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Rail Embankment Stabilization Needs on the Hudson Bay Railway

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DISCLAIMER

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TECHNICAL SUMMARY

Rail Embankment Stabilization Needs on the Hudson Bay Railway

INTRODUCTION

Since its construction in 1929, the Hudson Bay Railway (HBR) located in northern Manitoba, Canada, has been witnessing track deterioration through differential settlements. These differential settlements, termed “sinkholes”, have been linked to the degradation of the underlying permafrost, especially at areas where warm, ice-rich and discontinuous permafrost are prevalent (Figure 1). Sinkholes consist of short sections of track that experience up to five inches of settlement during a single summer thawing season (EBA, 1977). The permafrost thawing is further accelerated by the warming trend in climate. The differential settlements along the embankment necessitates placement of large volumes of ballast annually to keep the track safe and operational.

Between 1977 and 1991, EBA Engineering, was tasked to undertake extensive research to understand the geothermal regime of the subsurface, to uncover the mechanism of the sinkholes formation, and to propose long term stabilization measures. The long term stabilization measures proposed in the study were not fully put in place. Consequently, the HBR currently continues to go through its seasonal deteriorations. This follow-up study by researchers at Michigan Technological University attempted to provide updated analyses on the current conditions of rail corridor, using both historical and newly acquired data, and supplementing past approaches with modern technologies.

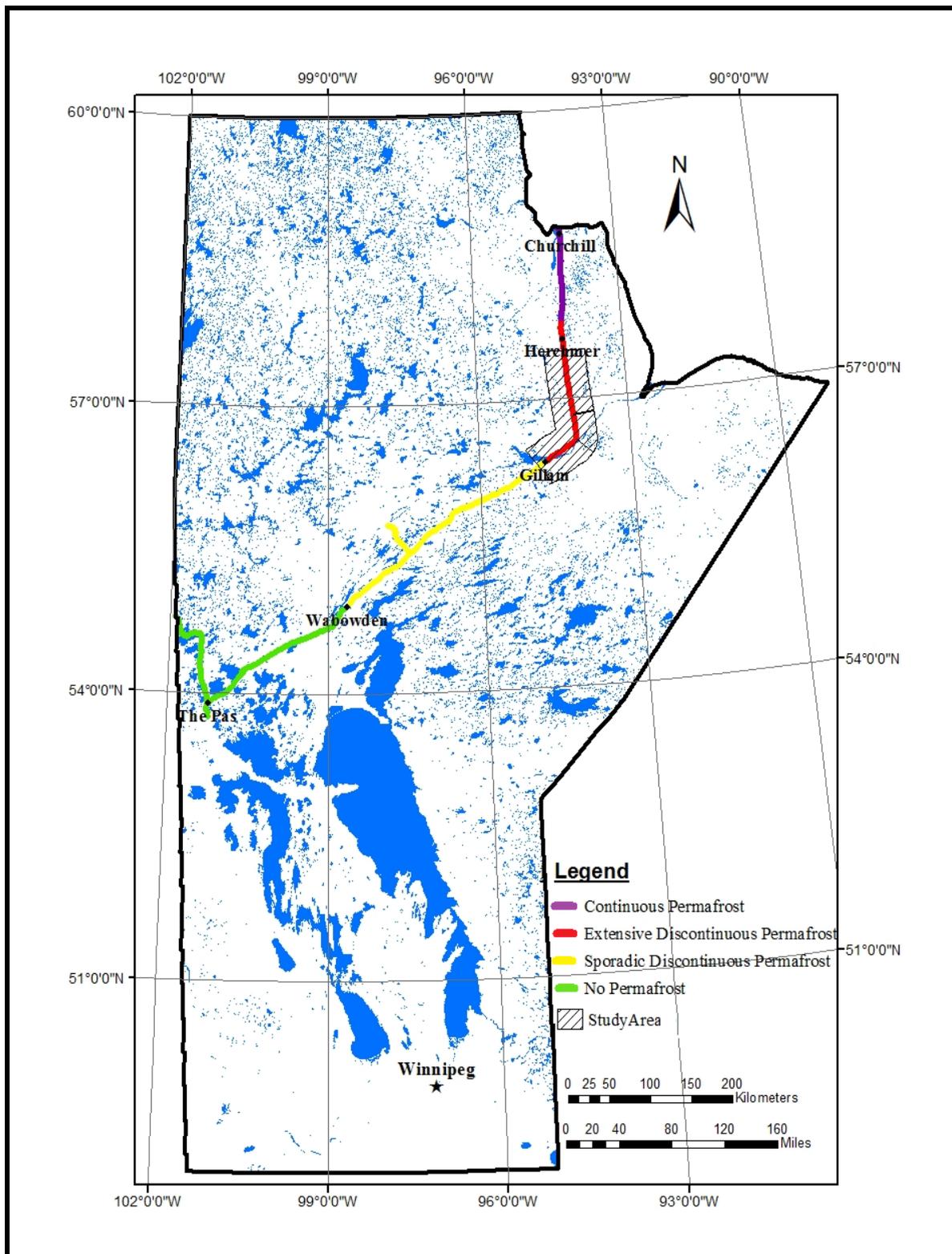


Figure 1. Location of the HBR from The Pas to Churchill showing the varying permafrost conditions in the different colors.

Michigan Technological University was tasked by HBR in early 2014, to undertake research, concentrating on the following three objectives:

- **Objective 1** – *Define a rating system for severity of railway conditions in permafrost affected areas:* This entails remote sensing and field based studies to map the current condition of the HBR corridor (surficial and sub-surficial), compare them to historic studies performed by EBA Engineering, and develop a rating scheme for the permafrost affected regions.
- **Objective 2** – *Design a “Best Practices Guide” to diagnose, document, and perform corrective actions addressing each severity rating:* This includes documenting the best field and remote sensing strategies to diagnose embankment instability, performing detailed literature review of the best practices of mitigation techniques that can be used along the rail line in permafrost regions, and identifying potential solutions for corrective measures for each severity category.
- **Objective 3** – *Investigate a long term solution for embankment stability:* This includes researching the effectiveness and suitability of various embankment stabilization techniques and their applicability to the HBR.

APPROACH AND METHODOLOGY

Budget constraints and limited project time necessitated the selection of a subsection of the HBR for analyses. Past reports by EBA delineated the extensive discontinuous region between mileposts 330 and 430 to be the most problematic segment of the HBR (Figure 2). Recent track surfacing records, slow order distribution, and interviews with HBR personnel revealed that this section remains the most active and thus was chosen as the focus of the study. Considering the close linkage between project objectives, methodologies to meet objective 1 and the first part of the objective 2 (“...documenting the best field and remote sensing strategies to diagnose embankment instability...”) have both been described in this section under a single sub-header. Same approach has been used for the latter part of objective 2 (“...performing detailed literature review of the best practices of mitigation techniques that can be used along the rail line in permafrost regions, and identifying potential solutions for corrective measures for each severity category.”) and objective 3.

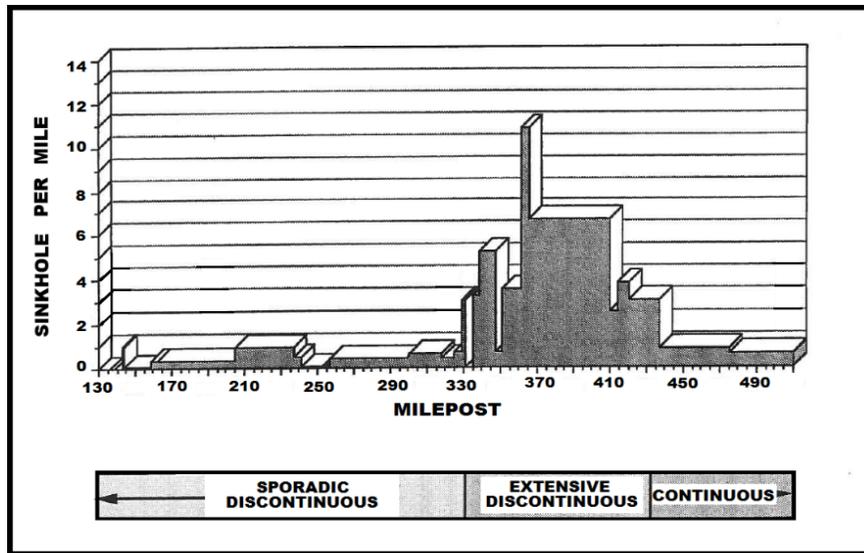


Figure 2. Sinkhole distribution along the HBR (EBA, 1990)

Objectives 1 & 2

Objective 1 and the first part of objective 2 formed the main focus of the project and the approach has been summarized in Figure 3, followed by brief explanations.

