PermaRail: A transdisciplinary approach to increase railway resilience to degrading permafrost terrain under a warming climate

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ABSTRACT

Across the Canadian permafrost zones, access to stable linear infrastructure networks is critical for the well-being of Northern Communities and the Canadian economy. The Hudson Bay Railway (HBR), the first major transportation infrastructure built over permafrost in Canada, is now facing significant climate-driven stability and drainage issues that have been exacerbated by climate change. These issues increase maintenance costs and threaten user safety. The focus of this transdisciplinary project is to identify and characterize permafrost-related hazards along the railway corridor and investigate potential mitigation measures for improving rail stability and minimizing risk. A multi-year comprehensive field program is currently underway to map, characterize, assess, and monitor ground and rail conditions, including permafrost, ice, soil, and surface water conditions. This field program, supplemented with experimental and numerical analyses at targeted pilot sites, will provide the basis to identify high-risk locations and support a quantitative assessment of mitigation and adaptation options under different climate scenarios. By developing a risk-based framework to assess degrading permafrost-related hazards, as well as design and mitigation best practices for railways, the long-term goal of this project is to improve the resilience, sustainability, performance, and safety of the Hudson Bay Railway. This project aims to address the unique transportation needs and priorities of specific communities in Northern Manitoba and contribute to Canadian expertise and leadership in the management of current and future linear infrastructure in permafrost regions around the world.

1 INTRODUCTION

Climate change affects our physical environment, ecology, health, socio-cultural fabric, and infrastructure performance. The effects of climate change are felt acutely in Canada's North, which is warming two to four times faster than the global average due to polar amplification (Rantanen et al. 2022). Permafrost underlies over a third of Canada's landmass, but climate change is causing permafrost to warm and thaw. As permafrost thaws, positive feedbacks can further accelerate its degradation (Schuur et al. 2022). For life in Canada's North, permafrost thaw is a significant issue that results in large scale ground disturbances, such as subsidence and landslides, damage to infrastructure, changes in surface and groundwater flow, and ecological transformations.

There are many unique engineering challenges in permafrost regions, as the ground thermal regime is often changed by infrastructures, which can affect stability and safety of the built environment. Furthermore, crucial transportation infrastructures such as the Hudson Bay Railway (HBR) were designed for stable, equilibrium permafrost conditions and are now facing significant climate-driven stability and drainage issues, requiring significant funds to maintain. These include challenges such as surface subsidence and settlement, flooding and washouts, and infrastructure damage. The PermaRail research program was developed to better understand the vulnerability of the HBR to climate change and extreme weather events and to establish reliable engineered solutions to increase resilience.

1.1 The Hudson Bay Railway

Much of Canada's early development was shaped by the Hudson Bay region, where exploration voyages sought the Northwest Passage and the establishment of a fur trade post at York Factory. In the early 1800s, it became evident that a railway linking Winnipeg to Hudson Bay to export grain and beef to foreign markets was needed. Surveys for the HBR began in 1908, with clearing of the right-of-way starting in 1912. Although the track would have to cross extensive regions of muskeg, the port of Churchill was selected as the railway terminus. The HBR officially opened on September 10, 1929.

The HBR is a 1,012 km (632 mi) railway located in northern Manitoba that connects with southern Canadian National Railway (CNR) routes in The Pas. The HBR traverses in a north easterly direction to Gillam (kilometer post (KP) 524.8), and then northward to the port of Churchill (KP 820.4). Between Gillam and Churchill, there is a gradual

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northward transition from a discontinuous to continuous permafrost distribution (Figure 1).

In 2018, the Arctic Gateway Group, which is entirely owned by Indigenous groups and Northern communities through OneNorth, took ownership of the HBR and port facilities of Churchill. The HBR provides trackage rights to VIA Rail Canada for passenger services to remote and isolated communities, and is a critical transportation corridor in Northern Manitoba, supporting both economic and social activities in the region.

1.2 50 years of Permafrost-Related Hazards and Mitigation Along the Hudson Bay Railway

The previous railway owners, CNR (1929–1997) and Omintrax (1997–2018), experienced operational constraints and increased maintenance costs due to permafrost thaw. During and after the construction of the rail, several locations experienced severe subsidence, commonly referred to as sinkholes, due to surface disturbance associated with construction and water ponding along the right of way (EBA Engineering Consultants Ltd. 1979). Thaw subsidence caused short sections of track to experience as much as 100 mm to 150 mm of settlement during a single summer season which required significant amounts of additional granular fill to restore the roadbed to a usable condition.

