PERMAFROST RESEARCH APPLICATIONS:

Transport Canada’s Northern Transportation Adaptation Initiative (NTAI) 2011-2021

Peel Plateau NT km 62, Dempster Highway, September 2020

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TRANSPORT CANADA'S

Northern Transportation Adaptation Initiative (NTAI)

BY CHRIS BURN (CARLETON UNIVERSITY)

CONTENTS

From 2011 to 2021, Transport Canada's Northern Transportation Adaptation Initiative (NTAI) has helped northern agencies to prepare for challenges anticipated from climate change for transportation infrastructure built in the permafrost environment. The program has linked northerners with academic researchers and consulting engineers in southern Canada to conduct a series of projects aimed at providing innovative understanding and approaches to specific problems. The ethos of the program issued from experience with the Alaska Highway test section near Beaver Creek, Yukon, and work by the Québec Ministry of Transport on airstrips in Nunavik. Both initiatives were stimulated by infrastructure failing due to permafrost thaw and both were partnerships between transportation agencies and the university sector.

By 2010, the federal government was aware that risks would be posed by climate change to the transportation network in the North and knew that partnerships would be needed to stimulate innovation for infrastructure construction and maintenance practices. The NTAI also recognised the need for capacity development in permafrost engineering and northern applied science. Relatively few personnel qualified in these areas entered the workforce between 1980 and 2005 and by 2010 only two Canadian universities retained research interest in permafrost engineering. Part of the NTAI's mandate has been to train research students in permafrost issues relevant to transportation infrastructure and to provide short courses for professional development in this area.

When the NTAI was conceived, the primary risk to the transportation network was considered to be from thawing and loss of embankment integrity. The research conducted through the program identified a range of other geohazards, especially derived from a more active hydrologic regime and from thermokarst development close to infrastructure. These are perhaps more pressing and require immediate risk management. The program and its northern partners have also benefitted from opportunities to study infrastructure performance *ab initio* due to construction of the Inuvik-Tuktoyaktuk Highway.

The Dempster Highway, northern Yukon (August 2016).

Maxine Bilodeau is the Director of Climate Change Adaptation & Planning for Transport Canada. She says that "the NTAI has played a unique role in Transport Canada's climate change agenda, influencing the way the department designs and implements programs, and helping to inform funding decisions. Northern jurisdictions own much of the transportation infrastructure in Arctic regions, and their active involvement in this program has helped target permafrost research to areas of most pressing need, ensuring the program's continued relevance. Overall, the NTAI is a great example of how research/industry/government collaboration can drive policy change and action to enhance the climate resilience of transportation systems in Canada's permafrost regions." The reports that follow outline some of the initiatives undertaken by the program. The projects have characteristically integrated permafrost science and engineering.

NTAI (2011-2021)

BY CHRIS BURN (CARLETON UNIVERSITY)

Fig. 1. Aufeis from subpermafrost groundwater discharge into Blackstone River, Yukon (2014).

During the last 10 years, permafrost has become a focus of international scientific attention. Amplification of climate change in the polar regions, regular transits of the Northwest Passage, awareness of climate risks posed by potential release of the 1600 billion tonnes of carbon stored in permafrost, and increased tourism in the Arctic have all raised public and scientific awareness of the North. The number of publications catalogued by the Web of Science with *permafrost* in the title has increased exponentially from approximately 10 per year in 1980, to 25 in 1990, 50 in 2000, 200 in 2010, 400 in 2015, and 700 in 2020. The vast majority of this published research concerns environmental aspects of the changing permafrost environment. Relatively little has addressed the challenges posed by climate change for northern infrastructure.

The NTAI is the first organized national program in Canada to address northern transportation infrastructure stability in anticipation of climate change. Several Canadian initiatives complemented the NTAI at its inception. First, the Transportation Association of Canada (TAC) sponsored development of *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions* (2010). Second, the Canadian Standards Association released CSA PLUS 4011-10 *Infrastructure in permafrost: A guideline for climate change adaptation* (2010), now revised as PLUS 4011-19, and began a program of standards development for northern infrastructure construction. Third, the Beaver Creek test section at km 1865 of the Alaska Highway had been initiated as a full-scale experiment to examine the efficacy of several design approaches to address deteoriation of highway embankments above permafrost.

Fourth, the Government of Québec had begun geoscience and engineering programs to address similar aspects of its northern airports. Finally, by 2011 the Inuvik-Tuktoyaktuk Highway (ITH), the first major new infrastructure project in the North for 40 years was being designed. Most of these initiatives were primarily concerned with managing the disturbance to permafrost terrain brought about by construction and operation of infrastructure, rather than anticipating and preparing for the effects of climate change. The NTAI's focus on climate change was distinctive and forward looking at the time. Now it is recognised as integral to long-term management of transportation infrastructure.

During 2011-21, the NTAI contributed to several important developments in our understanding

Fig. 2. Left: new culvert installed at YT km 32, Dempster Highway in the North Klondike River Valley after failure of the infrastructure due to ice blockage in 2014. Photo taken in 2017. Right: failure of the culvert due to icing development two years later (2019).

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Fig. 3. A recurring sinkhole in the Dempster Highway embankment due to ground water flow at YT km 82 (2017).

of climate change impacts on infrastructure and potential strategies to manage these effects. First, the role of groundwater has been reassessed because increasing late summer and fall rainfall and longer freeze-up of northern streams has led to culvert blockage and failure due to icing, as, for example at YT km 32 of the Dempster Highway and at several points on the ITH (Figs 1, 2). The sinkhole at YT km 82 that develops perennially is also formed due to groundwater movement below the road (Fig. 3). Groundwater-induced thawing of permafrost led to closure of the east end of the runway at Inuvik in 2013 for six weeks of repairs.

Second, snow management techniques have been effective in arresting permafrost degradation either using snow sheds or by reducing embankment slopes. These techniques require capital investment; other maintenance approaches to snow management on slide slopes continue to be evaluated. Third, integrated tools for planning and risk assessment are now developed which take advantage of GIS platforms and data analytics. These allow hazard and risk assessments on a km-by-km basis or even over shorter spreads in advance of construction using available data. They are constrained by the quality of information and do not, of course, cover unanticipated events, such as icing development beneath bridges on the ITH (see p. 18).

Fourth, geohazards due to permafrost thaw outside the Right-of-Way, such as the retrogressive thaw slump at NT km 28.5 of the Dempster Highway are now recognised as presenting risk of highway failure. Fifth, catastrophic effects, such as the landslides and washouts in 2016 that closed the Dempster Highway for 2 weeks, while infrequent, are to be anticipated in sloping terrain, not just due to increases in precipitation but also forest fires that destabilize the active layer (Fig. 4). Finally, although the TAC guidelines promoted winter construction of new infrastructure, as employed on the ITH, the extent and rate of subsidence of the embankment is unpredictable if built with frozen and, perhaps, ice-rich fill. Progress has been made in characterizing the extent of embankment deformation and deformation progress over time to enable better assessment of the quantities of materials initially required by projects.

