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AN OVERVIEW OF MAJOR ENGINEERING CHALLENGES FOR DEVELOPING TRANSPORTATION INFRASTRUCTURE IN NORTHERN CANADA

EVA STEPHANI
JULIE MALENFANT LEPAGE
GUY DORÉ

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FOREWORD

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This paper is part of a special series in *The School of Public Policy Publications*, investigating a concept that would connect the nation's southern infrastructure to a new series of corridors across middle and northern Canada. This paper is an output of the Canadian Northern Corridor Research Program.

The Canadian Northern Corridor Research Program at The School of Public Policy, University of Calgary, is the leading platform for information and analysis on the feasibility, desirability, and acceptability of a connected series of infrastructure corridors throughout Canada. Endorsed by the Senate of Canada, this work responds to the Council of the Federation's July 2019 call for informed discussion of pan-Canadian economic corridors as a key input to strengthening growth across Canada and "a strong, sustainable and environmentally responsible economy." This Research Program will benefit all Canadians, providing recommendations to advance the infrastructure planning and development process in Canada.

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Dr. Jennifer Winter
Program Director, Canadian Northern Corridor Research Program

AN OVERVIEW OF MAJOR ENGINEERING CHALLENGES FOR DEVELOPING TRANSPORTATION INFRASTRUCTURE IN NORTHERN CANADA

Eva Stephani
Julie Malenfant Lepage
Guy Doré

OUTLINE

The transportation corridor proposed to support the development of northern Canada travels extensively through areas of permafrost. The main concern for sustainably developing infrastructure in permafrost terrain arises from melting the ground ice contained in the frozen soils, which can yield to ground subsidence and other geohazards. Permafrost degradation may be triggered by natural processes or anthropogenic activities; it is compounded with climate change, and its impacts on infrastructure are widespread in the Arctic. Advancing our understanding of permafrost dynamics is critical to minimize impacts from geohazards on infrastructure and detrimental consequences on the surrounding natural environment. Permafrost dynamics involve the interactions between factors from the climate, ground surface and subsurface, and in some instances with anthropogenic activities (e.g., infrastructure). Assemblage of these components forms a permafrost geosystem where interactions and feedback are key to the state of permafrost; this aligns with Aristotle's concept that "the whole is greater than the sum of its parts." To comprehend permafrost dynamics and interactions with infrastructure, we must characterize the system components and monitor changes. Using comprehensive and interdisciplinary approaches is important because critical linkages may fall at the intersection of disciplines.

Infrastructure construction in the North is challenging in many ways. Construction and material sites are remote, harsh weather conditions are frequent and construction methods and infrastructure maintenance in permafrost-affected soils can be difficult and costly. The most common approach is to build and maintain. This strategy involves allowing permafrost degradation to occur and preserving serviceability by intensive maintenance. It generally results in a reduced level of service, comfort, safety and shorter life cycles. Stabilization techniques are required when loss or low level of service are not acceptable. In the context of climate change and widespread permafrost degradation, mitigation techniques are also becoming important for infrastructure that was previously developed according to the build-and-maintain strategy. The different mitigation methods used to limit permafrost degradation along infrastructure can be classified into four main categories:

- Limitation of ground heat intake in summer;
- Enhancement of heat extraction from the ground in winter;
- Reinforcement of the infrastructure embankment and ground stability improvement; and
- Water management to reduce thermal erosion.

There is no generic solution to control permafrost degradation along infrastructure, and rather, the selection of mitigation methods is based on site-specific conditions and is part of the infrastructure management strategy. Maintaining adequate structural and functional conditions of infrastructure, which implies proper investments, is at the heart of solutions for sustainable northern development. All governments, designers, contractors and operators must recognize the need for proper infrastructure management and embrace the role it plays in ensuring the predictability and safety of our public infrastructure.

Our understanding of permafrost science and engineering has largely progressed in the last decades, yet important knowledge gaps remain and these need to be addressed for sustainably developing infrastructure in northern Canada. The following were identified as important remaining challenges: intensify efforts to develop knowledge, expertise and reference documents using an interdisciplinary and collaborative approach; foster communication between stakeholders, scientists, engineers and planners and involve First Nations; develop new, affordable and effective technology for permafrost characterizations and monitoring; improve infrastructure design and develop new adaptation technologies; and develop management tools for infrastructure and risk management adapted to northern conditions.

EXECUTIVE SUMMARY

There is a growing demand to provide services and transportation pathways to remote communities in northern Canada, whereas the country also needs to develop long-term solutions for interregional and international trade that support Canada's growth and diversification. The Canadian Northern Corridor is a concept for multimodal infrastructure that could respond to these necessities. To establish a transportation corridor in a sustainable manner, it is imperative to recognize challenges specific to northern regions and adapt conventional engineering approaches, construction methods and management strategies. This overview paper intends to inform the Canadian Corridor Research Program of engineering challenges related to the development of northern infrastructure, with the goal of providing the awareness needed to evaluate the corridor feasibility. This paper summarizes the main geohazards and their impacts on infrastructure, some comprehensive geohazard assessment

approaches and the current mitigation techniques and management strategies. It also identifies important remaining challenges to support the sustainable development of northern Canada.

The proposed corridor crosses extensive areas of permafrost, including sporadic to continuous permafrost distribution. It also travels through areas that are not perennially frozen, but that are exposed to seasonal freeze-thaw cycles and to other cold-region processes that can become geohazards for infrastructure. Some of the northern geohazards, such as solifluction, frost heave and icing, can develop either in seasonally or perennially frozen ground. Despite the difficulties that may exist to develop infrastructure in seasonally frozen ground, this overview paper focuses mainly on permafrost-related issues because of the significant challenges and important knowledge gaps in permafrost, whereas engineering of seasonally frozen ground is more advanced and commonly used in southern Canada.

The main concern for sustainably developing infrastructure in permafrost terrain arises from melting the ground ice contained in the frozen soils. When ice changes to water, its volume decreases and this modifies the soil structure and strength, resulting in ground subsidence and other geohazards and consequently may damage infrastructure. Thawing of ice-poor permafrost soils may yield little to no changes in subsurface conditions, whereas melting the ground ice of ice-rich soils may cause significant subsidence of the ground surface that can threaten the structural integrity of infrastructure. Varying types of slope instabilities may also be triggered as permafrost is thawing. Degradation of permafrost may arise independently from the existence of nearby infrastructure and yield to geohazards, but permafrost degradation can also be triggered by the surface disturbances from infrastructure. In both scenarios, infrastructure becomes at risk of geohazards, and consequently, to subsequent damage. Impacts of permafrost degradation on infrastructure are widespread in the Arctic and expected to increase as permafrost continues thawing with climate change.

It is essential to understand permafrost dynamics so we can evaluate terrain vulnerability to geohazards, minimize impacts on infrastructure and thus support the sustainable development of this sensitive environment. Permafrost dynamics are controlled by interactions between factors from the climate, surface and subsurface conditions (Table 1). This can be conceptualized as a permafrost geosystem with multiple components that interact and trigger positive and negative feedbacks, which regulate the state of permafrost; this reflects Aristotle's concept that "the whole is greater than the sum of its parts." In this manner, implementation of new infrastructure combined with climate change adds complexity to permafrost geosystems and requires that the initial system adapt to new conditions. It is critical to recognize at a local scale the main interactions and feedbacks of the system with impacts for infrastructure, and to do so in varying types of permafrost environments so we can evaluate variations throughout the corridor. This involves the combination of interdisciplinary methods to characterize and monitor the geosystem in these key permafrost environments along a corridor. This way, we can identify geohazards and recognize critical conditions that indicate the terrain's vulnerability to future geohazards (Table 1).

Table 1. Main Components of the Permafrost Geosystem Involving Infrastructure

Component		Description
Climate	Air temperature	Air temperatures above 0°C warm ground temperatures.
		Air temperatures below 0°C help to extract heat from the ground (cools permafrost).
	Precipitation	Rainfall increases risk of water impoundment and thermal erosion.
		Snow (see Surface component).
	Wind	Dominant wind in winter influences the snow distribution and compaction.
	Solar radiation	Solar radiation warms the ground surface and melts exposed ground ice (thermal denudation).
Surface	Topography	Slope orientation (e.g., south vs. north) impacts permafrost temperatures. Linear infrastructure on hillslopes can intercept water (i.e., cross-drainage water). Slope gradient contributes to mass movement activity.
	Water impoundment and flow	Water is a strong modifier of the underlying ground temperatures, while flowing water combines thermal and mechanical actions (i.e., thermal erosion) to degrade permafrost.
	Snow	Snow is a strong modifier of the ground temperature. It acts as an insulation layer that limits the heat exchange with the atmospheric air in winter that would otherwise contribute to extract heat from the ground.
	Vegetation	Vegetation is a strong modifier of the ground temperature, especially the organic mat that supports permafrost stability due to its insulation properties.
Subsurface	Ground ice	The type and spatial distribution of ground ice is critical as it is a dominant factor in permafrost degradation and its impact on overlying infrastructure.
	Soils	Fine-grained soils tend to be more ice-rich, poorly drained and thaw sensitive.
	Salinity	Saline soils may remain unfrozen at temperatures below 0°C.
	Ground temperatures	Permafrost is especially thaw sensitive when ground temperatures are near 0°C.
	Groundwater	Supra-permafrost flowing water combines thermal and mechanical actions (i.e., thermal erosion) to degrade permafrost.
Infrastructure	Embankment	Geometry (e.g., slope, height), material and seasonal construction timing are key factors controlling interactions with the local natural conditions (i.e., geosystem components) and impact on permafrost stability.
	Pile	Material, depth and seasonal construction timing are key factors controlling interactions with the local natural conditions (i.e., geosystem components) and impact on permafrost stability.
	Trench (buried infrastructure)	Size and seasonal construction timing are key factors controlling interactions with the local natural conditions (i.e., geosystem components) and impact on permafrost stability.

Characterizing the system's conditions along a proposed corridor involves integrating data and knowledge on regional trends (e.g., permafrost distribution, permafrost depth, permafrost temperature, borehole logs, digital elevation models, climate conditions, surficial deposits, topography, surface water bodies and drainage patterns, etc.) in a geographic information system (GIS) to allow for a gap analysis. These data are combined in GIS with additional desktop analyses and data collected in the field to evaluate the system conditions (climate, surface and subsurface) and interactions at varying temporal and spatial scales. Remote sensing analysis is done to evaluate surface conditions that indicate potential permafrost conditions; although remote sensing technology is advancing relatively rapidly, there are still considerable limitations for permafrost studies, including the possibility to make direct measurements of critical subsurface conditions such as ground ice. Field-based investigations of permafrost conditions include drilling and sampling the soils and ground ice and measuring the geotechnical properties of the representative layers. Geophysical methods that target mostly near-surface conditions can be used as a non-evasive reconnaissance method prior to drilling or to evaluate ground conditions between boreholes. Geophysical surveying should be ground truth with borehole data for study robustness, or at least combined with other geophysical systems.

Build-and-maintain is the main strategy for developing transportation infrastructure in northern regions. It involves allowing permafrost degradation and thaw settlement to occur and maintaining serviceability by intensive maintenance to repair damages as they occur. Typically, it involves reduced levels of service and shorter life cycles, as well as reduced comfort and safety and higher travel costs for road users. With global warming and in cases where loss or low level of service are not acceptable, thermal and/or mechanical stabilization techniques are required. The choice of mitigation measures applied at a site is based on different factors such as permafrost temperature and its thaw susceptibility, the implementation cost of the technique, the material and machinery availability, risk analysis and safety. Methods can be combined to provide better permafrost protection throughout the entire year. Methods used to protect building and structure foundations on thaw-sensitive soils generally use the same principles as some of the techniques for linear infrastructure. The low tolerance to deformation and the presence of heating systems in most buildings increase the need for highly effective protection systems. The different mitigation methods currently used to limit permafrost degradation along infrastructure can be classified into four main categories that are summarized below with a focus on road infrastructure:

1) The purpose of methods limiting ground heat intake in summer is to reduce thaw penetration. The most common method used to protect roads against permafrost degradation is to build an embankment that is thick enough to maintain the thaw front within the granular material, or at least within the active layer in the underlying natural ground; this method is efficient mainly for continuous permafrost areas. Other methods include adding insulation layers to protect embankments or building foundations in cold, continuous permafrost and using high albedo surface to reduce the absorption of solar radiation. Cool paving material technology is still in development and no standard exists for its application in civil infrastructure.

2) The purpose of enhancing heat extraction from the ground in winter is to raise the top of permafrost, or at least to prevent thaw settlement. These methods include air ducts, thermosyphons, air convection embankments and heat drains. Limiting snow accumulation on the embankment side slopes by plowing them regularly helps heat extraction, especially as snow thicknesses increase on the upper slopes when snow is plowed off from the road surface, but the feasibility of this method may be challenging.

3) In cases where thermal stabilization is difficult to apply or too expensive, mechanical stabilization and ground improvement can become good strategies to mitigate structural damage due to permafrost degradation.

4) Engineering methods for drainage systems are poorly adapted to permafrost environments, yet water impoundment and flow along infrastructure are substantial problems that are now widely reported throughout Canada. Some techniques have been proposed to reduce the risk of damage caused by drainage water, but further research is needed to establish robust guidelines.

Infrastructure management in northern regions is challenging in many ways. Contrary to southern Canada, northern regions have a deficiency of professionals who are properly trained for local ground conditions like permafrost and there is a lack of documents on infrastructure design and construction that are adapted to northern conditions. Also, construction is complex and costly. When construction is done in the summer, operations must be planned considering a very short construction season, while in the winter the workflow can be impeded by harsh working conditions for equipment and workforce. Due to the remoteness and limited access to a transportation network, it is difficult to supply and support construction. Despite these important challenges, investing in northern infrastructure is critical to support the social and economic development of northern Canada. Communities and the resource industry rely on this infrastructure every day to stay connected with the rest of the country and to access natural resources.

