate modelling for researchers; (2) Produce downscaled climate projections to 2050 and identify relevant information for transportation infrastructure development in areas of interest; (3) Identify potential applications for this information.

Link: N/A

Summary:

The project aims to (1) contribute a shared state of knowledge about climate change impacts; (2) produce downscaled climate projections to 2050 and information related to transportation infrastructure development at locations of interest (Kivalliq corridor, Slave Geological-Grays Bay corridor and Iqaluit); and (3) identify potential applications of this information for transportation infrastructure. The project aimed to model climate projections at an ultra-high resolution of 4 km scale using a variety of climate variables and indices. This resolution is appropriate for engineering applications, allowing for important feedbacks and interactions. Sourced data could be used for climate-resilient engineering systems.

Methods/ Approaches: (1) Determine the climate model to be used, describe it, and explain the reasoning for its selection; (2) Arrange an introductory meeting with TC, McGill University, any other interested parties to discuss the project; (3) Perform climate modelling at a resolution of 4 km for 20 to 30-year simulations for many climate variables; (4) Identify how the modelling results may be used in support of climate-resilient transportation infrastructure or engineering methods.

Key findings/ suggestions: Determined upon project completion.

Additional information/ links: N/A

Report title: Arctic Climate Change Vulnerability Index (ACCVI): Northern Aviation, Shipping, and Infrastructure

Project lead: Dylan Clark (dgclark92@gmail.com)

Affiliation: McGill University

Dates: 2016//2017, 2017/2018

Themes: Adaptation; Modelling; Climate Change; Aviation; Marine;

Key terms: Socio-Environmental Assessment; Vulnerability Index; Interview; Literature Review; Community;

Objectives: (1) Develop an ACCVI for aviation and marine infrastructure; (2) Application of the index to Inuit Nunangat communities.

Link: https://www.nature.com/articles/s41467-019-10347-1

Summary:

Transportation systems across the Canadian Arctic are of utmost importance to the health and economic wellbeing of communities. In this report, an Arctic Climate Change Vulnerability Index (ACCVI) is developed for aviation and marine infrastructure. The approach integrates both climatic and social drivers of vulnerability to assess current and future exposure, sensitivity and adaptive capacity. The index is developed through interviews with decision makers and a systematic literature review, and applied to 50 Inuit Nunangat communities.

Across the Inuit Nunangat, climate models predict an increase in annual mean temperature and precipitation of 6.4-10.6 °C and 0.8-1.43 mm/day, respectively, by 2100. The most vulnerable aviation systems are in Nunatsiavut and the most vulnerable marine systems are in Nunavut. These systems are subject to vulnerabilities projected to increase over the next 20-70 years. Mean modeled vulnerability will increase by 58% for future scenarios when compared to present vulnerability. Considering these results, the report outlines key areas in air and marine transportation sectors which require adaptation.

Methods/ Approaches: (1) Review of available data; (2) Qualitative interviews and document review; (3) Systematic literature review; (3) Vulnerability modelling.

Key findings/ suggestions: (1) Nunatsiavut and Nunavut are the most vulnerable regions; (2) Rigolet, Coral Harbour, and Whale Cove are the most vulnerable communities; (3) Weather observations and forecasts need to be reliable and regularly available; (4) Runway lengths need to be appropriate for community needs and population growth; (5) Improvements in coverage of detailed marine charting and navigational information is needed in the Arctic Archipelago, Hudson Bay, and Inuvialuit regions; (6) New ports should account for sea level decrease or rise; (7) Policies are needed to improve education, health, income equality, and foster Inuit Traditional Knowledge; (8) Emergency and disaster response is needed across the Canadian Arctic.

Additional information/ links: N/A

Report title: Northern Transportation Literature Review

Project lead: Andrew Colombo (andrew.colombo@nrc-cnrc.gc.ca)

Affiliation: National Research Council (NRC)

Dates: 2019/2020

Themes: Infrastructure; Engineering; Guidelines; Standards;

Key terms: Roads; Bridges; Railways; Airports; Pavements; Construction; Design; Maintenance; Considerations; Climate change; Geotechnical;

Objectives: Summarize literature and documentation which support the design, construction, operation, and maintenance of surface transportation in the Canadian North.

Link: N/A

Summary:

Significant thought is being paid to transportation infrastructure in the Canadian North, a sensitive region underlain by permafrost. The prospect of climate change adds an extra dimension to the issue and imposes an urgency to better understand the processes that underpin northern transport infrastructure to determine how best to conceive and preserve vital assets. This report summarizes literature and documentation on surface transportation in the Canadian North.

Literature is divided into (1) standards and guidelines by public organizations, governments and industry pertaining to practitioners and asset owners; (2) research articles reflecting knowledge which has influenced practical standards; and (3) publications associated with larger geo-environmental issues such as climate change. The report addresses the geotechnical context and considerations for northern transportation infrastructure including bridges, buildings, railways, roads, and airstrips. Some international publications and case studies are included to assist Canadian practitioners and standards makers.

Methods/ Approaches: Synopses of available literature on Canadian and international infrastructure (i.e., reports, standards, guides, manuals, books, journal articles, and conference proceedings).

Key findings/ suggestions: Over seventy-five recommended documents listed therein.

Additional information/ links: N/A

Report title: Update on: Transportation Risk in the Arctic to Climatic Sensitivity (TRACS) Project

Project lead: Stephen Wolfe (stephen.wolfe@canada.ca)

Affiliation: Natural Resources Canada (NRCan)

Dates: 2013/2014; 2014/2015; 2015/2016

Themes: Mapping; Modelling; Climate Change; Remote Sensing; Field Survey;

Key terms: Surficial Geology; Geotechnical; Great Slave; Risk Assessment; Terrain Mapping; Transportation; Satellites; Optical Imagery; Roads;

Objectives: Develop a geoscientific approach for terrain-climatic risk mapping to aid maintenance and remediation of road infrastructure in the Great Slave region.

Link: N/A

Summary:

TRACS is a collaborative project established to reduce costs and risks of transportation infrastructure in the Great Slave region. The resource-rich area is critical for economic development in the North and requires ground transportation to the south. These include all-weather road access across discontinuous permafrost terrain and winter-road access across frozen lakes. Knowledge of permafrost, land cover, and geotechnical conditions for this region are limited. This project provided geoscientific information to understand risks to transportation infrastructure and guide adaptation practices.

The TRACS field program included extensive fieldwork around Yellowknife between 2010 and 2011. Field data was collected by the Geological Survey of Canada (GSC), Carleton University, University of Ottawa, and BGC Engineering Inc. Field data included CRREL boreholes, ecological descriptions of sixty-eight sites, water and air temperature measurements, snow depths and densities, pond ice thickness, and snow depth transect surveys across highway embankments.

The presentation highlights key TRACS activities supported by aforementioned field survey data. Terrain mapping of the region using LiDAR and related optical imagery provided a surficial geological context for terrain stability. Winter conditions were established using RADARSAT-2 to determine lake ice conditions and hazardous conditions in winter road routings. Mapping and modelling for changes in permafrost terrain conditions and permafrost sensitivity to thermal and hydrological changes was determined from satellite imagery.

Methods/ Approaches: (1) Field surveys; (2) Terrain mapping; (3) RADARSAT-2 imagery; (4) Permafrost modelling and mapping; (5) Optical imagery; (6) Boreholes.

Key findings/ suggestions: (1) Field data provided baseline information on permafrost conditions in the Great Slave region; (2) All-season road routes were proposed according to terrain stability; (3) Assessments of ice cover conditions on winter roads are needed; (4) Risks associated with highway infrastructure considering climate change are needed.

Additional information/ links:

(1) Wolfe, S.A., Fraser, R., and Kokelj, S.V. (2011). Great Slave TRACS - transportation risk in the Arctic to climatic sensitivity. 39th Annual Yellowknife Geoscience Forum, 15-17 November 2011, Yellowknife, NT. In *Yellowknife Geoscience Forum Abstracts Volume 2011*, Northwest Territories Geoscience Office, vol. 2011, p. 124.

(2) Wolfe, S.A., Duchesne, C., Gaanderse, A., Houben, A.J., D'Onofrio, R.E., Kokelj, S.V., and Stevens, C. (2011). Report on 2010-11 permafrost investigations in the Yellowknife area, Northwest Territories. *Geological Survey of Canada*, Open File 6983. 75 p. DOI: 10.4095/289596.

Report title: Reporting on 2017-18 Activities under TC-NRCan MOU, Schedule A: Geoscientific Information for Highways Management in Northwest Territories and Yukon Territory

Project lead: Peter Morse (peter.morse@canada.ca)

Affiliation: Natural Resources Canada (NRCan)

Dates: 2016//2017; 2017/2018

Themes: Remote Sensing; Roads; Climate Change; Mapping;

Key terms: Dempster Highway; ITH; LiDAR; Geotechnical; Water Quality; Terrain Mapping; Geochemical; Geohazards;

Objectives: (1) Analyze field data on permafrost conditions near the ITH to validate and characterize current conditions; (2) Hire students or recent graduates and acquire high resolution satellite images to map potential permafrost landscape geohazards along the Dempster Highway and ITH corridors.

Links: N/A

Summary:

The Transportation Resilience in the Arctic Informed by Landscape Systems (TRAILS) aimed to develop a pan-Canadian Arctic perspective on transportation resilience to permafrost change. The program's main objectives were to (1) compile datasets on permafrost characteristics across terrain types; (2) develop and test new methods of detecting permafrost landscape change; and (3) quantify the rates and process of permafrost change due to natural and human disturbance.

Four-hundred permafrost samples were processed and analyzed by the GSC to characterize subsurface materials essential for assessing the response of permafrost to climate change and infrastructure. Five-hundred complimentary water samples were geochemically analyzed to provide information on the effects of transportation development on aquatic ecosystems. TRAILS hired a student and recent graduate to assist with developing an image analysis and mapping protocol and carry out feature mapping. Five test sections were established along the Dempster Highway and ITH corridor and utilized high-resolution imagery to identify geomorphological features and landscape types. Digitized features are classified based on their genesis and available geoscience data. A mapping protocol has been derived and tested.

Methods/ Approaches: (1) Perform laboratory analyses on permafrost and water samples collected in 2016-2017; (2) Develop field-based and remotely-sensed data sets.

Key findings/ suggestions: Mapping and QA/QC protocols have been developed.

Additional information/ links:

(1) Morse, P., and Kokelj, S.V. (2017). Trails – ITH: collaborative geoscience to support infrastructure management in the changing north. 45th Annual Yellowknife Geoscience Forum, 14-16 November 2017, Yellowknife, NT. In *Yellowknife Geoscience Forum Abstracts and Summary Volume 2017*, Northwest Territories Geoscience Office, p. 53-54.

(2) Sladen, W.E., Parker, R.J.H., Morse, P.D., Kokelj, S.V., Smith S.L., Jardine, S., Kokaszka, J., and van der Sluijs, J. (2017). Trails: collaborative permafrost terrain mapping, Dempster and Inuvik to Tuktoyaktuk Highways Corridor. Poster presented at: *45th Annual Yellowknife Geoscience Forum*, 14-16 November 2017, Yellowknife, NT.

Report title: Reporting on 2017-18 Activities under TC-NRCan MOU, Schedule B: Permafrost and Surficial Material Active Archive (PSMAA) for Climate Change Resilient Northern Infrastructure

Project lead: Sharon Smith (sharon.smith@canada.ca)

Affiliation: Natural Resources Canada (NRCan)

Dates: 2017/2018; 2018/2019; 2019/2020; 2020/2021

Themes: Data; Mapping; Infrastructure;

Key terms: Collaboration; Database; Surficial Geology; Ground Ice;

Objectives: (1) Develop a Permafrost and Surficial Materials Active Archive (PSMAA), building on an existing framework in collaboration with federal and territorial partners and facilitate the linking of multiple datasets through a common portal; (2) Develop improved ground ice maps from national to regional scales to better evaluate potential infrastructure risk; (3) Develop a free and open web-based portal, the Permafrost Information Network (PIN) to improve public accessibility of permafrost data.

Link: https://pin.geosciences.ca/

Summary:

The purpose of the project was to address gaps in permafrost knowledge and support informed decision making regarding northern transportation infrastructure. An important outcome of an improved and accessible knowledge base for permafrost will be to enable better identification of potentially problematic terrain in infrastructure development areas. In turn this will support decisions regarding the focus of site-specific surveys and investigations leading to reduced costs and increased resilience of transportation infrastructure in a changing climate.

The project comprised three interrelated objectives. Activities included the development of a web portal (PIN) to link to a GSC geotechnical database (and eventually, to permafrost databases of Northwest Territories Geological Survey and Yukon Geological Survey), development of new surficial geology maps, and progress towards creating additional layers that would be housed on the PIN. Achievements related to an improved permafrost map and model included a revised national ground ice map, initiation of advanced modelling of excess ice content in the upper 5 m, preparation of data sets for PIN dissemination, completion of an interactive 3-D component of PIN map, initiation of thermokarst modelling, preparation of a draft atlas on ground ice and thermokarst observations, completion of mapping of permafrost features in the Dempster Corridor and initiation of similar mapping in Nunavut corridors.

Methods/ Approaches: (1) Stakeholder engagement; (2) PSMAA Steering Committee; (3) Database development; (4) Permafrost map/model development.

Key findings/ suggestions: Determined upon project completion.