The importance of all these aspects will increase in the next decade as climate warming and increases in precipitation continue. New considerations will arise as the reality of the extent of anticipated climate change is incorporated in planning of new infrastructure, such as the Mackenzie Highway, and presents further challenges to maintenance crew and highway authorities. Hazard warning strategies operating at various time scales will be required and initiation of preventative maintenance works must be considered. This will require a significant adjustment in management strategies that are now characteristically reactive because of the high costs of a transportation network that serves part of Canada with a relatively low population density.

Fig. 4. Landslide that blocked the Dempster Highway at YT km 243 following heavy rain (2018).

Assessment and monitoring of a new retrogressive thaw slump, km 1456 Alaska Highway

BY MUHAMMAD IDREES (TRANSPORTATION ENGINEERING BRANCH, GOVERNMENT OF YUKON), FABRICE CALMELS, LOUIS-PHILIPPE ROY, CYRIELLE LAURENT, FANNY AMYOT (YUKON UNIVERSITY), AND PANYA LIPOVSKY (YUKON GEOLOGICAL SURVEY)

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A retrogressive thaw slump (RTS), initiated by riverbank erosion was found close to the Alaska Highway at km 1456 in April 2019 (Figs 5, 6). Permafrost is discontinuous and ice-rich in places throughout the area. Satellite and aerial imagery show the RTS to have been active since 2014, with the headwall approaching the highway at an average rate of 8 m/yr.

A field program is in progress to assess development of the RTS and risk of highway failure. This includes drilling boreholes, now instrumented with ground temperature cables, humidity sensors, and inclinometer arrays to monitor ground conditions and RTS failure in real-time; monitoring of ground surface movement with differential GPS; aerial surveys by UAV; two- and tri-dimensional electrical resistivity tomography and electromagnetic surveys to map permafrost properties and groundwater movement.

Aerial surveys show the headwall to be approximately 80 m away from the road in May 2019 but with ablation of 12 m in summer 2019 and 14 m in summer 2020, the headwall is now 55 m from the road. Geophysical surveys suggest ice-rich permafrost under the road, indicating the risk posed by the RTS to the highway.

Real-time borehole monitoring through an array of sensors has shown initial stages of failure that could be used to trigger an alarm system. This information can be used to determine the relations between various measured parameters and the timing/rate of RTS failure. Ultimately, similar programs may be used to monitor other RTSs impacting transportation systems, and alert highway operators to anticipated road failure.

Fig. 5. Headwall of the Takhini RTS, Alaska Highway km 1456, July 2019.

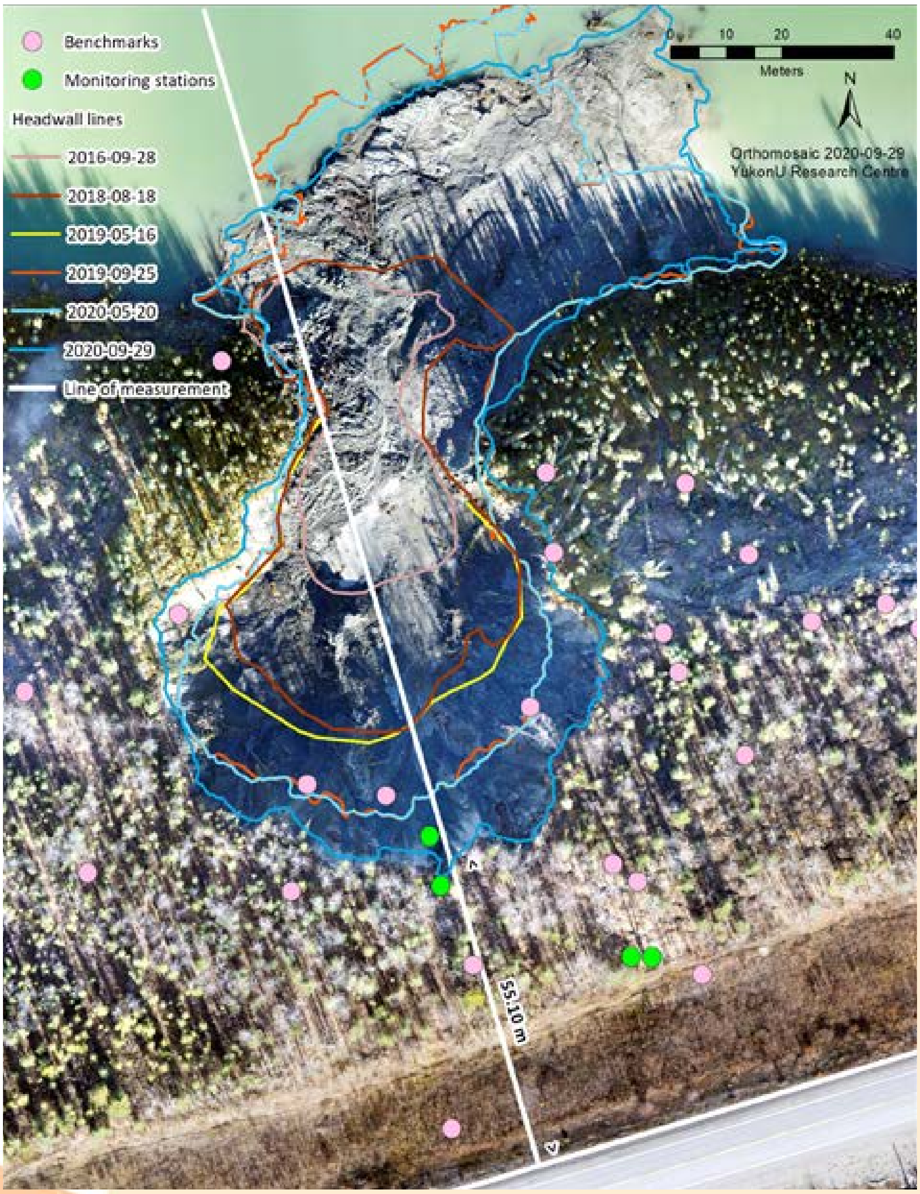

Fig. 6. Geospatial monitoring of Takhini RTS using drone imagery and benchmark surveys.

Aufeis on the Inuvik-Tuktoyaktuk Highway (ITH)

BY TIM ENSOM (WILFRID LAURIER UNIVERSITY), STEVEN KOKELJ (NORTHWEST TERRITORIES GEOLOGICAL SURVEY), AND PHILIP MARSH (WILFRID LAURIER UNIVERSITY)

Contact: enso5730@mylaurier.ca

The distribution, growth mechanisms, and effects on infrastructure of aufeis (icings) along a transportation corridor in a permafrost environment are being investigated along the Inuvik-Tuktoyaktuk Highway (ITH), NT.