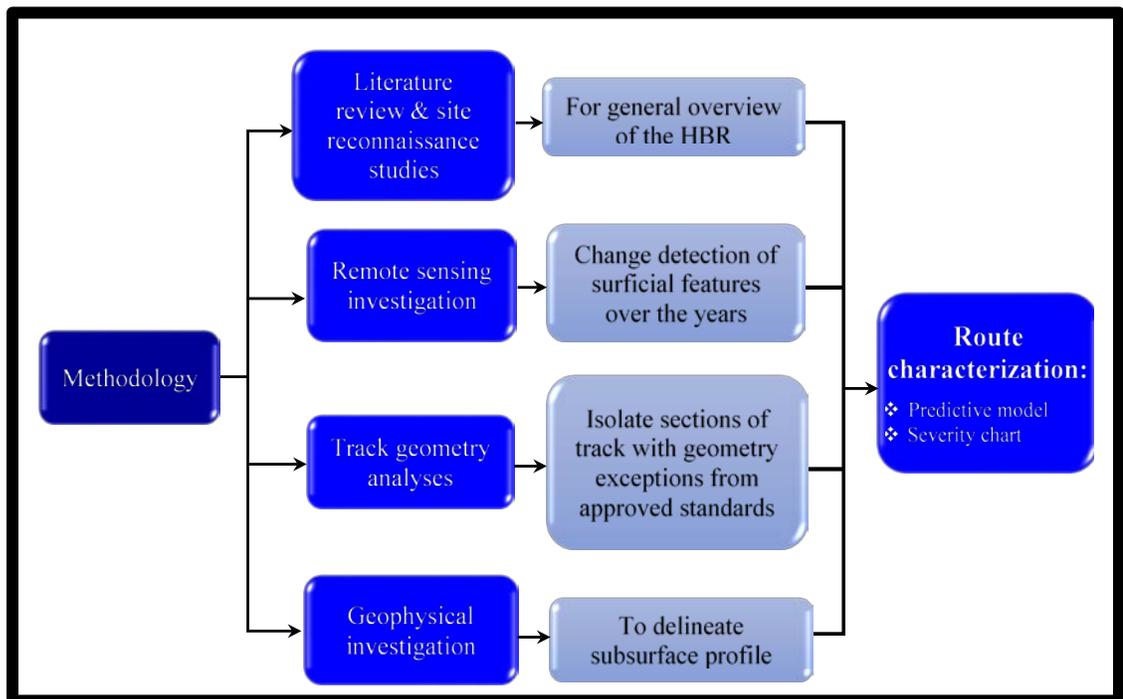


Figure 3. Flowchart of methods to achieve objectives 1 & 2

- ❖ An extensive literature review of EBA's past work was first performed to get familiar with their approaches, findings and recommendations. Summary of this review was published in the 2015 Joint Rail Conference paper (Addison et al., 2015a) (Appendix A).
- ❖ Remote sensing analyses employing NASA's Landsat sensors were done to observe changes of descriptors such as vegetation, surface water, temperature etc. throughout the years and their possible effects on the health of the underlying permafrost. Detailed research approach and findings from this study were summarized in a 2015 ASCE Cold Region Engineering conference paper (Addison et al., 2015b) (Appendix B).
- ❖ Track geometry data acquired from 2010 to 2014 along the study segment were supplied by HBR. Analyses were done to isolate locations where track geometry deviated from standards (*track exceptions*). Track exception data from the different years were analyzed to identify changes in the underlying permafrost health.
- ❖ Three different field visits were conducted in June 2014, October 2014 and September 2015 to document site condition through geospatially located image acquisition of the entire study site and to undertake geophysical explorations for delineation of the current subsurface permafrost profile.
 - The geophysical explorations were conducted in the fall season when the soil layer on top of the permafrost table (active layer) was fully thawed to evaluate the extent to which the permafrost thaws in the area and harness the sharper contrast in profile delineation offered by the frozen/ unfrozen boundary. Two methods were employed for the exploration: electrical resistivity tomography (ERT) and ground penetrating radar (GPR).
 - The ERT works on the principle that different materials offers different resistance to the flow of current. ERT test sites were mainly chosen to match locations with historical borehole and geophysical data from EBA's past work. ERT provided confirmatory data and tracked the subsurface evolution over the years. A total of 15 sites were investigated.
 - The GPR utilizes the differences in dielectric properties to differentiate between materials. The GPR survey was conducted by HyGround

Engineering, LLC with four antennas— three 400MHz antennas and one 270 MHz antenna— mounted on a hi-rail truck that collected data continuously along the entire 510-mile corridor. However, full analyses of the data was done for only 20-mile section. Results from the integration of the ERT survey and past EBA borehole data were used to prove the effectiveness of the GPR in delineating the permafrost profile, as GPR is expected to form the basis for future interpretations of the entire 510-mile route.

- ❖ Results from all four individual analyses: site reconnaissance study, remote sensing analyses, track geometry analyses, and geophysical investigation were integrated to characterize the HBR corridor. This involved development of both a predictive model for permafrost degradation and a permafrost degradation severity chart. The model attempted to predict locations likely to produce permafrost degradation (realized as track surface exceptions) as well as determine which particular predictors, or combination of them, were the best indicators of permafrost degradation. The three level severity chart, on the other hand, was developed to delineate locations representing high, moderate, and low susceptibility to permafrost degradation. These outputs are described in more detail in the MS Thesis by Priscilla Addison: *Characterizing Rail Embankment Stabilization Needs on the Hudson Bay Railway*.

Objectives 2 & 3

While the main concentration of the study was on the route characterization under objective 1 and first part of objective 2, an extensive literature review of existing and hypothesized stabilization measures ranging from passive to more rigorous active techniques was performed to meet the latter part of objective 2 and objective 3. The focus of the literature review was to identify the advantages and disadvantages of the different measures, as well as the unique conditions under which they can be employed. Findings have been summarized and documented in a 2016 Joint Rail Conference paper (Addison et al., 2016a) (Appendix C).

FINDINGS

Literature review of EBA reports provided background to the permafrost conditions of the HBR corridor. It revealed the underlying permafrost to be warm and ice-rich in the study area. In these circumstances the temperature of the underlying permafrost is close to 32°F and any disturbance that causes energy gain could potentially lead to permafrost thaw. The *ice-rich* description means that the underlying permafrost is interspersed with frozen chunks of ice, which get dissipated and create voids when thawed. When compressed, these voids consequently result in the sinkholes manifested at the ground surface. EBA reported that sinkholes were more prevalent in the discontinuous permafrost zones, especially in the *extensive discontinuous* permafrost zone under investigation, at locations where there is contact between permafrost ground (peat plateau) and non-permafrost ground (fen)— transition zones. Permafrost thaw was found to occur at these transition zones when the relatively warm fen loses its heat to the cold peat plateau. EBA’s overall investigation concluded that the railway was in need of mitigation measures; deterioration of the embankment was predicted if nothing was done. A stabilization approach using thermosyphons was recommended for the thawing sections of the discontinuous permafrost zones, as prototype testing over the course of a four-year study had proved them effective. However, this extensive stabilization measure recommended by EBA was not put in place after the study and consequently our initial geophysical exploration work revealed that some locations initially delineated by EBA as underlain by permafrost were now thawed (Addison et al., 2016b). This confirmed the predicted worsening site conditions. In addition to confirming EBA predictions, the study also resulted in other findings, as described in the sections below.

Possible Contributors to Permafrost Degradation

Temperature

A plot of average air temperatures of the study location from EBA’s investigative period (1975) to 2015 revealed an upward trend (Figure 4). This increase suggests warming weather as a likely contributor to the degradation of underlying permafrost.

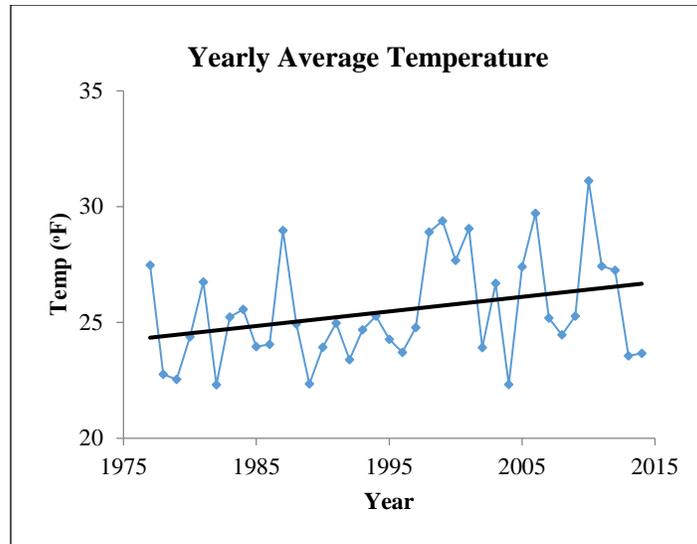


Figure 4. Average yearly temperatures from 1977 to 2014 (Gillam Airport Weather Station)

Wildfires

It is a known fact that the health of permafrost is linked to fluctuations in climate, but a review of existing permafrost related literature revealed that four other variables impact permafrost health even more than climate: depth of snow cover in the winter, thickness of the organic soil layer, soil moisture content, and presence/absence of vegetation (Smith, 1975; Smith and Riseborough, 1983; Williams and Burn, 1996).