Under CNR ownership, thaw subsidence was characterized in a study of 696 active sinkholes (EBA Engineering Consultants Ltd. 1991). Comparison of sinkhole distribution over the four-year period from 1986 to 1990 demonstrated fundamental changes: the total number of sinkholes has increased, and the frequency distribution shifted northward as previously stable peat plateaus, which underly a significant portion of the rail bed, began to thaw (Figure 2).

Between 1977 and 1991, EBA Engineering undertook several studies to characterize the subgrade soils and geothermal regime to better understand sinkhole formation and assess long-term stabilization measures to mitigate permafrost degradation along the rail. Borehole logs from those studies confirmed the presence of ice-rich (30% to 70% by volume), warm permafrost (-0.4 °C to 0 °C) in the degrading areas. Mitigation techniques were designed and tested at five locations along the Herchmer Subdivision between Gillam and Weir River (KP 600.9) from 1976 to 1979 (Figure 3). Among the tested techniques, heat pipes (Cryo-Anchor Model 800) appeared to be the most efficient in stabilizing permafrost. However, the long-term stabilization measures outlined in the EBA studies were not fully implemented, and the HBR continues to experience deterioration and increased maintenance needs due to permafrost degradation.

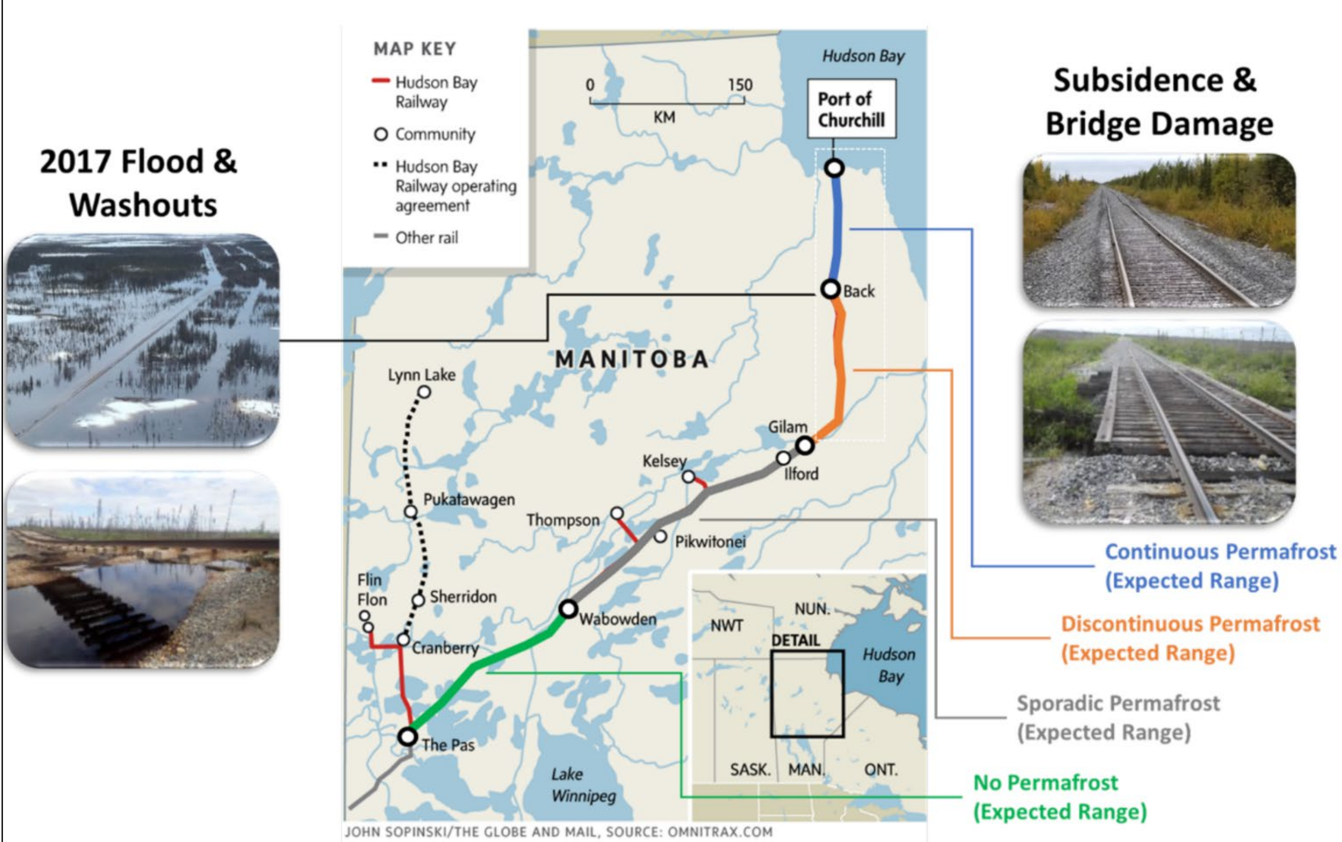

Figure 1. Map of the Hudson Bay Railway, highlighting the expected permafrost zones and observed permafrost hazards along the rail.

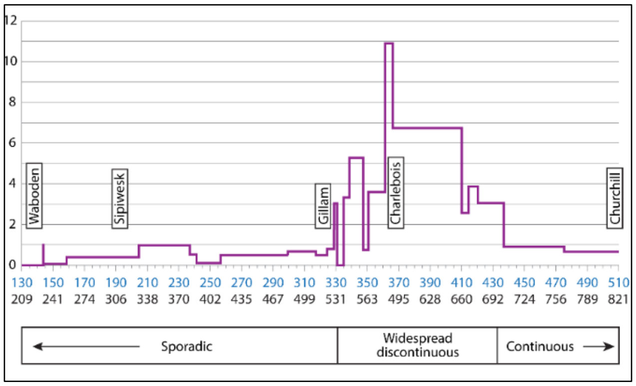

Figure 2. Frequency of sinkholes along the HBR (modified from EBA Engineering Consultants Ltd. 1991).