Additional information/ links:

(1) Wolfe, S.A., Duchesne, C., O'Neill, H.B., and Parker, R.J.H. (2017). Modelling ground ice potential in Canada. Poster presented at: *45th Annual Yellowknife Geoscience Forum*, 14-16 November 2017, Yellowknife, NT. DOI: 10.4095/306461.

(2) O'Neill, H.B., Wolfe, S.A., and Duchesne, C. (2019). New ground ice maps for Canada using a paleogeographic modelling approach. *The Cryosphere*, 13(3), 753-773. DOI: 10.5194 /tc-13-753-2019.

(3) O'Neill, H.B., Wolfe, S.A., and Duchesne, C. (2020). Ground ice map of Canada. *Geological Survey of Canada,* Open File 8713, DOI: 10.4095/326885.

Report title: Dry Creek Highway Section Preliminary Design and Thermal Modelling

Project lead: Christopher Stevens (cstevens@srk.com)

Affiliation: SRK Consulting

Dates: 2016/2017

Themes: Roads; Climate Change; Mitigation; Thaw; Modelling;

Key terms: Dry Creek; Boreholes; Air Convection Embankment; Thermosyphons; Design; Massive Ice; Thermal Regime;

Objectives: (1) Develop a preliminary design of the Dry Creek Highway section using natural air convection and thermosyphons to mitigate permafrost thaw beneath the highway embankment; (2) Model expected thermal performance of each design considering climate change.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Dry%20Creek%20Highway%20Section%20Preliminary%20Design%20and%20Thermal%20Modeling.pdf

Summary:

This project evaluated two strategies for permafrost thaw mitigation below a 500 m test section of the Alaska Highway at Dry Creek. The test section embankment was constructed over warm, ice-rich permafrost, and was previously damaged by differential thaw settlement due to massive ice. The first strategy was to remove the current standard embankment and replace it with poorly graded crushed rock to create an air convection embankment (ACE), while the second strategy was to install thermosyphons in the existing embankment.

A plan for the construction of each design was created after a detailed analysis of the highway alignment, surface water and drainage, climate data, geotechnical data from nearby boreholes and electrical resistivity tomography. Performance of the ACE was assessed using a two-dimensional coupled model for thermal conduction and air flow, while the thermosyphon embankment was modelled using only thermal conduction. The models were run under a variety of scenarios including varying massive ice depth and a nearby water body. The ACE model was also run with covered side slopes, while the thermosyphon model had varying radiator size, distance between evaporators, and a berm. The models were verified using field measurements.

The models suggested both designs reduced permafrost thaw below the embankment. The thermosyphons provided more immediate and dependable cooling of the ground, while the ACE required a longer period (1.75-9 years) for the cooling effect to reach massive ice at 5-10m depth.

Methods/ Approaches: (1) Assess site conditions; (2) Design ACE and thermosyphon embankments; (3) Model embankment performance; (4) Verify with field measurements.

Key findings/ suggestions: (1) Massive ice underlying the ACE cools significantly after an isothermal period of 1.75-9 years, this is comparable regardless of side slope covering; (2) Thermosyphon performance has a positive relation with radiator size and evaporator pipe frequency; (3) The thermosyphon embankment requires a 1.5 m berm for sufficient cooling where massive ice is shallow (5 m depth).

Additional information/ links: Stevens, C. (2019). Thermal design of the Dry Creek permafrost stabilization project. [Conference Presentation], *18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, 18-22 August 2019, Quebec City, QC.

Report title: Concept Study of Phase Change Materials to Limit Permafrost Thaw Beneath Highways

Project lead: Christopher Stevens (cstevens@srk.com)

Affiliation: SRK Consulting

Dates: 2018/2019

Themes: Roads; Climate Change; Thaw; Mitigation; Modelling;

Key terms: Concept Study; Embankment; Design; Geosynthetics; Thaw Settlement; Latent Heat; Specific Heat Capacity; Active Layer; Ground Temperature;

Objective: Conduct a preliminary evaluation on the ability of phase change materials (PCM) to control heat transfer and limit permafrost degradation beneath embankments.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Concept%20Study%20of%20Phase%20Change%20Materials%20to%20Limit%20Permafrost%20Thaw%20Beneath%20Highways.pdf

Summary:

Phase change materials (PCM) are manufactured materials with the capacity to store or release large amounts of latent heat. A wide variety of PCMs are commercially available due to their usage in other industries. This project evaluated their potential to absorb thermal energy that would otherwise go towards thawing permafrost, causing a reduction in active layer thaw depth. Based on phase change temperature, latent heat, change in density, and biodegradability, eight PCM products were considered and two were chosen. Product '3' was biodegradable with a phase change temperature of 5 °C, and product '2' had a phase change temperature of -2 °C and a higher latent heat, but the biodegradability was unknown.

Two methods of integration with the highway embankment were considered. The first method encapsulated the PCM and mixed with ordinary embankment fill. The second method filled a vessel with the PCM and placed horizontally within the embankment. Both methods were compared using a one-dimensional heat flow model. The PCM vessel was deemed impractical given the unrealistic thickness necessary for sufficient energy absorption.

The PCM fill results were more promising and the technique was evaluated using a more detailed two-dimensional model which accounted for geometric effects of the highway embankment. This model indicated an embankment comprising 40% product '2' PCM would reduce thaw depth to within 50 cm of the ground surface. However, thaw depth increased towards the embankment side slopes where the fill was thinner. The model ran again with the top 1.5 m of the embankment comprising 40% PCM fill and the bottom 0.5 m comprising 60% PCM fill. Results indicated the thaw depth was limited to within 35 cm of the ground surface.

Methods/ Approaches: (1) Review suitable PCMs; (2) Develop design options for the integration of PCMs in embankments; (3) Model and assess long-term embankment performance.

Key findings/ suggestions: (1) PCMs effectively store seasonal energy and delay propagation of the freezing front; (2) Suitable PCMs are commercially available; (3) Embankment integration using a PCM modified fill was estimated to have the best thermal performance; (4) PCMs with a phase change temperature below that of porewater were more effective; (5) PCMs ability to promote heat loss is limited.

Additional information/ links: Stevens, C. (2019). Phase Change Materials: Innovation in adaptation technology to address permafrost thaw. [Conference Presentation], *18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, 18-22 August 2019, Quebec City, QC.

Report title: Collection of Socio-environmental Information about Hydro-geo Hazards from Users of Dempster Highway, Yukon

Project lead: Kevin D. Rumsey (Kevin79rumsey@gmail.com)

Affiliation: Sustaineo Blue Water Consulting

Dates: 2016/2017

Themes: Adaptation; Climate Change; Community; Infrastructure; Roads;

Key terms: Dempster Highway; Geohazards; Socio-Environmental Assessment; Interview;

Objectives: (1) Contribute valuable qualitative data related to environmental changes of the Highway, towards the long-term planning process of the Dempster Highway; (2) Integrate report findings into the planning process and development of the Yukon Government's Functional Plan.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Community%20Consulation-Collection%20of%20socio-environmental%20information%20about%20hydro-geo%20hazards%20from%20users%20of%20Dempster%20Highway%2C%20Yukon.pdf

Summary:

Around eighty individuals, with diverse backgrounds and varied connections to the Dempster Highway, participated in a socio-environmental assessment, sponsored by Transport Canada and based in Yukon. For context, the report includes past engineering assessments that observed environmental change along the highway. Data collection centered around interviews was conducted using an on-line (anonymous) survey with elders from the First Nations of Na-Cho Nyak Dun and Tr'ondëk Hwëch'in, Yukon Government employees, and a former park guide.

The key findings indicate users of the Dempster Highway are aware of changes to weather conditions from what was considered 'normal' and the rapid influence this has on the landscape. Users reported numerous areas of perceived and real vulnerability impacting the Highway. The bridge-crossing areas of Ogilvie and Blackstone rivers and Engineer Creek were mentioned more than once, and Two Moose Lake and Chapman Lake were recognised as rough sections. Users have observed increased summer storm intensity, landslides, slumps, permafrost thaw, potholes, sink holes, meandering rivers, and rapid shrub growth. Road safety conditions and peoples' lack of preparedness were also noted.

Methods/ Approaches: (1) Interviews; (2) online (anonymous) survey.

Key findings/ suggestions: (1) Initiate phase II of a similar contract, and extend its scope to NWT; (2) Improve relationships between the Transportation Engineering Branch (TEB) and First Nations, and within government departments and highway users; (3) Promote road safety awareness and preparedness among highway users; (4) New and ongoing research, monitoring and inspections of the highway; (5) Initiate the development of a group or committee of representatives from the Dempster user community to build relationships, improve trust, and resolve problems early; (6) Develop two different short training workshops for TEB staff.

Additional information/ links: N/A

Report title: Climate Change Vulnerability Assessment for Airports: Yellowknife, Fort Simpson, Norman Wells and Inuvik, NWT

Project lead: Ed Hoeve (ehoeve@eba.ca)

Affiliation: Tetra Tech EBA Inc.

Prepared by: Kumari Karunaratne

Dates: 2012/2013; 2013/2014

Themes: Airports; Climate Change; Ground Ice; Drainage;

Key terms: Yellowknife; Inuvik; Fort Simpson; Norman Wells; Risk Assessment; Modelling; Thaw Settlement; Thermal Regime; Boreholes; Interview;

Objectives: (1) Complete climate change vulnerability assessments for airports in Yellowknife, Fort Simpson, Norman Wells, and Inuvik to identify current and future hazards; (2) Adhere to the Tunnicliffe and Burn (2011) methodology.

Link: N/A

Summary:

Following the methodology of Tunnicliffe and Burn (2011), climate change vulnerability assessments were conducted for airports at Yellowknife, Fort Simpson, Norman Wells, and Inuvik. Current and emerging climate change hazards were assessed based on scientific publications, geotechnical reports, air photos and imagery, stakeholder interviews, historic climate data, and climate models. By 2071-2100, mean annual air temperatures (MAAT) are expected to rise 3.0-4.6 °C in the four communities along with 10-25% more total annual precipitation under a moderate emissions scenario (relative to 1971-2000).

At Yellowknife Airport, the main concerns are poorly drained and/or thermally sensitive terrain. Permafrost is ice-rich below parts of the runways and subsidence and settling have been observed due to permafrost degradation. Poorly drained areas below the runways increase the vulnerability of permafrost degradation under climate change. Permafrost under runways at Fort Simpson and Norman Wells is thermally stable, but increased snowfall at Fort Simpson Airport would insulate the ground surrounding the runway, possibly degrading permafrost and interrupting drainage patterns. Surface drainage in the region near Inuvik Airport is poor and a pre-existing subsurface drainage network resulted in settling of the eastern end of the runway. Permafrost in the Inuvik area is ice-rich and thaw subsidence and thermokarst formation are concerns in and around the airport.

Methods/ Approaches: (1) Consult geotechnical reports and scientific literature for site condition data; (2) Consult historic and current air photos and imagery; (3) Analyze historic climate data and future projections; (4) Stakeholder interviews in Yellowknife.

Key findings/ suggestions: (1) Across many categories, Inuvik Airport is the most vulnerable to climate change, Yellowknife is the least, and Fort Simpson and Norman Wells are intermediate; (2) Terrain sensitivity is high at Inuvik Airport, and low elsewhere; (3) Building vulnerabilities are high at Inuvik airport and low elsewhere; (4) Climate indicators are of similar risk at all four airports; (5) Complete subsequent project phases.

Additional information/ links: Tunnicliffe, J., and Burn, C.R. (2011). Towards a Protocol for Airport Infrastructure Risk Assessment - Managing Long-Term Infrastructure Risks in Permafrost Terrain. *Carleton University*. Report submitted to the Government of the Northwest Territories, Department of Transportation.

Report title: Technical Report on Installation, Set-up and Measurement for Air Convection Duct Equipment

Project lead: Daniel Fortier (daniel.fortier@umontreal.ca)

Affiliation: Université de Montréal

Dates: 2012/2013

Themes: Mitigation; Infrastructure; Roads;

Key terms: Air Convection Ducts; Alaska Highway; Beaver Creek; Embankment; Monitoring; Performance Response; Data Quality; Thermal Regime; Modelling;

Objectives: Test the air convection duct technique;

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-07/Innovation%20in%20Convective%20Heat%20Transfer%20Modelling-Performance%20of%20Air%20Convection%2C%20Temperature%2C%20and%20Heat%20Loss%20Monitoring%20Technology.PDF

Summary:

In 2008, eleven test sections were constructed along the Alaska Highway near Beaver Creek, YT. Three types of mitigation techniques were tested to control permafrost degradation, (1) reduce heat gains in the embankment, (2) reinforce the embankment, and (3) extract heat from the embankment. This report discusses the latter in the form of air convection ducts. Initial analysis showed this technique to be sufficiently effective in lowering embankment temperatures. A subsequent experimental protocol was developed to account for heat transfers and air movements to aid digital modelling.

To test the air convection technique, temperature sensors were installed in the inlet, middle, and outlet of the duct. Measurements were taken from the duct wall, and air inside and outside the duct. In 2013, new instruments were installed in three sub-ducts to obtain temperature, pressure, and air speed data. The equipment was duplicated to assess its accuracy and guide selection decisions in subsequent project phases and ensure the collection of reliable data.