Wildfires have been known to affect all four surface variables listed above and as such potentially accelerate permafrost degradation. Our remote sensing study revealed the occurrence of at least 19 fires along the study site since EBA's investigation, most of them resulting in moderate to high damage to the organic layer. The wildfires were seen to have a two-fold effect— first, affected areas had an average of 20°F warmer temperature that persisted for three to five years after the fires, even up to a decade in some instances. The second effect was that the fire consumed the vegetation and organic layer, leaving the existing permafrost unprotected and thus vulnerable to accelerated thawing. Locations that had occurrences of wildfires were also correlated with an increase in the frequency of track geometry exceptions, supporting the hypothesis that these fires have a detrimental effect on the underlying permafrost (Addison et al., 2015b; 2015c).

Poor Drainage Conditions

Geospatially located imagery acquired of the study area revealed that there were worsening drainage conditions, as one moves northwards in the discontinuous permafrost zone (Figure 5). Available literature has shown that poor drainage to be one of the contributing factors of permafrost degradation (Shur and Jorgenson, 2007); the ponded water conducts the sun's heat and transfers it to the underlying permafrost. This was evident at our study site, as locations with large areas of ponded water close to embankment shoulders recorded higher track geometry exceptions.



Figure 5. Drainage conditions found along the extensive discontinuous permafrost zone of HBR corridor

Current Permafrost Condition

A comparison of results from the geophysical investigation and track geometry exceptions showed that locations delineated as transition zones by the geophysical investigation recorded higher numbers of track geometry exceptions. However, locations underlain by well-defined permafrost tables, or entirely devoid of permafrost recorded low numbers of track exceptions. This suggested relationship between the underlying permafrost health and the track geometry exceptions; this relationship was therefore used as the basis for further investigations (Addison et. al., 2016b). The hypothesis was that high quantities of track exceptions represent an actively thawing permafrost section (transition zone) and low values represent stable subsurface conditions, underlain either by a well-defined permafrost table, or by fully thawed stable subgrade.

A predictive model was developed to forecast the underlying permafrost health as represented by track geometry exceptions. The model used remotely sensed descriptors of the HBR route, including vegetation, surface water, burn severity, and temperature indices. The goal of this model was to identify combinations of descriptors that could accurately predict potentially degrading transition zones. This analysis showed that a combination of the surficial indicators of vegetation and surface water were the best predictors of the underlying permafrost health, giving an accuracy of 64.7% (Addison, 2015c).

Results of the subsurface profile obtained from the ERT surveys were compared to those from historical borehole and geophysical analyses by EBA to observe changes over the years. The comparison revealed that most of the locations indicated by EBA to be underlain by permafrost in the *extensive discontinuous permafrost* zone are now devoid of it. It was also found that some locations in the *continuous permafrost* zone that were considered to be underlain by well-defined permafrost table are now underlain with thawing transition zones. These suggest that earlier permafrost zone classifications along the HBR route defined by EBA are changing. Permafrost degradation seems to be moving northwards, as previously stable permafrost tables in the discontinuous zones were seen to be thawing and the southern boundary of the continuous zone is moving further north.

The results from remote sensing, track geometry analyses and the ERT analyses were used to develop an integrated permafrost degradation severity rating scheme and a three level degradation susceptibility chart (Figure 6 and Table 1). This rating chart can be used to delineate sections in the extensive discontinuous permafrost zone, based on susceptibility to permafrost degradation and related maintenance needs. The scheme used the *Normalized Differenced Vegetation Index* (NDVI) from the remotely sensed data, together with the average number of track geometry exceptions as an indicator of permafrost health. NDVI ranges from -1 to 1, representing no vegetation to highly vegetated areas, respectively. Low NDVI was found to correlate with high amounts of ponded water (poor drainage). An earlier study on using track exceptions to infer railway track performance conducted by researchers from the University of Alberta, Canada, found that locations along a track that recorded less than one exception per year are generally considered stable and within acceptable performance levels, whereas locations that develop more than 2.5 exceptions are of concern and need to be mitigated (Roghani et al., 2015).

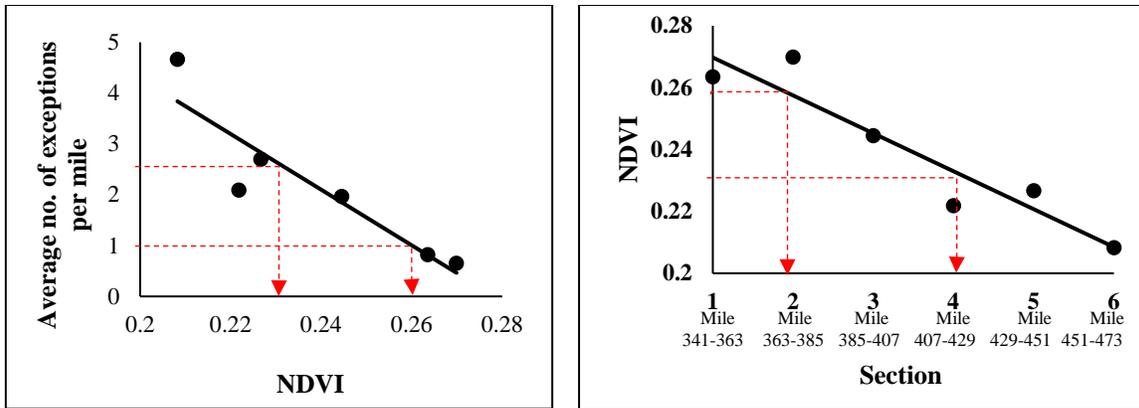


Figure 6. Defining ranges for developing severity chart

Table 1. Permafrost severity chart developed for study section along the HBR

Rating	Degradation Susceptibility	Vegetation	Exceptions	Mileposts
1	Low	NDVI > 0.26	E < 1	341-363
2	Moderate	0.23 ≤ NDVI ≤ 0.26	2.7 ≥ E ≥ 1	363-407
3	High	NDVI < 0.23	E > 2.7	407-473

A rating of 1 represents a low degradation susceptibility region, which for our study location was found to be between the southernmost mileposts 341 and 363. This region is predicted to develop at most one track exception per mile annually, is well vegetated and without ponded water (NDVI of 0.26 or higher). The region is rated as less susceptible to permafrost degradation. While not confirmed by this study, we would expect the section to be underlain by a thawed subsurface.

A rating of 2 represents a medium degradation susceptibility region, which was found to be between mileposts 363 and 407. This region is predicted to develop between 1 to 2.5 track exceptions per mile annually, with an NDVI between 0.23 and 0.26.

A rating of 3 represents the northernmost high degradation susceptibility region between mileposts 407 and 473. This region is predicted to develop at least 2.5 track exceptions per mile every year. It has minimal vegetation and water ponded close to the embankment shoulders, having an NDVI of 0.23 or lower. The region is rated as most susceptible to permafrost degradation due to the fact that it is likely underlain by an actively thawing permafrost table with many transition zones.

Summary of this has been submitted and published in *The American Institute of Mathematical Sciences* journal; it is also attached to this report as Appendix D (Addison et al., 2016b).

Permafrost Stabilization Measures

An extensive literature review of potential stabilization techniques was performed to fulfill objectives 2 and 3. Available literature showed that local site conditions including soil type, permafrost temperature, ice content, and precipitation are of high importance when selecting a method(s) for a particular site. Also, the best stabilization solution in most cases is a combination of two or more alternatives.

Some of the potential stabilization measures that can be applied to existing rail embankments include crushed rock revetments, convection boards, awnings, ventiducts, and thermosyphons. Findings on these methods from the literature review have been summarized and documented in a 2016 Joint Rail Conference paper (Addison et al., 2016a) (Appendix C). Past investigation and monitoring efforts by EBA recommended the *use of thermosyphons* along the HBR. This recommendation was made following a 4-year prototype testing in the 1980s that proved their effectiveness in the two discontinuous permafrost zones (EBA, 1991). In the current state no definitive recommendation of any stabilization measure or a combination of them can, however, be made as part of this report, as much more comprehensive investigation of the local site conditions through prolonged experimentation and monitoring must be conducted for such recommendation.

CONCLUSIONS AND RECOMMENDATIONS

This study looked into characterizing the current condition of permafrost found along the HBR, and performed limited investigations on potential techniques to stabilize the most challenging locations along the corridor. The findings showed higher level of track geometry exceptions (often due to sinkholes) to be more prevalent in the discontinuous permafrost zones where there is contact between permafrost ground (peat plateau) and non-permafrost ground (fen). Permafrost thaw was found to occur at these transition zones, as the relatively warm fen loses its heat to the cold peat plateau. An investigation into the potential factors that are causing permafrost degradation revealed the occurrence of at least 19 wildfires along the study site since 1977 as one such factor, as locations affected by fires recorded more track deviations than those that were not affected. Other

potential factors were loss of vegetation and poor drainage conditions, both identified as important indicators of permafrost health by the developed predictive model.