Flooding has also caused widespread damage to the HBR. In May 2017, along the Herchmer Subdivision between Gillam (KP 524.8) and Churchill (KP 820.4), a 200-year flooding event resulted in 31 locations with washouts and damage to culverts and bridges. The railway was temporarily shut down between May 2017 and November 2018, which severely affected Churchill and all of the communities dependent on the HBR. This event precipitated the sale of the assets from Omnitrax to Arctic Gateway Group on September 1, 2018. The Arctic Gateway Group immediately began repairs and repaired heavy washout locations using Geocell Technology. The flooding along the HBR emphasized the need to improve mitigation measures for risks related to permafrost hydrology along this linear infrastructure.

As the climate continues to warm, hazards related to permafrost thaw and extreme weather events are expected to increase. Using the high emissions scenario (RCP 8.5), the Climate Atlas of Canada projects an annual mean temperature of -1.4 and 2620 Freezing Degree Days (FDD) for Gillam by 2050. Relative to the period 1976–2005, the projections represent an increase of 2.4 °C and a decrease of 527.3 FDD. Continued warming in this area is expected to result in permafrost thaw and subsidence, degradation of peat plateaus, and thermokarst processes (Dyke and Sladen 2010). The impacts of fire, such as the burn between Cromarty and Belcher (Figure 4), will likely accelerate permafrost degradation. Understanding the influence of climate change on geotechnical and hydrological hazards along the HBR is a focus of the PermaRail research program.

Figure 3. Mitigation techniques designed and tested along the Herchmer Subdivision between Gillam and Weir River from 1976 to 1991. Top images: 800 Cryo-Anchor heat pipes and 6H:1V gentle slope with wood chips insulation. Bottom image: Thermo-probes.