Our understanding of permafrost science and engineering has progressed intensely over the last decades, yet several knowledge gaps remain. The past and predicted temperature increases stress the necessity to advance our permafrost knowledge, and to further adapt our strategies for developing and maintaining infrastructure in northern regions. The advancement of our permafrost knowledge and the development of new technology are essential to evaluate permafrost-infrastructure interactions and related impacts on infrastructure. We must improve our capacity to characterize the varying permafrost systems in northern Canada and monitor changes of the system components over time. This comprehensive systemic approach that integrates interdisciplinary methods is critical for a sustainable development of infrastructure in northern regions, yet several challenges remain to improve our capacity of bridging gaps between disciplines and entities involved in infrastructure development. There is also an urgent need to improve Canadian education programs in permafrost science and engineering to form professionals that will support the sustainable development of infrastructure in northern regions.

1. INTRODUCTION

Northern Canada encompasses numerous communities separated by vast uninhabited areas where industrial activities have been generally increasing (Lemly 1994; NWT and Nunavut Chamber of Mines 2021) and with important economic potential remaining (Conference Board of Canada 2010). Anthropogenic activities, however, tend to be challenging in these remote regions with little to no service available, and where harsh weather conditions are frequent. Northern Canada and its sensitive environments are also widely affected by climate change. The mean (1948-2016) annual air temperatures in northern Canada have been increasing at a rate about three times faster than the global mean warming rate (Bush and Lemmen 2019). Impacts of climate change in northern regions can be especially severe due to permafrost[1] thawing that can result in ground subsidence and trigger other environmental changes that affect ecosystems and anthropogenic activities. Permafrost ground temperatures in Canada have been steadily increasing for decades (Smith et al. 2005; Smith et al. 2010), and these observations are consistent with changes occurring outside of the country (Harris 2003; Isaksen et al. 2007; Wu and Zhang 2008; IPCC 2019). In its latest assessment, the Intergovernmental Panel on Climate Change (IPCC) reports a warming in permafrost ground temperatures (≤ 30m deep) that began three to four decades ago, whereas it projects that 25 per cent of remaining near-surface permafrost (≤ 3m deep) will thaw for each additional one degree Celsius of warming (IPCC 2019). Impacts of permafrost degradation on infrastructure and the need for adaptation strategies have been well documented in the Canadian eastern subarctic region (Beaulac and Doré 2006; Allard et al. 2007; LeBlanc et al. 2010; Allard and Pollard 2011; Fortier, LeBlanc and Yu 2011; Mathon-Dufour, Allard and LeBlanc 2015; Oldenborger and LeBlanc 2015), and similar assessments are also being done elsewhere in the country (Laxton 2010; Hoeve 2012; Batenipour et al. 2013; Stephani et al. 2014; Arenson et al. 2015; De Guzman et al. 2021) and abroad (Beloloutskaia and Anisimov 2003; Instanes 2003; U.S. Arctic Research Commission Permafrost Task Force 2003; Bosikov 2012; Kreig 2012; Hjort et al. 2018; Ni et al. 2021; Schneider von Deimling et al. 2021; Hjort et al. 2022).

The current state of northern infrastructure and the predicted temperature increases stress the need to adapt our strategies for developing and maintaining infrastructure in northern Canada. A multimodal infrastructure corridor that traverses northern regions could support social and economic activities in northern Canada, while providing a long-term solution to foster the competitiveness, growth, diversification and property of the country (The School of Public Policy 2021). This also aligns with the United Nations Sustainable Development Goals and the need to invest in sustainable solutions (United Nations 2022). It is crucial for sustainable development of northern Canada, however, that the corridor is based on a comprehensive understanding of the challenges specific to these regions and the necessity to adapt conventional engineering and construction methods to northern conditions.

The purpose of this overview paper is to inform the Canadian Northern Corridor Research Program of major engineering challenges for sustainable development of infrastructure in northern regions and identify remaining knowledge gaps to help direct further research. The paper provides a summary of the main problems affecting soils and structures, and examples of mitigation measures developed to address those problems. The state of knowledge in permafrost science and engineering, the progress made and the remaining challenges are also highlighted in the paper.

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1 Definitions and additional information relevant to this review manuscript are provided in Appendix B.

2. GEOHAZARDS

The proposed transportation infrastructure corridor in northern Canada travels extensively through areas of permafrost, including areas of continuous distribution in the northernmost regions to areas of discontinuous and sporadic occurrence at lower latitudes (Figure A1). The occurrence of permafrost in infrastructure foundation soils is critical because the mechanical behaviour of frozen ground is different than in unfrozen conditions. Moreover, the thermal state may vary throughout the infrastructure's lifetime, which implies that it should be designed to sustain potential important changes in ground conditions. The corridor also crosses areas that are not perennially frozen, but that are still subject to seasonal freeze-thaw cycles and to other cold region processes that can become geohazards for infrastructure. However, this overview paper focuses mainly on permafrost-related issues as there are important gaps in our knowledge, whereas engineering of seasonally frozen ground is more advanced and commonly used in southern Canada.

Permafrost Dynamics

It is essential to understand permafrost dynamics so we can evaluate terrain vulnerability to geohazards, minimize impacts on infrastructure and thus support the sustainable development of this sensitive environment. Permafrost dynamics are controlled by interactions between factors from the local climate and surface and subsurface conditions (Table 1). This can be conceptualized as a permafrost geosystem with multiple components that interact and trigger positive and negative feedbacks, which regulate the state of permafrost (Stephani et al. 2014; Vincent, Lemay and Allard 2017; Slaymaker, Spencer and Embleton-Hamann 2021); this reflects Aristotle's concept that "the whole is greater than the sum of its parts." In this manner, implementation of new infrastructure and climate change both add complexity to permafrost geosystems and require that the initial systems adapt to new conditions. Implementation of linear infrastructure represents a greater challenge compared to single structures such as buildings because its alignment typically crosses a wide range of landscapes characterized by different climatic, surface and subsurface conditions.

Developing a multimodal infrastructure corridor in northern Canada also requires the integration of multiple temporal and spatial scales. To comprehend permafrost dynamics at the corridor scale, we must understand and recognize permafrost dynamics at a local scale where most interactions with infrastructure and feedbacks that result in environmental disturbance and/or infrastructure damage are occurring (Stephani 2021), and to do so in varying types of permafrost environments so we can evaluate variations throughout the corridor. This involves the combination of interdisciplinary methods to characterize and monitor the geosystem conditions in key permafrost environments along a corridor. Geohazard assessment is further discussed in Section 2.6.

Permafrost Degradation and Thawing Slope Instability

The main concern for sustainably developing infrastructure in permafrost terrain arises from melting the ground ice contained in the frozen soils (Figures A2 and A3), which yields to the formation of thermokarst landforms that may become geohazards for infrastructure. When ice changes to water, its volume decreases and this modifies the soil structure and strength, which consequently may damage overlying infrastructure. Thawing of ice-poor permafrost soils may yield little to no changes in subsurface conditions, whereas melting the ground ice of ice-rich soils may cause significant subsidence of the ground surface that can threaten the structural integrity of infrastructure. As the ground ice content may vary substantially within short distances (French and Shur 2010; Murton 2013), permafrost thawing can also yield significant local variations in ground surface subsidence and differential thaw settlement. Degradation of ice-rich permafrost may arise independently of nearby infrastructure and yield to various thermokarst landforms that may affect this infrastructure. Infrastructure also may trigger permafrost degradation and become affected by the degradation processes. In both scenarios, infrastructure becomes at risk of geohazards, and consequently, subsequent damage.

The development of thermokarst landforms results from the effects of heat transfer processes (e.g., conductive, convective and radiative) and movements of material across landscapes that affect the permafrost thermal equilibrium and increase the active layer depth (Jorgenson 2013). Some differentiate the processes involved to define the term "thermokarst" (Czudek and Demek 1970); however, this may be confusing as most thermokarst landforms result from the interaction of multiple heat and mass transfer processes and, therefore, it may be preferable to distinguish patterns from processes and use the term "thermokarst" to define the resulting landforms (Jorgenson 2013). Table 2 summarizes the main thermokarst landforms that may constitute geohazards along infrastructure, which we divided into the following categories: thaw subsidence, thermokarst lakes and other water impoundment, hillslope thermokarsts (slope instabilities) and wetland thermokarsts. Descriptions and additional information on thermokarsts can be found in Kokelj and Jorgenson (2013), Jorgenson (2013) and Shur and Osterkamp (2007).

Table 2. Thermokarst Landforms and Processes Associated with Permafrost Degradation (modified from Jorgenson (2013); see this reference for photograph examples)

Type	Landform	Size	Heat Source	Depth (m)	Dominant Ice Type
Thaw subsidence	Ground subsidence (thaw settlement)	1-100 m^2	Water, air	0.2-2.0	Segregated ice, ice wedge
	Thermokarst troughs and pits (differential thaw settlement)	1-100 m^2	Water, air	0.5-5	Ice wedge
	Sink holes	1-10 m^2	Water	2-5	Ice wedge
Thermokarst lakes and other water impoundment	Thermokarst lake (deep, shallow and glacial)	1-1,000 ha	Water, air	1-30	Ice wedge, segregated ice, buried glacial ice
	Thermokarst drained-lake basin	1-1,000 ha	Water, air	1-10	Ice wedge
	Beaded stream	0.1-10 ha	Water	1-3	Ice wedge
Hillslope thermokarst (slope failure)	Thaw slump	0.1-40 ha	Water, air	1-35	Segregated ice, ice wedge, glacial ice
	Active-layer detachment slides	0.1-10 ha	Water, air	0.5-2	Segregated ice
	Thermokarst water-tracks	10-1,000 m^2	Water	0.2-1	Segregated ice
	Thermal erosion gully	10-1,000 m^2	Water	1-3	Ice wedge
	Ice-block landslides	10-1,000 m^2	Water, air	3-35	Large syngenetic ice wedges
Wetland thermokarst	Thermokarst bog and fen	0.1-100 ha	Water	1-2	Segregated ice

In the 1970s, McRoberts and Morgenstern (1973) classified landslides occurring in permafrost soils in the Mackenzie Valley, following the general mass-movement categories (flow, fall and slide) previously established by Varnes (1958) in geotechnical studies. Later, McRoberts and Morgenstern (1974) determined that an abundance of the flow-dominated landslides was related to permafrost slopes thawing, while also identifying sub-categories of flow (solifluction, skin flow, bimodal flow and multiple retrogressive flow). Other terms were used as synonyms of these landslide types; however, it was later recommended in the *Multi-language Glossary of Permafrost and Related Ground-ice Terms* (Van Everdingen 1998) to avoid the terminology of “skin flow” and “bimodal flow,” and instead refer to “active-layer detachment slide” (ALDS) and “retrogressive thaw slumps” (RTS), respectively. The terms ALDS and RTS are now widely used, and can be categorized as hillslope thermokarsts (Jorgenson 2013).

ALDS is a flow-dominated landslide that develops in the discontinuous and continuous permafrost zones (McRoberts and Morgenstern 1973; Lewkowicz and Harris 2005; Lipovsky et al. 2006; Lipovsky and Huscroft 2007; Rudy et al. 2016). ALDS occurs when pore-water pressure at the base of the active layer is high and exceeds soil shear strength. These conditions can develop after wildfires (Lipovsky 2006; Jones et al. 2015) or in response to warm summer events (Lewkowicz 1990; Harris and Lewkowicz 2000; Lewkowicz and Harris 2005). An ALDS exposes the upper ice-rich permafrost to the atmospheric air conditions (e.g., solar radiation, air temperatures, rainfalls), which can yield to RTS formation (French 2007; Lacelle, Bjornson and Lauriol 2010; Swanson and Nolan 2018). RTS is a geomorphic feature, whereas thaw slumping is the process that yields to RTS when ice-rich soil thaws and flows downslope (Van Everdingen

1998). RTS morphology typically includes a steep upper headwall in a semi-circular shape above a gently sloping floor composed of thawed sediments and meltwater (Van Everdingen 1998 (revised 2005); French 2007). Some RTS have a low-angled debris tongue flowing downslope that may be as low as one to two degrees (McRoberts and Morgenstern 1974). Thaw consolidation and ablation are two important mass movement models coexisting in RTS. The thaw-consolidation model explains the initiation of slope instabilities at much lower angles than estimated by the traditional limit equilibrium analysis concept used in southern regions due to excess pore pressure that develops in soils rapidly thawing but slowly draining (Morgenstern and Nixon 1971; Morgenstern and Smith 1973; Nixon and Morgenstern 1973; McRoberts and Morgenstern 1974; Nixon and Morgenstern 1974). The coefficient of consolidation reflects the expulsion rate of excess pore water in thawing soils, and therefore, stability analysis of thawing slopes requires a detailed knowledge of soil geotechnical properties, including the coefficient of consolidation and effective stress parameters, while the detailed thermal solution may be secondary (McRoberts and Morgenstern 1974). In well-developed features, the ice-rich permafrost exposed in the steep head scarp often is affected by ablation (McRoberts and Morgenstern 1974; Pufahl and Morgenstern 1980), yet other failure modes of head scarps have been described (Mackay 1966; Kerfoot 1969).

Thaw slumping is one of the dominant mass-wasting processes that controls geomorphic changes in areas of ice-rich permafrost (Lewkowicz 1987; Lacelle, Bjornson and Lauriol 2010; Lantuit et al. 2012; Kokelj, Tunnicliffe, Lacelle, Lantz, Chin and Fraser 2015; Kokelj, Tunnicliffe,, Lacelle, Lantz and Fraser 2015; Lacelle et al. 2015). From initiation to stabilization, RTS involves coupling of thermal, mechanical, geomorphological and hydrological processes (Burn and Lewkowicz 1990; Zwieback et al. 2018). Typically, RTS stabilization occurs when there is no more ground ice to melt or when it is covered by reworked sediments (Burn and Lewkowicz 1990); however, the self-stabilization mechanisms also may be more complex, as they can result from the interaction of multiple factors that change through time. In many cases, these complex interactions manifest in polycyclic RTS development. Impacts from these mass-wasting processes occur at variable spatial and temporal scales, and include: increasing stream sediment and solute loads, up to several orders of magnitude greater than in undisturbed streams (Kokelj, Zajdlik and Thompson 2009; Kokelj et al. 2013; Malone et al. 2013; Brooker et al. 2014; Kokelj et al. 2015; Rudy et al. 2017; Lewkowicz and Way 2019); affecting water quality (Kokelj et al. 2005); and releasing organic carbon (Cassidy, Christen and Henry 2017). Mass wasting processes and delivery of sediment to stream valleys raise the base level and enhance valley-side erosion that may lead to the development of secondary RTS, including in proximity to infrastructure (van der Sluijs et al. 2018) (Figure A4). RTS mass movements can be considerable, therefore raising concerns for nearby infrastructure (Burn and Lewkowicz 1990). Although RTS occurrence is widespread (Kokelj et al. 2015), most disturbances occur in remote regions at a distance from communities and industrial activities in Canada. Nonetheless, some features are located near linear infrastructure, such as roads and pipelines, and may represent a safety, economic and/or environmental concern.