Our findings also indicate that permafrost boundaries defined by EBA during earlier studies in 1980s seem to be changing and permafrost degradation is moving northwards. Previously stable permafrost tables in the discontinuous zones were seen to be thawed and the southern boundary of the continuous zone now has discontinuous permafrost in its extent. As part of the project, a three-level permafrost degradation susceptibility chart with ratings 1, 2, and 3 representing low, moderate and high susceptibility regions, respectively, was developed as a first step to provide a more quantifiable ratings to identify the permafrost condition.

A literature review of existing and hypothesized permafrost stabilization measures was done which identified a spectrum of passive to more rigorous active techniques. The development of specific stabilization recommendations was far beyond the current scope of works therefore it is recommended that next steps for this project should be aimed at conducting a more detailed investigation of alternative measures, potentially followed by a prototype testing to identify the most effective solutions.

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Appendix A

**A Review of Past Geotechnical Performance of the Hudson Bay Rail
Embankment and Its Comparison to the Current Condition.
Proceedings of the 2015 ASME Joint Rail Conference. March 23-26,
2015. San Jose, California.**

JRC2015-5780

A REVIEW OF PAST GEOTECHNICAL PERFORMANCE OF THE HUDSON BAY RAIL EMBANKMENT AND ITS COMPARISON TO THE CURRENT CONDITION

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ABSTRACT

The Hudson Bay Railway (HBR) is a 510 mile railway completed in 1929 in northern Manitoba, Canada. It connects domestic locations in North America with international destinations through the Port of Churchill.

Permafrost was encountered during construction at milepost 136 in isolated peat bogs which continued in a gradual northward transition from discontinuous to continuous permafrost. Over the past 80 years, warming climate combined with poor engineering properties of the railway embankment material has resulted in further thawing of the discontinuous permafrost leading to differential settlement along the rail embankment and high annual maintenance costs.

In a bid to understand the geothermal regime of the embankment, underlying subsurface condition, and to seek for solutions to stabilize the embankment, extensive work has been done from 1977 to the present time. This paper seeks to review reports of the past projects and compare the results against current conditions at selected test locations.

INTRODUCTION

The Hudson Bay Railway (HBR) is a 510-mile railway built within the permafrost region of Northern Manitoba, Canada. Its construction began in the early 1900s and was completed in 1929. The line was operated by Canadian National Railway (CN) from 1929-1997 before being sold to the current owner, OmniTRAX. It runs north from The Pas to Churchill, along the route shown in figure 1. During construction, isolated permafrost bodies were first encountered in Wabowden (milepost 136). As the line pushed forward to the east and north,

an increase in the size and frequency of permafrost bodies was encountered. From the Pas to Churchill there is gradual northward transition of permafrost condition from non-existent to sporadic discontinuous to extensive discontinuous and finally to continuous permafrost in Churchill (figure 1).

Construction was temporarily suspended between 1917 and 1926 and during this time little or no maintenance was done on the line. When work resumed, it was observed that the line had settled in many places which necessitated the placement of large volumes of additional granular fill to restore the embankment to usable condition once more. This subsidence experienced was a precursor to long term behavior of this rail corridor which has since necessitated significant and continuous maintenance. Track settlements were termed 'sinkholes' by Canadian National Railway (CN) maintenance personnel and these sinkholes consist of short sections of track that may experience as much as 100 to 150 mm of settlement during a single summer thawing season. These seasonal sags reflect thaw-settlement of ice-rich permafrost soils within the subgrade (EBA, 1977). To obtain a better understanding of the processes responsible for sinkhole development, EBA Engineering Consultants Ltd. (EBA) was engaged in 1976 by CN to investigate the technical feasibility of mitigating the railway grade settlements. This paper presents a comprehensive review of the studies done by EBA from 1976 to 1991 and compares their results to the current condition of the line at spot locations, as determined through recent field investigations.

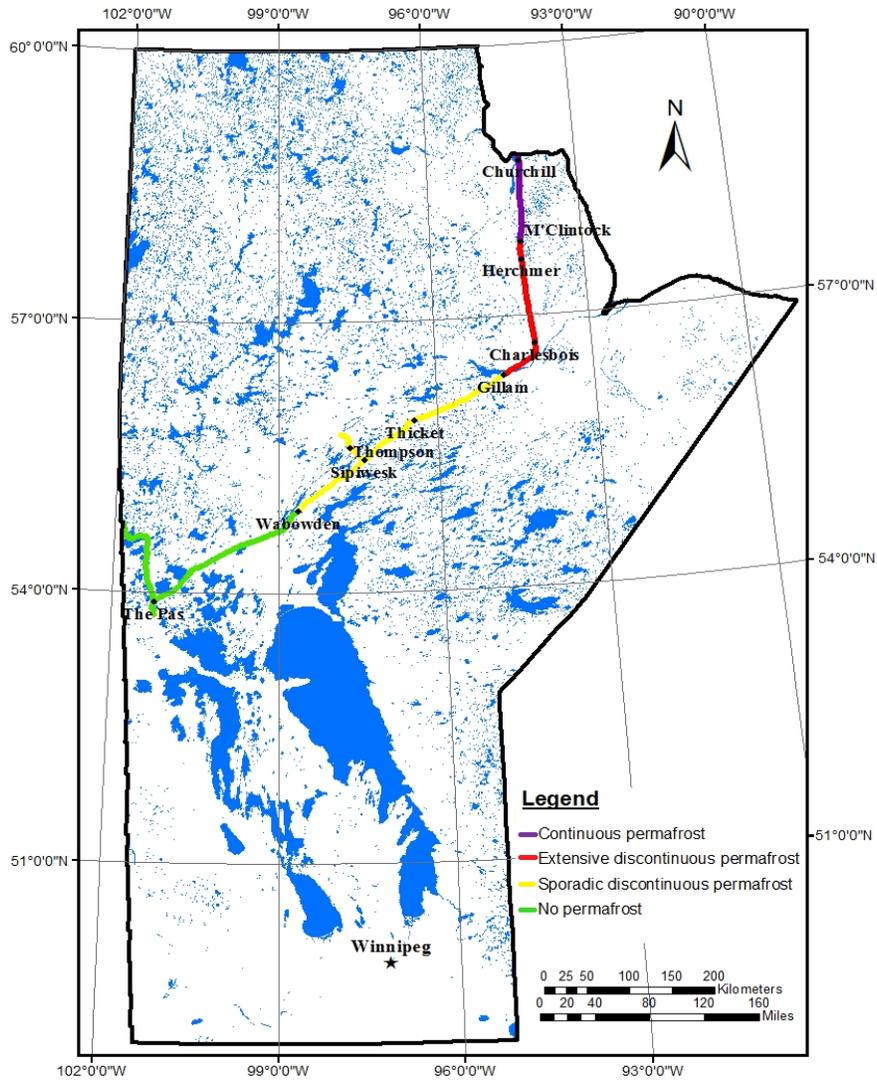


Figure 1. Location of the Hudson Bay Railway (HBR) from The Pas to Churchill

EBA REPORTS ON PERMAFROST RESEARCH

Pertaining to their contract EBA undertook studies of the HBR from 1976-1991 and wrote several reports to detail their findings and recommendations. Table 1 gives a summary of the key reports relevant to the stabilization efforts and the following sections document their findings.

Report 1

This report marks the first study performed along HBR line. The objectives were to define the mechanism that had resulted in sinkholes formation and why the embankments had not stabilized in spite of some 50 years of maintenance involving track lifting and placement of new granular fill. Field drilling and reconnaissance showed a clear linkage between the location of sinkholes and transitions from permafrost to non-permafrost terrain. The land was observed to be frequently overlain by raised peatlands which were termed *peat plateaus*

by EBA engineers. The relief of these areas was found to be due to the presence underlying ice rich soil. The land was however subdued in some areas, resulting in poor drainage conditions. The subdued wetlands were termed *fens*. The two landforms are shown in figure 2. Permafrost was found to be present in the elevated peat plateaus but non-existent in the fen.

A thaw subsidence “model” was developed that related sinkhole occurrence to progressive decay of the underlying permafrost as the roadbed crossed from the unfrozen fens to the peat plateaus. The results of this work have been summarized in a paper by Hayley et al (1983). A number of passive methods to aid in stopping the thawing process were examined analytically. The conclusion reached was that self-stabilization would not occur in the foreseeable future unless an active method that changes the annual air-ground heat balance was put in place. The active method of installing heat pipes was analyzed and proved to be effective as it actively removes heat

from the ground during the winter months. It was recommended that the spacing of the heat pipes be studied and monitored in a test section installation to evaluate its performance and optimize its design before its adoption as a remedy.