Temperature data shows the duct wall to be warmer than the inside air, confirming the loss of heat through the duct. The temperature difference is greatest at the inlet and decreases through the duct. At the middle section there is heat loss potential but at the outlet temperatures have equalized. Closing the ducts in summer, to avoid heating the walls, is also effective at limiting heat exchange. Therefore, air travel time and heat exchange are determined by the length and width of the ducts, wind speed and direction, and the heterogeneity of duct wall temperatures.

Methods/ Approaches: (1) Compare thermal exchanges between the duct wall and air inside and outside the duct; (2) Test the accuracy of equipment.

Key findings/ suggestions: (1) Air temperatures are coldest at the inlet and gradually warm until the outlet; (2) Duct wall is coldest at the inlet and warmer elsewhere; (3) Duct wall is typically warmer than inside the duct; (4) Duct wall and inside air temperatures equalize at the outlet; (5) Closing the ducts in summer reduces heat exchange between the air and duct wall; (6) Permafrost table is shallower below the embankment; (7) Further analysis is necessary to explain warmer temperatures in the duct wall.

Additional information/ links: Coulombe, S., Fortier, D., and Stephani, R. (2012). Using air convection ducts to control permafrost degradation under road infrastructures: Beaver Creek experimental site, Yukon, Canada. 15th International Conference on Cold Regions Engineering, 19-22 August 2012, Quebec City, QC. In *Cold Regions Engineering 2012, ASCE*, 21-31. DOI: 10.1061/9780784412473.003.

Report title: Innovation in Geotechnical Permafrost Engineering: Evaluation of a New Technique for Measuring Soil Hydraulic Conductivity

Project lead: Daniel Fortier (daniel.fortier@umontreal.ca)

Affiliation: Université de Montréal

Dates: 2012/2013

Themes: Engineering; Laboratory;

Key terms: Hydraulic Conductivity; Geotechnical; UMS KSAT; UMS HYPROP;

Objectives: Evaluate KSAT and HYPROP devices for obtaining soil hydraulic conductivity.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Innovation%20in%20Geotechnical%20Permafrost%20Engineering%20-%20Evaluation%20of%20a%20New%20Technique%20for%20Measuring%20Soil%20Hydrolic%20Conductivity.pdf

Summary:

The report explains the theoretical principles and measurement processes of UMS KSAT and HYPROP. Saturated hydraulic conductivity was evaluated using a falling head permeameter and a mini disk tension infiltrometer. In section 1 of the report, the values obtained by the KSAT are evaluated against those from the permeameter and infiltrometer for ease of use, speed, precision, and accuracy. HYPROP tests are described in section 2, this method provides different data by establishing a desaturation curve to obtain the unsaturated conductivity.

The KSAT device provides precise and accurate measurements of the hydraulic conductivity of non-cohesive soils and fine soils. This device yields data closer to field data than the permeameter, provides greater precision than the infiltrometer, and minimizes the time required on site. It improves the efficiency of laboratory measurements by allowing multiple measurements per day. Automated data logging reduces the sources of user-related errors. The limitations are an inability to measure very low hydraulic conductivities, typical of clays, and sampling could also be problematic in cases of gravels or dried sediments, which are difficult to keep intact.

The HYPROP device makes it possible to extend the measurements of the desaturation data, and the software allows the user to add the air-entry pressure during curve fitting. This device requires attention to detail during assembly to derive the maximum information from it. The software allows the user to fit the retention and conductivity curves based on various models from the scientific literature. The choice of model and parameterization are critical during modelling, to obtain curves that accurately reflect reality but are still significant. One drawback of the software concerns the extrapolation of conductivity measurements close to saturated conductivity.

Methods/ Approaches: KSAT and HYPROP device performance compared to the permeameter and the infiltrometer using three soil samples, each with a replicate.

Key findings/ suggestions: *KSAT:* (1) Provides precise and accurate hydraulic conductivity measurements in non-cohesive and fine soils; (2) Minimizes time required on site; (3) Improves laboratory efficiency and reduces user-related errors; (4) Limited when measuring very low hydraulic conductivities and in the case of gravels or dried sediments. *HYPROP*: (1) Results depend heavily on the experience of the user; (2) Choice of model and parameterization is critical; (3) Limited when extrapolating conductivity measurements close to saturated conductivity.

Additional information/ links: N/A

Report title: Impact Assessment of Groundwater Flow and Surface Flow on Permafrost Degradation and Road Infrastructure Stability

Évaluation des impacts de l'écoulement de surface et de l'écoulement souterrain sur la dégradation du pergélisol et la stabilité des infrastructures routières

Project lead: Daniel Fortier (daniel.fortier@umontreal.ca)

Affiliation: Université de Montréal

Dates: 2013/2014; 2014/2015; 2015/2016

Themes: Groundwater; Convection; Conduction; Drainage;

Key terms: Modelling; Soil Material; Slope; Thermal Regime; Soil Stability; Erosion; Time-Domain Reflectometry (TDR); Culverts; Embankment;

Objectives: Understand influences of groundwater flow on permafrost degradation.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/%C3%89valuation%20des%20impacts%20de%20l%C3%A9coulement%20de%20surface%20et%20de%20l%C3%A9coulement%20sur%20la%20d%C3%A9gradation%20du%20perg%C3%A9lisol%20et%20la%20stabilit%C3%A9%20des%20infrastructures%20routi%C3%A8res_0.PDF

Summary:

Increased heat transfer into the ground associated with climate change could degrade permafrost and reduce soil stability. Heat transfer by convection in fluids is more efficient than conduction in the ground. In permafrost regions, degradation may proceed more quickly where flowing groundwater is perched on the water table. Physical and numerical simulations were conducted in the Geocryolab at Université de Montréal to understand how flowing groundwater affects the thermal regime of permafrost. Simulations were conducted for three soil types, sand, silt, and ice-rich. Physical simulations comprised twenty-eight sets of frozen soil boxes cooled to -17 °C. Water flow into the boxes was controlled by a dripper to 0.0-0.6 mL/s. The boxes were inclined at varying angles (1-25°) in contact with different air temperatures (5 °C or 15 °C). The influencing factor of convection (relative to conduction) was introduced to quantify vertical thaw front penetration into soil with groundwater flow. For each unit increase in the factor the thaw speed is doubled. This factor was 2-3 times greater near convective sources. Increasing water temperature (T_w) increased the factor of convection, while increasing air temperature (T_a) decreased it by 0.33-0.5 times. The factor was twice as high in silt as sand, and three times as high in sand as ice. The numerical model confirmed the physical simulations which allowed for simulations of additional conditions, but these were only accurate near the box centres.

Methods/ Approaches: (1) Influencing factor for convection and conduction; (2) Physical and numerical simulations.

Key findings/ suggestions: (1) Convection becomes 2-3 times higher nearer convection sources; (2) The factor is greatly increased when $T_w > T_a$ and slightly decreased when $T_a > T_w$; (3) The factor was greatest for silt, moderate for sand, and lowest for ice-rich soils; (4) Numerical modelling well-represented the physical modelling near the box centres; (5) Perform in situ tests in permafrost environments, such as drainage ditches, culverts and embankments of transportation infrastructure.

Additional information/ links: Veuille, S., Fortier, D., Verpaelst, M., Grandmont, K., and Charbonneau, S. (2015). Heat advection in the active layer of permafrost: physical modelling to quantify the impact of subsurface flow on soil thawing. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 722.

Report title: Mapping Techniques and Characterization of Ice Wedges

Project lead: Daniel Fortier (daniel.fortier@umontreal.ca)

Affiliation: Université de Montréal

Dates: 2014/2015; 2015/2016

Themes: Remote Sensing; Mapping; Ground Ice; Climate Change;

Key terms: Ice Wedges; ITH; Dempster Highway; Alaska Highway; Geotechnical; Design; Validation; LiDAR; Multi-spectral Imagery; Photogrammetry;

Objectives: Evaluate the limitations and applicability of airborne remote sensing and near-surface geophysical techniques to map and characterize ice wedges

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Mapping%20Techniques%20and%20%20Characterization%20of%20Ice%20Wedges.PDF

Summary:

Degradation of ice wedges leads to significant structural damages to northern infrastructure. This research aimed to determine the limitations and applicability of airborne remote sensing and near-surface geophysical techniques to map and characterize ice wedges. New and promising remote sensing techniques were evaluated, and results were calibrated and validated by field testing along three northern highways representing a range of permafrost conditions.

Results indicate the value in all techniques, but their applicability depends on the objective and scale of interest. Remote sensing approaches would be the best choice for large-scale characterization. LiDAR has a higher precision than multispectral imagery, but multi-spectral satellite imagery has the ability to visualize spectral bands that are not part of the visible spectrum and identify the location of non-visible ice wedges. Drone photogrammetry has the highest resolution and should be used when the need of high-precision data is required at a medium to large scale. Geophysical techniques are more expensive and time consuming than remote sensing techniques but are the best choice for precise localization, size and volume of ice wedges, and for road design purposes. Greater precision and confidence in mapping and characterization of ice wedges could be achieved by combining several of these techniques.

Methods/ Approaches: (1) Remote sensing techniques (LiDAR, multispectral satellite imagery, photogrammetry by drone, Ground Penetrating Radar (GPR), Capacity-Coupled Resistivity, Electrical Resistivity Tomography and microgravimetry); (2) Field surveying (vegetation survey, drilling operation, and geotechnical analyses) for calibration and validation of results

Key findings/ suggestions: (1) Satellite-based remote sensing approach is best for large-scale characterization; (2) Multi-spectral satellite imagery can identify non-visible and visible ice wedges; (3) LiDAR has great potential for identification of visible ice wedges, especially in shrubby environments; (4) Photogrammetry by drone provides the highest resolution; (5) Resistivity and GPR are good complementary techniques; (6) Gravimetry is the only geophysical technique able to detect buried ice-wedges in ice-rich zones; (7) Geophysical techniques are best for precise localization of ice wedges and road resign purposes.

Additional information/ links: Gagnon, S., *et al.* (2020). Remote sensing and geophysical techniques to detect and map ice wedges. CPA & NSERC PermafrostNet Virtual Annual General Meeting, 16-18 November 2020, Online, In *Canadian Permafrost Association Virtual Annual General Meeting Abstracts*, p. 15.

Report title: Performance Assessment of the Thermo-reflective Snow-sun Sheds at the Beaver Creek Road Experimental Site

Project lead: Daniel Fortier (daniel.fortier@umontreal.ca)

Affiliation: Université de Montréal

Dates: 2017/2018; 2018/2019

Themes: Roads; Engineering; Mitigation; Thaw; Maintenance;

Key terms: Beaver Creek; Embankment; Design; Construction; Concept Study; Monitoring; Thaw Settlement; Thermal Regime;

Objective: Identify the potential and limitations of the thermo-reflective snow-sun shed (TRS-Shed) for the preservation of ice-rich permafrost under embankments in discontinuous permafrost.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Performance%20assessment%20of%20the%20thermo-reflective%20snow-sun%20sheds%20at%20the%20Beaver%20Creek%20road%20experimental%20site%20%E2%80%93%20Technical%20Report.PDF

Summary:

This report analyzes the performance of TRS-Sheds installed at Beaver Creek in 2009. Each wooden structure (30 m long, 15 m wide, 1 m high), with a white corrugated sheet metal roof, covers the embankment and is open on all sides apart from the road. It passively cools the ground surface by providing shade, reflecting solar radiation from its high albedo roof, and allowing free air convection during the winter.

Sensors suspended from the roof and buried 10 cm beneath the ground surface recorded air and ground temperatures beneath the TRS-Shed. On average, temperatures in shed were slightly lower than air temperatures. Ground temperatures were lower in the test section (-25 °C) than the control section (-18 °C) in winter and peak ground temperatures were lower in the test section (12 °C) than the control section (17 °C) in summer. Using freezing and thawing, the test section absorbed 62% of the heat absorbed by the control section during the summer and released 411% more heat during the winter. TRS-Sheds are recommended for controlling permafrost thaw under embankments, notwithstanding cost considerations. However, edge effects along the sides of the shed reduced cooling and differential thaw of the surrounding ground damaged the supporting structure. Therefore, some elements may need to be redesigned before TRS-Sheds can be practically implemented.

Methods/ Approaches: The project assesses the effectiveness of the snow-sun sheds, by (1) creating a reference terrain model; and (2) analysis of thermal data collected at the site, principally from an automated data acquisition system and local meteorological stations

Key findings/ suggestions: (1) TRS-Sheds could be applied to permafrost environments across Canada for various types of embankments; (2) The elevation between the lower and upper edges of the TRS-Shed should be maximized to enhance free convection during winter; (3) Some design elements should be reviewed (i.e., geometry to reduce snow accumulation, anchoring system and frame to accommodate deformation, and an additional water drainage component).

Additional information/ links: Fortier, D., Sliger, M., and Rioux, K. (2018). Performance assessment of the thermo-reflective snow-sun sheds at the Beaver Creek road experimental site – Report for Policymakers. Université de Montréal, https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Performance%20assessment%20of%20the%20thermo-reflective%20snow-sun%20sheds%20at%20the%20Beaver%20Creek%20road%20experimental%20site%20%E2%80%93%20Report%20for%20Policymakers_1.PDF.

