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

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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.