Several studies show that RTS activity has been increasing (Lantuit and Pollard 2008; Lantz and Kokelj 2008; Kokelj et al. 2015; Segal, Lantz and Kokelj 2016) and vulnerability may increase further with continued climate change, thus potentially increasing the size and frequency of RTS near infrastructure. The intensification of northern development activities also may increase the exposure of infrastructure to RTS and ALDS that evolve into RTS. Managing infrastructure potentially exposed to RTS can represent a significant challenge, especially as there is currently no standard or guideline in place to mitigate RTS impact on linear infrastructure. The possibility to relocate infrastructure threatened by these geohazards may be limited and/or cost prohibitive. Therefore, management strategies that include mitigation techniques and address climate change risks must be developed. The development of efficient mitigation measures requires a thorough understanding of the interaction mechanisms of RTS with infrastructure and RTS natural stabilization (self-healing capacity); however, these topics have not been widely studied and, in this context, the Northern Transportation Adaptation Initiative Program (NTAI) recently supported a study on RTS self-stabilization (Stephani et al. 2020; Stephani 2021). Likewise, variations in RTS characteristics and rates of change across regions and climates still need to be better understood (Segal, Lantz and Kokelj 2016). Identifying factors and processes involved in RTS initiation and growth, and recognizing them as conditions limiting RTS stabilization, may help to understand the self-healing capabilities of RTS. Hence, understanding the processes of RTS failure and growth supports the development of remedial measures (Wang, Paudel and Li 2009).

Frozen Slope Instability

Deep-seated permafrost landslides may occur even though frozen soils are typically stronger than unfrozen soils due to the bonding effect between ice and soil particles. Movements in frozen ground can occur as slow deformation, while sometimes they may evolve into downslope movements occurring at relatively faster rates where underlying unfrozen soils become involved, known as block and multiple retrogressive slides.

When frozen soils are subject to stresses such as overlying infrastructure load and passing vehicles, which are lower than those that would otherwise trigger slope failure, the frozen soils may start to deform slowly. This slow deformation is called creep. Frozen soil strength varies with several factors such as ground temperature, particle size, salinity and ground ice content and structure (Johnston 1981; Brouchkov 2003; Andersland and Ladanyi 2004; Bray 2008, 2012, 2013). For example, strength decreases with rising temperatures because the resulting increase in unfrozen water content reduces the bonding strength between the ice and particles. Although permafrost creep typically involves an assemblage of frozen soils with ground ice, creep behaviour of buried massive ice also has been reported (Foriero et al. 1998). Creep may affect overlying infrastructure, such as causing roadway settlement that creates driving hazards (McHattie and Esch 1988). Concerns further arise in the context of climate change, as creep along infrastructure may increase with warmer ground temperatures (Konrad and Boisvert 2015).

Slow creep deformation may be common, whereas observations of block and multiple retrogressive slides have been limited (McRoberts 1978). The latter were well documented in permafrost areas of the Mackenzie River Valley (McRoberts 1973) and in the warm permafrost soils in south-central Alaska (Darrow, Bray and Huang 2012). Other frozen ground slope processes that may constitute geohazards for infrastructure include rock glaciers and frozen debris lobes (FDL), although their distribution in Canada may be limited. Rock glaciers consist of perennially frozen ice-rich debris that steadily creeps downslope on unglaciated mountain slopes (Haeberli et al. 2006). The factors controlling rock glacier movement include temperature, which may induce significant changes in creep rate, especially when the temperature is close to the melting point (Arenson 2002). FDL can be differentiated from rock glaciers by their source area, composition, processes and rate of movement (Daanen et al. 2012). FDL are formed of soil, rock, organic material and ice that move downward on a permafrost-affected slope; these features are highly sensitive to pore-water pressure and cohesion, which implies that increased thawing will result in increases in pore-water pressure and decreases in shear strength (Simpson, Darrow and Huang 2016). In northern Alaska, eight FDL were documented in the Dalton Highway transportation corridor located in the southern Brooks Range, including a large one that could potentially reach the highway by 2023 (Darrow et al. 2016).

Geohazards in Seasonally and Perennially Frozen Ground

Solifluction, frost heave and icing are geohazards commonly observed both in seasonally and perennially frozen ground. They are summarized below.

Solifluction is a shallow downslope movement of unfrozen soils that occurs in permafrost areas but is not restricted to these regions. Typically, the ground movements occur in the near-surface soils that thaw and freeze seasonally, known as the active layer, at depths ranging between 0.5m and 2.0m (Williams and Smith 1989). Solifluction generally forms distinctive lobes on the slopes that tend to be larger and composed of coarser soil particles in the lower slope areas (French 2007).

Frost heave corresponds to the upward or outward movement of the ground surface that is caused by the formation of ground ice that exceeds the soil pore size, thus forming excess ice, known as segregation ice (Van Everdingen 1998). Segregation ice generally forms in fine-grained soils when the ground temperature gradient is negative and there is an availability of water in a soil that is permeable enough to allow water to travel to the freezing front. Frost heave may represent a geohazard for infrastructure because objects that are buried, such as pile foundations, or located on the ground surface, such as embankments and culverts, may also move as ground ice accumulates and large freezing pressures develop. Similar to differential thaw settlement that is caused by a variation in ground ice content, non-uniform frost heave may occur as it reflects the heterogeneity in ground conditions and processes occurring within short distances.

Icing has been traditionally defined as a sheet-like mass of layered ice that forms on the ground surface, river or lake ice, and included synonyms such as aufeis and naled (Van Everdingen 1998). Recently, Ensom et al. (2020) summarized the fundamental knowledge and advances in this field of study, and differentiated the term “aufeis” to refer to the ice landform while “icing” is the general process by which aufeis is formed when water emerges from the subsurface and freezes. The aufeis formation process is complex (Ensom et al. 2020), but broadly, it involves the freezing of successive water flows that may seep from the ground or emerge through cracks from underneath the ice cover of a lake or river (Van Everdingen 1998). The factors controlling aufeis development, which are presented in Ensom et al. (2020), include the water availability and freezing conditions that are influenced by local geology, topography, permafrost, hydrology, climate and meteorology. Aufeis formation occurs throughout the circumpolar region (Tolstikhin and Tolstikhin 1974; Veillette and Thomas 1979; Li et al. 1997; Yoshikawa et al. 2003; Yoshikawa, Hinzman and Kane 2007; Morse and Wolfe 2015; Shan, Guo and Hu 2015; Ensom et al. 2020) and is not restricted to permafrost-affected terrains. Infrastructure can be impacted by nearby aufeis development due to terrain disturbances or when an ice blockage is formed in culverts (McGregor et al. 2010). For example, aufeis may develop in slope cuts where shallow groundwater flow is intercepted and emerges at the surface. Similarly, aufeis may develop in natural hillslope thermokarst (not from anthropogenic action), such as observed in retrogressive thaw slumps in the N.W.T. (Stephani et al. 2020). Aufeis may accumulate on roadways (Londagin 1971; Vinson and Lofgren 2003), thus raising safety and economic concerns, as it restricts vehicle passage.

Impacts on Infrastructure

As geohazards vary in severity and size, the impacts on infrastructure also widely vary. Not all geohazards are catastrophic; more often they are not, but their long-term environmental, social, economic and safety impacts can still be considerable and require quasi-constant maintenance and frequent repairs. Table A1 lists several cases of permafrost degradation processes and impacts observed throughout northern Canada, while Figure 1 illustrates some examples.

Figure 1.

Examples of geohazards affecting infrastructure: (a) differential thaw settlement (Umiujaq, Nunavik QC) (photograph by Guy Doré); (b) longitudinal cracking and embankment spreading, Alaska Highway, Yukon (photograph by Julie Malenfant-Lepage); (c) thermokarst lake occurring near infrastructure, Alaska Highway, Yukon (photograph by Guy Doré); (d) icing, Alaska Highway, Yukon (photograph by Kate Grandmont); (e) sudden collapse as a result of massive ice melting, Alaska Highway, Yukon (photograph by Eva Stephani); (f) failure of a road drainage system, Dalton Highway, Alaska (photograph by Guy Doré); (g) thermal erosion in a longitudinal ditch, Alaska Highway, Yukon (photograph by Chantal Lemieux); (h) cut slope instability, Alaska Highway, Yukon (photograph by Julie Malenfant-Lepage); (i) retrogressive thaw slump in northwest Alaska (photograph by Kenji Yoshikawa from Williams and Ferrigno (2012)); (j) creeping underneath the Alaska Highway (photograph by Guy Doré); (k) road thaw settlement at the bridge connection, Alaska Highway, Yukon (photograph by Yukon Highways and Public Works).

Thaw settlement is probably the most common geohazard affecting infrastructure in permafrost regions. When the permafrost soils are ice-rich and the ground ice melts, this results in ground subsidence, or thaw settlement, that induces damage to overlying infrastructure. Often, the subsidence has an irregular topography (i.e., differential thaw settlement) because the spatial distribution of ground ice typically varies. Thaw settlement under roadways may cause sinking of the embankment material into the underlying thawing natural ground (Figure A5) (Stephani et al. 2014), while tension cracks and depressions appear at the surface (Figure 1). In such cases, frequent surface grading and other maintenance operations may alleviate the safety impacts; however, other types of infrastructure such as railways (Kondratiev 2002; Ling, Zhang and Zhang 2003; Niu, Cheng and Lai 2003; Cheng, Sun and Niu 2008; Li et al. 2008; Qihao et al. 2008; Cheng, Wu and Ma 2009; Ashpiz et al. 2010; Kondratiev 2010; Ma et al. 2011; Mu et al. 2012; Niu, Liu, Cheng et al. 2015; Niu, Liu, Wu, et al. 2015), airstrips (McFadden and Siebe 1986; Hoeve and Hayley 2015; Mathon-Dufour, Allard and LeBlanc 2015) and pipelines (Nixon, Morgenstern and Reesor 1983; Burgess, Oswell and Smith 2010; Oswell 2011) may not be able to sustain such ground deformations and thus their design often incorporates mitigation techniques (see Section 3). The problem of thaw settlement along infrastructure increases the maintenance requirement and/or reduces the structure's lifespan. In extreme cases, it can become a severe safety issue as the ground surface and overlying infrastructure may collapse. In many cases, climate warming was not anticipated during infrastructure design, and the effects of climate warming increase the vulnerability of the structural and functional capacities of northern facilities. Among abundant circumpolar examples of permafrost degradation affecting infrastructure throughout northern Canada (Table A1), Figure A6a illustrates an example of settlement and cracking patterns observed at Iqaluit Airport in Nunavut as a result of ice-rich permafrost thawing underneath the runway (LeBlanc 2013).

Table 1 summarizes main factors and interactions that are known to aggravate permafrost degradation and induce damage to infrastructure. Among the detrimental interactions widely observed, we know for example that snow tends to accumulate along infrastructure, which warms the underlying ground and results in thaw settlement. Common feedback is that deeper snow accumulation and water impoundment will form in the subsided areas, thus further exacerbating permafrost degradation and aggravating damage to the structure. This adverse cycle compounded with other common processes results in quasi-constant need for infrastructure maintenance and frequent repairs. If water flows along or across infrastructure, even along a low-gradient slope, it combines mechanical and thermal processes (thermal erosion) that are particularly effective in degrading ice-rich permafrost and thus can be detrimental for overlying infrastructure (de Grandpré, Fortier and Stephani 2012). The rate and magnitude of thermal erosion tend to increase with finer grained soils and higher ice content, thus becoming more destructive. In 2008, heavy rains and flooding along the Duval River in Pangnirtung (Nunavut) caused extensive thermal erosion of ice-rich soils along the riverbanks, resulting in significant damage to the foundations and the loss of two bridges (Figure A6b) (Hsieh, Tchekhovski and Mongeau 2011). Thermal erosion from cross-drainage water that is accrued from heavy rainfall and collected in thermokarst ditches formed by thaw settlement along linear infrastructure can also lead to mass movements, such as the development of RTS (Stephani et al. 2020; Stephani et al. in review). The likelihood of permafrost degradation by thermal erosion may continue increasing as more frequent extreme precipitation events associated with climate change are expected to occur (IPCC 2019). Water inevitably disturbs permafrost stability and thus, regardless of the infrastructure type, potential for water impoundment and flow near infrastructure must always be minimized during site selection, construction, foundation design and in infrastructure management strategies. Culverts are installed to control cross-drainage water along infrastructure, but they also often act as heat sources and cause deeper thawing. The excessive settlement of culverts leads to frequent pipe breakage, sediment blockage, internal water ponding and subsequent freeze-up, which can completely block the drainage system. Culverts can also become completely submerged due to underlying permafrost thaw that leaves them below stream grade (McGregor et al. 2010) (see more in Section 3).

Geohazard Assessments

The overarching goals of geohazard assessments for developing a multimodal infrastructure corridor in northern regions are to limit impacts of permafrost degradation and other geohazards on infrastructure, and limit feedback with adverse consequences on the surrounding environment. The main objectives are to identify existing geohazards and recognize critical conditions that could eventually lead to geohazards (Table 1). To predict this terrain vulnerability and resilience to geohazards, it is essential to understand permafrost dynamics and potential interactions with infrastructure. Our knowledge on these topics has advanced in the past decades, especially through Transport Canada NTAI in regard to infrastructure interactions (Stockton, Burn and Humphries 2021), but several knowledge gaps remain.