The ITH traverses sparse taiga forest and tundra over continuous permafrost and crosses hundreds of small streams, some of which have winter baseflow supplied by lakes. Under natural conditions the accumulation of snow in stream channels may provide adequate insulation to maintain winter water movement above the streambed or through a sub-channel talik.

The disturbance or elimination of snow in channels by infrastructure can promote channel refreezing (Fig. 7) and bed-fast ice, often initiating the icing process whereby pressurized water is forced to the surface and freezes in layers.

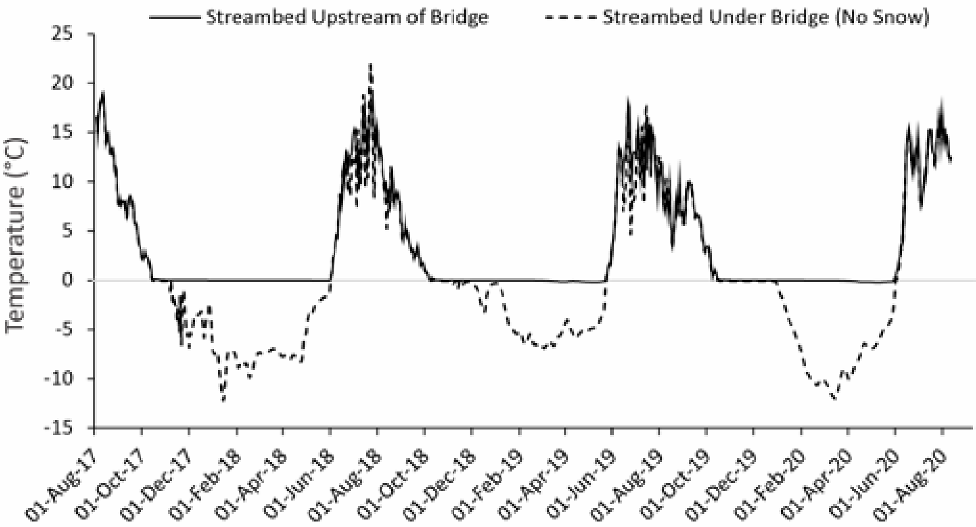

Fig. 7. Streambed temperatures under and upstream of an ITH bridge. Under the bridge the streambed refreezes during winter, likely due to an absence of snow.

Aufeis may occur at several ITH stream crossings (Fig. 8) where topography, minimal vegetation, or highway structures limit snow accumulation. Ice can fill channels and adjacent riparian terrain well above peak flood levels, potentially resulting in hazardous road ice conditions or embankment scouring by spring runoff if rerouted by thick ice. The high water pressure that leads to icing during the refreezing of the active layer can also heave streambanks, lift culverts or other structures, and lead to streambank injection ice and subsequent summer subsidence and bank erosion.

Aufeis surveys and inventories have been conducted along the ITH to investigate relations between winter runoff in permafrost catchments, catchment terrain parameters, and antecedent weather conditions. This work is intended to aid the planning and management of linear infrastructure in continuous permafrost.

For more information see:

Ensom, T., *et al.* (2019). Thermal Regime of Stream Channels in Continuous Permafrost, Western Canadian Arctic. In *Cold Regions Engineering 2019, ASCE*. DOI: 10.1061/9780784482599.030.

Fig. 8. Large body of aufeis beneath the km 8 bridge on the ITH. Viewed from downstream, February 2017.

Surveying permafrost-thaw-induced landslides along linear infrastructure using RPAS

BY JURJEN VAN DER SLUIJS (GOVERNMENT OF THE NORTHWEST TERRITORIES), STEVEN KOKELJ, AND ASHLEY RUDY (NORTHWEST TERRITORIES GEOLOGICAL SURVEY)

NORTHWEST TERRITORIES GEOLOGICAL SURVEY

Fig. 9. Debris tongue from RTS at NT km 28.5, Dempster Highway.

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Permafrost thaw has increased risks to northern transportation corridors creating a growing need for innovative monitoring tools. This project demonstrated that Remotely Piloted Aircraft Systems (RPAS), or drones, can enable timely and detailed three-dimensional reconstructions of thawing slopes at scales that bridge the gap between conventional remote-sensing and field observations. RPAS surveys were implemented in order to monitor permafrost landslides, focussing on a rapidly evolving retrogressive thaw slump (RTS) at km 28.5 on the Dempster Highway, NT (Figs 9, 10).

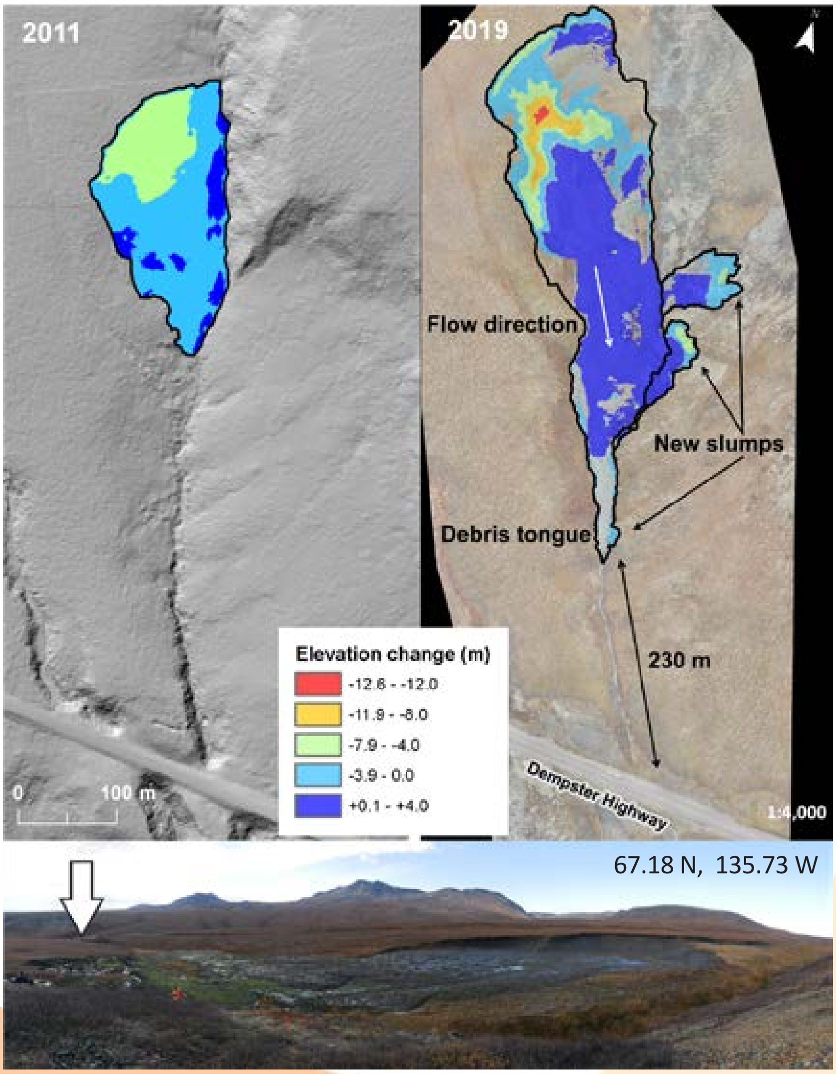

Fig. 10. Top: Images showing the growth and topographic difference in 2011 and 2019 of the RTS at NT km 28.5, Dempster Highway. Bottom: Looking west at the RTS (right) and new slumps (left) in September 2020, with arrow indicating the highway.