Table 1. List of reports by EBA Engineering on the HBR

No.	Title	Date
1	Settlement of a Railway Embankment Constructed on Permafrost Peatlands	March 1977
2	Embankment Stabilization Research Program, Test Site Construction and Instrumentation	April 1979
3	Embankment Stabilization Research Program, Interim Test Site Performance and Monitoring (a)	July 1980
4	Embankment Stabilization Research Program, Interim Test Site Performance and Monitoring (b)	April 1981
5	Embankment Stabilization Research Program, Branch Line Rehabilitation Hudson Bay Railway, Herchmer Subdivision	September 1982
6	Embankment Stabilization Research Program, Interim Report, Route Data Collection and Comparative Heat Pipe Study	February 1986
7	Requirements for Subgrade Stabilization, Hudson Bay Railway	January 1987
8	Heat Pipe Installation Phase, Hudson Bay Railway Prototype Stability Program	March 1988
9	Hudson Bay Railway Embankment Stabilization Program, Progress Report No. 2, Initial Performance Monitoring Data	May 1988
10	Hudson Bay Railway Stabilization Program, 1988 Progress Report No. 3	January 1989
11	Prototype Stability Program, Hudson Bay Railway	February 1990
12	Prototype Stability Program, Hudson Bay Railway, 1990/91 Heat Pipe Effectiveness and Geotechnical Investigations	August 1991



Figure 2. Typical sections of peat plateau (left) and fen (right)

Report 2

This described the research program on the heat pipes recommended in EBA (1977). Five test sites were selected on the basis of similarity and conformance to the pattern of sinkholes formation. Construction began in October 1978 and the mitigation techniques employed at each site is summarized in table 2.

Table 2. Configuration of Test Sites (EBA, 1979)

Site No.	Mile-post	Embankment Slope (H:V)	Wood Chip Insulation	Heat Pipes	
				Number	Spacing (m)
1	368.8	2:1	No	10	4
2	368.8	6:1	Yes	-	n/a
3	365.4	2:1	Yes	12	4
4	363.0	2:1	No	8	4
5	340.7	2:1	Yes	10	3

Instrumentation installed to monitor the results of the various stabilization techniques included:

- Thermistors cables
- Surface settlement plates
- Snow depth measurement gauges, and
- Permanent benchmark to provide a stable reference point for settlements surveys.

The relative effectiveness of each mitigation technique employed was to be evaluated by undertaking detailed analyses of at least three years of monitoring data.

Reports 3 - 5

Reports 3, 4, and 5 detailed the monitoring program that was undertaken after the installation of the test sections. Monitoring activities at each site included:

- Snow depth surveys during the winter months.
- Ground temperature measurements.
- Elevation surveys on settlement plates installed in the embankment fill.

- Elevation surveys along the top-of-rail over the entire length of each designated test site.

The results indicated positive response in favor of the heat pipes. It indicated that permafrost degradation can be halted or even reversed by installing heat pipes along either side of the track at the fen/peat plateau transition zones. The optimal spacing between adjacent heat pipes was determined to be 4 m. It also appeared that flattening the embankment slope to 6:1 could achieve similar results, but at a much slower pace.

Report 6

Report 6 documented the collection of route data to assist in the development of a practical stabilization system. A set of air photos covering Wabowden to M'Clintock was secured at a scale of 1:6,000 and was used as a tool to map the probability of the presence of permafrost and help pinpoint the location of the fen/peat plateau transition zones. From these analyses, 14 sites representing a variety of permafrost conditions were earmarked for geophysical testing.

In December 1985, a ground penetrating radar (GPR) survey was conducted at the 14 sites with a 120 mHz Subsurface Interface Radar (SIR) unit. The purpose was to determine if GPR could assist in locating the permafrost boundaries. Particular care was taken to obtain the best available records at the five experimental test sites constructed in 1979 in order to allow direct comparison with other available data at these locations. From this it was concluded that using GPR was effective but it needed to be used in conjunction with air photos and track maintenance records.

Report 7

This report evaluated the extent and distribution of sinkholes from Wabowden to Churchill and addressed methodology for a route stabilization program. A combination of maintenance records together with site reconnaissance, surficial geology interpreted from air photos and transition zones delineation by GPR were all put together into a computer database. This constituted information on approximately 700 active sinkholes from Wabowden (milepost 136) to Churchill (milepost 510). It was recommended that a prototype test sections (3-mile stretches) should be set up to test the feasibility of stabilizing these continuous 3-mile segments of track with heat pipes.

Report 8

Report 8 documented the prototype test installations recommended in report 7. Four sections were initially considered as candidates for the prototype testing; two in the northern portion of the line, representative of extensive discontinuous permafrost condition, and two in the southern portion, representative of sporadic discontinuous permafrost condition. Field drilling and GPR testing were conducted and Charlebois (mileposts 362-365) and Sipiwesk (mileposts 196-199) sites emerged winners because they represented the

“worst” case scenarios for the northern and southern sites, respectively.

GPR surveys were later conducted again to locate the fen/peat plateau transition zones in order to situate the heat pipes at these spots. A total of 400 heat pipes were installed at an optimum spacing of 4 m between adjacent pipes and also 4m away from the near rail to provide clearance for load and maintenance activities. In addition, heat pipes were installed as high as possible to ensure that their efficiency was not hampered by snow accumulation. Settlement plates and benchmarks were installed to monitor embankment settlements and thermistors were also installed to monitor ground temperatures over time.

Reports 9 - 11

Reports 9, 10 and 11 summarized the operation and monitoring of the prototype installations. The second aspect of these reports documented a hydrology study that was conducted to identify critical areas where the roadbed impeded the natural drainage system and to suggest mitigation measures to reduce ponding along the railway.

Ground temperature measurements revealed that heat pipes were indeed lowering the ground temperature and had even created frozen ground at some sites. The magnitude of frozen ground was higher further north at the Charlebois test site than at southern Sipiwesk. Track settlements however, still continued at both sites but at reduced magnitudes. Success rate of stabilized subgrade was 90% at the Charlebois site and 60% at the Sipiwesk site.

Infrared and pressure testing were conducted to confirm operation of heat pipes. 18% of the pipes were found to be non-operative due to complete loss of charging gas and 23% were operating at reduced capacity due to partial loss of the gas. Field repairs were done for the total 166 faulty pipes and a monitoring procedure was recommended to confirm the effectiveness of the repairs and to identify pipes that could not be repaired in the field.

The hydrology study was conducted on six sites representative of the hydrological problems along the entire line. The study was conducted with topographical maps, culvert inventory data, site reconnaissance data and air photos. The size and distribution of existing culverts and bridges were found to be adequate to handle design peak flows. Most culverts were, however, found to have been installed at fen/peat plateau boundaries which were contributing to permafrost thaw in the peat plateau and creating new ponds in thaw-settlement depressions. A well-engineered culvert placement program was recommended to reposition these culverts at the lowest points in the middle of the fens. Beaver dams and debris in the natural drainage courses, culvert inlets and offtake ditches were also found to be major impediments and their immediate and continued clearance was recommended.

Report 12

Report 12 provides a conclusion of tasks completed under past reports, a general assessment of the railway corridor, and summary of the final monitoring program of the prototype heat pipes installation. As final monitoring, the entire route from Wabowden to Churchill was visually inspected in September 1990. This was to evaluate changes in sinkhole frequency, as well as changes in their severity. The number of active sinkholes along the route was found to be greater in 1990 (775 sinkholes) than it was in 1987 (700 sinkholes). The frequency of distribution was shifting northward, as previously stable peat plateaus had begun to thaw due to warming climate.

Sinkhole stabilization success rate of 90% at the Charlebois site and 60% at the Sipiwesk site reported in reports 9-11 were found to be still representative. EBA however, did realize that the thaw-subsidence “model” developed in report 1 did not fit the Sipiwesk site hence it was proposed that additional geotechnical studies should be done to confirm and revise the distribution of permafrost in order to clearly define the transition zones for effective placement of heat pipes in the future.

CONCLUSIONS AND RECOMMENDATIONS MADE BY EBA

It was concluded that stabilization of the roadbed with heat pipes should be adopted as the prototype test sections had proved their effectiveness. Accelerated deterioration of the embankment was predicted if the stabilization measures were not applied. A total of 8,000 heat pipes were projected to be required to stabilize the whole route. It was however, recommended that the construction be planned in phases, as the tests had demonstrated the difficulty in properly locating the heat pipes in a single installation.

CURRENT CONDITION OF THE HBR

In 2013, Michigan Technological University was tasked by the current owners of the HBR, OmniTRAX Inc., to undertake research on the current state of the line, to define a rating system for the severity of railway conditions in permafrost affected areas, and to investigate long term solutions for

embankment stability. After a review of past reports and maintenance documentation provided by OmniTRAX, a field reconnaissance survey was done in June 2014, to obtain a general overview of the line, and to confirm EBA’s reported observations. Water was seen ponded at the toes of several portions of the embankment. The peat and fen landforms described in report 1 were observed (figure 2). It was also observed that the large scale heat pipes stabilization program recommended by EBA had not been put in place. According to OmniTRAX’s maintenance records, most of the settlement problems now are between the northern Herchmer subdivision as depicted in table 3 below. A closer look at these maintenance records revealed a general annual increase in the number of miles that need re-surfacing (figure 3). This confirms EBA’s prediction of accelerated deterioration in the absence of stabilization measures (EBA, 1977).