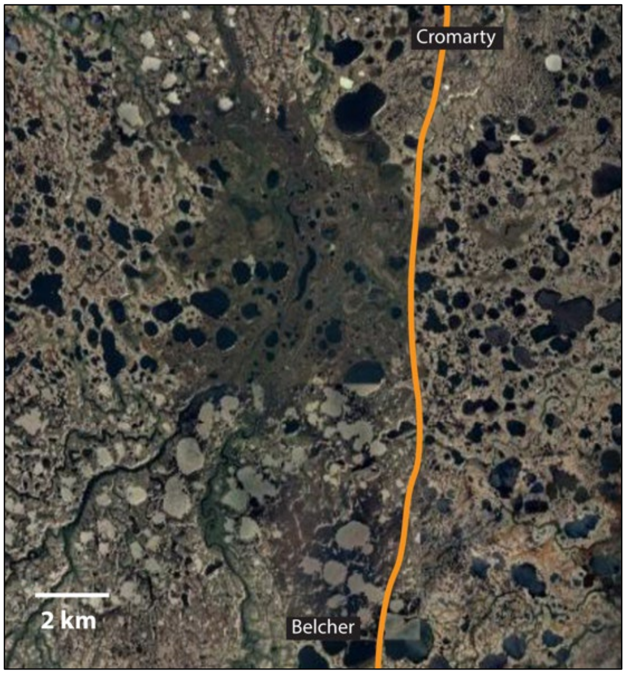

Figure 4. Fires, such as the one shown here between Cromarty and Belcher, are expected to accelerate permafrost degradation along the HBR.

1.3 The PermaRail Research Program

The PermaRail research initiative, funded by the National Trade Corridors Fund (NTCF), is a collaborative seven-year research program (2022–2028) involving the Arctic Gateway Group, who own the HBR, as well as the University of Calgary, Carleton University, Royal Military College of Canada, Queen's University, and Université Laval. Understanding vulnerability of railways, and other linear infrastructure located on permafrost, requires a transdisciplinary approach. Therefore, the team includes HBR operators, civil and geotechnical engineers, geophysicists, geotechnicians, and permafrost geomorphologists.

The PermaRail project aims to address the following key issues surrounding this unique and important northern transportation asset: 1) lack of permafrost data and characterization, 2) water management, 3) surface stabilization, and 4) infrastructure management. In addressing these four specific challenges, the overall goal of the PermaRail project is to identify, characterize, and mitigate permafrost-related and hydrological hazards along the HBR.

We plan to improve understanding of geophysical and geotechnical conditions along HBR, assess the effects of climate change on geohazards along the rail, improve understanding of the influence of permafrost thaw on hydrology, and identify strategies to bolster the resilience of HBR infrastructure. Initial research activities include permafrost characterization and an assessment of infrastructure and geohazards along the rail. Next, monitoring will provide real-time data at instrumented locations. Finally, mitigation techniques and materials will be tested to assess adaptation options, enhance rail performance and resilience, and inform engineering best practices for future infrastructure development.

The findings are intended to guide creation and testing of innovative strategies for monitoring, mitigating, and remediating permafrost-related hazards, ultimately ensuring the safety, reliability, and resilience of the railway. Based on insights from the HBR study, we plan to formulate recommendations and guidelines for future rail and linear infrastructure development in permafrost regions to increase Canadian expertise and leadership in the management of permafrost railways globally.

2 METHODOLOGY

The project combines field investigations, in-situ monitoring, laboratory experiments, physical and numerical modelling, and field tests to comprehensively study permafrost-related hazards and mitigative strategies. An overview of the methodologies and related timeline for the PermaRail project are outlined in Figure 5.

The comprehensive field investigation program will involve utilizing geophysical, geotechnical, and remote sensing techniques to characterize the ground and rail conditions, including permafrost, ice, soil and surface water conditions, properties, and behaviours. Experimental and numerical analyses will supplement the field program and provide the basis to explore future climate scenarios, identify high risk locations, and evaluate the impact of mitigation and adaptation techniques. Selected mitigation techniques will be installed and tested in the field for full-scale evaluation of performance.

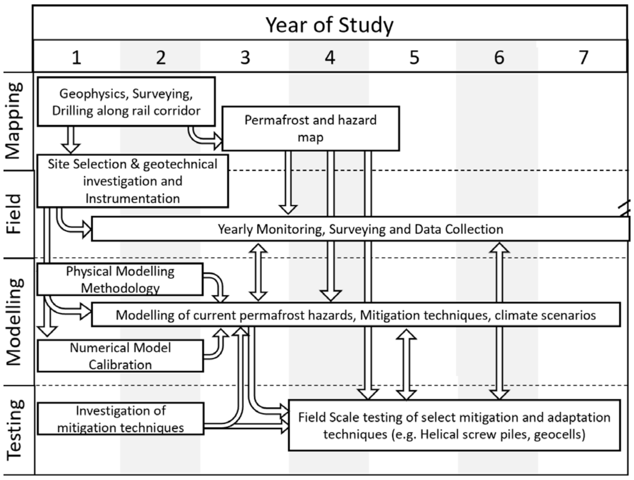

Figure 5. Flow chart of PermaRail methodologies and their timeline.