The RTS was monitored through repeat surveys and field observations, enabling processes of disturbance enlargement to be studied, and resulting in detection of a major thaw-driven landsliding event, where about 20,000 m³ of slumped materials flowed up to 450 m downslope, coming within 230 m of the highway. The acceleration of thaw slumping has created a spectacular exposure of icy permafrost 15-20 m in height, which has increased thaw season production of saturated slurry.

Monthly monitoring in summer 2019 indicated successive debris flow events reaching within about 300 m of the highway, indicating a sustained period of summer risk. Coupled with remote cameras, RPAS surveys have become an important tool to monitor growth of the disturbance and to inform the development of a real-time monitoring system that has been implemented by the Department of Infrastructure to minimize risk to the highway and ensure public safety.

For more information see:

Van der Sluijs, J., *et al.* (2018). Permafrost Terrain Dynamics and Infrastructure Impacts Revealed by UAV Photogrammetry and Thermal Imaging. *Remote Sensing*, 10, 1734. DOI: 10.3390/rs10111734.

Structural stability of highway embankments along the Inuvik-Tuktoyaktuk Highway (ITH)

BY MAROLO ALFARO (UNIVERSITY OF MANITOBA)

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This project is aimed at understanding the thermal and mechanical performance of highway embankments in the Arctic following winter construction. Two test sections were constructed in April 2015 as part of the Inuvik-Tuktoyaktuk Highway (ITH), NT. One section is reinforced with layers of wicking woven geotextiles at its side slopes (Fig. 11) to provide both reinforcement against lateral movements and drainage during the thawing season. The use of wicking geotextiles to reinforce fill slopes is a climate change adaptation measure to reduce the impact of thawing. The other test section is unreinforced and serves as the control section. Both test sections were instrumented with thermistor strings for temperature monitoring and ShapeAccelArrays to measure lateral movements and settlements. The geotextile reinforcement has been instrumented with strain gauges to measure tensile forces. The instrumentation has been monitored remotely using a satellite connection.

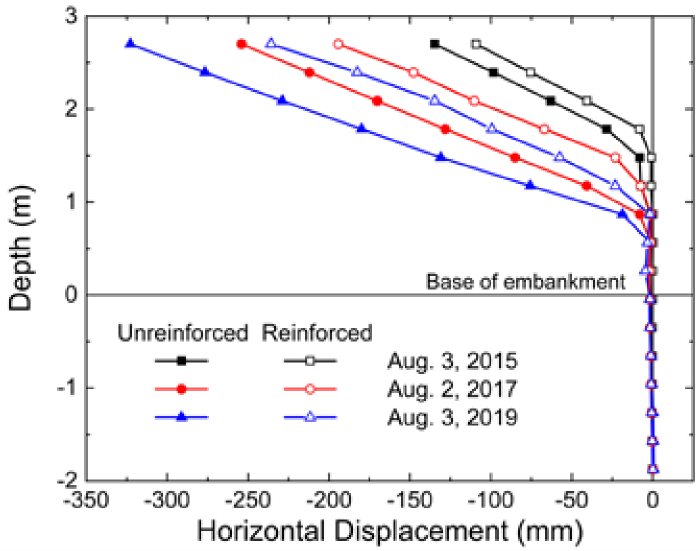

Fig. 12. Lateral movements at the mid-slope of the embankment. *Open symbols* = reinforced section; *Solid symbols* = unreinforced section.

Fig. 11. Wicking geotextiles laid during construction of a reinforced section of the ITH.

Field data show warming of the embankment fill and foundation soil. The frozen core of the embankment has reduced in size since end-of-construction. Thaw depths at the embankment toes have increased.

Figure 12 shows recorded lateral movements in the mid-slope of the embankment over four years since construction. The lateral movements in the reinforced section (open symbols) are consistently less than the those of the unreinforced section (solid symbols). Seasonal thaw depths at the slopes have increased and led to additional lateral movements. Mobilization of tensile forces in the geotextile reinforcement reduced lateral slope movements.

For more information see:

De Guzman, E.M., *et al.* (2021). Performance of Highway Embankments in the Arctic Constructed under Winter Conditions. *Canadian Geotechnical Journal*. DOI: 10.1139/cgj-2019-0121.

Air-convection-reflective sheds to reduce permafrost warming, Alaska Highway, Yukon

BY SAMUEL GAGNON AND DANIEL FORTIER (UNIVERSITÉ DE MONTRÉAL)

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The 600 m long Beaver Creek experimental test site was established in 2008 at km 1865 on the Alaska Highway in Yukon to assess the performance of different mitigation techniques in reducing permafrost warming and subsidence of the highway embankment. The site is in the discontinuous permafrost zone and had an annual mean air temperature of -4.5 °C for the 1990-2019 period.

The mitigation techniques were designed to enhance heat extraction from the embankment or reduce absorption of solar radiation at the ground surface. One of the test sections included two air-convection-reflective sheds (ACRS) installed on each side of the road in fall 2009 to cover the shoulders and slopes of the embankment (Fig. 13). The ACRS were wooden structures, 30 m long by 15 m wide by 1 m high, with a roof made of white corrugated sheet metal, which reflected incoming solar radiation and shaded the ground. The ACRS prevented rainwater infiltration in summer and snow accumulation directly on the embankment sides in winter. Ground temperatures to 15.5 m depth were recorded hourly with instrumentation installed before the ARCS were erected under one of the sheds and in an unmitigated reference section.

From 2009 to 2016, mean annual soil surface temperatures under the two ACRS were on average 8 °C lower than at the reference section (Fig. 14). Calculation of seasonal heat exchanges shows that the ACRS allowed 311% more heat extraction in winter and 38% less heat influx in summer over the test period. The design of the ARCS promoted free air convection at the ground surface, which enhanced heat extraction from the embankment in winter when windspeeds in the area are very low (<5 km/h). Small-scale implementation of ACRS along vulnerable sections of highways or airstrips represent a viable approach for arresting permafrost thaw beneath side slopes of embankments.