To achieve the geohazard assessment objectives, we must characterize the system components (e.g., climate, surface, subsurface) and monitor conditions identified as critical for the sustainable development of multimodal infrastructure (Table 1). This involves a combination of field-based and desktop methods, and the integration of interdisciplinary knowledge and investigation approaches. Geohazard assessments in a corridor typically involve evaluating the system conditions from the landscape to the site-specific scale, and finally to the infrastructure scale with detailed geotechnical investigations that support foundation design (i.e., from coarse to fine scales). Due to the large extent of northern Canada and key processes occurring at the local scale, assessments must integrate various spatial scales. Likewise, processes occurring at multiple temporal scales must be considered to support sustainable development. Geographic information systems (GIS) allow integrating these varying scales and different types of data to conduct spatial analyses and produce useful tools for decision-making, such as risk maps.

Characterizing the system conditions along a proposed corridor should start by integrating data and knowledge on regional trends in GIS to allow for a gap analysis and increase the assessment robustness: this includes, but is not limited to, permafrost distribution, depth and temperature, borehole logs, digital elevation models, climate conditions, surficial deposits, topography, surface water bodies and drainage patterns. However, important challenges arise as data quality and format can vary greatly, and data availability may be limited, for example, with proprietary data or hardcopy reports (see more in Section 4). Remote sensing analyses are combined with the existing data in GIS. Important advances in remote sensing have allowed us to evaluate ground surface features indicative of potential subsurface conditions, but the direct assessment of permafrost conditions, especially ground ice, remains limited (Jorgenson and Grosse

2016). Another significant challenge in the application of remote sensing to permafrost environments is that the data spatial resolution and/or temporal coverage are often too coarse for permafrost studies, including for change detection analysis, to evaluate recent permafrost degradation. Combining remote-sensing systems increases analysis robustness (Rheault et al. 2015), while remotely sensed data can also be used as input in models to estimate permafrost conditions such as ground temperatures (Ou et al. 2016), maximum thaw depth and/or talik occurrence and potential for groundwater flow. Repeat usage of remote sensing systems that measure surface position, such as airborne light detection and ranging, structure from motion and synthetic-aperture radar, allows for evaluating ground surface movement that could indicate permafrost degradation and abundance of ground ice in the landscape (Jones et al. 2013), including in wet terrain under forested canopies in discontinuous permafrost (Stevens and Wolfe 2012), or under infrastructure (Fortier et al. 2015). Methods like airborne electromagnetic (AEM) surveys can measure the ground resistivity, which can then be related to the thermal state (Pastick et al. 2013; Foley et al. 2019; Best, Fage and Ryan 2021) of soil (most frozen soil has a greater electrical resistivity than unfrozen soil) to identify potential areas affected by permafrost degradation, although the type of material and the moisture content complicate this relationship (Pastick et al. 2013). In select areas, a detailed visual assessment of terrain conditions can be performed using high-resolution imagery from satellites or airborne photography.

Similar to remote sensing analysis, field investigations for geohazard assessment evolve from coarse to fine scales. Some field programs are intended to ground truth remote sensing analyses, while detailed geotechnical investigations will support the final site selection and foundation design. During this stage, soils are sampled using drilling methods, soil properties are measured in the laboratory and instrumentation may be installed to monitor local conditions such as ground temperatures, ground movement and groundwater. Such field investigations should be done at sites that represent the different types of environments occurring along the proposed corridor and at sites with high risk to geohazards. The permafrost geosystem and terrain-cryofacies approaches help us estimate subsurface conditions over extended areas by recognizing the linkages between permafrost and surface conditions, and using a combination of detailed field investigations with remote sensing analysis; these methods and their applications for infrastructure in permafrost are presented in Stephani et al. (2010, 2014, 2020) and Stephani (2021).

Field-based geophysical surveying using ground-penetrating radar or electrical resistivity, a non-invasive approach, may also supplement subsurface investigation in between boreholes (Trochim et al. 2016) or as a reconnaissance tool prior to drilling. Borehole data are important to ground truth geophysical surveying results, but when drilling data are unavailable, a combination of geophysical methods is recommended at a minimum to improve the robustness of such analysis. Geophysical surveying can also be used after infrastructure is in service and permafrost degradation issues arise, such as underneath roads (Fortier, LeBlanc and Yu 2011), airstrips (Fortier and Savard 2010; Oldenborger and LeBlanc 2015) or across mining dikes (Stephani, Musial and Anderson 2015). Although geophysical surveys of natural resources are done in northern Canada, most of these data have limited applications for infrastructure development as they generally target ground conditions deeper than the near-surface conditions that are critical for infrastructure stability. Often, the upper two to three metres of permafrost are the ice-rich zone, or intermediate layer (Shur 1988). Massive ice bodies can also be buried in this layer or underneath (Kanevskiy et al. 2010; Kanevskiy et al. 2013; Stephani et al. 2014; Stephani 2021). The occurrence of massive ice, such as ice wedges, is often intermittent compared to the upper part of permafrost that forms laterally, a relatively homogeneous ice-rich intermediate layer. Typically, this translates into more widespread thaw settlement as the intermediate layer degrades, whereas massive ice that melts tends to form thermokarst features that are more acute and circumscribed in the landscape, and that may extend to depths of tens of metres (e.g., RTS).

Geohazard assessments are essential for the sustainable development of multimodal corridors; however, they are not the only criteria controlling site selection, as the social and economic components are also key for decision-making (see more in Section 4).

3. ADAPTING CONVENTIONAL CONSTRUCTION AND DESIGN

Linear Infrastructure

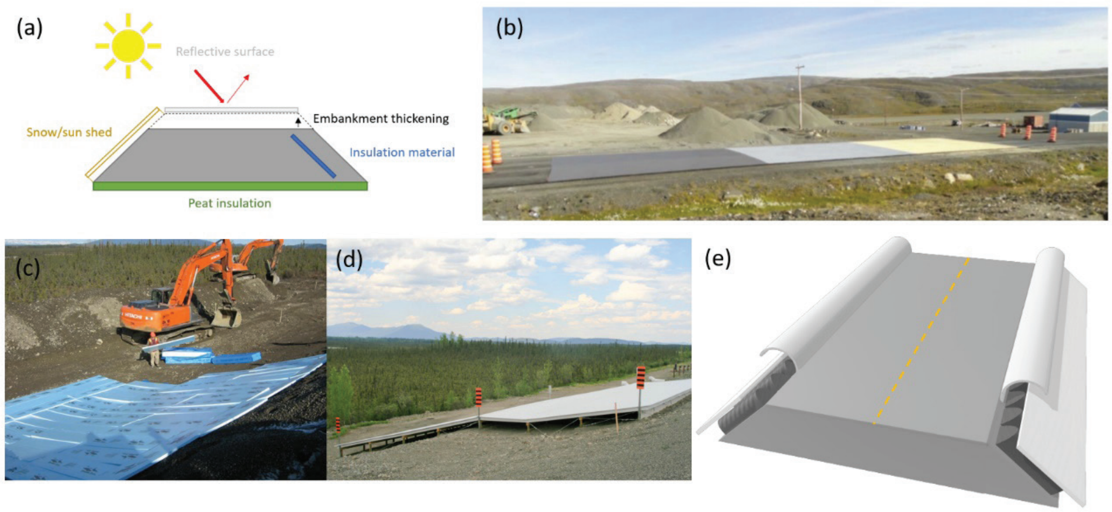
Recognizing critical terrain and subsurface conditions along linear infrastructure alignments is essential for sustainable foundation design. Some specific construction practices and designs are now well known to be relevant in permafrost terrain while others have been identified as detrimental, especially when the terrain is vulnerable to permafrost degradation. In some cases, pipelines and telecommunication lines are buried along transportation infrastructure, including in ice-rich permafrost, yet extensive permafrost degradation can result from trenching ice-rich terrain (Figure A8). Adequate construction methods can minimize the impact of trenching into ice-rich soils, but such practices should be limited as much as possible as they increase the risk of degradation due to disturbance of the organic mat and exposure of ground ice.

The most common approach is to build and maintain. This strategy involves building infrastructure above the ground surface, allowing permafrost degradation and thaw settlement to occur and maintaining serviceability by intensive maintenance to repair damages as they occur. It generally involves a reduced level of service and shorter life cycles, as well as reduced comfort and safety and higher travel costs for road users. With global warming, maintenance costs are expected to increase significantly, and this approach can easily become non-cost effective. In this context, and in cases where low level of service or loss of service are not acceptable, thermal and/or mechanical stabilization techniques are required. The different mitigation methods currently used to limit permafrost degradation along infrastructure can be classified into three main categories (Hjort et al. 2022), to which we added another class: 1) methods limiting heat intake in permafrost during summer; 2) methods enhancing ground heat extraction in winter; 3) methods reinforcing the embankment and improving ground stability; and 4) water management methods limiting advection and thermal erosion. Methods can be combined to provide better permafrost protection throughout the entire year. The choice of mitigation method applied at a site is based on different factors such as permafrost temperature and its thaw susceptibility, the implementation cost of the technique, the material and machinery availability, risk analysis and road safety. The four categories of mitigation methods are discussed below with a focus on road applications.

Heat Intake Limitation

Surface modifications, such as building a road embankment, typically increase the underlying ground temperatures. During construction of the Alaska Highway, after the vegetation cover and topsoil were removed and permafrost was allowed to thaw, the thawing process rapidly spread and, in many cases, could not be stopped (Muller 2008). It is now recommended to leave the original vegetation cover in place and to cover it with sufficient fill to insulate permafrost from summer heat. For example, a 75-cm thick layer of consolidated peat can provide significant thermal protection for an embankment built on permafrost (Esch 1996). Even when the original organic cover is left in place, surface disturbances from infrastructure construction still tend to induce permafrost degradation. The purpose of the following methods is to impede ground heat intake in summer, thus reducing thaw penetration and limiting permafrost degradation. Figure 2 illustrates different methods used or tested in thaw-sensitive permafrost.

Figure 2.



Examples of mitigation methods: a) schematic illustrating mitigation methods preventing heat intake; b) cool paving materials tested in Salluit, Nunavik, QC (photograph by Caroline Richard); c) extruded polystyrene placed in the road embankment shoulders, road test site, Beaver Creek, Yukon (photograph by Yukon Highways and Public Works); d) snow/sun shed, road test site, Beaver Creek, Yukon (photograph by Julie Malenfant-Lepage); e) schematic illustration of the half-pipe cover (Malenfant-Lepage and Doré 2019).

Embankment thickening: The most common method used to protect roads against permafrost degradation is to build an embankment that is thick enough to maintain the thaw front within the granular material, or at least within the active layer in the underlying natural ground; this method is recommended mainly for continuous permafrost areas. The thick fill material may limit permafrost degradation beneath the roadway centre, but embankment thickening does not adequately protect the side slopes. If the mean annual surface temperature is near the freezing point, the thawing front in granular embankments can reach depths of five metres or more (McGregor et al. 2010). In those conditions, the thickness of gravel required to protect permafrost can become too important and the technique uneconomical (Beaulac and Doré 2006). Thick embankments also increase the risk of permafrost degradation due to accrued snow accumulation along the side slopes. Finally, according to Kong et al. (2019), the thermal effectiveness of this method decreases significantly for embankment thicknesses less than 4.0m.

Embankment insulation: Extruded polystyrene and polyurethane are two insulation materials frequently used to improve the thermal resistance of gravel and/or peat due to their low thermal conductivity. Maximum benefit will be obtained from an insulation technique if the insulation material is installed in winter or early spring when the snow cover has just disappeared and the ground is still completely frozen (Doré, Niu and Brooks 2016). The use of insulation in road embankments has proven its effectiveness in cold, continuous permafrost in several experimental studies and is now frequently used to protect embankments or building foundations on thaw-sensitive permafrost (Esch 1973; Gandahl 1978; Johnston 1983; Sheng et al. 2006). Insulation can, however, have a negative impact on permafrost stability when installed in warm ground conditions during summer. Insulation can then trap heat in the ground and exacerbate the thawing problem. In all cases, thermal modelling should be conducted for the design of insulation layers.

High albedo surface: Absorption of solar radiation by dark road surfaces contributes to warming of the soil beneath gravel or paved transportation embankments. Several products have been tested to increase the albedo of the road surface such as white paint, light-coloured aggregates bituminous surface treatment, light-coloured pavement and light-coloured surface coating products (Richard et al. 2015) with synthetic asphalt-based and resin-based materials. In all cases, the thermal regime under paved surfaces improved. The use of white paint on roads reduces the average pavement temperatures by about one degree Celsius (Esch 1996); however, it does not provide good skid resistance, which can be a major safety problem in areas with heavy traffic, high speeds or sharp curves. The light-coloured aggregates bituminous surface treatment tested at the Beaver Creek experimental road site (Yukon) succeeded in keeping the thaw front within the embankment, compared to the standard road section where the thaw front reached a depth of 1.5m in the underlying natural ground (Malenfant-Lepage 2016). Light-coloured pavement and surfacing products with synthetic asphalt-based and resin-based materials were recently tested on road surfaces in Burwash Landing (Yukon) and Salluit (Nunavik, QC); over a yearly cycle, the thermal gains calculated near the surface were 0.7°C and 1.0°C, respectively (Richard 2018). Cool paving material technology is still in development and no standard exists for its application in civil infrastructure.