To understand the current subsurface condition, electrical resistivity tomography (ERT) was conducted in October 2014, at selected locations. This helped in imaging the permafrost table underneath and estimating its depth. The fall season was chosen for the fieldwork because this is when the active layer of the subsurface is fully thawed (depth of unfrozen top layer to the permafrost table is at its highest). When accessible, test locations were chosen to coincide with or be as close as possible to locations of past site investigation records by EBA. As the coarse grained ballast is highly resistive to the flow of current, the tests were conducted just outside the ballast shoulder. A typical arrangement is shown in figure 4.

The results of the ERT showed good correlation with past EBA tests. A representative result from milepost 382 is shown in figure 5. This was compared against a past profile at milepost 381.5 (figure 6), developed after the field drilling and GPR program that was carried out by EBA in 1987. The ERT estimated the depth to permafrost table at 5 m, providing close correlation with the 3 - 5m depth recorded by EBA. It is observed from the comparison of the ERT data with the EBA report that the permafrost has not deteriorated much at this location even after 27 years. However, it is recognized that since the ERT was done to the sides of the embankment the subsurface condition under the roadbed might be different.

Table 3. Details of track re-surfacing done annually from 2008 - 2013

Sub-Division	Milepost	Percentage of Miles Surfaced in a Year						Yearly Average per Subdivision
		2008	2009	2010	2011	2012	2013	
The Pas	0.0 - 4.7	0%	0%	0%	138.3%	0%	12.8%	25%
Wekusko	0.0 - 136	4.6%	13.0%	52.6%	20.9%	85.4%	21.3%	33%
Thicket	136 - 326	8.1%	50.5%	62.8%	88.6%	22.6%	41.2%	46%
Herchmer	326 - 510	66.0%	142.4%	59.8%	88.1%	142.3%	91.2%	98%

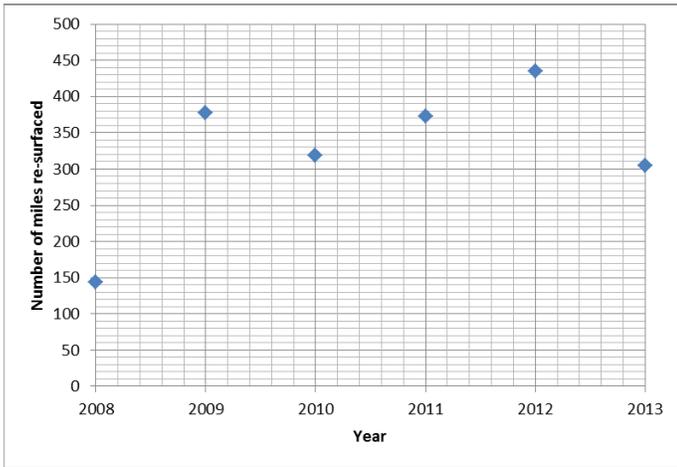


Figure 3. Number of miles re-surfaced each year due to thaw settlement



Figure 4. Running surveys at an offset distance parallel to the rail embankment

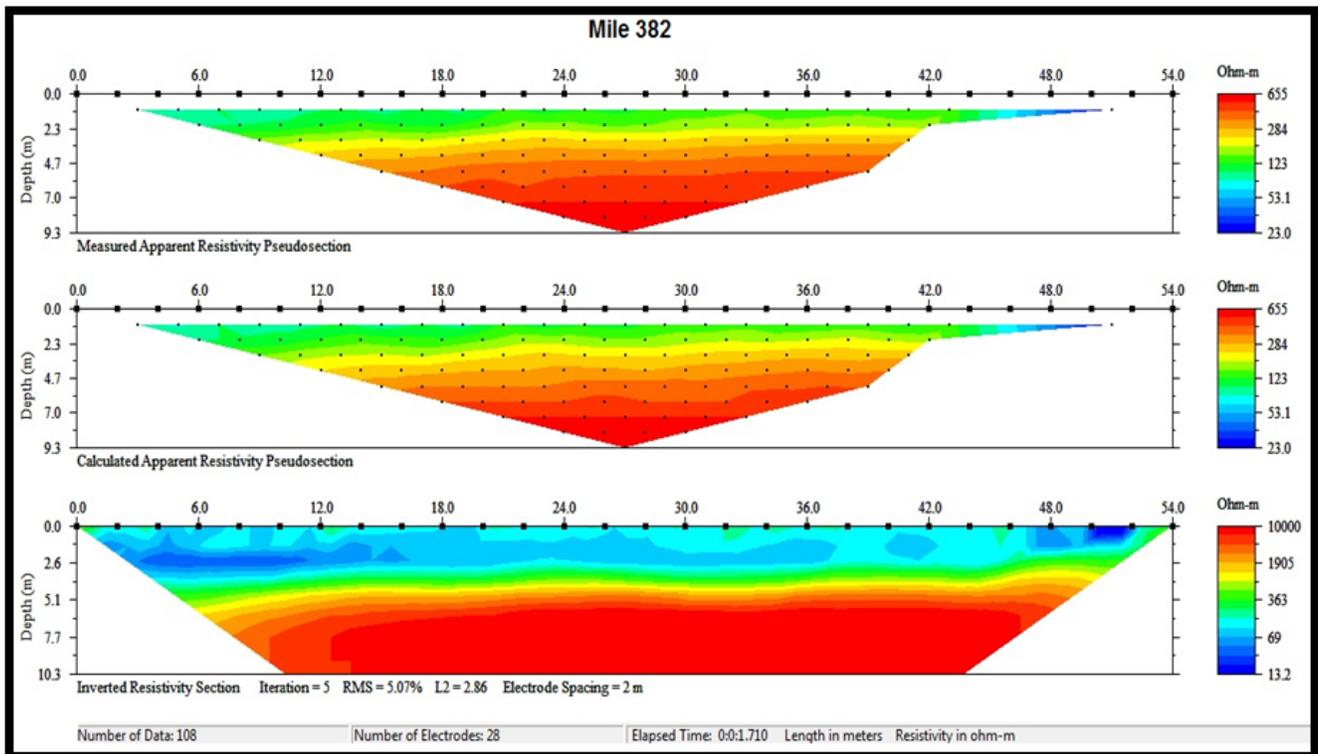


Figure 5. Results of ERT conducted October 2014 at milepost 382

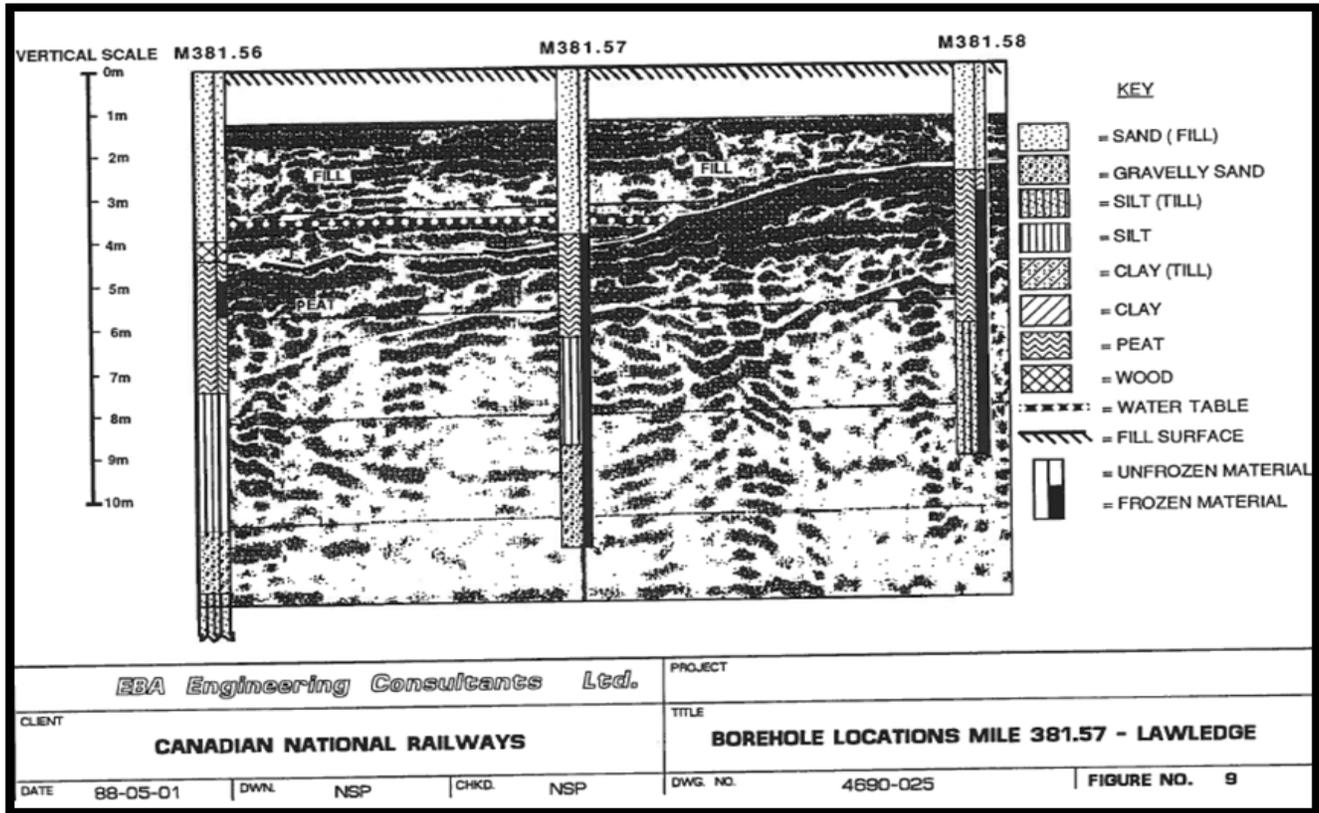


Figure 4. Borehole and GPR profile at Milepost 381.5 (EBA Engineering, 1987)