Report title: Innovation in Permafrost Geotechnics: Assessment of a New Technique for Measuring the Heat Capacity of Soils

Innovation en géotechnique du pergélisol: Évaluation d'un nouvelle technique pour la mesure de la capacite calorifique des sols

Project lead: Daniel Fortier (daniel.fortier@umontreal.ca)

Affiliation: Université de Montréal

Dates: 2013/2014

Themes: Geophysics; Guidelines; Data Sharing; Laboratory;

Key terms: Thermal Regime; Specific Heat Capacity; Differential Scanning Calorimetry (DSC); Database;

Objectives: (1) Develop a new technique to measure specific heat at different temperatures; (2) Develop a procedure to make the technique accessible; (3) Produce a database containing frozen and unfrozen heat capacity for permafrost materials.

Link: DOI: 10.13140/RG.2.1.4705.3521

Summary:

Heat capacity is a key parameter used in understanding and modelling the thermal evolution of permafrost. This study evaluates Temperature Modulated Differential Scanning Calorimetry (TM-DSC) as a new technique to measure the heat capacity of various soils. It was used to determine the heat capacity of clay, peat, silt, and organic silt in frozen saturated, unfrozen saturated, dry, and burnt states. The report presents the theory behind the measurement, the device's selection process, optimal procedure for the TM-DSC device, series of measurements from different soils from the Yukon and a database of heat capacity values for soils in different states.

Specific heat capacity functions resulting from this technique represent measurements over a continuous temperature range from -40 °C to 40 °C, while avoiding the effect of latent heat. Measurements from the TM-DSC indicate, when at the same temperature, specific heat of a material increases as the water content increases. Additionally, results demonstrate the specific heat of dry organic matter is higher than any other material tested. The step-by-step procedure presented provides a guideline for TM-DSC to achieve the same results and produce new comparable data.

Methods/ Approaches: (1) Temperature Modulated Differential Scanning Calorimetry (TM-DSC); (2) Establish an optimal procedure for measuring specific heat of soils in different states; (3) Produce a database.

Key findings/ suggestions: (1) Specific heat capacity of soils increases as water content increases; (2) Inclusion of organic matter increases specific heat capacity of a soil when frozen saturated, unfrozen saturated and dry; (3) Specific heat measurements for various materials from this database can produce accurate thermal models simulating permafrost degradation; (4) TM-DSC procedure developed in this report can be shared and improved by others.

Additional information/ links: N/A

Report title: Assessment of Transportation Indicators for Northern Canada

Project lead: Hugo Asselin (hugo.asselin@uqat.ca)

Affiliation: Université du Québec en Abitibi-Témiscamingue (UQAT)

Dates: 2012/2013

Themes: Community; Connectivity;

Key terms: Literature Review; Transportation; Transportation Indicators;

Objectives: (1) Provide a status update on existing definitions of the North; (2) Identify the transportation indicators specific to Canada's North, if any; (3) Address the concept of connectivity in the North; (4) Advise on further research needed to improve the development of transportation indicators for northern Canada.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Assessment%20of%20Transportation%20Indicators%20for%20Northern%20Canada.PDF

Summary:

This report explores the available literature on transportation indicators in northern Canada, with a focus on the existing and future definitions of the North, existing transportation indicators, and northern connectivity considerations. The review reinforces the need for a clear functional definition of the North. The definition should be investigated to design a new index that is dynamic and adaptive. Determining if a location is or is not in the North depends on the context, question, or objective. The framework proposed by Duhaime *et al.* (2004) could be updated through a pan-Canadian survey of experts to validate the criteria and identify northern transportation indicators. An adaptive electronic decision-making tool could be developed to integrate the updated northern transportation criteria and indicators framework and the new definition of the North.

Among the specific issues that will require particular attention are the integration of industrial and local needs in the design of the transportation network. The focus on providing industry with access to natural resources has led to major infrastructure developments, often with important public funding without direct benefits to local populations. This calls for a better understanding of connectivity (both North-South and North-North), especially in a context where remote northern industries increasingly rely on fly-in/fly-out workers. Sustainable transportation in the Canadian North must consider the production of greenhouse gases. Increased multi- and inter-modality should also receive greater attention, especially as means to increase accessibility and reliability of the transportation offer. Finally, the needs and views of local populations, especially aboriginal people, must be better integrated in the decision-making process regarding transportation.

Methods/ Approaches: Literature review

Key findings/ suggestions: (1) The definition of the North should be investigated, and a new, more flexible index developed; (2) The framework by Duhaime *et al.* (2004) could be updated to identify northern transportation criteria and indicators; (3) Particular attention should be paid to integrating the needs of local populations, particularly aboriginal people, in the design-making process and design of the transportation network.

Additional information/ links: Duhaime, G., Baert, J., and Ampleman, L. (2004). Gestion intégrée des réseaux de transport dans le Nord-du-Québec. Groupe d'études inuit et circumpolaires (GÉTIC), *Université Laval*, Québec, Collection Recherche, Numéro 42, 104 p.

Report title: Processing of Temperature Measurements Linearly Distributed under Transport Infrastructure

Traitement des mesures de températures linéairement distribuées sous les infrastructures de transport

Project lead: Jonathan Roger (jonathan.roger@cen.ulaval.ca)

Affiliation: Université Laval

Dates: 2013/2014

Themes: Data; Roads; Infrastructure; Monitoring;

Key terms: Salluit; Fibre Optics; Distributed Temperature Sensing (DTS); Monitoring; Geotechnical; Ground Temperature; Thermal Regime;

Objectives: Develop a method for processing the large mass of data produced by DTS experimentally installed at Salluit and produce a graphical visualization interface.

Link: N/A

Summary:

The Salluit road to the community airport was rebuilt due to serious impacts from permafrost degradation. About 900 m of embankment were rebuilt in 2012 with specially designed heat drains buried under one side of the road, while the geometry of ditches and culverts was redesigned on the other side. Around 3.4 km of DTS cable was buried under the embankments slopes on both sides of the road. On one side, the cable was buried at two depths (0.3 m and 0.8 m) to detect heat carrying water seepage in the ground. On the other side, it was buried under the heat drain to assess its efficiency in cooling permafrost under the roadside. A section of cable measures ground temperature at 0.25 m depth in the natural terrain several meters away from the road as a reference. The cable also runs in loops across the road under four culverts. This report presents a data validation and treatment method and a graphic visualization method developed at Centre d'études nordiques to analyze large datasets produced by automated DTS readings.

Results show the different timing of freeze back in the embankment under the roadside in relation with wet and dry sections of terrain on which the road is built. Differential insulation provided by unequal snow cover on the sides of the road can be observed. At springtime, heat intake in the ground by water flow in the culverts and the impact of seepage under the road at a few points could be detected. The linearly measured temperature data now allows detection of sensitive spots anywhere along the road and monitoring of the new engineering designs.

Methods/ Approaches: (1) Installation of DTS cable under embankment slopes; (2) Data acquisition and structuring; (3) Integration of data into GIS; (4) Preliminary interpretations.

Key findings/ suggestions: (1) DTS data made it possible to observe and analyze the thermal regime of the ground along a road infrastructure continuously over time and space; (2) DTS allows precise identification of problematic areas, observation of heat transfers between air and soil temperature, and assessment of the effectiveness of engineering concepts (drains heat, fitted systems of ditches and culverts) to retain permafrost; (3) The validation and data processing procedure and the visual analysis method developed in this report are easily transferable to other projects in which the DTS could be used.

Additional information/ links: N/A

Report title: Quantitative Risk Analysis of Linear Infrastructure on Permafrost: State of the Practice Literature Review

Project lead: Heather Brooks (hbrooks@bgcengineering.ca)

Affiliation: Université Laval

Dates: 2014/2015

Themes: Engineering; Infrastructure; Guidelines; Project Development;

Key terms: Risk Assessment; Roads; Literature Review; Mitigation; Climate Change; Design; Considerations; NWT Highway 3; Yellowknife;

Objective: Present a state of the practice literature review on quantitative risk analyses of linear infrastructure on permafrost.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/Quantitative%20Risk%20Analysis%20of%20Linear%20Infrastructure%20on%20Permafrost%20State-of-the-Practice%20Literature%20Review.PDF

Summary:

Risk is defined as the product of the probability of failure (P) multiplied by the consequences of failure (C). A qualitative risk analysis will assign a value to these variables, while a Quantitative Risk Analysis (QRA) will calculate one. QRA provides the benefits of objectivity, ease of fine tuning to specific needs, and being less likely to cause disagreement during subsequent review and decision making. Its usage has not yet been recorded in the literature in permafrost environments. A variety of methodologies are viable when conducting a QRA, including step-by-step or event tree approaches. Generally, methodologies identify and define risk events and the scope of analysis, gather relevant and available information to define P and C, sort possible events by risk factor, and identify and recommend methods of mitigation.

The impacts of climate change were assessed on a section of Highway 3 near Yellowknife. The study did uncover data gaps, but the traditional two-dimensional approach of infrastructure stability and climate data was limiting in an environment shaped by permafrost. Regardless of the various methods for determining P and C, aleatory uncertainty should be recognized, and epistemic uncertainty should be reduced. Methods for determining P include focusing on the aleatory uncertainty within each input parameter, a mathematical method for determining total uncertainty within an equation from Taylor series expansion, and a load factor design method. C should be determined using direct costs or a more complicated analysis of the value of indirect impacts to local communities and/or the cost of human fatalities.

Methods/ Approaches: (1) Identify optimal risk analysis technique based on needs and goals; (2) Identify probability and consequence of failure; (3) Minimize epistemic uncertainty; (4) Use risk analysis to inform decision making.

Key findings/ suggestions: (1) Risk analysis can be completed using quantitative or qualitative methods depending on needs and goals; (2) Aleatory uncertainty cannot be reduced, but epistemic uncertainty can be reduced with more information; (3) Climate change can be addressed by repeating a risk analysis with changing climate data.

Additional information/ links: Brooks, H., Doré G., Locat, A., and Lemieux, C. (2015). Quantitative risk analysis of linear infrastructure: state of the practice and research plan. 16th International Conference on Cold Regions Engineering, 19-22 July 2015, Salt Lake City, UT. In *Cold Regions Engineering 2015, ASCE*, 629-640. DOI: 10.1061/9780784479315.055.

Report title: Adaptation of Airport Infrastructure to Climate Change in Northern Environments: Kuujjuaq Airport

Adaptation d'infrastructures aéroportuaires aux changements climatiques en milieux nordiques: Aéroport de Kuujjuaq

Project lead: Valérie Mathon-Dufour

Affiliation: Université Laval (subcontractor for Groupe Stavibel)

Dates: 2016/2017; 2017/2018

Themes: Airports; Climate Change; Monitoring; Drainage;

Key terms: Kuujjuaq; Nunavik; Thermal Regime; Active Layer; Groundwater; Water Table; Albedo; Pavements; Embankment;

Objectives: (1) Monitor the climate and ground thermal and hydraulic regimes at Kuujjuaq Airport; (2) Characterize permafrost conditions; (3) Predict runway structural behaviour to support decision-makers in identifying climate change adaptations.

Link: N/A

Summary:

Climate and ground data from 2015-2017 is synthesized with data starting in 2006 and analysed for the Kuujjuaq Airport. Until 1990, the climate of Kuujjuaq was relatively stable, but summer rainfall and mean annual air temperatures (MAAT) have since increased by 0.07 °C per year. Kuujjuaq was originally at the transition between the discontinuous and continuous permafrost zones, but now lies within sporadic permafrost. From 2006-2017, average MAAT and annual precipitation were -3.92 °C and 581 mm, respectively.

Thermistors installed at three sites ('2006', 'Humide', and 'Albédo') measured the ground thermal regime intermittently for 2006-2017. Average maximum thaw depths under the runway and shoulder were 2.88 m and 2.55 m for '2006', and 2.76 m and 2.34 m for 'Humide', respectively. For dark and light pavements at Albédo, average maximum thaw depths were 4.34 m and 3.49 m, respectively. In recent years, active layer depths appeared to increase at 'Albédo' and decrease at the other sites. Thaw depths were greatest under the runway and dark surfaces. Data from fourteen piezometric wells recorded average perched water table depths of 1.11-1.37 m for 2015-2017, which were closer to the surface under higher summer rainfall. In a longitudinal transect along runway, groundwater flow was typically northeasterly, but reversed during heavy precipitation. For an oblique transect across runway, flow was downslope to the Koksoak River, but in the thaw season water drains from the embankment towards the centre of the runway.

Methods/ Approaches: (1) Analysis of historic and current climate trends; (2) Installation of thermistors and piezometers for monitoring of near-surface thermal and hydraulic regimes.

Key findings/ suggestions: (1) MAATs in 2015 and 2016 were the coldest of the reference period (2006-2017) and dryer than usual, 2017 was cooler than average; (2) Maximum 2017 thaw depths were 2.76 m to 4.65 m with differences of roughly 0.5 m under dark and light surfaces, and below the runway and shoulder; (3) Cooler MAATs for 2013-2016 may promote ground ice formation; (4) Groundwater flow was from the northwest end of the runway with drainage southeast towards the Koksoak River; (5) Regular maintenance and monitoring of equipment is needed; (6) Identify improvements to the instrument network and locations for additional data collection; (7) Improve knowledge of ground conditions under Runway 13-31.