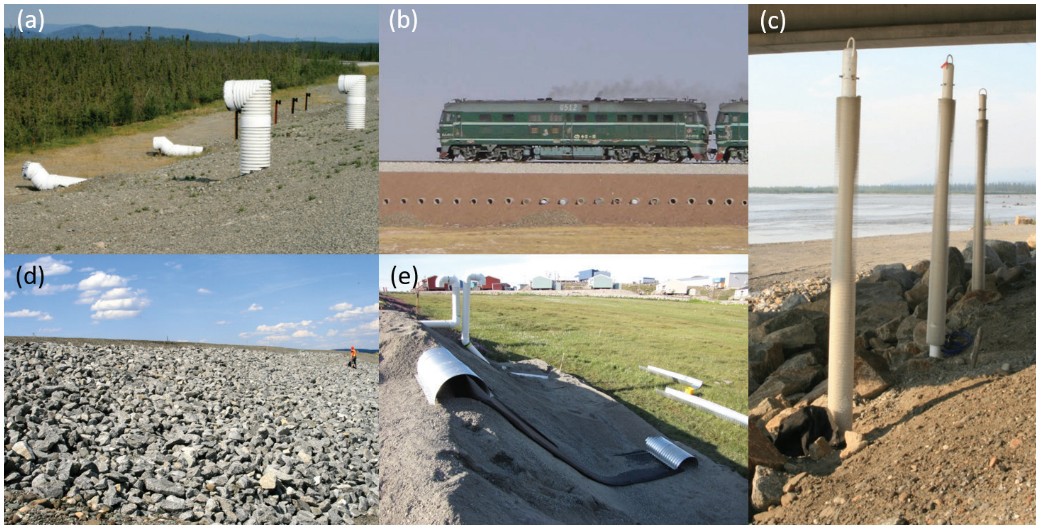
Snow/sun shed: The snow/sun shed is built on an embankment side slope. This method is highly efficient because it provides protection throughout the year by preventing snow accumulation directly on the ground, thereby eliminating snow's insulating effect; allowing convective air circulation between the shed and the soil surface; shading the embankment material to maintain surface temperatures close to air temperatures during summer; and reducing the absorption of solar radiation due to its white cover (Malenfant-Lepage and Doré 2019). In Alaska, shed installation decreased the average slope surface temperatures by 6.2°C (Esch 1988a). Along the Qinghai-Tibet Highway in China, the difference in maximum surface temperature reached eight to 15°C (Wenjie et al. 2006). In the Yukon, the thaw front receded by 1.5m underneath the embankment side slopes within the first year of shed installation (Malenfant-Lepage 2016). Safety concerns and high construction costs have, however, restricted the widespread use of snow/sun sheds for embankment protection. An alternative solution has recently been proposed using a half-pipe structure applied directly on the slope surface (Figure 2e). The technique, tested in the laboratory at Quebec's Laval University, showed significant cooling, thus with potential for a future implementation on a road test section (Malenfant-Lepage and Doré 2019).

Heat Extraction

The purpose of these mitigation methods is mainly to enhance heat extraction from the ground in winter to raise the top of permafrost, or at least to prevent thaw settlement. Limiting snow accumulation on the embankment side slopes by plowing them regularly helps heat extraction, especially as snow thicknesses increase on the upper slopes when snow is plowed off from the road surface (Figure A6), but the feasibility of this method may be challenging.

Air duct: Two types of air duct systems have been developed (Doré, Niu and Brooks 2016). The first type uses the chimney effect to induce air movement in ducts placed parallel to the road alignment in the embankment side slopes. The air duct is connected to inlet and outlet chimneys, which extend above the embankment surface (Figure 3a). During winter, cold air flows by convection through the inlet, is heated by the surrounding ground and exits via the outlet. This air duct demonstrated cooling potential within the first year of implementation at the Beaver Creek road test site. After three years of monitoring, the active layer thickness decreased by 0.5m and a strong cooling trend was observed (Malenfant-Lepage 2016). The second type of air duct consists of open-ended ducts in a pad or roadbed oriented perpendicular to the road alignment and in the direction of prevailing winds (Figure 3b). At the Beiluhe railway test site on the Qinghai-Tibet Plateau, ventilated embankments with air ducts positioned 0.7m above the natural ground surface cooled the subgrade soils and kept the infrastructure thermally stable (Niu et al. 2006).

Figure 3.



Heat extraction mitigation methods: a) air ducts with chimneys, road test site, Beaver Creek, Yukon (photograph by Julie Malenfant-Lepage); b) open-ended air duct used along the Qinghai-Tibet plateau (Niu et al. 2006); c) thermosyphons under the Donjek Bridge, Yukon (photograph by Julie Malenfant-Lepage); d) air convection embankment, road test site, Beaver Creek, Yukon (photograph by Julie Malenfant-Lepage); and e) heat drain implemented along the airport access road in Salluit, Nunavik (photograph by Guy Doré).

Thermosyphon: A thermosyphon is composed of a pipe that contains a refrigeration fluid in liquid and gas states. When the ground temperatures are warmer than the air temperatures, the liquid refrigeration evaporates, absorbing heat from the ground and the gas released rises in the pipe because of its lower density. Subsequently, when the gas reaches the upper section of the pipe that extends above the ground surface, the gas condenses due to the colder air temperatures, releases heat and flows back down into the pipe. The main advantage is that this cycle repeats itself without any power source. Thermosyphons have been used since the late 1960s for permafrost cooling and have proven their effectiveness at several test sites in Alaska (McFadden and Siebe 1986; Zarling and Braley 1986; Xu and Goering 2008) and Canada (Hayley 1983) (Figure 3c). Their current design has widespread application in Canada, Alaska, Russia and China; however, the initial cost is high, which makes them more suitable for localized applications, such as buildings, bridges, transmission towers or certain sections of transportation infrastructure highly affected by permafrost degradation.

Air convection embankment (ACE): ACE consists of an embankment built with coarse, poorly graded aggregates with large openings in between or pores that increase air permeability (Goering 1998). When pores between the rocks are large enough and interconnected, temperature differences between the surface and the base of the embankment during cold winter periods create convective cells. Air cooled in the upper part of the convective material sinks down into the embankment because of its higher density, displacing warm air upwards and out of the embankment. ACE increases heat loss, thus providing a cooling effect. Different rock size particles and ACE configurations have been tested in Alaska, Canada and China (Figure 3d). In 1996–1997, an air convection embankment was constructed in Fairbanks, Alaska, using coarse (25- to 150-mm diameter) and poorly graded crushed rock fill material. After five years of monitoring, the maximum temperatures at the embankment base decreased from more than 4.4°C to near 0°C (Saboundjian and Goering 2002). At the Beaver Creek test site, the uncovered ACE slopes with 150- to 300-mm diameter crushed rocks successfully cooled the ground underneath the embankment side slopes and the roadway centre during the three years of monitoring (Malenfant-Lepage 2016). The ACE technique also has been widely used along the Qinghai-Tibet plateau, on up to 60 per cent of the 550-km long railway. Its cooling effectiveness has been validated in many models, field tests and practical applications by numerous authors (Sun, Ma and Li 2005; Zhang et al. 2005; Guodong et al. 2007; Cheng, Sun and Niu 2008; Li et al. 2008; Mu et al. 2012; Wang and Ma 2012; Niu et al. 2015).

Heat drain: This protection technique is based on the use of a 25-mm thick, highly permeable geocomposite that is made of a corrugated plastic core and covered on both sides by geotextile, which is placed in the embankment shoulders. The geocomposite needs to be connected to inlet and outlet pipes located at the base and top of the drainage layer to support heat exchange by convection using the chimney effect. Heat drains implemented at the Tasiuaq airstrip and Salluit airport access road in Nunavik (Figure 3e) performed well in both cases. In Tasiuaq, the mean annual surface temperature at the embankment/natural ground interface was reduced by 2.2°C after three years of experimentation, and the permafrost table had risen by more than two metres compared with the reference section (Doré et al. 2012). In Salluit, the permafrost table also rose above the embankment base after three years of implementation (Lamontagne et al. 2015).

Embankment Reinforcement and Ground Improvement

In cases where thermal stabilization is difficult to apply or too expensive, mechanical stabilization and ground improvement can become good strategies to mitigate structural damage due to permafrost degradation.

Geogrids and geotextiles can be used to reinforce embankments, reduce differential thaw settlement and prevent lateral embankment spreading and subsequent opening of longitudinal cracks (Figure 4a). Induced thawing or excavation and replacement can be used to improve soil conditions. Thawing can be induced using different techniques, including removal of vegetation and topsoil layer, solar thawing, flooding, injection and circulation of steam, electrical heating, covering the surface with clear or black polyethylene film or covering with a thin gravel pad (Johnston 1981; Saboundjian 2008; Shur and Goering 2009; Doré 2021). Excavation and replacement involve partial or complete removal of ice-rich soils and replacement with a non-frost-susceptible filling material. This is also used when time is not available for more economical pre-thawing operations (Esch 1988b). It is critical to understand the local permafrost conditions and dynamics prior to selecting this method, as in some instances it could trigger significant permafrost degradation that extends laterally and with depth, rather than mitigating an initially local issue. When the method is deemed appropriate for local permafrost conditions, soil excavation and replacement should be done during the cold season to limit thaw-related water problems. Mechanical stabilization of embankments can also be improved by designing gentle slopes or using berms (Figures 4b and 4c). These techniques provide better lateral support to the core of the embankment and limit failure occurring within the road surface (Doré and Zubeck 2009); however, berms have also been linked to permafrost degradation by increasing the embankment footprint and consequently the underlying ground temperatures and active-layer depth. When feasible, building embankments with gentle slopes can be a simple and effective method to limit permafrost degradation because it reduces snow accumulation on embankment side slopes during winter and thus decreases the snow insulation effect that limits ground heat extraction.

Figure 4.

Examples of methods used to reinforce embankments and improve soil stability: a) use of geotextiles in a wrap-up method called the "pillow method," Alaska Highway, Yukon (photograph by Julie Malenfant-Lepage); b) gentle side slope, Tasiujaq runway, Nunavik (photograph by Sylvain Juneau); and c) rock berm, Alaska Highway, Yukon (photograph by Guy Doré).

Drainage Management

Drainage issues along linear infrastructure in permafrost terrain have traditionally been underestimated during design and construction, yet they can lead to substantial problems and are now widely reported throughout Canada. Engineering methods for the design of drainage systems are poorly adapted to permafrost environments and limited to a set of recommendations to avoid excessive permafrost degradation. The experience developed in Canada is local and differs from one region to another. Drainage designs typically do not consider thermal impact on permafrost and further research is needed to develop design principles and criteria for permafrost conditions, especially as we only recently started understanding the considerable impact of water impoundment and flow on permafrost conditions along infrastructure (de Grandpré, Fortier and Stephani 2012; Stephani et al. 2020; Stephani et al. in review). This development of design principles and criteria must be built upon the identification and understanding of the natural drainage patterns, such as water tracks and inter-hummock flows, and their roles in the local permafrost-infrastructure geosystem. McGregor et al. (2010) propose the following techniques to reduce the risk of damage caused by drainage water, yet further research is needed to establish robust guidelines.

To extend the lifetime of culverts, the Yukon Department of Transportation proposes the use of geotextiles to reinforce the drainage structure and polystyrene to insulate the culvert granular cushion, thus limiting heat transfer from the running water to the ground below (Figure 5a). Minimizing water concentration using closely spaced culverts is another alternative to reduce water flow through them and limit permafrost degradation caused by advective heat transfer. Interceptor ditches built at a distance from the embankment also help to reduce heat transfer from drainage water to ice-rich embankment foundations (Figure 5b). Permafrost degradation will likely occur where the water is diverted, but it will not directly affect the infrastructure; however, it is critical to consider the potential for lateral spread of permafrost degradation over extended areas. Deviation channels can also be used to divert subsurface water away from thaw-sensitive soils when surface topography allows. Water should be preferably deviated to a stream, a lake or to thaw-stable ground. Finally, permeable rockfill embankments can be built across diffuse natural drainages directly on the organic cover with quarry rockfill less than 0.5m in diameter. Their use allows water to flow freely through the embankment, prevents changes to the natural drainage, avoids ditch excavation and limits water concentration at culvert inlets and outlets that can enhance permafrost thawing.

Figure 5.

Examples of methods used to reduce thermal degradation caused by drainage water: a) construction of an insulated culvert (Alaska Highway, Yukon) (photograph by Simon Dumais); b) interceptor ditch built at a 10-metre distance from the highway (Alaska Highway, Yukon) (photograph by Guy Doré).

Buildings and Structures

Methods used to protect building and structure foundations on thaw-sensitive soils generally use the same principles and some of the techniques described above for linear infrastructure. The low tolerance to deformation and the presence of heating systems in most buildings increase the need for highly effective protection systems. For small buildings, the use of ventilation spaces under the buildings is generally sufficient to maintain cold ground conditions due to the cold air circulation in the winter and the shade at the ground surface in the summer (Figure 6a). For buildings requiring slabs on the ground, thermal insulation is commonly used in combination with thermosyphons to remove heat underneath the slab and maintain permafrost thermal stability (Figure 6b). Alternatively, ventilation systems can be used to remove heat from the foundations (Figures 6c and 6d). For structures built on deep foundations (piles), using thermosyphons is the most common technique to maintain thermal stability along the piles (Figure 6e) (Technical Council on Cold Regions Engineering 2007).

Figure 6.

Methods used to protect buildings and structures built on thaw-sensitive permafrost: a) ventilation space under a building allowing cold air circulation in the winter and providing shade in the summer (Puvirnituq, Nunavik); b) thermosyphons used to cool the foundations of Inuvik's hospital (N.W.T.); c) and d) ventilated building foundation with inlet and outlet chimneys (Kangerluusaq, Greenland); and e) thermosyphons used along the piles of the TAPS. Photographs by Guy Doré.

Most of the engineering solutions presented above are much more expensive than standard construction practices. Their use is generally restricted to localized structures or short sections of linear structures built in areas of highly thaw-sensitive permafrost. The need for these systems can be justified by a cost-effectiveness analysis comparing the long-term cost of maintenance of an unprotected structure to the cost of a stabilized structure. It can also be justified by the low tolerance to the risk of poor performance or service disruption caused by permafrost degradation. For example, closure of a pipeline or road due to localized distress can have severe economic and social impacts.

4. MANAGEMENT OF NORTHERN INFRASTRUCTURE

Northern Canada is experiencing severe environmental, social and economic impacts that can be attributed to poorly adapted design compounded with the effects of climate change. In Arctic regions, warming is taking place at a faster rate than in the rest of Canada and more rapidly than many climate models predicted (Erikson 2020). Of critical importance to the North in the face of a changing climate is the protection of the region's infrastructure. Given the associated costs and the complexities that exist in geographically isolated and climatically harsh regions, efficiency and resiliency are critical elements of northern infrastructure.

Lifetime Engineering

Lifetime engineering supports the sustainable development of infrastructure by proposing an approach that solves the dilemma between the infrastructure as a long-term product and the short-term approach used in its design and management strategies (Gaspar 2016). The lifetime engineering approach that Gaspar (2016) presents includes the following key principles:

- Lifetime investment planning and decision-making;
- Integrated lifetime design;
- Lifetime principles in construction;
- Integrated lifetime management and maintenance planning;
- Modernization, reuse, recycling and disposal; and
- Integrated lifetime environmental impact assessment and minimization.