2.1 Mapping Permafrost Conditions

The first stage of PermaRail activities, which is the assessment of permafrost conditions along the rail, entails the development of a regional map of permafrost distribution and characteristics with an inventory of potential permafrost-related hazards and where they are most likely encountered. The corridor will be divided into terrain units based on a set of biophysical factors including latitude, surficial geology, geomorphic features, hydrology, surface conditions, vegetation, topography, and climate.

Extensive field campaigns are being carried out to characterize each terrain unit. Drilling and core extractions using portable drills (Calmels and Allard 2005) are informing assessments of permafrost, including extent, temperature, thickness, and vertical ice distribution (Figure 6). Geophysical methods include ground penetrating radar (GPR) and electrical resistivity tomography (ERT), which are well-suited to permafrost and hydrology applications (e.g., Hinkel et al. 2001; Kneisel et al. 2008; Walvoord and Kurylyk 2016). GPR will provide high-resolution stratigraphic information in the near-surface to map boundaries between frozen and unfrozen ground (i.e., permafrost table, taliks, etc.) near or beneath the railway. ERT surveys will provide insights into the distribution and characteristics of frozen and unfrozen ground. High-resolution drone mapping was also carried out along specific sections of the rail to characterize surface conditions and to produce high resolution digital elevation models at a representative subset of sites.

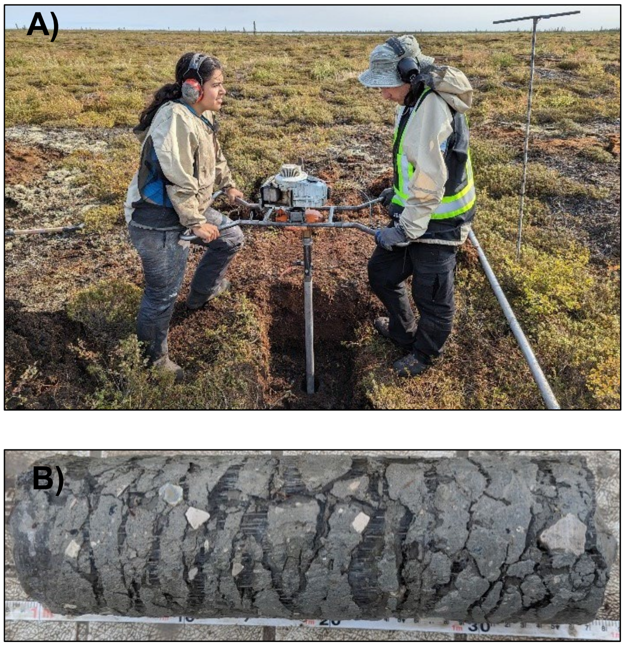

Figure 6. A) Drilling and core extractions using a portable drill at Lamprey (KP 769). B) From this site, ice-rich permafrost cores were recovered between 1.0 and 1.37 m.

This work is enabling the development of high-resolution maps of permafrost ice content, which is a key parameter that influences whether thawing ground is vulnerable to subsidence and erosion. Permafrost distribution and ground ice maps along the rail corridor will be cross-validated using existing and new borehole data, field observations, and existing maps. These enhanced maps will be a valuable tool for identifying permafrost hazards, predicting thaw settlement, and reliability mapping along the railway under changing climatic conditions.

Ground temperature monitoring stations are being initiated in strategic locations. For instance, previously instrumented sites from older studies (EBA, 1977, 1979, 1988) are being gradually re-equipped for temperature monitoring, and new instrumentation added in strategic locations (Figure 7). To monitor the temperature at the surface and at the top of the permafrost (≈ 1 m depth), 16 two-channel external data logger (interchangeability tolerance of ±0.21 °C from 0 °C to 50 °C, and 0.02 °C resolution at 25 °C) were installed for different environmental setting and surface conditions. The dataloggers were placed in a sealed 2-inch ABS casing connected to a 0.5-inch diameter, and one-meter-long PVC casing.