Additional information/ links: N/A

Report title: Quantitative Risk Assessment of the Iqaluit International Airport, Iqaluit, Nunavut

Project lead: Heather Brooks (hbrooks@bgcengineering.ca)

Affiliation: Université Laval

Dates: 2016/2017; 2017/2018

Themes: Airports; Climate Change; Engineering; Financial; Thaw;

Key terms: Iqaluit; Risk Assessment; Geohazards; Thaw Settlement; Repairs; Interview;

Objectives: (1) Present a QRA methodology for analyzing thaw settlement and bridge formation dangers within the embankment; (2) Conduct a fragility assessment to determine changes in risks due to changing mean annual air temperature; (3) Conduct a cost benefit analysis for an insulated embankment section.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-07/Risk%20Assessment%20and%20Cost-Benefit%20Analysis%20for%20the%20Reconstruction%20of%20the%20Runway%20and%20Taxiways%20at%20the%20Iqaluit%20Airport--Quantitative%20Risk%20Assessment%20of%20the%20Iqaluit%20International%20Airport%2C%20Iqaluit%2C%20Nunavut.pdf

Summary:

A Quantitative Risk Assessment (QRA) was conducted for bridging dangers and thaw settlement in five geological cases for the Iqaluit International Airport. Hazards and costs were determined from site data, project documents, stakeholder interviews, and a new permafrost risk analysis method. The hazard analysis used Monte Carlo simulation and standard permafrost engineering calculations to determine thaw settlements using a stochastic analysis. Bridging dangers were determined through laboratory testing of model ice wedges. Direct cost information came from earned value report data and the construction area calculations on the plans.

Repair costs for insulated, uninsulated, milling/asphalt, and sinkhole sections were $185,000, $166,500, $52,700 and $30,000, respectively. Human and societal impacts were determined from rubrics and stakeholder interviews. The highest risks for thaw settlement occur in bridging, and glaciomarine ice wedge and lacustrine cases. A climate fragility analysis of a 2.5 °C temperature increase from 2010-2050 resulted in steadily increasing or constant hazards. When the cumulative thaw settlement exceeds 3.5 cm a required repair is assumed. From this analysis, repairs are necessary on a 12 to 15-year cycle, which is consistent with historical trends. The present cost for the five cases mimicked the risk order from highest to lowest. The insulated glaciomarine ice wedge section cost 35% and 19% of the present cost for the glaciomarine and glaciomarine ice wedge sections, respectively.

Methods/ Approaches: (1) QRA of five geological cases; (2) Climate fragility assessment: (3) Cost benefit analysis; (4) Monte Carlo simulation; (5) Sinusoidal Temperature Model;

Key findings/ suggestions: (1) Ice wedge glaciomarine and lacustrine sediments had the highest hazards and risks for thaw settlement; (2) Adding insulation to infrastructure fill sections significantly reduced the hazard and risk of thaw settlement in ice wedge glaciomarine sediments; (3) Climate fragility analysis showed a steady increase or constant hazard for the five cases; (4) Present costs for the five cases mimicked the risk order from highest to lowest; (5) Costs for an insulated ice wedge in glaciomarine sediments was 19-36% of the present cost for other cases; (6) Adding insulation to infrastructure fill sections is a cost-effective measure.

Additional information/ links: N/A

Report title: Scientific Support to the Performance Monitoring and Maintenance of the Iqaluit Airport

Project lead: Valérie Mathon-Dufour

Affiliation: Université Laval

Dates: 2017/2018

Themes: Adaptation; Airports; Climate Change; Engineering; Monitoring;

Key terms: Iqaluit; Ground Penetrating Radar (GPR); Maintenance; Monitoring; Geohazards;

Objectives: Set up a strategic plan to initiate and implement long-term monitoring of the performance of the repaired airport infrastructure in Iqaluit.

Link: N/A

Summary:

Due to new concerns about global warming in permafrost environments and the risks associated with thaw, the Iqaluit International Airport was the object of a detailed study starting in 2010 and funded by Transport Canada and the Government of Nunavut. The methods used in this project included maintenance of existing instrumentation such as temperature and water level sensor networks beneath the runway, taxiways, aprons and natural terrain, and a new monitoring protocol for two runway frost crack repairs and Taxiway A. This protocol includes ground temperature and water level monitoring, and GPR surveys of the repairs and Taxiway A. Regular comparison of the GPR surveys will allow for the detection of eventual changes, such as the formation of new differential settlements and frost cracks.

All previously gathered data were integrated into a geodatabase, built during the previous research project. The geodatabase was improved during this project to include geolocated data and observations from 2016 and 2017. It is available to share with stakeholders and aims to make data easily updatable and user-friendly for information seekers. The geoscientific data and instrument network are available to provide essential inputs for decision-making and future risk analyses related to climate change.

Methods/ Approaches: (1) Maintenance of previously installed instrumentation; (2) Establishment of a new monitoring protocol for frost cracks and Taxiway A; (3) Design a GIS application for data storage.

Key findings/ suggestions: (1) The geoscientific data and instrument network established during this project are available to provide essential inputs for decision-making and future risk analyses related to climate change; (2) The planned instrumentation and performance assessment program can still be pursued provided the well covers are located and cleared of their asphalt layer in early summer 2018; (3) Keeping data acquisition active will allow a sound understanding of the causes of eventual failures, and the selection of better remediation solutions; (4) Collaboration with the Government of Nunavut, airport operators and other stakeholders is essential to assess the performance of the infrastructure and the newly implemented adaptation strategies.

Additional information/ links: Mathon-Dufour, V., *et al.* (2015). Assessment of permafrost conditions in support of the rehabilitation and adaptation to climate change of the Iqaluit airport, Nunavut, Canada. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 146.

Report title: Study of the Thermal Regime around Highway Culverts Built on Permafrost

Project lead: Loriane Périer

Affiliation: Université Laval

Dates: 2013/2014

Themes: Adaptation; Infrastructure; Roads; Modelling; Monitoring; Drainage;

Key terms: Alaska Highway; Beaver Creek; Culverts; Design; Embankment; Thermal Regime; Performance Response;

Objectives: (1) Instrument two culverts; (2) Document the thermal regime as a function of water flow and temperature before entering the culvert; (3) Develop a 2D thermal model on TEMP/W calibrated using field observations; (4) Quantify the effects of water flow, air and water temperature, culvert diameter, embankment height, and position of insulation; (5) Determine the key factors to design a culvert;

Link: N/A

Summary:

In 2013, two culverts were instrumented on the Alaska Highway near the Beaver Creek test site and near the Alaska-Yukon border. Temperature probes were placed underneath and on the side of the culverts. A flow measurement system was also placed upstream of the Beaver Creek culvert. This report summarizes objectives one to three. Results showed the culvert to have a warming effect on the ground in summer, and a cooling effect in winter. A 2D thermal model of Beaver Creek, developed and calibrated on TEMP/W, matched well with these field observations.

A mathematical model of the water temperature inside and at the entrance of the culvert showed a linear relationship, whereas the water temperature entering the culvert and the water flow is logarithmic. Flow rates and water temperatures before entry into the culvert were modified in TEMP/W to model the effects on the thermal regime. Observations showed a ±10% variation in flow rate had no impact below the culvert, but a ±10% variation in water temperature had a slight influence on thermal regime. The final simulation assessed the thermal regime of an uninsulated culvert. Results showed a change in thaw depth from 30 cm to 120 cm without insulation.

Methods/ Approaches: (1) Measure water temperature and flow rate; (2) Thermal and mathematical modelling in TEMP/W;

Key findings/ suggestions: (1) Culvert has a warming effect on the ground in summer, and a cooling effect in winter; (2) 2D thermal models were consistent with field data; (3) Variations of ±10% in the flow rate do not impact the thermal regime beneath the culvert; (4) Variations of ±10% in water temperature before entry into the culvert have a slight influence on the thermal regime; (5) Uninsulated culverts have greater thaw depths than insulated culverts; (6) A new water flow measuring system will be installed at the border culvert for modelling planned in 2014; (7) Other parameters will be modified in TEMP/W, including culvert diameter and embankment height;

Additional information/ links:

(1) Périer, L., Doré, G., and Burn, C.R. (2014). The effect of water flow and temperature on thermal regime around a culvert built on permafrost. *Science in Cold and Arid Regions*, 6(5), 10 p. DOI: 10.3724/SP.J.1226.2014.00415.

(2) Périer, L., Doré, G., and Burn, C.R. (2015). Influence of water temperature and flow on thermal regime around culverts built on permafrost. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 089.

Report title: Retrogressive Thaw Slump (RTS) Self-stabilization – Phase I

Project lead: Eva Stephani (eastephani@alaska.edu)

Affiliation: Université Laval

Dates: 2017/2018; 2018/2019; 2019/2020

Themes: Ground Movement; Thaw; Mitigation; Infrastructure; Climate Change;

Key terms: Risk Assessment; Thaw Settlement; Literature Review; Interview; Remote Sensing; Geohazards;

Objectives: (1) Determine typical patterns of interaction between RTS and linear infrastructure; (2) Understand positive and negative feedbacks controlling RTS self-stabilization; (3) Determine variations of RTS self-stabilization across landscapes, climates, and regions.

Link: N/A

Summary:

There are currently no standards or guidelines in place to mitigate Retrogressive Thaw Slump (RTS) impacts on linear infrastructure. This project was developed to identify typical patterns of interaction between RTS and infrastructure, feedbacks which control RTS self-stabilization, and variations in healing capacity across landscapes, regions, and climates. The study reviewed literature, conducted interviews, and utilized remote sensing and climatic analysis, fieldwork, laboratory testing, and data integration in ArcGIS.

RTS developed independently from infrastructure or due to linear infrastructure interacting with existing natural conditions, such as embankment interception of local drainage. RTS can impact linear infrastructure by growing towards infrastructure or from a debris tongue flowing towards it. RTS feedbacks result from changes in key factors used to predict the vulnerability of permafrost systems to thaw slumping. These factors include local cryostratigraphy, drainage, precipitation, vegetation, and topography. There were no distinctive trends observed in self-stabilization variations across regions and climates. However, some similarities may arise depending on the RTS initiation mechanism and hosting unit.

Methods/ Approaches: (1) Literature review; (2) Interviews; (3) Remote sensing; (4) Field surveys; (5) Laboratory testing.

Key findings/ suggestions: Key steps to manage risk to infrastructure include, (1) Recognize the pattern of interaction between the RTS and infrastructure; (2) Identify the types of processes initiating RTS and contributing to sustained growth; (3) Evaluate the potential vulnerability or resilience of the terrain; (4) Evaluate the risk level to infrastructure and act consequently.

Additional information/ links: Stephani, E., Kanevskiy, M., Darrow, M.M., Croft, P., Drage, J., and Wuttig, F. (2018). Early self-stabilization conditions of a retrogressive thaw slump, North Slope, Alaska. 5th European Conference on Permafrost, 23 June – 1 July 2018, Chamonix, France, *EUCOP5 Book of Abstracts*, 207-208.

Report title: Development of a Methodology for the Design of Low-impact Drainage Systems Along Transportation Infrastructure in Permafrost Environments

Project lead: Julie Malenfant-Lepage (julie.m.lepage@ntnu.no)

Affiliation: Université Laval

Dates: 2016/2017; 2017/2018

Themes: Drainage; Infrastructure; Roads; Laboratory; Field survey;

Key terms: Salluit Airport; Alaska Highway; Ilulissat Airport; Culverts; Ditch; Electrical Resistivity Tomography (ERT); Active Layer; Shear Stress; Cohesive Strength; Modelling;

Objectives: (1) Validate the design method and effectiveness of the new drainage system built in 2012; and (2) Develop fieldwork and laboratory procedures for the use of a Cohesive Strength Meter (CSM) on permafrost.

Link: N/A

Summary:

The study was part of a PhD project intended to develop a method for assessing the maximum quantity of water that can be concentrated in one channel to control heat transfer and limit soil erosion. Three sites were chosen: Salluit Airport Access Road (Nunavik), Ilulissat Airport Access Road (Greenland), and km 1984 of the Alaska Highway (Yukon).

In 2017, an assessment of the thermal performance of the new drainage system in Salluit was undertaken. This involved a study of the watershed and subsurface flow network, culvert monitoring, water flow measurements, ERT and topography surveys, and active layer depths. A CSM was applied to the Salluit test site to measure critical shear stress and assess the mechanical performance of the drainage system. A laboratory method was successfully developed to reproduce CSM on any fine-grained frozen soil.

ERT surveys collected in 2014 from Illulissat revealed a plunging permafrost table at the edge of a stream. The flow rate influences permafrost degradation but is more important when water is ponded. Along the Alaska Highway, ERT surveys were collected to assess permafrost degradation associated with a 300 m ditch constructed in 2014. Critical shear stress values were also obtained to test the CSM.

Methods/ Approaches: (1) Adapt the Peclet number to infrastructure drainage systems; (2) ERT surveys; (3) Adapt a Cohesive Strength Meter; (4) Develop a 3D road model;

Key findings/ suggestions: (1) The CSM successfully reproduced critical shear stress values measured in the field; (2) ERT surveys at Illulissat revealed unfrozen ground below a stream; (3) Ponded water influences permafrost degradation more than flowing water;

Additional information/ links: Malenfant-Lepage, J., Doré, G., and Lubbad, R. (2018). Critical shear stress of frozen and thawing soils. 5th European Conference on Permafrost, 23 June – 1 July 2018, Chamonix, France, *EUCOP5 Book of Abstracts*, 182.