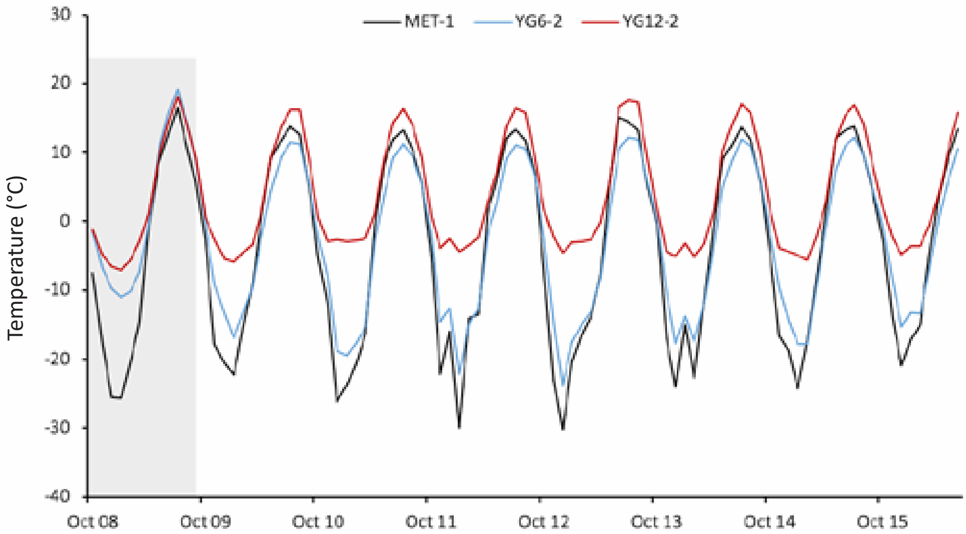

Fig. 14. Monthly air temperature (MET-1) and monthly soil surface temperatures under the southern ACRS (YG6-2) and the unmitigated reference section (YG12-2). The shaded area shows the period before the ACRS were installed.

Fig. 13 ACRS on the embankment slope of the Beaver Creek test site, Alaska Highway, Yukon.

For more information see:

Malenfant-Lepage, J., *et al*. (2012). Thermal effectiveness of the mitigation techniques tested at Beaver Creek experimental road site based on a heat balance analysis: Yukon, Canada. In *Cold Regions Engineering 2012, ASCE*. DOI: 10.1061/9780784412473.005.

Permafrost science for improvement and adaptation to climate change, Iqaluit International Airport, Nunavut

BY MICHEL ALLARD (UNIVERSITÉ LAVAL) AND VALÉRIE MATHON-DUFOUR (MINISTÈRE DE L'ENVIRONNEMENT ET DE LA LUTTE CONTRE LES CHANGEMENTS CLIMATIQUES, MELCC)

UNIVERSITÉ LAVAL

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Fig. 16. Thermal contraction cracks mapped at Iqaluit Airport (green). Active cracks in the runway inherited from the original terrain conditions are shown in red (2010).

Iqaluit airport is a hub for air transportation in the eastern Canadian Arctic. It was built during World War II and since then has undergone repeated repairs and upgrades (Fig. 15). Repairs to the pavement during the last 70 years have been caused by structural failures from differential frost heave and thermal contraction cracking. Partial melting of ice wedges has also caused linear settlements in the runway surface.

As with most infrastructure in the Canadian Arctic, permafrost conditions were not investigated before construction. They were characterized in detail between 2010-18 in preparation for major renovations and upgrading in 2018-19 because the risks associated with thawing permafrost are now recognized. Data from air photo interpretation, archival research, geophysics, drilling and coring, ground temperature monitoring, and numerical modelling were integrated in a GIS application.

Mapping of surficial geology and terrain conditions indicative of the presence of ground ice was combined with analysis of 24 deep boreholes (~ 8 m) and 7 shallow boreholes (~ 3 m) drilled in natural terrain, embankment shoulders, and through paved surfaces. Ground Penetrating Radar was used to delimit cryostratigraphic units and locate features under the embankments, particularly cracks and ice wedges (Fig. 16).

Terrain conditions prevailing before airport construction still impact the stability and thermal regime of the infrastructure. Ice-rich near-surface permafrost and many ice wedges will continue to generate thaw settlement and loss of bearing capacity should climate warming continue.

Temperature profiles under asphalt pavement show warmer ground and faster, deeper, and longer thaw penetration than the shoulders and natural terrain, causing pooling of water under paved surfaces. The newly acquired geoscientific data on the airport's permafrost has oriented risk analyses and engineering design implemented during the recent improvements in order to make a modern infrastructure that is better adapted to the impacts of climate warming.

Fig. 15. Looking northwest over Iqaluit Airport, Nunavut (2012).

For more information see:

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, 68th CGC and 7th CPC*, Québec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 146.

Sinkholes related to permafrost thaw, Dempster Highway, Yukon

BY FABRICE CALMELS, LOUIS-PHILIPPE ROY, CYRIELLE LAURENT (YUKON UNIVERSITY), AND SANDRA MACDOUGALL (TRANSPORTATION ENGINEERING BRANCH, YUKON GOVERNMENT)

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The Permafrost and Geoscience Research Group at Yukon University leads studies along the Dempster Highway investigating permafrost-related geohazards affecting the road and its surroundings. Sinkholes pose particular challenges for maintenance and safety as they may form almost instantly and be expensive to repair. A recurring sinkhole forms at km 82 on a west-facing hillslope at least annually and even several times per summer (see p. 17). A field study at the site including drilling, electrical resistivity tomography, and installation of ground temperature monitoring instruments started in 2016.

Results show snow accumulation on the embankment shoulder may have increased active layer thickness and opened new pathways through the soil for ground water flowing downslope. The repetitive sinkholes, first observed in 2011, indicate fine sediment in the roadbed is being removed by the flow. The loss of fine material creates a cavity that later collapses to form the sinkhole. Increasing precipitation in the area during the last two decades has likely contributed to the situation. Ground temperature records show infiltrated waters significantly affect the ground thermal regime at this site (Fig. 17).

Sinkholes result from various mechanisms. While intra- or supra-permafrost groundwater flow may induce some of them, in other cases icings impair drainage and channel water from the surface to the top of ice wedge troughs. Thermal erosion of ice wedges beneath the road leads to tunnels under the embankment, as at km 93 and 123 (Fig. 18). In some instances, the process begins in the field before reaching the road (km 123). Maintenance staff have noticed an increasing frequency of sinkhole development, possibly as an impact of climate change. Groundwater movement is a relatively new consideration for management of infrastructure above permafrost.

Fig. 18. Sinkhole forming due to thermal erosion at km 123, Dempster Highway.

For more information see:

Calmels, F., *et al.* (2018). Summary of climate- and geohazard-related vulnerabilities for the Dempster Highway corridor. Northern Climate ExChange, Yukon Research Centre, *Yukon College*, 204 p.