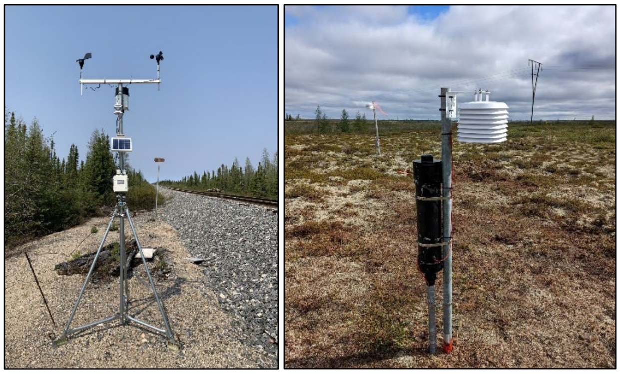

Figure 7. Weather station installed near Herchmer subdivision (left) and air and ground temperature instrumentation installed at Chesnaye subdivision (right) during summer 2022.

The selected monitoring sites reflect distinctive terrain units where a more detailed understanding is needed. Surface, ground, and air temperatures measured at those sites will be used to adjust and validate the regional scale temperature at the top of the permafrost map currently under production. Those data will also support physical model calibration.

The resulting maps and geodatabase will be the first project deliverables and will be used to identify priority areas for further instrumentation, modelling, and study in collaboration with Arctic Gateway Group. Throughout the research program, maps and associated databases will be updated as new findings improve our understanding of permafrost conditions and related hazards.

2.2 Assessing Geohazards

In parallel with the field investigation and monitoring, comprehensive physical modelling and numerical modelling studies of key geohazards identified are being performed. Some of the major geohazards include thaw subsidence, thermo-erosion, frost heave, culvert icing and flooding.

Physical models will provide conceptual understanding of the field data with highly instrumented benchtop, full-scale experiments in a cold room, and with a geotechnical centrifuge. This will allow the control of boundary conditions and materials in a 1:1 model while accelerating time for environmentally driven processes with the geotechnical centrifuge.

Numerical and physical modelling of field site geohazards will help to bridge the gaps between discrete measurement points in the field. For each key geohazard, calibrated numerical models will use climate model outputs (i.e., CMIP6 climate scenarios) to predict the impact of the future climate on hazard frequency and magnitude.

2.3 Testing Mitigation Techniques

The earlier phases of the project will characterize permafrost distribution, material properties, the seasonal variability of selected sites along the rail (i.e., multi-year monitoring of track geometry changes and thermal and groundwater changes in the subgrade under the track structure, etc.), and track performance. In the final phase of the project, we will choose new field monitoring sites exhibiting poor track behaviour as well as sites already mitigated and equipped by EBA in the 1970s to quantitatively assess the success of different mitigation options. Candidate mitigation strategies will be examined first using physical and numerical modelling techniques to identify strategies with the highest possibility of success. Subsequently, a select number of full-scale field tests will be conducted, whereby mitigation techniques are tested in real-time on the rail. Potential mitigation techniques may include, but are not limited to, gentle slope, thermosyphon, culvert management, geogrid cells, and helical screwpiles. However, the final selection of mitigation techniques will be based on the findings and information gained from the mapping, field investigation, and modelling activities.

3 Preliminary Results

The project officially began in June 2022. During this first year, the primary focus has been on characterizing and mapping permafrost conditions along the rail in the Barrens region (≈ KP 690 to KP 790). A field characterization program, including drone mapping, geophysical surveying, and drilling, was carried out in August–September 2023 at five different sites: Umiskwuska Lake (KP 717), Belcher (KP 728), Burn (KP 737), Chesnaye (KP 751), Lamprey (KP 769).

To characterize surface conditions at each site and to produce high resolution digital elevation models (DEM), drone mapping images were obtained. An example of a high-resolution image obtained by the drone is depicted in Figure 8. The drone's aerial perspective illustrates the extensive network of ice-wedge polygons that characterize the Barrens region. Drone imagery and DEMs will be used to pinpoint sections where the railway intersects ice wedges.