Report title: Evaluating the Performance of Highway Embankments on Degrading Permafrost

Project lead: Marolo Alfaro (marolo.alfaro@umanitoba.ca)

Affiliation: University of Manitoba

Dates: 2012/2013; 2013/2014; 2014/2015

Themes: Engineering; Thaw; Modelling; Roads;

Key terms: Embankment; Drilling; Monitoring; Manitoba; Viscoplasticity; Thermoplasticity; Validation; Performance Response;

Objective: (1) Improve understanding of mechanisms and processes associated with highway embankment performance on degrading permafrost; (2) Validate an elastic-thermo-viscoplastic (ETVP) model for the stress-strain characteristics of clays and peats.

Link: N/A

Summary:

Thawing has led to significant and ongoing deformation of a highway constructed in the discontinuous permafrost zone of northern Manitoba. In 2008, a highway test section was instrumented with thermistors, piezometers and standpipes, settlement plates, and slope inclinometers to improve understanding of site conditions and the occurrence of deformation. Monitoring was terminated in early 2011 due to a lack of funding but was resumed in 2012.

Data from the test site was used to validate a newly developed elastic-thermo-viscoplastic (ETVP) model in a field application for the first time. The model builds on a previously developed elastic-viscoplastic model which describes the performance of embankments built on soft clays, by incorporating the effects of temperature on plasticity. A limitation of the ETVP model is that the physics regarding thermal expansion and contraction and phase change have not been implemented. Based on 2008 borehole data from the embankment toe and mid-slope, it was assumed the embankment and foundation had thawed, but more recent drilling discovered about 6 m of ground ice at the highway centreline and 3 m at the shoulder. This made ETVP model validation impractical at the site. However, the model results qualitatively match laboratory data from other research studies, therefore it can be applied with some confidence in appropriate field applications. ETVP is expected to be further developed and applied to embankments and foundations to validate the model and gain an understanding of how changes in temperature and viscosity affect their performance.

Methods/ Approaches: (1) Install field instrumentation; (2) Conduct laboratory testing on field conditions; (3) Input data to validate ETVP model.

Key findings/ suggestions: (1) The ETVP model qualitatively matches data from literature; (2) The ETVP model should be further developed to increase understanding of how changes in temperature and viscosity affect embankment and foundation performance.

Additional information/ links:

(1) Batenipour, H., Kurz, D., Alfaro, M., and Graham, J. (2009). Highway embankment on degrading permafrost. 14th Conference on Cold Regions Engineering, 31 August – 2 September 2009, Duluth, MN. In *Cold Regions Engineering 2009, ASCE*, 512-521. DOI: 10.1061/41072%28359%2950.950.

Batenipour, H., Alfaro, M., Kurz, D., and Graham, J. (2014). Deformations and ground temperatures at a road embankment in northern Canada. *Canadian Geotechnical Journal*, 51(3), 260-271, DOI: 10.1139/cgj-2012-0425.

Report title: Climate Change Adaptation by Canada's Northern Railways: Best Practices and Strategies

Project lead: Naomi Happychuk (Naomi@cftn.ca)

Affiliation: University of Winnipeg

Dates: 2014/2015; 2015/2016

Themes: Adaptation; Climate Change; Railways; Guidelines; Standards;

Key terms: Railways; Interview;

Objectives: (1) Provide an overview of physical, operational, and business environments of northern railways, focusing on (a) the current physical backdrop; (b) climate-related vulnerabilities; (c) state of knowledge of climate change among northern rail operators; (d) climate change adaptation strategies with cost estimates of climate change impacts and adaptation measures; (5) transferability of strategies or practices to northern rail practitioners to mitigate climate change effects.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Climate%20Change%20Adaptation%20by%20Canada%27s%20Northern%20Railways-Best%20Practices%20and%20Strategies.pdf

Summary:

This report includes an assessment of northern rail operations, environment, adaptation plans and transferability. Northern rail operations and infrastructure are dependent on local conditions which dictate the challenges and risks to rail lines, and the strategies used to mitigate these risks. Lessons between northern rail operators can therefore be shared but not replicated without the consideration of the individuality of rail sites. The North is most sensitive to and most impacted by climate change and will experience environmental variations which will impact the engineering and operations of cold climate rail. Rail lines overlying permafrost and/or peatland will continue to face significant challenges to roadbed and track stability. Presently, adaptation planning has been more reactive than proactive with little indication of formalized long-term adaption plans.

An absence of information on northern rail operations and adaptation strategies makes it difficult to evaluate risks and level of preparedness to climate change. A higher standard of operational reporting may improve information sharing within the industry and eliminate risks and uncertainties by employing best practices. The rail industry is highly adaptive to varying conditions under a relatively short time frame. The risks and uncertainties of northern rail in the face of climate change would be greatly reduced if practitioners incorporated longer-term planning into their decision-making processes. While the cost benefits of adaptation planning (as opposed to a do-nothing approach) have been illustrated, they may not be realized in the short time frame of rail industry decisions. The public sector should provide incentives and support to enable longer-term decision making and informed adaptation planning.

Methods/ Approaches: (1) Interviews with key rail operators and experts; (2) Secondary data attained through academic journals, climate and rail research portals, and rail industry websites; (3) Annotated bibliography.

Key findings/ suggestions: Adaptation planning can be strengthened through (1) Publicly available documentation of rail operations, risks and engineering and operational strategies; (2) Long-term planning which incorporates climate change adaptation; (3) Strong support from the public sector.

Additional information/ links: N/A

Report title: Economic Implications of Climate Change on Transportation Assets: An Analysis Framework

Project lead: N/A

Affiliation: Yukon University

Dates: 2013/2014

Themes: Financial; Climate Change; Adaptation; Guidelines; Infrastructure;

Key terms: Risk Assessment; Economic Tools; Framework;

Objectives: (1) Determine the costs associated with climate-induced damage to transport infrastructure; (2) Evaluate available economic tools; (3) Establish a seven-step framework to incorporate economic analysis into climate risk assessments.

Link: N/A

Summary:

This guide focuses on aiding practitioners to understand how to reveal the economic implications of damages to transport infrastructure and the benefits of investing in infrastructure resiliency. A taxonomy of transportation benefits to communities, business and governments is presented to highlight lost opportunities that manifest as climate change impairs infrastructure services. Basic information is provided on how economic tools such as cost benefit analysis and economic impact analysis can complement climate damage and adaptation assessments. A seven-step framework is suggested to incorporate economic analysis into climate risk assessments. Case studies related to northern transportation impacts are used with a focus on permafrost, roads and airports.

Costs triggered by climate change include increased maintenance/repair and capital costs, accelerated infrastructure replacement costs, and loss of infrastructure service and activity disruption. From the economic tools considered, cost benefit analyses consider alternative adaptation actions that maximize benefits and minimize costs, but economic impact analyses highlight changes in activity levels and other macroeconomic indicators. The Climate Risk and Economic value model (CR-EVm) is used in the framework to monetize economic damages under alternative adaptation action and climate scenarios.

Methods/ Approaches: (1) Identify benefits of transportation infrastructure; (2) Assess economic tools for climate risk assessment; (3) Develop seven-step framework.

Key findings/ suggestions: (1) Provide a conceptual framework for economic analysis in climate risk assessment; (2) Economic analysis should complement climate risk assessment; (3) Probability analysis is the best practice in climate risk and economic value models; (4) Data and information on historical business losses, government-held data on losses associated with climate change, performance thresholds at which a defined hazard will generate damage or interrupt service, institutional capacities to minimize loss and damage, and reliability requirements of key economic activities are needed to support assessments.

Additional information/ links: Sawyer, D. (2014). The economic implications of climate change on transportation assets: an analysis framework. *The International Institute for Sustainable Development*, 27 p.

Report title: Assessment of Recent Past and Current Permafrost Conditions under Front Street, Dawson City, Yukon

Project lead: Fabrice Calmels (fcalmels@yukonu.ca)

Affiliation: Yukon University

Dates: 2014/2015

Themes: Roads; Climate Change; Monitoring;

Key terms: Dawson City; Active Layer; Pavements; Boreholes; Albedo; Data Quality; Thermal Regime; Surficial Geology;

Objectives: (1) Monitor the near-surface thermal regime after road resurfacing efforts; (2) Analyze the effects of light-coloured asphalt on the ground thermal regime.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-06/Assessment%20of%20Recent%20Past%20and%20Current%20Permafrost%20Conditions%20Under%20Front%20Street%2C%20Dawson%20City%2C%20Yukon.pdf

Summary:

In 2009, Front Street in Dawson City, Yukon, was resurfaced with a light-coloured asphalt by the Department of Highways and Public Works, Government of Yukon to reduce surface albedo and slow permafrost degradation. The resurfacing effort occurred in two stages, (1) application of a standard black asphalt in August, and (2) application of lighter asphalt over the top in September. In June, nine boreholes were drilled and four (Gray, Ivory, Gold, and Berm) were instrumented with thermal sensors to 5 m depth. Vandalism and logger failure resulted in intermittent data records, limiting analysis capabilities. Permafrost below Dawson City may exist to a depth of 60 m but is absent under the south end of the community. At north end of Front Street, permafrost may have up to 30% excess ice content, especially in coarse sediments. The Ivory borehole was ice-rich. Long-term increasing temperatures and decreasing precipitation trends have occurred since the start of the 20th Century.

From 2009-2013, mean annual ground temperatures were -0.5 °C. Mean monthly ground temperatures suggested warming at Gold, cooling at Gray, slight warming at Ivory, and slight cooling at Berm. Summer temperatures were similar for Gray, Ivory, and Berm but warmer at Gold, possibly due to a lack of surface shading. Active layer thinning apparently occurred at Gray and Ivory, while significant deepening occurred at Gold. Trumpet curves suggested cooling throughout the profile at Gray, and surface cooling and warming at depth for Gold. Unfortunately, due to the poor data quality, conclusions on the effect of the new asphalt could not be made.

Methods/ Approaches: (1) Surficial geology and sediment core analyses; (2) Analysis of climate trends; (3) Data correction; (4) Monitoring of ground thermal regime.

Key findings/ suggestions: (1) Long-term climate warming, especially during winter, and precipitation decreases, especially in winter and summer, have increased permafrost temperatures under Dawson City possibly for a century; (2) Data issues limited analysis and resulted in no clear conclusions on the effects of the light asphalt; (3) Mean annual ground temperatures were -0.5 °C at 5 m depth; (4) There is evidence of ground cooling but is limited in spatial and temporal extents; (5) Establish a regular maintenance routine for data acquisition; (6) Create a dedicated database for logger data; (7) Identify and install data loggers at two additional sites: undisturbed permafrost and dark-coloured asphalt.

Additional information/ links: N/A

Report title: ERT and Temperature Monitoring to Assess the Effectiveness of Insulating Culverts on Northern Highways

Project lead: Fabrice Calmels (fcalmels@yukonu.ca)

Affiliation: Yukon University

Dates: 2016/2017; 2017/2018

Themes: Adaptation; Drainage; Monitoring; Geophysics; Roads;

Key terms: Culverts; Dempster Highway; Construction; Design; Electrical Resistivity Tomography (ERT); Performance Response; Thermal Regime; Considerations; Groundwater;

Objectives: (1) Monitor the impact of a culvert on underlying permafrost using temperature monitoring and ERT; (2) Assess the effectiveness of an insulating layer installed below the culvert through temperature monitoring.

Link: https://tcdocs.ingeniumcanada.org/sites/default/files/2019-05/ERT%20and%20Temperature%20Monitoring%20to%20Assess%20the%20Effectiveness%20of%20Insulating%20Culverts%20on%20Northern%20Highways_0.PDF

Summary:

In 2016, a layer of foam insulation was installed under a new culvert at Dempster Highway km 381, to provide a buffer between the culvert and the permafrost underneath. Researchers at the Northern Climate ExChange (NCE), Yukon University, monitored the effectiveness of the insulation using temperature sensors and electrical resistivity tomography (ERT). The system monitored the difference between ground directly influenced by heat-transfer from the culvert, and ground protected by the insulating layer. Unfortunately, the culvert could not be insulated along its entire length.

Ground temperatures near the culvert were warm, close to 0 °C. At 4.55 m depth permafrost is -0.2 °C and still recovering from construction. Under the culvert, winter temperatures are cooler above the foam than below, but reverse during freshet in May. The foam acts as a mitigator of cold surface air temperatures in winter and warm air temperatures in summer. Winter temperatures show less variability above the foam than below but show greater variability in summer. This suggests possible penetration of groundwater below the foam. ERT surveys indicated two areas of higher resistivity along the culvert, likely representing ice-rich ground or colder permafrost. Ground under the culvert was less resistive nine months after installation but assumptions should be cautioned because the site may not have reached thermal equilibrium.

Methods/ Approaches: (1) Culvert construction; (2) Ground temperature measurements; (3) ERT surveys;

Key findings/ suggestions: (1) Ground temperatures are close to 0 °C; (2) Winter temperatures are cooler above the foam than below, and reverse in summer; (3) Insulating foam slows cooling in winter and warming in summer; (5) Winter temperatures are less variable above the foam than below, but more variable in summer (6) ERT indicates areas of higher resistivity along the culvert; (8) The site hasn’t reached thermal equilibrium following disturbance from construction; (9) Covering the foam with an impervious membrane may protect against groundwater infiltration;

Additional information/ links: Calmels, F., Roy, L-P., Grandmont, K., and Pugh, R. (2018). Summary of climate- and geohazard-related vulnerabilities for the Dempster Highway corridor. Northern Climate ExChange, Yukon Research Centre, *Yukon College*, 204 p.