Northern infrastructure, such as roads, runways, bridges, power lines, pipelines and telecommunication grids, is a long-term facility, and therefore lifetime engineering approaches starting with the investment planning and decision-making should be applied. Lifetime engineering considerations in the integrated design, management and maintenance planning and in recovery and re-use of construction materials are all vital for wise use of resources.

Cultural and environmental considerations are also vital components of the lifetime engineering methodology, and their importance increases in cold regions with Indigenous populations and fragile ecosystems. For example, the selection of the wearing course for a road is affected by considerations to respect cultural inheritance, while preservation of local environmental conditions must also be considered.

Ground movements, thermal stresses and intensive loading by traffic, wind and ice are responsible for aggravated damage on cold regions' infrastructure. Infrastructure design needs to meet the performance function, but also the project feasibility in a northern context. Limited budgets in sparsely populated areas may not cover the capital and operating costs required for ideal infrastructure performance. Optimization is needed to use funds wisely so that northern infrastructure is functional, safe and meets desired performance levels. For cold regions' infrastructure to perform according to the desired level of service, four main elements need to be considered: design, material, construction and maintenance. These components act as links in a chain; when the weakest link fails, the entire chain fails. Design strongly depends on site-specific ground conditions with critical factors in permafrost areas that include ground ice content (ice-rich), grain-size distribution (fine-grained soils) and ground temperatures (warm permafrost) (Table 1). In addition, proper lifetime design must consider available capital, desired performance, operation and maintenance funding, access to the site, local traffic, subgrade soils, available construction materials and equipment, skilled labour availability and weather conditions (Gaspar 2016). Infrastructure in cold regions is often built expeditiously, and with an inexperienced workforce.

Arctic Engineering Knowledge and Capacity

The quality of foundation design can be directly related to the success or failure of a structure on frozen ground. In southern Canada, design and construction of different types of infrastructure are well supported by standards and engineers are well trained to work in this climatic context. Documents such as the *Canadian Foundation Engineering Manual* (Canadian Geotechnical Society 2006) and the *Canadian Highway Bridge Design Code* (Canadian Standards Association 2019), as well as several technical guides, serve as strong references for design, procurement and construction of infrastructure in southern Canada. Most of these documents include a section on building in permafrost regions, but these sections rarely provide the level of detail required for adequate thermal and mechanical design of structures on permafrost.

Efforts are being made to improve this situation. The Standards Council of Canada (SCC) has been working with different experts and stakeholders to support the development of standards and related guidance that consider climate change impacts in northern infrastructure design, planning and management. These standards, developed under the Northern Infrastructure Standardization Initiative (NISI) or under Transport Canada's NTAI, provide guidance to building owners and operators, as well as those responsible for public and community infrastructure, to build and maintain infrastructure in a changing climate. Examples of documents produced so far include "Design and Construction Considerations for Foundations in Permafrost Regions" (Canadian Standards Association 2019) and "Geotechnical Site Investigation for Building Foundations in Permafrost" (Canadian Standards Association 2017). Other agencies have developed best-practice guidelines for the design and construction of different types of structures on permafrost. The Transportation Association of Canada has sponsored the development of the document "Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions" (McGregor et al. 2010), while the Nunavut government has published the "Homeowner's Guide to Permafrost in Nunavut" (Government of Nunavut 2013). These initiatives have contributed to place Canada among the leading countries for the advancement of knowledge and expertise in Arctic engineering. NTAI had an ambitious plan to develop a series of engineering standards and guidelines to support Arctic engineering in Canada, but it was terminated when the NTAI program was not renewed in the 2021 federal budget.

Qualification and training of engineers and other professionals working in the North is also an important issue. Most civil engineering programs in Canadian universities do not include specific courses in Arctic engineering and permafrost, and there are currently no requirements from provincial/territorial licensing agencies for professionals to complete a minimum training that could at least raise their awareness of potential critical conditions that need to be avoided for safe and sustainable practice in these sensitive environments. In comparison, professional engineer (PE) licensing in Alaska requires the completion of the course "Arctic Engineering" with a standardized content that is given under various formats, such as semester-based, intensive, in-person and online. The availability of specialized Arctic engineering courses is limited in Canadian universities. Specific courses, developed based on personal initiatives, have been taught at the University of Alberta, Yukon University and at Aurora College (N.W.T). Most are based in a specific university department and not well known beyond there. It is highly concerning to see that the lack of experienced and qualified personnel, as well as the scarcity of guidelines and standards on Arctic engineering, still leads to poor designs and premature failures.

A genuine partnership with First Nations in the development and maintenance of transportation infrastructure is also likely to improve infrastructure quality and extend its viability. Traditional knowledge of the territory can help site selection and routing of linear infrastructure and, with proper training, local manpower is essential to improve the capacity to maintain northern infrastructure.

Challenging Construction Conditions

Construction projects in northern Canada often involve important logistic challenges. When construction is done in the summer, operations must be planned considering a very short construction season, while in the winter the workflow can be impeded by harsh working conditions for equipment and workforce. Due to the remoteness and limited access to a transportation network, project logistics should consider how to supply and support construction (McGregor et al. 2010). Remote construction sites might only be accessible by sea, air or on frozen ground in the winter. Using winter roads may be the only practical way to bring construction equipment and supplies on site without building permanent roads; yet, the window of winter road operation is limited, usually in the order of two to four months. Overland winter roads can consist of either lightly tracked, low-pressure vehicles travelling over the snow on the tundra or highway trucks operating on engineered snow and ice roads. Ice roads over frozen lakes require construction and maintenance to ensure adequate ice thickness and clearance of snow.

Roads constructed in permafrost regions typically require more fill material than construction projects in non-permafrost regions. At the same time, good construction materials are often rare and difficult to access. Finding material and planning for its sustainable use are important considerations to reduce costs and to minimize the impact footprint (McGregor et al. 2010).

Construction Costs

Due to the conditions described above, the cost of construction in northern Canada is much higher than in the rest of the country. The cost of construction materials is typically 25 to 220 per cent higher in the Canadian territories than in the provinces (Applied Research Associates 2006). The cost of road construction can be eight times higher in remote areas of northern Canada, and the cost of bridge construction in the Canadian territories is typically twice the cost of similar construction in southern Canada (Applied Research Associates 2006).

According to the Yukon government, road distress already causes major construction and maintenance issues. For example, nearly 50 per cent of the northern part of the Alaska Highway is highly vulnerable to permafrost thaw and is already showing important signs of degradation (Calmels et al. 2015). In those conditions, construction costs are doubled, maintenance costs are up to 10 times higher, dramatic embankment failures are an important safety consideration and the poor performance requires resurfacing every three to four years compared to 13 to 15 years in the absence of permafrost (Reimchen et al. 2009; Murchison 2011). The cost of infrastructure damage induced by permafrost degradation in the Northwest Territories is estimated to be $51 million per year (Levitt 2019).

Infrastructure Management Strategies

Investing in northern infrastructure is critical for the social and economic development of northern Canada. Communities and the resource industry rely on this infrastructure every day to stay connected with the rest of the country and to access natural resources. Maintaining adequate physical conditions of infrastructure, which implies proper investments, is at the heart of solutions for sustainable northern development. All governments, designers, contractors and operators must recognize the need for proper infrastructure management and embrace the role it plays in ensuring the predictability and safety of our public infrastructure.

Infrastructure management involves a set of tools that aligns strategic planning at the local and national levels, with value that stakeholders and citizens place on the functionality and reliability of their public infrastructure. To manage northern infrastructure effectively in a context of climate change and support sustainable development in permafrost areas, Hjort et al. (2022) identified critical actions that we adapted: 1) develop relevant data resources; 2) improve modelling (e.g., climate, ground ice and temperatures, hydrology, etc.) on varying temporal and spatial scales; 3) comprehensively map permafrost conditions and geohazards; 4) assess and manage risk; 5) adapt design and construction practices, and develop and implement infrastructure adaptation plans; and 6) communicate and distribute information among scientists and stakeholders. These requirements are summarized below:

1) The availability of relevant and reliable data resources is essential for management and decision-making processes. Even though permafrost underlies 40 per cent of Canada's landmass, we still have little information and data on this large part of the territory. It is important that, for every site or region, the data on annual thaw depths and permafrost temperatures are made publicly accessible, as well as all other important known variables on local climate, terrain, subsurface and infrastructure condition and performance (e.g., ice content, soil, vegetation, air temperatures, precipitation, geotechnical parameters). Several agencies, research institutes and universities developed online tools with free access and are now gathering permafrost data; examples include the Geological Survey of Canada (GSC), the Permafrost Information Network (PIN), the Global Terrestrial Network for Permafrost (GTN-P) and the Nordicana D database from Université Laval. However, many valuable data collected in northern Canada

in the last decades through industrial activities are proprietary. Consultant engineers, especially those who have operated in the territories for many years, may have accumulated large datasets that are also typically proprietary. Providing free access to critical data, digitizing historical data and encouraging long-term monitoring of sites are key to supporting the sustainable development of northern Canada. It will help reduce costs associated with the design, construction and maintenance of infrastructure. Besides their accessibility, data must be properly managed and archived. This includes validating the data reliability with quality assurance (QA) processes. Data on infrastructure need to include contextual factors affecting its performance.

2) Numerical modelling of thermal, hydraulic and mechanical behaviours of structures and permafrost foundations are now essential engineering activities to support design and performance assessment of structures built in northern Canada. Numerical modelling needs to represent the infrastructure conditions and its spatiotemporal behaviour over the structure's design life. The models need to be calibrated properly and must consider climate change scenarios. High-quality data from well-managed databases (Point 1) or from published research results are essential to calibrate numerical models and validate simulation results, yet important difficulties remain to bridge the gaps between fine- and coarse-scaled models.

3) Mapping permafrost conditions and geohazards in the vicinity of infrastructure is critical. As discussed in Section 2, several geohazards can affect the integrity and serviceability of infrastructure built on sensitive permafrost. Several of these geohazards, such as thaw slumping or thermal erosion, can be triggered by natural events occurring at great distances and yet still impact infrastructure. Other geohazards can be triggered by the disturbance caused by the infrastructure construction and/or operations, and affect the landscape, ecosystem and/or other structures located at a distance from the geohazard's original location. The existence of these geohazards must be known at the planning stage and accounted for during design, construction and operation of the structure.

4) Improved infrastructure risk assessment and management approaches are needed. The sustainable development of linear infrastructure in permafrost areas necessitates an evaluation of the permafrost geohazard risks and the implementation of effective management strategies, whereas these require a comprehensive understanding of permafrost dynamics, including the various processes of permafrost degradation that often occur concurrently. It involves the ability to recognize landforms related to ongoing permafrost degradation (Table 2) and critical terrain and subsurface conditions (Table 1) indicating terrain vulnerability to future geohazards. It also involves the ability to assess the vulnerability and resilience of the infrastructure to permafrost degradation and the consequences of a reduced level of service, or ultimately of a failure, for the population and/or the industry using the infrastructure (Brooks, Doré and Smith 2018; Hjort et al. 2022).

5) Developing and testing mitigation strategies in various types of environments is critical to supporting the sustainable development of infrastructure with a lifetime engineering approach. Some of the mitigation techniques, such as thermosyphons and air convective embankments, have already been widely applied while others are still in the early research stages with needs to quantify their cooling effectiveness and ground stabilization in different site-specific conditions. In Canada, from the 2000s, the Quebec Ministry of Transport, Yukon Highways and Public Works and the government of the Northwest Territories have led important research projects involving the establishment of test sites in collaboration with Transport Canada and several Canadian research centres. Various permafrost mitigation methods have been developed as part of these collaborative projects. This was an important step forward for improved sustainable construction methods in permafrost environments, yet much remains to be done. It is important to be aware that the best solution will not be unique across northern Canada but rather it will be site specific, which justifies the need for the development of many solutions. The choice of the mitigation method to be applied at a site should be based on many factors, such as the permafrost conditions and its thaw susceptibility, the technique's implementation cost, the material and machinery availability, the labour availability in remote areas, the risk analysis and the expected lifespan of the infrastructure. Geohazard alarm systems, such as for RTS, may need to be implemented at select sites in the event of a potential embankment failure, and there is a need to develop such systems. One system is currently under study along the Alaska Highway in Yukon Territory (Idrees et al. 2021).

6) Last, it is essential that professionals from several disciplines work together to combine their expertise and data, which will support the infrastructure development processes, including implementing mitigation techniques. The former NTAI program and the recent establishment of the Canadian Permafrost Association in 2018 helped to meet this need on a Canadian scale, but much remains to be done to bring together northern communities, scientists, engineers, practitioners and stakeholders to advance our understanding of permafrost interaction with infrastructure. This interdisciplinary approach also implies that construction and maintenance plans must be shared and discussed with experts and stakeholders, while managers must be open to modifications to infrastructure management plans based on technical and local needs considerations.

5. CONCLUSION: REMAINING CHALLENGES

A Canadian Northern Corridor concept may address the growing need to provide services and transportation pathways to remote communities in northern Canada, while also providing a long-term solution to foster the competitiveness, growth, diversification and property of the country (The School of Public Policy 2021). To establish this corridor sustainably, it is imperative to recognize challenges specific to northern regions and adapt conventional engineering approaches, construction methods and management strategies to these northern conditions. Developing transportation infrastructure in permafrost-affected terrains, which are extensively present in northern Canada, is one of the critical engineering challenges. Here, we have summarized the main geohazards and their impacts on infrastructure, geohazard assessment approaches, mitigation techniques and management strategies. Our understanding of permafrost science and engineering has progressed intensely over the last decades, yet several knowledge gaps remain. The past and predicted temperature increases (Bush and Lemmen 2019; IPCC 2019) also stress the need to advance our permafrost knowledge, and to further adapt our strategies for developing and maintaining infrastructure in northern regions. We must improve our capacity to characterize the varying permafrost systems in northern Canada and monitor changes of the system components. A comprehensive systemic approach that integrates interdisciplinary methods is critical for a sustainable development of infrastructure in northern regions, yet challenges remain to improve our capacity of bridging gaps between disciplines and entities involved in infrastructure development. We complete our overview paper by summarizing some of these remaining challenges.