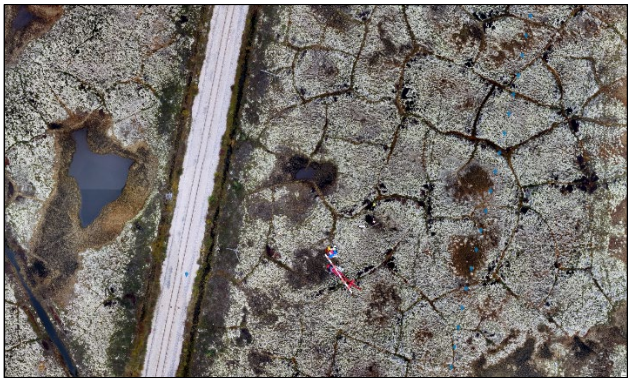

Figure 8. Drone image illustrating the extensive network of ice-wedge polygons that characterize the Barrens region and that intersect the railway embankment (Belcher site).

ERT data were collected at 5 sites along the northern portion of the rail in summer 2023. In these ERT surveys, surface conditions were shown to play a critical role in permafrost conditions; surface water, vegetation, and the railway embankment all influenced subsurface resistivity distributions. For example, a survey near Belcher indicated that active layer thickness increases significantly near the embankment (Figure 9), likely due to a more pronounced snow insulation effect and surface water ponding. Thaw depths were measured in the natural terrain by frost probing along ERT profiles and were observed to be an average of 52 cm deep away from the embankment where detectable with an 80 cm probe.

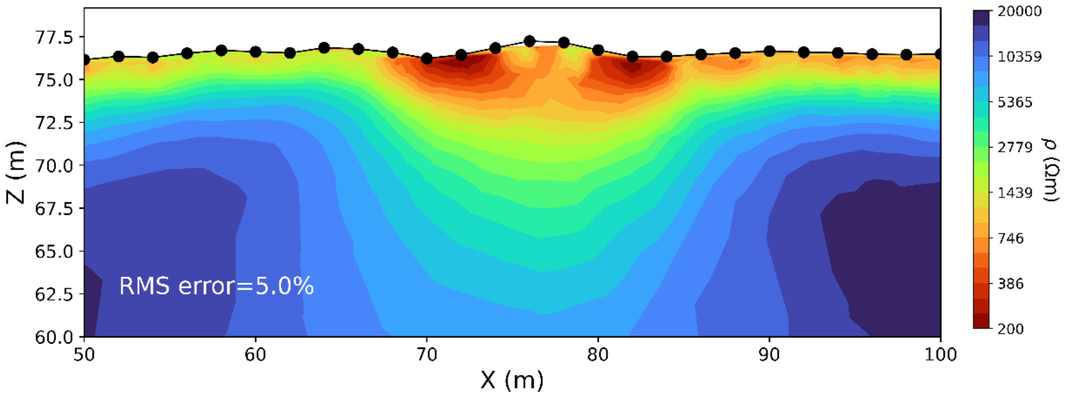

Figure 9. Electrical Resistivity Tomography (ERT) profile across the railway embankment (Belcher site).

A selection of newly drilled boreholes was instrumented during summer 2022 and 2023 to monitor ground temperatures along the rail. To date, four boreholes were instrumented with 15-thermistor strings and dataloggers. At each thermistor string location, one thermistor was placed inside a radiation shield placed 1.5 m above the ground level to monitor air temperature. Ground and air temperatures are recorded every hour and are stored in the datalogger internal flash memory. Figure 10 shows the minimum, mean, and maximum ground temperature profiles measured in the natural terrain beside the railway at Chesnaye and Belcher stations between 2022 and 2023.