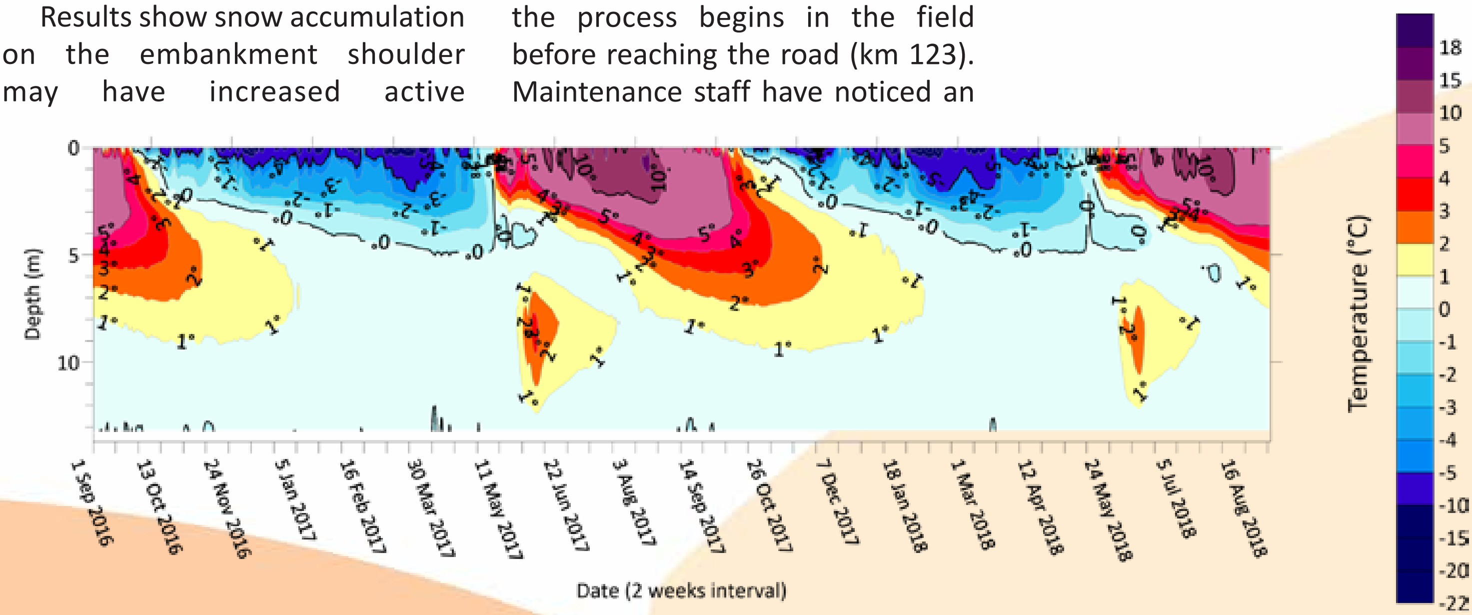

Fig. 17. Ground temperature record at km 82 over two years showing the impact of seasonal groundwater flow on thermal regime and flow in a conduit between 6 and 12 m depth for two months beginning in early June (see p. 17).

CAPACITY BUILDING

NTAI-supported students

BY CHRIS BURN (CARLETON UNIVERSITY)

An early priority of the NTAI was training of highly qualified personnel to become designers and managers of infrastructure in the permafrost regions of Canada.

Given that research programs in permafrost engineering were only active at Université Laval and the University of Manitoba in 2011, there were few students graduating who might have been able to assist with the challenges anticipated for infrastructure from climate change. Ironically, just at this time, international interest in permafrost science expanded, driven by biogeochemical considerations around the climatic risks from permafrost carbon, with little comparable interest in infrastructure.

In China, interest and experience developed regarding construction on the Qinghai Tibet Plateau, but language barriers precluded close cooperation, as with Russian engineers, regardless of motivation similar to the NTAI. Capacity development has therefore been an emphasis of the program for both advanced students and professionals in the private sector.

The NTAI encouraged student participation in projects and workshops. Thesis projects by several students were supported by the NTAI either directly or through a territorial agency. Below, we profile six students supported by the NTAI who have graduated and now assume positions in government and industry directly related to their training or who are engaged in further study. A preponderance of women in the group reflects the current Master student population in permafrost science and engineering and reflects the steps that are being made to develop a representative workforce in this area.

For professionals and students in related fields, the NTAI sponsored a series of short courses in Whitehorse and Inuvik that involved both classroom instruction and field visits to the north Alaska Highway and ITH. These courses have provided over a hundred people with a formal foundation in permafrost engineering and the scientific knowledge on which it is based. Professional participants at the courses have attended from engineering consultants and territorial transportation agencies. There have also been a few participants from Alaska, Scandinavia, and China.

The success of these courses is not simply reflected in their oversubscription, as at Inuvik in 2019 when enrollment doubled the anticipated numbers, but also in that they have formed the basis for the joint Canada-Norway project *Landscape & infrastructure dynamics of frozen environments undergoing climate change in Canada, Norway and Svalbard (NOK 6.57M)* funded by the Research Council of Norway. The courses stress to participants the importance of understanding the formation, occurrence, and properties of ground ice as a solid close to its melting point, because it may be thawed following a small change in the ground thermal regime. This is key background for successful engineering design.

PROJECT: The ground thermal regime of Peel Plateau, Northwest Territories, Canada

GRADUATED: 2016

NOW: Permafrost Research Scientist, Geological Survey of Canada (GSC)

Brendan O'Neill **PhD, Carleton University**

My PhD project at Carleton University investigated the ground thermal regime of continuous permafrost on Peel Plateau, NT. Extensive road maintenance has been necessary due to ground ice thaw near the Dempster Highway embankment. The research examined permafrost conditions in disturbed and undisturbed terrain near the road.NTAI supported my project and workshop attendance in Fairbanks, AK. Instruments from my PhD are still in operation and used by Government of the Northwest Territories and other students. A similar initiative would be useful for students because it provides 1) support for infrastructure-related research projects; 2) experience in formulating research questions relevant to applied infrastructure issues; 3) excellent networking opportunities that lead to connections with potential future employment; and 4) potential for collaborations with researchers outside immediate circles.

Snow accumulation and shrub growth, Dempster Highway, Peel Plateau, March 2014.

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

Heather Brooks PhD, Université Laval

My PhD project at Université Laval developed a methodology and tool for the quantitative analysis of risk to embankment infrastructure due to the presence of permafrost. The methodology used Monte Carlo statistical analysis techniques which formed the basis of an Excel macro for calculating the risk associated with linear infrastructure on permafrost. As an early-career researcher, I really enjoyed the collaboration with other researchers working other aspects of transportation in northern regions. The NTAI program gave me the opportunity to connect with researchers in my field and broaden my professional connections. I now work at BGC Engineering Inc. as a practicing geotechnical engineer with some northern projects. A similar initiative would be useful to students in the future for developing collaborations that would not have been thought of or addressed if researchers were working independently.

PROJECT: Quantitative Risk Assessment of Embankment Infrastructure on Permafrost

GRADUATED: 2019

NOW: Geotechnical Engineer, BGC Engineering Inc.

Brooks, H., *et al.* (2019). Quantifying Hazard and Climate Change Fragility for the Airport Access Road in Salluit, Nunavik, Quebec. In *Cold Regions Engineering 2019, ASCE*. DOI: 10.1061/9780784482599.060.