Knowledge and Expertise

It is essential to increase efforts to promote higher education specialized in cold-regions science and engineering through micro-programs in Canadian universities and colleges and through continuing education:

- Programs such as the recently abandoned NTAI (Transport Canada) should be reestablished, or replaced, and reinforced to foster technical exchange and interdisciplinary collaborative development of knowledge and practices;
- The lack of widely accepted reference documents to support high-quality design, procurement, construction and maintenance of foundations on permafrost remains a major problem for Canada's northern infrastructure.

Communication and Inclusion

- The success of northern infrastructure development and management will rely on improved communication between all entities involved. Upstream, planners must work closely and communicate effectively with qualified engineers and scientists to assess potential problems likely to affect the serviceability of existing or planned infrastructure;
- Major efforts should be made to involve First Nations in the development and maintenance of sustainable infrastructure in northern Canada.

Technical Advances

- Key objectives for future work should include the use of spatial information and physical characterization of permafrost and geohazards. Consistent approaches should be used for broad-scale mapping and cataloguing of different types of permafrost conditions and geohazards. Established and new field methods should be used for continued investigation of the physical basis of the degradation development, and to quantify their distribution and variability to understand the environmental and socioeconomic significance;

- Further study is needed to better understand processes of permafrost degradation and interactions with infrastructure, especially in a context of climate change. Evaluating and predicting the effects of infrastructure must extend beyond the direct footprint of infrastructure (Walker and Peirce 2015);
- Of particular importance is the understanding of the role of groundwater and unfrozen interstitial water on the thermal state and the mechanical properties of permafrost. Unfrozen water content is a key parameter that will become even more important with climate change;
- Permafrost characterization for research and for infrastructure construction projects is still a major challenge. Determination of spatial distribution and characterization of thaw-sensitive permafrost are of paramount importance for infrastructure routing and design, and for risk assessment;
- Many of the mitigation and adaptation techniques are promising, but few have proven to be reliable and effective over the lifespan of northern infrastructure. These techniques need to be further developed and optimized to become viable alternatives that provide effective long-term protection in the context of climate change. Also, new techniques need to be developed to provide a range of cost effective options to be considered in adaptation strategies, as well as mitigation techniques for mass movement geohazards, such as RTS, that are becoming more important for northern infrastructure.

New Technology

- Development of new methods or improvement of existing methods based on remote sensing and geophysical and geotechnical technologies is required to improve our capacity to detect and to characterize thaw-sensitive permafrost and other northern geohazards;
- Baseline condition data and long-term monitoring are needed to detect and understand geohazard processes, including permafrost degradation, and to estimate remaining service life of critical northern infrastructure. This involves the development of advanced monitoring systems, including smart sensors combined with remotely accessible data acquisition systems and alarm systems for geohazards such as RTS;
- There is a need for easy and effective laboratory and field measurements of unfrozen water content.

Infrastructure Management

- Infrastructure and risk management methods must be adapted to permafrost conditions. Information required to feed management systems is almost non-existent and decision-making systems are not adapted for infrastructure built on permafrost. Decision-making requires reliable information on the cost of different development and maintenance strategies, as well as on the benefits and the risks related to each of these strategies;
- Advanced analysis tools are needed to assess risk of failure and remaining service life, which rely heavily on the thermal state of the foundation. Analysis tools need to combine climate projection scenarios with thermal modelling to provide reliable estimates of infrastructure performance and relevant failure criteria to assess remaining service life.

6. ACKNOWLEDGMENTS

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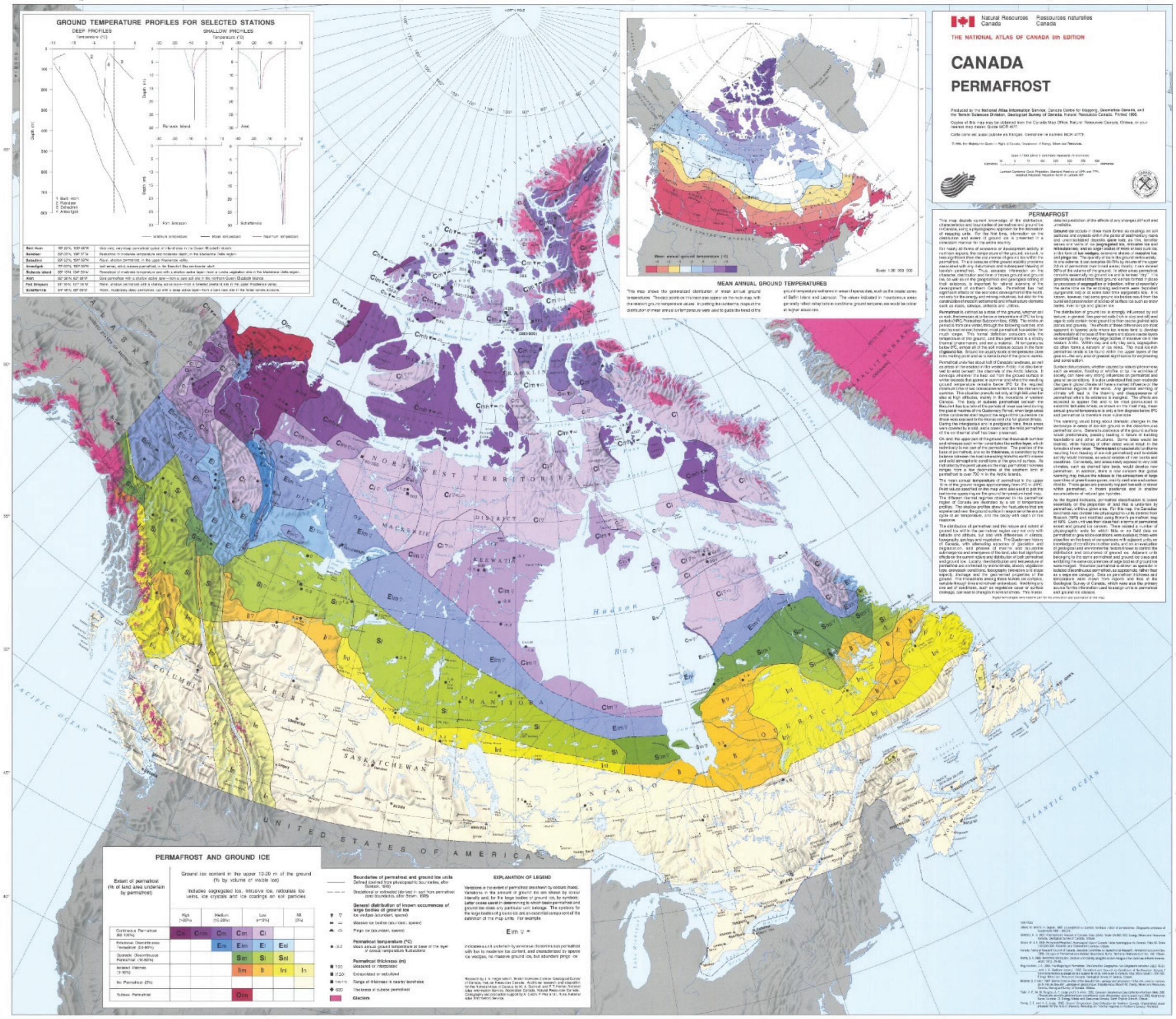
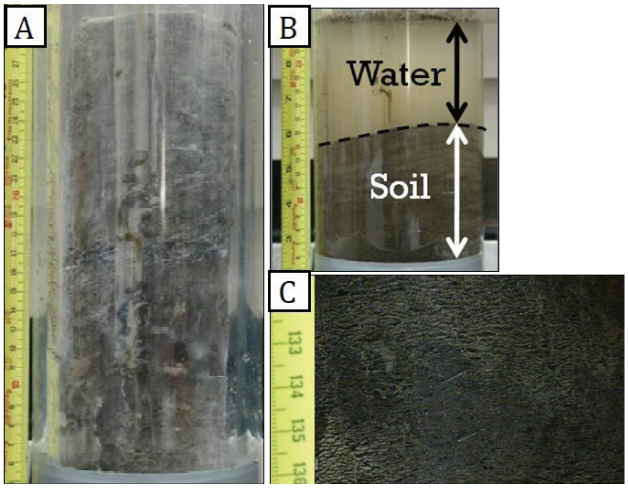
APPENDIX A: ADDITIONAL FIGURES AND TABLES

Figure A1.



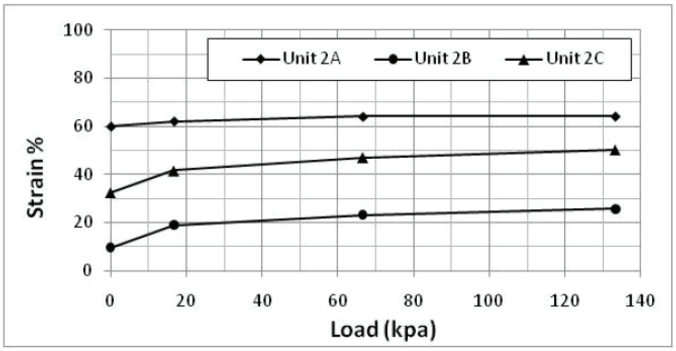
Permafrost map of Canada with purple tones indicating continuous distribution, blue tones indicating discontinuous permafrost, green tones indicating sporadic permafrost and yellow and oranges for isolated patches of permafrost (Heginbottom, Dubreuil and Harker 1995).

Figure A2.



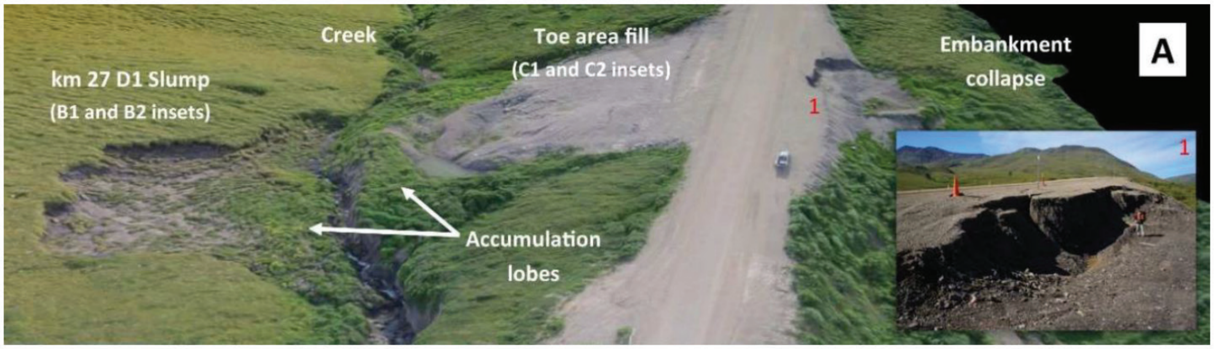
Thaw-strain test on a sample of ice-rich permafrost underlying the Alaska Highway (Yukon) which indicates that thawing this layer of soils and ground ice would lead to significant ground subsidence as the volume of thawed soils is nearly 50 per cent smaller than in its frozen state. A) frozen core in thaw-strain cell; B) thawed core; C) microlenticular cryostructure (type of ice) observed in the core prior to the test (black is sub-mm ice lenses) (Stephani, Fortier and Shur 2010).

Figure A3.



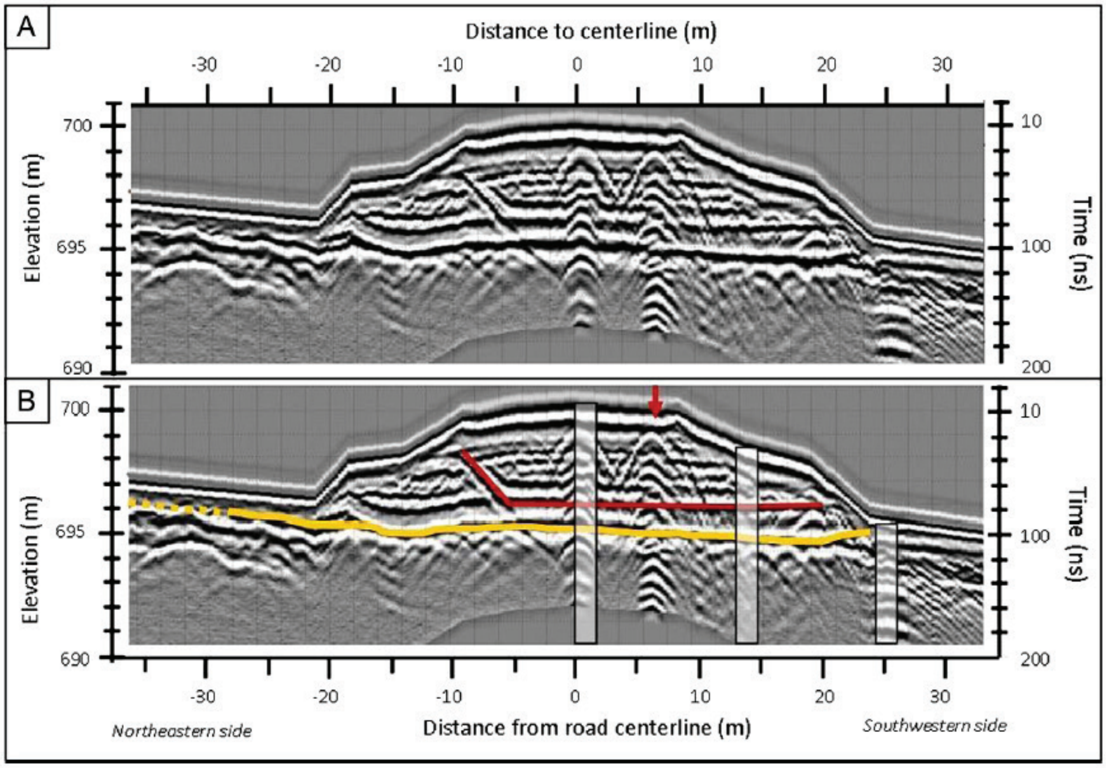
Thaw strain with incremental loading on ice-rich soils (Units 2A and 2C) and ice-poor soils (Unit 2B) sampled under the Alaska Highway (Yukon) (Stephani, Fortier and Shur 2010).