CONCLUSIONS AND FUTURE WORK

This paper summarized the results of an extensive research program conducted over two decades on the Hudson Bay Railway (HBR) and related attempts to stabilize the substructure. It also compares the outcomes with a recently conducted field research at a selected location. From the maintenance records it is evident that the HBR is experiencing accelerated deterioration indicating the lack of effective stabilization measures in place; this was predicted by EBA in their concluding remarks. The formation of sinkholes along the line has continued, as effective stabilization measures have not been implemented and past solutions have lost their effect. Electrical resistivity results obtained to evaluate the current condition of the line showed great promise in identifying the permafrost layers and good correlation with past data by EBA. Since no single geophysical data is conclusive on its own, the intention is to use the ERT data as validation points for an ongoing GPR study that covers the study section. This will enable development of a more conclusive profile of the subsurface and assist in the identification of cost effective stabilization measures.

ACKNOWLEDGEMENTS

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Appendix B

Rail Embankment Investigation Using Remote Sensing For a Permafrost Region. Proceedings of the ASCE International Conference on Cold Regions Engineering. pp. 90-101.

Rail Embankment Investigation Using Remote Sensing for a Permafrost Region

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ABSTRACT: Remote sensing was used as a site investigative tool for the portion of the Hudson Bay railway embankment underlain with discontinuous permafrost in northern Manitoba, Canada. Imagery from Landsat 5's Thematic Mapper (TM) were analyzed to observe changes in land surface temperatures, vegetation cover, and water content in vegetation canopies over the past three decades.

The Landsat image analyses show evidence of the occurrences of significant wildfires near the railroad over the years. Temperature data indicate that land surfaces that have been burned are approximately 20°F warmer on average than the surrounding unburned areas. The data also show that significant amounts of vegetation have been destroyed by these wildfires, and that fire scars and temperature anomalies often persist for several years. Satellite imagery has also been used to map the severity of these wildfires by calculating normalized burn ratios (NBR) before and after the fires and then solving for the differenced normalized burn ratio (dNBR). Previous studies have shown fire damage results in the removal of the insulating organic layer of the permafrost, exposing the mineral soil which causes a decrease in thermal conductivity, thereby increasing the active layer depth. Such increase in the depth of active layer typically results in ground subsidence and can be detrimental to engineered structures, such as rail embankments. However, ground subsidence is not exclusive to regions affected by fire and therefore, more ground data,

such as ground penetrating radar (GPR), maintenance records, and track geometry survey data are needed to validate this relationship.

KEY WORDS: Site investigation, permafrost, remote sensing, railway.

1 INTRODUCTION

The Hudson Bay Railway (HBR) was the first major transportation facility constructed over permafrost in Canada in 1929. It was a key trade link that connected domestic origins and destinations in Northern America with export origins and destinations in Europe through the Port of Churchill. The 510 mile railway runs north from the non-permafrost zone in The Pas (milepost 0) to the continuous permafrost zone in Churchill (milepost 510) along the route shown in Figure 1. Over the past eight decades after its construction, thawing of the permafrost, combined with poor geotechnical properties of the underlying muskeg soil has led to the deterioration of the embankment. The worst conditions of the embankment lie within the discontinuous permafrost zone between Gillam (milepost 326) and Herchmer (milepost 420). This zone was chosen as our study site.

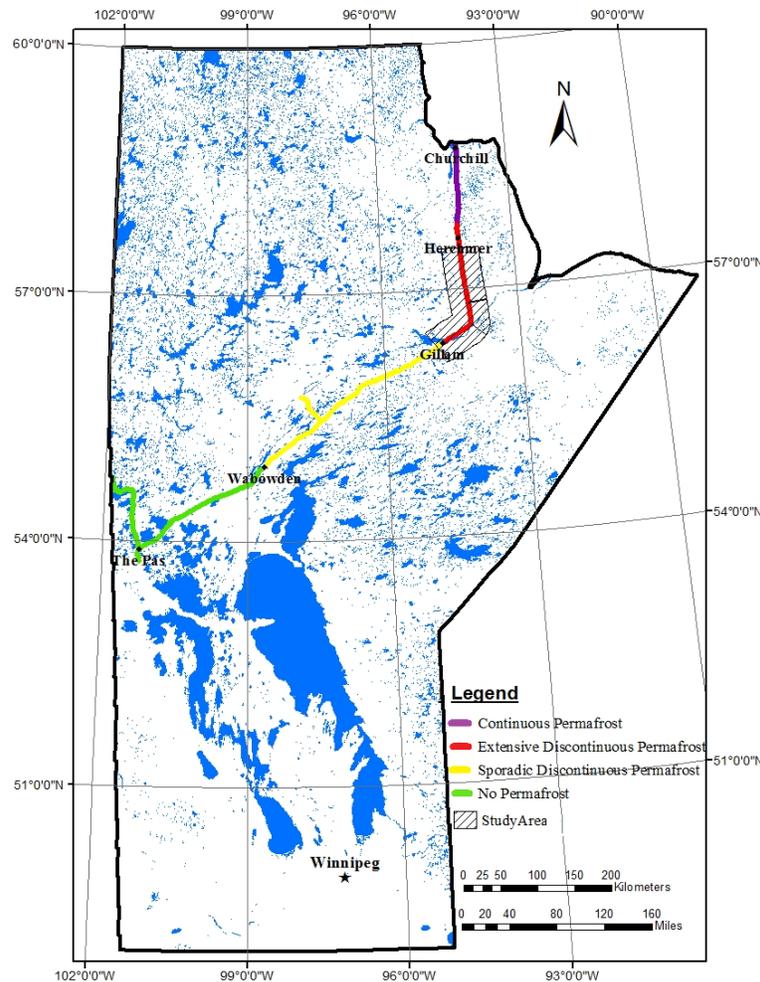


Figure 1. A map showing HBR route from The Pas to Churchill.

Previous studies have revealed the underlying discontinuous permafrost at the study site to be in a warm state (EBA, 1977). The presence or absence of permafrost in discontinuous zones have been known to be influenced by the depth of snow cover in the winter months, thickness of the organic soil layer, moisture content, and the nature of the vegetation cover (Smith 1975, Williams and Burn 1996). Changes in these variables have been known to control the degradation or aggradation of permafrost more than fluctuations in the climatic regime (Smith and Riseborough 1983). Degradation and aggradation of permafrost are most destructive to the stability of engineered structures such as highways and railroads (Jin et al. 2008).

Remote sensing has been employed as a site investigative tool to observe changes in temperature and vegetation cover over a period of 26 years (1984-2010) using Landsat 5's thematic mapper (TM). The objective was to observe how changes in these parameters could relate to degrading permafrost which in turn compromises the stability of the railroad embankment. Satellite data revealed several occurrences of wildfires along the railroad and its vicinity in the period under consideration. Wildfires are of significant interest in this study because past studies have cited wildfires to be one of the most widespread changes in surface conditions that cause permafrost degradation in most areas (Viereck 1982, Zoltai 1993). They are known to result in a decrease in evapotranspiration resulting in increased land surface temperature (Rouse 1976). Wildfires therefore usually lead to deepening of the active layer and permafrost degradation (Viereck 1982, Zhou et al. 1993, Mackay 1995).

Permafrost or perennially frozen ground is defined as "ground (soil or rock and included ice and organic material) that remains at or below 0 °C for at least two consecutive years, for natural climatic reasons" (Van Everdingen 1998). The layer on top of the permafrost table, the active layer, is a layer of ground that freezes and thaws annually. Permafrost is impermeable, causing a moisture content and low nutrient availability in the active layer resulting in the accumulation of organic material. This organic layer has reduced thermal properties because it traps stagnant air and acts as insulation helping to keep the underlying permafrost frozen (Jafarov 2013, Johnstone et al. 2010). With permafrost being a subsurface phenomenon, remote sensing cannot be used to directly observe its physical condition. However, it can be used to observe surface properties that affect the subsurface energy distribution such as surface temperatures, vegetation cover, distribution of surface hydrology, snow cover thickness, and water surface temperatures (Zhang et al. 2004).