Loriane Périer MSc, Université Laval

My masters project at Université Laval looked at the effects of water temperature and water flow on the thermal regime around culverts built on permafrost. Two culverts were monitored on the Alaska Highway near Beaver Creek, YT, to provide data used to develop and validate mathematical and thermal models. I attended a permafrost engineering course in Whitehorse, taught by professors Chris Burn and Guy Doré, which allowed me to learn about the challenges of building transportation infrastructure on permafrost. NTAI supported my attendance to the Permafrost Network of Expertise workshops as a speaker (Fairbanks, 2013) and participant (Nunavik, 2015). Most of all, I am proud to use the skills I have acquired for the analysis of permafrost in other complex and challenging environments.

PROJECT: Study of the influence of water flow and temperature on the thermal regime around culverts built on permafrost

GRADUATED: 2015

NOW: Transport Engineer, Stantec

Périer, L., *et al.* (2014). The effect of water flow and temperature on thermal regime around a culvert built on permafrost. *Science in Cold and Arid Regions*, 6. DOI: 10.3724/SP.J.1226.2014.00415.

Earl Marvin de Guzman PhD, University of Manitoba

My PhD project at the University of Manitoba looked at the structural stability of highway embankments in the Arctic, such as the Inuvik-Tuktoyaktuk Highway (ITH). The research focused on field monitoring of temperature and displacements of geotextile reinforced and unreinforced embankments, laboratory testing of thawing fill material, and numerical modelling for near- and long-term climate change conditions with the aim of improving existing design guidelines for Arctic highway embankments. NTAI supported my participation in workshops. The program allows students to communicate their research progress to an audience with special interest in permafrost, learn about on-going research and develop connections. NTAI allowed students to be part of, and learn from, the larger network of experts in Canada's north.

PROJECT: Structural stability of highway embankments in the Arctic corridor

GRADUATED: 2020

NOW: Geotechnical Engineer, Peter Kiewit Sons ULC

De Guzman, E.M., *et al.* (2021). Performance of Highway Embankments in the Arctic Corridor Constructed under Winter Conditions. *Canadian Geotechnical Journal*, 58. DOI: 10.1139/cgj-2019-0121.


Inuvik-Tuktoyaktuk Highway (ITH)

PROJECT: Development of a methodology for the design of low-impact drainage systems along transportation infrastructure in permafrost environments

Julie Malenfant-Lepage PhD Candidate, Université Laval

I am in the final writing stage of my PhD project on developing a methodology for the design of low-impact drainage systems along transportation infrastructure in permafrost environments at Université Laval. Water flow along embankments increases permafrost thaw and soil erosion resulting in settlement, loss of functional capacity and potential failure. The project focusses on validating the design method implemented along the airport access road in Salluit (Nunavik, QC) where drainage system has been adapted to climate change. The research will promote and identify adaptation strategies to counteract environmental changes caused by infrastructure in a changing climate. NTAI allowed me to conduct fieldwork which is essential in understanding basic concepts and assimilating theories related to permafrost science and engineering.

Malenfant-Lepage, J., *et al.* (2018). Critical shear stress of frozen and thawing soils. 5th European Conference on Permafrost, Chamonix, France, *EUCOP5 Book of Abstracts*, 182.

PROJECT: Retrogressive thaw slump self-stabilization

Eva Stephani PhD Candidate, University of Alaska Fairbanks

My current NTAI-funded PhD project at the University of Alaska Fairbanks aims to advance our understanding of retrogressive thaw slump (RTS) self-stabilization to support the development of effective adaptation strategies for infrastructure at risk. I am evaluating the climate, terrain, subsurface, and infrastructure conditions at various sites in the Northwest Territories and northern Alaska in order to assess the vulnerability and resilience of terrain to RTS, and interactions with infrastructure in sensitive permafrost. NTAI fulfilled and further motivated my desire to integrate permafrost science and engineering, and bridge gaps between industry, academia, and government. This perspective, supported by my experience at NTAI workshops, was highly valued by prospective employers.

Stephani, E., *et al.* (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.

CAPACITY BUILDING

Permafrost Engineering Courses

BY EMMA STOCKTON AND JEN HUMPHRIES (CARLETON UNIVERSITY)

Since 2011, professors Guy Doré (Université Laval) and Chris Burn (Carleton University) have run a one-week course on *"Permafrost engineering applied to transportation infrastructure"* for researchers and professionals. The course combines classroom lectures with field excursions and has been held six times at two northern research institutions. Most recently at Aurora College in Inuvik (2019), and at Yukon University in Whitehorse (2011-2016). One-day summary versions were also developed for the 2015 and 2019 Canadian Permafrost Conferences in Québec City.

The course was created because many geotechnical engineers with experience in permafrost terrain are no longer practicing or are expecting to retire, and environmental considerations are assuming an increasing role in project development and design. Transport Canada recognized and addressed these factors as part of the NTAI program. The course objectives were to:

- Understand the context and challenges of building linear infrastructure in permafrost environments
- Provide the basic principles for effective site investigation, design and management of linear infrastructure
- Apply principles of risk analysis to the development of linear infrastructure
- Analyze complex situations and propose solutions to unstable infrastructure
- Develop transversal skills, and international and multidisciplinary collaborations.

Local field trip to a long-term monitoring site near Inuvik. Photo: Weronika Murray.

Classroom lectures have been divided into two themes: the *permafrost environment* and *permafrost engineering*. Chris introduced

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topics on transportation infrastructure in northern Canada, permafrost characteristics, heat transfer, ground ice, climate change, and thermokarst terrain. Guy then discussed infrastructure design and considerations, freezing and thawing soil mechanics, slope stability, drainage, site investigations, and management strategies. Overall, the material applied theoretically based knowledge to practical situations.

Participants have also completed a practical exercise using TEMP/W, a 2D thermal modelling software, to examine the sensitivity of permafrost terrain to changes in temperature over time caused by surface disturbances and climate change.

Field excursions have typically included short local trips and day-long trips along the Alaska Highway or ITH where participants visited existing research sites and observed permafrost conditions and construction methods discussed in class.

The six courses have been attended by 111 participants including, students (44%), professionals (28%), government employees (15%), academics (7%), and others (5%) (Fig. 19). Women accounted for a third of total participants, and almost 60% of students. NTAI has also helped defray travel and accomodation costs for students who attended the courses. The courses have provided researchers and professionals from a variety of backgrounds the opportunity to network and collaborate, promote mutual learning, and initiate a multidisciplinary dialogue on potential environmental and socio-economic impacts of permafrost thaw.