Report title:	NTAI Design and Implementation of Early Detection and Warning Systems for Transportation Infrastructure Impacted by Permafrost-Related Geohazards
Project lead:	Fabrice Calmels (fcalmels@yukonu.ca)
Affiliation:	Yukon University
Dates:	2019/2020; 2020/2021; 2021/2022
Themes:	Monitoring; Data; Infrastructure; Ground Ice;
Key terms:	Remote Monitoring, Geohazards; Boreholes; Groundwater; Ground Temperature; Electrical Resistivity Tomography (ERT); Surficial Geology; Risk Assessment;
Objective(s):	(1) Design and implement an early warning system for preemptively detecting permafrost geohazards along at-risk sections of transportation infrastructure.
Link:	N/A

Summary:

This report summarizes the development and implementation of an early detection and warning system for permafrost related geohazards affecting northern transportation infrastructure. A detailed site evaluation is being conducted at km 115 on the Dempster Highway where thaw settlement and thaw slumps occur. To determine why these geohazards occur and if they can be detected, several monitoring parameters are being investigated such as, surficial geology, ground temperatures, ground ice properties and water movement. The evaluation is ongoing, and the resulting data will be implemented in the design of future early warning systems.

Extensive site characterization has already been achieved at Iqaluit, Salluit and Tasiujaq sites, and potential hazardous infrastructure zones have been identified. Existing instrumentation at these sites has been chronicled, and the additional monitoring systems necessary to complete an efficient geohazard surveillance system have been identified. The design of the communication system is ongoing with end users. One thermistor chain and data logger with wireless communication capabilities has been installed at both the Salluit and Tasiujaq sites, which will be incorporated into the geohazard surveillance system. Network configuration and data acquisition processes will be optimized using information from these sites and Iqaluit, where similar sensors will be installed. Once the systems have been fully implemented, their performance will be evaluated and discussed in a final report.

Methods/ Approaches:	(1) Determine relevant permafrost site conditions for detecting geohazards; (2) Design an interconnected sensor network to monitor site conditions; (3) Install a monitoring network as an early warning system along at-risk infrastructure; (4) Assess the real-world performance of the early warning system.
Key findings/ suggestions:	Determined upon project completion.
Additional information/ links:	Progress on the development of the Long-range Wide Angle (LoRaWan) communication technology to be used by the early warning system is attached to the project report.

Report title: NTAI Project Activity Report - Assessment and monitoring of a new retrogressive thaw slump at km 1456 of the Alaska Highway: A rare opportunity

Project lead: Fabrice Calmels (fcalmels@yukonu.ca)

Affiliation: Yukon University

Dates: 2019/2020; 2020/2021

Themes: Monitoring; Field survey; Geophysics; Ground ice; Ground movement;

Key terms: Alaska Highway; Whitehorse; Geohazards; Monitoring; Electrical Resistivity Tomography (ERT); Boreholes; Differential GPS (DGPS); Remote Sensing; Drone surveys; Timelapse Photography;

Objectives: (1) develop a better understanding of the retrogressive thaw slump (RTS) that impacts the road corridor; (2) test a multi-faceted technical monitoring approach to be used as a geohazard alarm system; (3) inform an approach to mitigate the threat caused by the RTS on the road corridor; and (4) advance Yukon transportation professionals and Yukon College students understanding of the threats posed by RTS's.

Link: N/A

Summary:

The study site is an active retrogressive thaw slump (RTS) adjacent to the Alaska Highway at km 1456. The headwall is 60 m wide, and 6 m high, and about 70 m from the road. Several multi-meter long tension cracks have formed between the failure and the road. The headwall has been retreating towards the highway at an average rate of 8 m/yr since 2014. The legacy of the project will be a monitored RTS site providing new knowledge and products in the coming years. The site will be used to generate or improve practices and guidelines relating to RTS impacting transportation networks and produce scientific articles. Results have been disseminated at three oral presentations and the project has supported the learning of two students.

To examine the distribution of ground ice, two ERT surveys were conducted parallel to the road on either side, and two at various distance between the road and RTS. Using DGPS, ground movement was measured at rebar monuments every 2-4 weeks in summer and fall. A 25 m borehole was drilled and instrumented with a thermistor and inclinometer to measure ground temperatures and displacement. A core was retrieved for ground ice and grain size analysis. Two time-lapse cameras recorded slump activity from June to November 2019. Repeat drone surveys from August to October 2019 produced photogrammetric 3D models. It is recommended that two 6 m boreholes be drilled and instrumented in May 2020 to ensure on-going monitoring.

Methods/ Approaches: (1) ERT surveys; (2) DGPS; (3) Borehole drilling, instrumentation, and lab analysis; (4) Time-lapse cameras; (5) Drone surveys.

Key findings/ suggestions: (1) Ice-rich permafrost is present to 20 m depth near the headwall, and ground ice thickness decreased towards the highway. However, ice is present across a 60 m section of the embankment indicating slumping could reach the road.

Additional information/ links:

(1) Calmels, F., Roy, L., Laurent, C., Amyot, F., and Lipovsky, P., (2020). Assessment and monitoring of a new retrogressive thaw slump at km 1456 of the Alaska Highway: A rare opportunity. *Yukon University Research Centre*, 62 p.

(2) Roy, L.-P., Calmels, F., Lipovsky, P., Godin, P., Laurent, C., and MacDougall, S. (2019). Assessment and Monitoring of thaw slumps along Yukon highways. [Conference Presentation], *ArcticNet Annual Scientific Meeting*, 2-5 December 2019, Halifax, Canada.

Associated Publications

Barón Hernández, M.F., Lemieux, C., and Doré, G. (2019). Long-term monitoring of mitigation techniques of permafrost thaw effects at Tasiujaq Airport in Nunavik, Canada. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 500-507. DOI: 10.1061/9780784482599.058.

Batenipour, H., Kurz, D., Alfaro, M., and Graham, J. (2009). Highway embankment on degrading permafrost. 14th Conference on Cold Regions Engineering, 31 August – 2 September 2009, Duluth, MN. In *Cold Regions Engineering 2009, ASCE*, 512-521. DOI: 10.1061/41072%28359%2950.950.

Batenipour, H., Alfaro, M., Kurz, D., and Graham, J. (2014). Deformations and ground temperatures at a road embankment in northern Canada. *Canadian Geotechnical Journal*, 51(3), 260-271, DOI: 10.1139/cgj-2012-0425.

Brooks, H., Doré G., Locat, A., and Lemieux, C. (2015). Quantitative risk analysis of linear infrastructure: state of the practice and research plan. 16th International Conference on Cold Regions Engineering, 19-22 July 2015, Salt Lake City, UT. In *Cold Regions Engineering 2015*, *ASCE*, 629-640. DOI: 10.1061/9780784479315.055.

Brooks, H., Doré, G., and Smith, S.L. (2018). Permafrost geotechnical index property variation and its effect on thermal conductivity calculations. *Cold Regions Science and Technology*, 148, 63-76. DOI: 10.1016/j.coldregions.2018.01.004.

Brooks, H., Doré, G., Locat, A., and Allard, M. (2019). Quantifying hazard and climate change fragility for the airport access road in Salluit, Nunavik, Québec. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 516-524. DOI: 10.1061/9780784482599.060.

Brooks, H., Doré, G., and Locat, A. (2021). Soil bridging effects within permafrost-supported embankment infrastructure. *Journal of Cold Regions Engineering*, 35(1), 9 p. DOI: 10.1061/(ASCE).CR.1943-5495.0000232.

Brown, N., *et al.* (2020). Permafrost Data Workshop Final Report. *NSERC PermafrostNet*, Ottawa, ON. DOI: 10.22215/pn/10120001.

Burn, C.R., Moore, J.L., O'Neill, H.B., Hayley, D.W., Trimble, J.R., Calmels, F., Orban, S.N., and Idrees, M. (2015). Permafrost characterization of the Dempster Highway, Yukon and Northwest Territories. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 705.

Calmels, F., Doré, G., Kong, X., Roy, L-P., Lemieux, C., Horton, B. (2016). Vulnerability of the north Alaska Highway to permafrost thaw: Design options and climate change adaptation. Northern Climate ExChange, Yukon Research Centre, *Yukon College*, 130 p.

Calmels, F., Roy, L-P., Grandmont, K., and Pugh, R. (2018). Summary of climate- and geohazard-related vulnerabilities for the Dempster Highway corridor. Northern Climate ExChange, Yukon Research Centre, *Yukon College*, 204 p.

Calmels, F., Roy, L., Laurent, C., Amyot, F., and Lipovsky, P., (2020). Assessment and monitoring of a new retrogressive thaw slump at km 1456 of the Alaska Highway: A rare opportunity. *Yukon University Research Centre*, 62 p.

Cameron, E.A., Lantz, T.C., O'Neill, H.B., Gill, H.K., Kokelj, S.V., and Burn, C.R., (2019). Permafrost Ground Temperature Report: Ground temperature variability among terrain types in the Peel Plateau region of the Northwest Territories (2011-2015); *Northwest Territories Geological Survey*, NWT Open Report 2017-009, 8 p.

Chen, L., Fortier, D., McKenzie, J.M., and Sliger, M. (2019). Impact of heat advection on the thermal regime of roads built on permafrost. *Hydrological Processes*, 34(7), 1647-1664. DOI: 10.1002/hyp.13688.

Chen, L., Voss, C., Fortier, D., and McKenzie, J.M. (2021). Surface Energy Balance of Sub-Arctic Roads with varying Snow Regimes and Properties in Permafrost Regions. *Permafrost and Periglacial Processes* (accepted).

Connon, R., and Quinton, W., (2020). Permafrost Ground Temperature Report: Scotty Creek Research Station, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-007, 8 p.

Coulombe, S., Fortier, D., and Stephani, R. (2012). Using air convection ducts to control permafrost degradation under road infrastructures: Beaver Creek experimental site, Yukon, Canada. 15th International Conference on Cold Regions Engineering, 19-22 August 2012, Quebec City, QC. In *Cold Regions Engineering 2012, ASCE*, 21-31. DOI: 10.1061/9780784412473.003.

De Guzman, E.M.B, Piamsalee, Alfaro, M., Arenson, L.U, Doré, G., and Hayley, D. (2015). Initial monitoring of instrumental test sections along the Inuvik-Tuktoyaktuk Highway. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 065.

De Guzman, E.M.B, Stafford, D., Alfaro, M., Doré, G., and Arenson, L.U. (2018). Large-scale direct shear testing of compacted frozen soil under freezing and thawing conditions. *Cold Regions Science and Technology*, 151, pp. 138-147. DOI: 10.1016/j.coldregions.2018.03.011.

De Guzman, E.M.B, Alfaro, M., Arenson, L.U., and Doré, G. (2019). Monitored thermal performance of varying embankment thickness on permafrost foundations. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 128-136. DOI: 10.1061/9780784482599.015.

De Guzman, E.M.B, Alfaro, M., Doré, G., Arenson, L.U., and Piamsalee, A. (2021). Performance of highway embankments in the Arctic corridor constructed under winter conditions. *Canadian Geotechnical Journal*, 53 p. DOI: 10.1139/cgj-2019-0121.

Doré, G., Fujun, N., and Brooks, H. (2016). Adaptation methods for transportation infrastructure built on degrading permafrost. *Permafrost and Periglacial Processes*, 27(4), 352-264. DOI: 10.1002/ppp.1919.

Ensom, T., Kokelj, S.V., and Marsh, P. (2019). Thermal regime of stream channels in continuous permafrost, western Canadian Arctic. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 254-262. DOI: 10.1061/9780784482599.030.

Ensom, T., Makarieva, O., Morse, P., Kane, D., Alekseev, V., and Marsh, P. (2020). The distribution and dynamics of aufeis in permafrost regions. *Permafrost and Periglacial Processes*, 31(3), 383-395. DOI: 10.10 02/ppp.2051.

Ensom, T., Kokelj, S.V., and Kamo McHugh, K., (2020). Permafrost Ground Temperature Report: Inuvik to Tuktoyaktuk Highway stream crossing and alignment sites, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-014, 8 p.

Ensom, T., and Kokelj, S.V., (2020). Permafrost Geotechnical Report: Inuvik to Tuktoyaktuk Highway stream crossing and alignment boreholes, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-009, 6 p.

Ensom, T., Kokelj, S.V., Morse, P.D., and Kamo McHugh, K., (2020). Permafrost Ground Temperature Data Synthesis: 2013–2019 Inuvik-Tuktoyaktuk Highway region, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-020; *Geological Survey of Canada*, Open File 8656, 13 p. DOI: 10.4095/3218700.

Ensom, T., Morse, P.D., Kokelj, S.V., MacDonald, E., Young, J., Tank, S., Subedi, R., Grozic, E., and

Castagner, A., (2020). Permafrost geotechnical borehole data synthesis: 2013–2017 Inuvik-Tuktoyaktuk region, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-012; *Geological Survey of Canada*, Open File 8652, 78 p. DOI: 10.4095/321869.