Figure A4.



Development of RTS and embankment collapse along the Dempster Highway (van der Sluijs et al. 2018).

Figure A5.

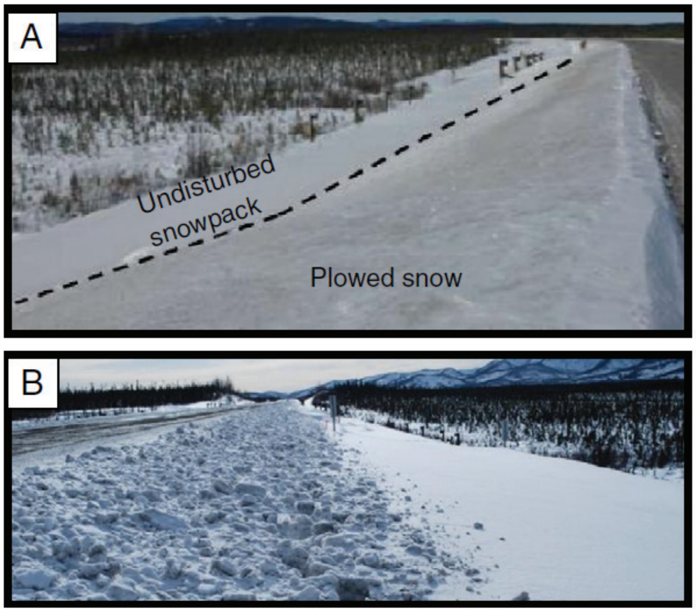


Ground-penetrating radar reflection profile across the Alaska Highway (Yukon) that indicates thaw settlement under the embankment, especially under the side slopes (pink arrows), as the natural ground surface under the road is now located below the adjacent natural ground surface level (wave velocity used for converting time into depth: 0.11 m/ns). Yellow and red lines show, respectively, the natural ground surface and the heat drain tested at the Beaver Creek road experimental site. Vertically shaded areas indicate location of boreholes containing thermistor cables that measure ground temperatures. Red arrow points at data acquisition system wires buried below the asphalt and yielding parabolic reflectors (Stephani et al. 2014).

Figure A6.

Damage to northern infrastructure associated with permafrost degradation and climate change:
a) settlement and cracking of the Iqaluit runway (photograph by Guy Doré);
b) Collapse of Permafrost and Failure of Bridges in the Community of Pangnirtung, Nunavut. (photograph reproduced from Hsieh, E., A. Tchekhovski, and R. Mongeau. 2011.)

Figure A7.



Average (n = 32) density, thermal conductivity, and SWE of the embankment undisturbed and plowed-snow covers (snow thickness average on embankment: 44 cm).

	Density (g/cm^3)	Thermal conductivity ($W/(m \cdot K)$)	SWE (cm)
Undisturbed snowpack	0.25	0.09	10.7
Plowed-snow cover	0.47	0.38	19.7

Undisturbed snowpack and plowed snow along the Alaska Highway that affects the snow density and thermal conductivity, and thus the insulation effect. A) Shows old plowed snow cover and B) shows recently plowed snow (Stephani et al. 2014).

Figure A8.

Trench with buried telecommunication lines along the Dalton Highway (Alaska); the white and yellow arrows indicate, respectively, the trench prior and after backfilling operations that were initiated following severe permafrost degradation (photograph by Eva Stephani).

Table A1:

Infrastructure Name	Thaw settlements	Cracking & embankment spreading	Sudden collapse , sinkhole	Thermokarst lake near infrastructure	Creep	Drainage system failure/ Thermal erosion	Mass movement	Thawing around bridges	Cut slopes instability	Icing	References
Alaska Highway, YT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	De Grandpré et al. (2012); Oldenborger et al. 2015; Camels et al. (2016); Malenfant-Lepage (2016); Stockton, Burn and Humphries (2021);
Akulivik Runway, QC	✓					✓					L'Hérault et al. (2012)
Campbell Highway, YT		✓									Thiam et al. (2018)
Dempster Highway, YT/NWT	✓	✓	✓	✓		✓	✓			✓	Lingnau (1985); Burn et al. (2015); Camels et al. (2018); Stockton, Burn and Humphries (2021)
Hudson Bay Railroad, MB	✓		✓			✓					Hayley et al. (1983); Oommen et al. (2017)
Highway 3, NWT	✓	✓				✓					Arenson and Seto (2011); Stirling et al. (2015); Wolfe et al. (2015);
Iqaluit Airport, NU	✓	✓	✓			✓					LeBlanc et al.(2013); Mathon-Dufour et al.(2015); Brooks et al.(2017)
Inukjuak Runway, QC	✓	✓				✓					L'Hérault et al. (2012)
Inuvik Runway, NWT			✓			✓					Tetra Tech EBA Inc. (2014a), (2014b)
Inuvik-Tuktoyatuk Highway, NWT		✓				✓				✓	Kaluzny et al. (2018); De Guzman, E.M., et al. (2020); Stockton, Burn and Humphries (2021)
Kangirsuk Runway, QC	✓	✓				✓					L'Hérault et al. (2012); Beaulac and Doré (2006);
Provincial Road 391, MB	✓										Batenipour et al. (2014); Flynn et al. (2016); Kurz et al. (2018)
Puvirnituq Runway, QC	✓	✓			✓	✓					L'Hérault et al. (2012); Gravel-Gaumond (2014)
Quaqtaq Runway, QC	✓					✓					L'Hérault et al. (2012)
Salluit Runway, QC	✓					✓					L'Hérault et al. (2012)
Salluit Airport Access Rd, QC	✓	✓				✓	✓				Boucher, Grondin, and Paquet-Bouchard (2012); L'Hérault et al. (2014); Lamontagne et al. (2015)
Shefferville mining development, QC						✓					Lewis (1977); Nicholson (1979)
Tasiujaq Runway, QC	✓					✓					Ficheur (2011); L'Hérault et al. (2012); Lanouette et al. (2015)
Umiujaq Airport Access Road, QC	✓						✓				L'Hérault et al. (2012)

Permafrost Geohazards and Impacts Documented in the Literature Along Transport Corridors Built on Permafrost in Canada (modified from Brooks (2019))

APPENDIX B: GLOSSARY

Below are the descriptions of some of the technical terms appearing in this overview paper. Many definitions are taken from the *Multi-language Glossary of Permafrost and Related Ground-ice Terms* (Van Everdingen 1998 (revised 2005)); the readers are encouraged to consult this glossary and the online Cryosphere Glossary from the National Snow and Ice Data Center (https://nsidc.org/cryosphere/glossary/) for additional technical definitions.

Term	Description
Active layer Intermediate layer Transient layer	Permafrost is a layered system with the uppermost layer that thaws and freezes seasonally (i.e., active layer). The active layer is underlain by a zone that goes through freeze-thaw cycles at lower frequency and plays a critical role in the thermal stability of permafrost; this transition zone consists of the transient layer underlain by the intermediate layer (Shur, Hinkel and Nelson 2005). The intermediate layer is typically dominated by the ice-rich suspended (ataxitic) cryostructure (type of ice), while the upper transient layer that thaws more frequently is less ice-rich; both of these layers contribute to the thermal protection of underlying ice-rich permafrost, especially when it contains ice wedges (Shur 1988; Shur, Hinkel and Nelson 2005; Kanevskiy et al. 2017).
Active layer detachment slide (ALDS)	Refers to slope failures occurring in the active layer. They are flow-dominated landslides that develop in the discontinuous and continuous permafrost zones (McRoberts and Morgenstern 1973; Lewkowicz and Harris 2005; Lipovsky et al. 2006; Lipovsky and Huscroft 2007; Rudy et al. 2016). ALDS occur when pore-water pressure at the base of the active layer is high and exceeds soil shear strength. These conditions can develop after wildfires (Lipovsky 2006; Jones et al. 2015) or in response to warm summer events (Lewkowicz 1990; Harris and Lewkowicz 2000; Lewkowicz and Harris 2005).
Air convection embankment (ACE)	ACE is a mitigation technique to limit permafrost degradation along infrastructure. It consists of an embankment built with poorly graded aggregates with large openings in between or pores that increase air permeability (Goering 1998). When pores between the rocks are large enough and interconnected, temperature differences between the surface and the base of the embankment during cold winter periods create convective cells. Air cooled in the upper part of the convective material sinks down into the embankment because of its higher density, displacing warm air upwards and out of the embankment. ACE increases heat loss, thus providing a cooling effect.
Air duct	Air duct is a mitigation technique to limit permafrost degradation along infrastructure. Varying designs may exist, but the main principle is that air flows by convection through an inlet, is heated by the surrounding ground and exits by an outlet.
Aufeis	Refers to the ice landform that results from the icing process (see icing). Naled is a synonym of aufeis.
Bimodal flow	See retrogressive thaw slump.
Continuous permafrost	The major subdivision of a permafrost region in which permafrost occurs everywhere beneath the exposed land surface with the exception of widely scattered sites (Van Everdingen 1998).
Creep	The slow deformation (or time-dependent shear strain) that results from long-term application of a stress too small to produce failure in the frozen material (Van Everdingen 1998).
Discontinuous permafrost	Permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost (Van Everdingen 1998).
Frost heave	The upward or outward movement of the ground surface (or objects on or in the ground) caused by the formation of ice in the soil (Van Everdingen 1998).
Frozen debris lobe (FDL)	FDL are slow-moving landslides in permafrost that are formed of soil, rock, organic material and ice that move downward on a permafrost-affected slope (Darrow et al. 2016).
Ice wedge	An ice wedge is a type of massive ice that is roughly shaped as a triangle pointing downwards, may be up to several metres wide and deep and typically joins other ice wedges to form a polygonal network that may be visible from the ground surface. Ice wedges are widespread in poorly drained tundra lowlands in the continuous permafrost (French 2007), either with or without surficial expression, whereas in discontinuous permafrost, ice wedge remnants have been identified buried underneath a thawed and refrozen layer and lacked surface expression (Stephani et al. 2014).
Icing	General process by which aufeis is formed when water emerges from the subsurface and freezes. It involves the freezing of successive water flows that may seep from the ground or emerge through cracks from underneath the ice cover of a lake or river (Van Everdingen 1998).
Massive ice	A comprehensive term used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice and large ice lenses (Van Everdingen 1998).
Naled	See aufeis.

Term	Description
Permafrost	Permafrost is defined as the “ground (soil or rock, including ice and organic material) that remains at or below 0°C for at least two consecutive years” (Van Everdingen 1998).
Retrogressive thaw slump (RTS)	RTS is a geomorphic feature formed by the process of thaw slumping when ice-rich soil thaws and flows downslope. Its morphology typically includes a steep upper headwall in a semi-circular shape above a gently sloping floor composed of thawed sediments and meltwater (Van Everdingen 1998 (revised 2005); French 2007).
Rock glacier	A mass of rock fragments and finer material, on a slope, that contains either an ice core or interstitial ice and shows evidence of movement (Van Everdingen 1998).
Skin flow	See solifluction.
Solifluction	Solifluction is a shallow downslope movement of unfrozen soils that occurs in permafrost areas but is not restricted to these regions. Typically, the ground movements occur in the near-surface soils that thaw and freeze seasonally (i.e., active layer) at depths ranging between 0.5m and 2.0m (Williams and Smith 1989). Solifluction generally forms distinctive lobes on the slopes that tend to be larger and composed of coarser soil particles in the lower slope areas (French 2007).
Thaw consolidation	Time-dependent compression resulting from thawing of frozen ground and subsequent draining of excess water (Van Everdingen 1998). When soils are rapidly thawing but slowly draining, excess pore pressure develops and can lead to slope instabilities at much lower angles than estimated by the traditional limit equilibrium analysis concept used in southern regions (Morgenstern and Nixon 1971; Morgenstern and Smith 1973; Nixon and Morgenstern 1973; McRoberts and Morgenstern 1974; Nixon and Morgenstern 1974).
Thermal erosion	Thermal erosion combines the mechanical (hydraulic transport) and thermal (melting ground ice) actions of water to erode ice-rich permafrost (Van Everdingen 1998).
Thermokarst	Landform that results from ice-rich permafrost thawing. Descriptions and additional information on thermokarsts can be found in Kokelj and Jorgenson (2013), Jorgenson (2013) and Shur and Osterkamp (2007).

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About the Authors

Eva Stephani, PhD, Eng. is a permafrost researcher based at the U.S. Geological Survey in Alaska (USA). Driven by a passion for permafrost science and its applications, she trained both as an engineer and geoscientist. Dr. Stephani has been working in permafrost research and engineering consultation with interdisciplinary teams throughout northern Alaska, Canada, Russia, and Tibet for over 17 years. Her research work focuses on a comprehensive understanding of permafrost dynamics and interactions with infrastructure.

Julie Malenfant-Lepage, Eng. is a PhD candidate at the Department of Civil and Water Engineering at Université Laval, in Quebec City, Canada. She started to be involved in Arctic engineering research in 2009 during her bachelor studies. She is currently living in Trondheim, Norway and collaborating with the Norwegian University of Sciences and Technology for her PhD project. Julie is also an executive member of the Norwegian-Canadian research partnership program FROZEN CANOES that recently created a course package for engineers and geoscientists working in cold environments.

Guy Doré, PhD, Eng. earned his doctoral degree (Ph.D.) in civil engineering at Université Laval. He recently retired from a professor position in pavement engineering at the civil engineering department of Université Laval. Dr. Doré has taught several pavement engineering and permafrost engineering courses, and he is still very active in research on pavement response and performance in cold climates as well as on permafrost engineering. Amongst other publications, Dr. Doré co-authored the books “Cold regions pavement engineering” published by ASCE press and McGraw Hill, and “Guidelines for development and management of transportation infrastructure in permafrost regions” published by the transportation association of Canada. He held the NSERC industrial research chair on the interaction between trucks, climate and pavements and he managed the “ARQULUK” research program on permafrost engineering applied to transportation infrastructure.

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