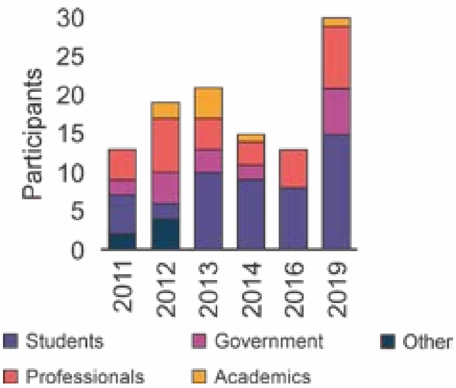

Fig. 19. Number of participants to NTAI-supported permafrost engineering courses from 2011-2019.

For more information on the 2019 course visit sentinelnorth.ulaval.ca/en/permafrostengineering2019.

CAPACITY BUILDING

Permafrost Workshops

BY EMMA STOCKTON AND JEN HUMPHRIES (CARLETON UNIVERSITY)

Annual permafrost workshops on NTAI projects began in 2010 with the inaugural 'Workshop of the Network of Expertise on Permafrost' in Haines Junction, YT. The workshop outlined existing highway research projects such as the Beaver Creek Test Section (Alaska Highway), Front Street (Dawson City), and Highway 3 (Yellowknife). Followed by a discussion on how the program will address knowledge gaps, capacity issues, and the practical problems of operating highways in the north.

Workshops have been held in Alaska and Canada in all three territories and two provinces. The 2021 meeting was held virtually, due to the COVID-19 pandemic. Workshops typically comprise technical and student presentations on proposed or existing projects, review of the program's objectives, and field trips. In 2017, discussions focussed on federal coordination, territorial adaptation needs and priorities, and capacity development. The intention was to determine how to better coordinate and collaborate with federal partners, disseminate information to support a common understanding of priority areas of action for northern partners, and build a community of practice.

Participants at the NTAI Workshop for Canadian Highways Built on Permafrost, held in Whitehorse, YT, February 2019. Photo: Tim Ensom.

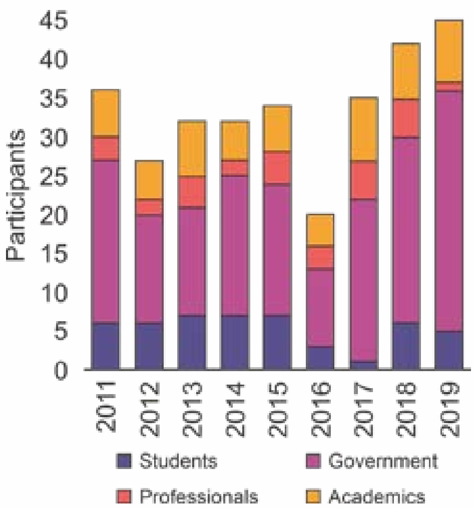

Fig. 20. Number of participants to NTAI-supported permafrost workshops from 2011-2019.

Over 300 participants have attended the meetings including, government employees (56%), academics (18%), students (16%), and professionals (10%) (Fig. 20). Women accounted for a quarter of total participants, and 28% of students. NTAI has helped defray travel and accomodation costs for students who attended these workshops.

Conclusion

BY CHRIS BURN (CARLETON UNIVERSITY)

The projects presented in this report indicate the first steps taken to develop resilience for northern transportation infrastructure in anticipation of the growing impacts of climate change in Canada's North. Over the next few decades, transportation agencies will need to watch closely the emissions trajectory of greenhouse gases to determine the conditions at which the climate may settle and a new ground thermal environment will reach equilibrium.

Projected warming in fall and winter will be the principal driver of climate change and a critical long-term challenge for effective operation of current technology, such as thermosyphons and air convection embankments (ACE), which relies on a significant differential between air and ground temperatures in winter to cool the ground. In the short term, however, we may expect rehabilitation and maintenance to continue as in the past with some adjustments to designs for new infrastructure components.

Maintenance activities may soon have to include off Right-of-Way conditions as part of their mandate, such as for control of icings to protect embankments and culverts. Maintenance may also require systems for predicting embankment failure with sufficient time for remedial action, perhaps based upon antecedent conditions (e.g., precipitation intensity and amount). Rehabilitation of highways will be required where permafrost thaw leads to instability or failure of infrastructure is anticipated. Cost management may require planning over several years to prepare stockpiles of ACE rock, for example. Re-routing of highways in response to permafrost thaw may be necessary in places and require significant planning and negotiation, such as Chapman Lake, Dempster Highway. Negotiation of new Rights-of-Way will need to recognize that Land Claims Agreements now affect most areas in the North.

Finally, ground ice and permafrost thaw sensitivity must be considered in the design of new northern infrastructure and the selection of routes and sites, as well as the associated increase in costs. Innovation in airborne geophysics for detection of ground ice will be required, especially south of treeline where on-ground access is difficult.

Other Publications

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Burn, C.R., *et al.* (2015). Permafrost characterization of the Dempster Highway, Yukon and Northwest Territories. *Proceedings, Proceedings, 68th CGC and 7th CPC*, Québec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 705.

Chen, L., *et al.* (2019). Impact of heat advection on the thermal regime of roads built on permafrost. *Hydrological Processes*, 34, 1647-1664. DOI: 10.1002/hyp.13688.

Coulombe, S., *et al.* (2012). Using air convection ducts to control permafrost degradation under road infrastructure: Beaver Creek Experimental Site, Yukon, Canada. In *Cold Regions Engineering 2012, ASCE*. DOI: 10.1061/9780784412473.003.

De Guzman, E.M., *et al.* (2018). Large-scale direct shear testing of compacted frozen soil under freezing and thawing conditions. *Cold Regions Science and Technology*, 151, 138-147. DOI: 10.1016/j.coldregions.2018.03.011.

De Guzman, E.M., *et al.* (2019). Monitored thermal performance of varying embankment thickness on permafrost foundations. In *Cold Regions Engineering 2019, ASCE*. DOI: 10.1061/9780784482599.015.

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

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Idrees, M., *et al.* (2015). Monitoring permafrost conditions along the Dempster Highway. *Proceedings, 68th CGC and 7th CPC*, Québec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 703.

Kurz, D., *et al.* (2020). Seasonal deformations under a road embankment on degrading permafrost in Northern Canada. *Environmental Geotechnics*, 7, 163-174. DOI: 10.1680/jenge.17.00036.

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Stephani, E., *et al.* (2020). Taliks, cryopegs, and permafrost dynamics related to channel migration, Colville River Delta, Alaska. *Permafrost and Periglacial Processes*, 31, 239-254. DOI: 10.1002/ppp.2046.

Thiam, P.-M., *et al.* (2018). Mitigating pavement shoulder cracking in northern, low volume highways by incorporating Tencate Mirafi® H_2Ri wicking geotextile. *71st CGC and 13th Joint CGS/IAH-CNC Groundwater Conference*, Edmonton, AB. Paper 329.

Veuille, S., *et al.* (2015). Heat advection in the active layer of permafrost: physical modelling to quantify the impact of subsurface flow on soil thawing. *Proceedings, 68th CGC and 7th CPC*, Québec City, QC, Canadian Geotechnical Society, Richmond, BC. Paper 722.