Flynn, D., Kurz, D., Alfaro, M., and Graham, J. (2016). Forecasting ground temperatures under a highway embankment on degrading permafrost. *Journal of Cold Regions Engineering*, 30(4), 20 p. DOI: 10.1061/(AS CE)CR.1943-5495.0000106.

Gagnon, S., Fortier, D., de Grandpré, I., Cavayas, F., Dawso, J., Deshaies, A., Grandmont, K., Lewkowicz, A., Loranger, B., Talbot, J., Piraux, O., and Wolfe, M. (2020). Remote sensing and geophysical techniques to detect and map ice wedges. CPA & NSERC PermafrostNet Virtual Annual General Meeting, 16-18 November 2020, Online, In *Canadian Permafrost Association Virtual Annual General Meeting Abstracts*, 15.

Gruber, S., Brown, N., Stewart-Jones, E., Karunaratne, K., Riddick, J., Peart, C., Subedi, R., and Kokelj, S.V., (2019). Permafrost Ground Temperature Report: Ground temperature and site characterization data from the Canadian Shield tundra near Lac de Gras, Northwest Territories, Canada; *Northwest Territories Geological Survey*, NWT Open Report 2018-009, 8 p.

Humphries, J., Burn, C.R., MacDougall, S., and Brais, C. (2019). Storm wind frequency and direction, Dempster Highway, Richardson Mountains, Yukon and Northwest Territories. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 137-145. DOI: 10.1061/9780784482599.016.

Idrees, M., Burn, C.R., Moore, J., and Calmels, F. (2015). Monitoring permafrost conditions along the Dempster Highway. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 703.

Janowicz, J.R., Pomeroy, J.W., Carey, S., Williams, T., and Krogh, S. (2014). *Sensitivity of Dempster Highway hydrological response to climate warming*. [Conference Presentation], 2nd Annual General Meeting of the Changing Cold Regions Network (CCRN), 20-22 October 2014, Waterloo, ON.

Karunaratne, K., (2020). Guide to Producing a Ground Temperature Report. *Northwest Territories Geological Survey*, NWT Open Report 2017-08.

Kurz, D., Flynn, D., Alfaro, M., Arenson, L.U., and Graham, J. (2020). Seasonal deformations under a road embankment on degrading permafrost in Northern Canada. *Environmental Geotechnics*, 7(3), 163-174. DOI: 10.1680/jenge.17.00036.

Malenfant-Lepage, J., Doré, G., and Fortier, D. (2012). Thermal effectiveness of the mitigation techniques tested at Beaver Creek experimental road site based on a heat balance analysis: Yukon, Canada. 15th International Conference on Cold Regions Engineering, 19-22 August 2012, Quebec City, QC. In *Cold Regions Engineering 2012, ASCE*, 42-51. DOI: 10.1061/9780784412473.005.

Malenfant-Lepage, J., Doré, G., Fortier, D., and Murchison, P. (2012). Thermal performance of the permafrost protection techniques at Beaver Creek experimental road site, Yukon, Canada. *Proceedings of the 10th International Conference on Permafrost*, 25-29 June, Salekhard, Russia, The Northern Publisher, v. 10, Vol. 1: 261-266.

Malenfant-Lepage, J., Doré, G., and Lubbad, R. (2018). Critical shear stress of frozen and thawing soils. 5th European Conference on Permafrost, 23 June – 1 July 2018, Chamonix, France, *EUCOP5 Book of Abstracts*, 182.

Mathon-Dufour, V., Allard, M., and Leblanc, A-M. (2015). Assessment of permafrost conditions in support of the rehabilitation and adaptation to climate change of the Iqaluit airport, Nunavut, Canada. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 146.

Morse, P., and Kokelj, S.V. (2017). Trails – ITH: collaborative geoscience to support infrastructure management in the changing north. 45th Annual Yellowknife Geoscience Forum, 14-16 November 2017, Yellowknife, NT. In *Yellowknife Geoscience Forum Abstracts and Summary Volume 2017,* Northwest Territories Geoscience Office, p. 53-54.

O'Neill, H.B., and Burn, C.R. (2015). Permafrost degradation adjacent to snow fences along the Dempster Highway, Peel Plateau, NWT. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 7 p. Paper 219.

O'Neill, H.B., Burn, C.R., and Kokelj, S.V. (2015). Field measurements of permafrost conditions beside the Dempster Highway embankment, Peel Plateau, NWT. *Proceedings of the 68th Canadian Geotechnical*

Conference and 7th Canadian Permafrost Conference, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 7 p. Paper 380.

O'Neill, H.B., and Burn, C.R. (2016). Talik Formation at a Snow Fence in Continuous Permafrost, Western Arctic Canada. *Permafrost and Periglacial Processes*, 28(3), 558-565. DOI: 10.1002/ppp.1905.

O'Neill, H.B., and Burn, C.R. (2017). Impacts of variations in snow cover on permafrost stability, including simulated snow management, Dempster Highway, Peel Plateau, Northwest Territories. *Arctic Science*, 3(2), 150-178. DOI: 10.1139/as-2016-0036.

O'Neill, H.B., Wolfe, S.A., and Duchesne, C. (2019). New ground ice maps for Canada using a paleogeographic modelling approach. *The Cryosphere*, 13(3), 753-773. DOI: 10.5194/tc-13-753-2019.

O'Neill, H.B., Wolfe, S.A., and Duchesne, C. (2020). Ground ice map of Canada. *Geological Survey of Canada*, Open File 8713, DOI: 10.4095/326885.

Périer, L., Doré, G., and Burn, C.R. (2014). The effect of water flow and temperature on thermal regime around a culvert built on permafrost. *Science in Cold and Arid Regions*, 6(5), 10 p. DOI: 10.3724/SP.J.1226.2014.00415.

Périer, L., Doré, G., and Burn, C.R. (2015). Influence of water temperature and flow on thermal regime around culverts built on permafrost. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 089.

Roy, L.-P., Calmels, F., Lipovsky, P., Godin, P., Laurent, C., and MacDougall, S. (2019). Assessment and Monitoring of thaw slumps along Yukon highways. [Conference Presentation], *ArcticNet Annual Scientific Meeting*, 2-5 December 2019, Halifax, Canada.

Rudy, A.C.A., Morse, P.D., Kokelj, S.V., Sladen, W.E., and Smith, S.L. (2019). A new protocol to map permafrost geomorphic features and advance thaw-susceptibility modelling. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 661-669. DOI: 10.1061/9780784482599.076.

Rudy, A.C.A., Kokelj, S.V., Morse, P.D., and Ensom, T., (2020). Permafrost Ground Temperature Report: Inuvik to Tuktoyaktuk Highway Sentinel sites; *Northwest Territories Geological Survey*, NWT Open Report 2019-017, 8 p.

Rudy, A.C.A., Kokelj, S.V., and Ensom, T., (2020). Permafrost Ground Temperature Report: Inuvik to Tuktoyaktuk Highway embankment sites, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-016, 8 p.

Rudy, A.C.A., Kokelj, S.V., Morse, P.D., and Ensom, T., (2020). Permafrost Geotechnical Report: Inuvik to Tuktoyaktuk Highway Sentinel Program Boreholes, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-008, 7 p.

Rudy, A.C.A., Kokelj, S.V., and Ensom, T., (2020). Permafrost Geotechnical Report: Inuvik to Tuktoyaktuk Highway embankment boreholes, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-011, 7 p.

Rudy, A.C.A., Grozic, E., and Kokelj, S.V., (2020). Permafrost Geotechnical Report: Remediation at Gunghi Creek on the Inuvik to Tuktoyaktuk Highway, Northwest Territories; *Northwest Territories Geological Survey*, NWT Open Report 2019-010, 6 p

Sawyer, D. (2014). The economic implications of climate change on transportation assets: an analysis framework. *The International Institute for Sustainable Development*, 27 p.

Short, N., Leblanc, A-M., Sladen, W., Oldenborger, G., Mathon-Dufour, V., and Brisco, B. (2014). RADARSAT-2 D-InSAR for ground displacement in permafrost terrain, validation from Iqaluit Airport, Baffin Island, Canada. *Remote Sensing of Environment*, 141, 40-51. DOI: 10.1016/j.rse.2013.10.016.

Sladen, W.E., Parker, R.J.H., Morse, P.D., Kokelj, S.V., Smith S.L., Jardine, S., Kokaszka, J., and van der Sluijs, J. (2017). Trails: collaborative permafrost terrain mapping, Dempster and Inuvik to Tuktoyaktuk Highways

Corridor. Poster presented at: 45th Annual Yellowknife Geoscience Forum, 14-16 November 2017, Yellowknife, NT.

Stephani, E., Fortier, D., Shur, Y., Fortier, R., and Doré, G. (2014). A geosystems approach to permafrost investigations for engineering applications, an example from a road stabilization experiment, Beaver Creek, Yukon, Canada. *Cold Regions Science and Technology*, 100, 20-35. DOI: 10.1016/j.coldregions.2013.12.006.

Stephani, E., Kanevskiy, M., Darrow, M.M., Croft, P., Drage, J., and Wuttig, F. (2018). Early self-stabilization conditions of a retrogressive thaw slump, North Slope, Alaska. 5th European Conference on Permafrost, 23 June – 1 July 2018, Chamonix, France, *EUCOP5 Book of Abstracts*, 207-208.

Stephani, E., Drage, J., Miller, D., Jones, B.M., and Kanevskiy, M. (2020). Taliks, cryopegs, and permafrost dynamics related to channel migration, Colville River Delta, Alaska. *Permafrost and Periglacial Processes*, 31(2), 239-254. DOI: 10.1002/ppp.2046.

Stevens, C. (2019). Thermal design of the Dry Creek permafrost stabilization project. [Conference Presentation], *18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, 18-22 August 2019, Quebec City, QC.

Stevens, C. (2019). Phase Change Materials: Innovation in adaptation technology to address permafrost thaw. [Conference Presentation], *18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference*, 18-22 August 2019, Quebec City, QC.

Stirling, J.L., Seto, J., Arenson, L.U., and Abu Bakar, M. (2015). NWT Highway 3 test sections near Yellowknife. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 343.

Stockton, E.J., Burn, C.R., Idrees, M., Calmels, F., and Elmer, K. (2019). Monitoring Ground Temperatures in Permafrost Along the Dempster Highway, Yukon and NWT. 18th International Conference on Cold Regions Engineering and 8th Canadian Permafrost Conference, 18-22 August 2019, Quebec City, QC. In *Cold Regions Engineering 2019, ASCE*, 92-101. DOI: 10.1061/9780784482599.

Thiam, P-M., Bradley, A.H., Laprade, R., Idrees, M., Drummond, S., and Murchison, P. (2018). Mitigating pavement shoulder cracking in northern, low volume highways by incorporating Tencate Mirafi® H2Ri wicking geotextile. *Proceedings of the 71st Canadian Geotechnical Conference and 13th Joint CGS/IAH-CNC Groundwater Conference*, 23-26 September 2018, Edmonton, AB. 8 p. Paper 329.

Tunnicliffe, J., and Burn, C.R. (2011). Towards a Protocol for Airport Infrastructure Risk Assessment - Managing Long-Term Infrastructure Risks in Permafrost Terrain. *Carleton University*. Report submitted to the Government of the Northwest Territories, Department of Transportation.

Van der Sluijs, J., Kokelj, S.V., Fraser, R.H., Tunnicliffe, J., and Lacelle, D. (2018). Permafrost Terrain Dynamics and Infrastructure Impacts Revealed by UAV Photogrammetry and Thermal Imaging. *Remote Sensing*, 10(11), 1734. 30 p. DOI: 10.3390/rs10111734.

Veuille, S., Fortier, D., Verpaelst, M., Grandmont, K., and Charbonneau, S. (2015). Heat advection in the active layer of permafrost: physical modelling to quantify the impact of subsurface flow on soil thawing. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 722.

Wolfe, S.A., Fraser, R., and Kokelj, S.V. (2011). Great Slave TRACS - transportation risk in the Arctic to climatic sensitivity. 39th Annual Yellowknife Geoscience Forum, 15-17 November 2011, Yellowknife, NT. In *Yellowknife Geoscience Forum Abstracts Volume*, Northwest Territories Geoscience Office, vol. 2011, p. 124.

Wolfe, S.A., Duchesne, C., Gaanderse, A., Houben, A.J., D'Onofrio, R.E., Kokelj, S.V., and Stevens, C. (2011). Report on 2010-11 permafrost investigations in the Yellowknife area, Northwest Territories. *Geological Survey of Canada*, Open File 6983. 75 p. DOI: 10.4095/289596.

Wolfe, S.A., Morse, P.D., Hoeve, T.E., Sladen, W.E., Kokelj, S.V., and Arenson, L.U. (2015). Disequilibrium permafrost conditions on NWT Highway 3. *Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, 21-23 September 2015, Quebec City, QC, Canadian Geotechnical Society, Richmond, BC. 8 p. Paper 115.

Wolfe, S.A., Duchesne, C., O'Neill, H.B., and Parker, R.J.H. (2017). Modelling ground ice potential in Canada. Poster presented at: 45th Annual Yellowknife Geoscience Forum, 14-16 November 2017, Yellowknife, NT. DOI: 10.4095/306461.

Zhu, L., Anello, R., Rühland, K.M., Pisaric, M.F.J., Kokelj, S.V., Prince, T., and Smol, J.P. (2019). Impacts of road dust on small subarctic lake systems. *Arctic*, 72(4), 434-457.

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