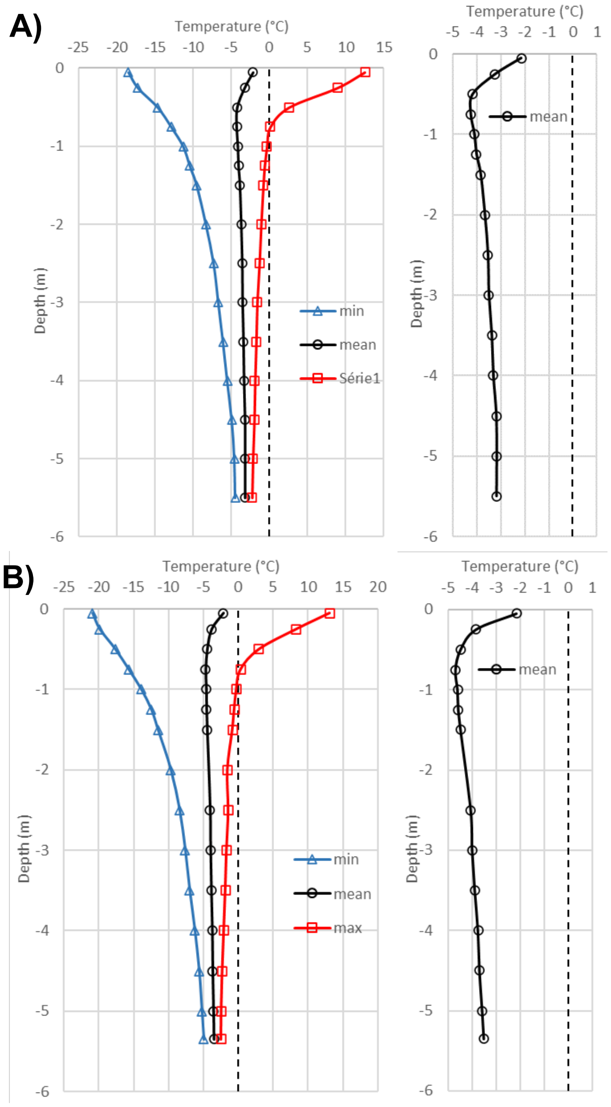

Figure 10. Minimum, mean, and maximum ground temperature profiles measured in polygon centers from 2022-09-01 to 2023-08-31 near A) Chesnaye and B) Belcher stations, Manitoba. Graphs on the right display the mean temperature profile to emphasize the thermal offset.

According to the monitoring results at Chesnaye site during the period 2022–2023, the calculated mean annual ground surface temperatures (0.05 m depth) and at the top of the permafrost (0.75 m depth) were respectively −2.14 °C and -4.25 °C (Figure 10A). These findings indicate a notable thermal offset exceeding 2 °C, primarily attributed to the substantial peat thickness (> 2 m) acting as an effective insulating layer in summer and a thermally conductive layer in winter. At 5 m depth, the mean annual ground temperature calculated was -3.17 °C. At the Belcher site, ground temperatures were slightly lower on average by about -0.4 °C. For 2022–2023, mean annual temperature at the surface and at 5 m depth were -2.14 °C and -3.57 °C respectively. As shown in Figure 10B, the thick peat cover at this site also contributes to the occurrence of a significant thermal offset.

4 UPCOMING WORK

As a result of the initial characterization and monitoring work done in summer 2023, a large-scale geophysical and geotechnical drilling program is being planned in coordination with HBR. The large-scale drilling is most likely to occur in 2024. Using a more powerful drill will enable thermistor strings to be installed throughout the embankment, as well as at greater depths to complete the ground temperature monitoring network along the rail.

Creep tests on frozen organic and mineral cores are currently being conducted under constant load at different temperature steps (-4 °C, -2 °C, and -1 °C) along with thaw strain consolidation tests. These tests will provide insight into long-term deformation behavior of frozen soil, and their potential settlement upon thawing. These geotechnical properties will also serve as input parameters for further thermomechanical simulations in order to assess long-term soil behavior under varying climate conditions.

More site-specific field work continues on the impact of drained lakes, understanding the frost jacking of bridges, and analysis of the track geometry data. These programs will continue to collect new field data in addition to analyzing data from monitoring sites. Over the next year, further numerical modelling work will improve our understanding of the thermal regime, how it has changed, and how it will continue to change in the future. Additionally, multi-hazard identification and vulnerability mapping will ramp up. These programs are supported by field data, which is essential for establishing appropriate model inputs, boundary conditions, and calibrations.

As the project team continues to gather data, we are also developing methodologies to share data and develop a useable database with associated map layers that includes both historical and predicted data. This will be ongoing throughout the project, and the structure of the overarching database and maps will be determined over the next 6–12 months. Establishing good data collection, documentation, and structure is a key project component.

5 CONCLUSIONS

This study will provide all stakeholders — the HBR communities and trades that use the rail corridor, Arctic Gateway Group, and the NTCF — with a proactive and forward-looking assessment of the current and future conditions of permafrost along the rail corridor. We aim to provide recommendations on effective mitigation strategies and tools for common permafrost hazards (e.g., flooding, thaw settlement, embankment stability, etc.). The results of this study will be used to develop monitoring, mitigation and remediation strategies and designs to ensure the safety, reliability, and resilience of both the HBR rail corridor and all other northern linear infrastructure networks against similar permafrost hazards.

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