Remote sensing has been used in the past to study permafrost distribution (Etzelmüller et al. 2001), active layer changes (Peddle et al. 1993), spatial patterns in surficial geology, vegetation types and distribution in permafrost regions (Zhang et al. 2004), and other variables. Several studies have also been done on how fires affect permafrost (Jafarov et al. 2013 and Burn 1998) and also on the deterioration of railroads and highways built on permafrost (Jin et al. 2008). However, research is lacking in studies that combine these challenges to investigate how wildfires affect railroad embankment stability in a permafrost region. This paper therefore makes an attempt to investigate how historic wildfires that have occurred along the HBR are affecting the railroad embankment stability.

2 METHODOLOGY

2.1 Data Acquisition

Satellite images of the study area were obtained from Landsat 5 TM sensor with <20% cloud coverage from 1984 to 2010 covering path 31 and row 20. Scenes were acquired in the summer months (June to August) when the ground was snow-free.

2.2 Monitoring Vegetation

The normalized differenced vegetation index (NDVI) was calculated for each scene to observe vegetation changes through the years. This was done by first converting the Landsat 5 digital numbers of the near infrared (NIR) and the visible red bands into reflectance values using the Exelis Visual Information Solutions (ENVI) software, and then calculating NDVI as follows (Rouse et al. 1973):

$$NDVI = \frac{TM 4 - TM 3}{TM 4 + TM 3} \quad [1]$$

where TM 3 = reflectance of the red band at a spectral resolution of 0.63-0.69 μm , and TM 4 = reflectance of the NIR band at a spectral resolution of 0.76-0.90 μm .

2.3 Monitoring Water Content

The normalized differenced water index (NDWI) was also calculated for each scene to show the distribution of water content in the vegetation canopies and surface water through the years. The NDWI was calculated with the following equation (Gao 1996):

$$NDWI = \frac{TM 4 - TM 5}{TM 4 + TM 5} \quad [2]$$

where TM 4 = reflectance of the NIR band 4 at a spectral resolution of 0.76-0.90 μm , and TM 5 = reflectance of the NIR band 5 at a spectral resolution of 1.55-1.75 μm .

2.4 Land Surface Temperature Estimation

To be able to retrieve land surface temperature (LST) from the thermal infrared band (TM 6), there was a need to first determine the emissivities of the different surfaces at the site. Because the Landsat 5 has only one thermal sensor the options to determine emissivities were limited. A modification of the NDVI Thresholds Method (NDVI^{THM}) (Van de Griend and Owe, 1993) was applied. Other variations of this method have also been used by several authors (Sobrino and Raissouni 2000, Sobrino et al. 2004, Valor and Caselles 1996). The method seeks to estimate the emissivities of different surfaces from their respective NDVIs by considering the following different categories:

Category 1: $NDVI < 0.2$

The NDVI of the pixel is less than the NDVI corresponding to a typical bare soil (0.2). Pixels meeting this criterion were assigned an emissivity value of 0.96, assuming a typical bare soil emissivity (Sobrino et al. 2008).

Category 2: $NDVI > 0.5$

The NDVI of the pixel is greater than the NDVI corresponding to a typical vegetation (0.5). Pixels meeting this criterion were assigned an emissivity value of 0.99, assuming a typical vegetation soil emissivity (Sobrino et al. 2008).

Category 3: $0.2 < NDVI < 0.5$

The pixel constitutes a mixture of bare soil and vegetation. Majority of our study section fell under this category. The emissivities of pixels meeting this criterion were determined as follows (Sobrino et al. 2008):

$$\varepsilon = 0.003 Pv + 0.982 \quad [3]$$

Where ε is the emissivity, and Pv is the proportion of vegetation defined by Carlson and Ripley, 1997 as:

$$Pv = \left(\frac{NDVI_{pixel} - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^2 \quad [4]$$

where $NDVI_{pixel}$ = the NDVI value of a pixel, $NDVI_{max} = 0.5$, and $NDVI_{min} = 0.2$.

The next step was to apply the various estimated emissivities to calculate the LST. First, the Landsat 5 thermal band (TM 6) raw digital numbers (DNs) were converted to spectral radiances using the following equation by Chander et al. 2009:

$$L_{\lambda} = \left(\frac{LMAX_{\lambda} - LMIN_{\lambda}}{Q_{cal\ max} - Q_{cal\ min}} \right) (Q_{cal} - Q_{cal\ min}) + LMIN_{\lambda} \quad [5]$$

where L_{λ} = Spectral radiance at the sensor's aperture ($W/(m^2\ sr\ \mu m)$), Q_{cal} = Quantized calibrated pixel value (DN), $Q_{cal\ min}$ = Minimum quantized calibrated pixel value corresponding to $LMIN_{\lambda}$ (DN), $Q_{cal\ max}$ = Maximum quantized calibrated pixel value corresponding to $LMAX_{\lambda}$ (DN), $LMIN_{\lambda}$ = Spectral at-sensor radiance that is scaled to $Q_{cal\ min}$ ($W/(m^2\ sr\ \mu m)$), and $LMAX_{\lambda}$ = Spectral at-sensor radiance that is scaled to $Q_{cal\ max}$ ($W/(m^2\ sr\ \mu m)$).

Using ε and L_{λ} , the LST, in kelvin, was estimated as follows using the Planck's equation:

$$LST = \frac{C_2}{\lambda \ln \left(\frac{\varepsilon C_1 \lambda^{-5}}{\pi L_{\lambda}} + 1 \right)} \quad [6]$$

where $C_1 = 3.742 \times 10^{-16}\ Wm^2$, $C_2 = 0.0144\ mK$, λ = wavelength in m.

This equation can be re-written for TM 6 as:

$$LST = \frac{1260.56}{\ln\left(\frac{607.76 \varepsilon}{L_\lambda} + 1\right)} \quad [7]$$

The LSTs were subsequently converted from kelvin to Fahrenheit. ArcMap software was used to extract NDVI, NDWI, and LST readings along the railroad. The values were then plotted against railway mileages in the study area to observe the variations of these parameters from Gillam to Herchmer.

2.5 Estimating Burn Severity

Satellite images revealed the occurrences of several wildfires through the years hence the Normalized Burn Ratios (NBRs) were calculated in scenes immediately before (NBR_{preburn}) and immediately after (NBR_{postburn}) wildfires to estimate the extent of fire damage at different locations (Miller et al. 2009):

$$NBR = \frac{TM\ 4 - TM\ 7}{TM\ 4 + TM\ 7} \quad [8]$$

where TM 4 = the reflectance of the NIR band at a spectral resolution of 0.76-0.90 μm , and TM 7 = the reflectance of the shortwave infrared (SWIR) band at a spectral resolution of 2.08-2.35 μm .

Fire severity is defined as the degree of change resulting from fire damage (Miller et al. 2009). Healthy vegetation reflects NIR strongly. Fires destroy vegetation and expose the bare soil which is highly reflective of SWIR radiation. Consequently a high positive NBR indicate low fire damage whereas a high negative NBR correspond to severe fire damage. Burn extent and severity is estimated by taking the difference between the pre-burn and post-burn images; this is known as the differenced NBR (dNBR). The dNBR isolates burned from unburned areas and serves as a measure to determine the absolute quantitative change in the NBR (Miller et al. 2009). dNBR was therefore determined as:

$$dNBR = NBR_{preburn} - NBR_{postburn} \quad [9]$$

The results of the dNBR were then used to map the fire severities into seven categories:

Table 1. Burn Severity Categories Defined by dNBR

Severity Category	dNBR Range
Enhanced Regrowth, High (ERH)	< -0.25
Enhanced Regrowth, Low (ERL)	-0.25 to - 0.10
Unburned (UB)	-0.10 to 0.10
Low Severity (LS)	0.10 to 0.27
Moderate-Low Severity (MLS)	0.27 to 0.44
Moderate-High Severity (MHS)	0.44 to 0.66
High Severity (HS)	> 0.660

3 RESULTS AND DISCUSSION

Temperature data from Landsat 5 TM band-6 revealed at least 18 incidences of wildfires in the proximity of the HBR from 1984 to 2010. The areas affected varied from small patches of about 7 square miles to big spreads of about 400 square miles. Increased LSTs from the fires were observed to last for at least three to five years. Figures 2 and 3 show the response of LST, NDVI, and NDWI to a fire that occurred in July 2003. This fire was of particular interest because its coverage encompassed a portion of the railway. It was interesting to note the progression of its coverage area from 26 square miles in July 2003, to 50 square miles in August 2003, and then to 300 square miles in July 2004. This indicates that the fire burned for a considerable amount of time, maybe even smoldered in the active layer throughout the winter. The portions of the railway that were affected were mileages 397 – 400 in July 2003 to mileages 377 – 402 in July 2004. The LST of the burned area was noted to be approximately 20°F higher than the neighboring unburned area in 2003 and 10°F higher after three years in the 2006 (Figure 3). A decrease in the NDVI and NDWI were observed within the burned area compared to the surrounding area in 2003 to 2006.

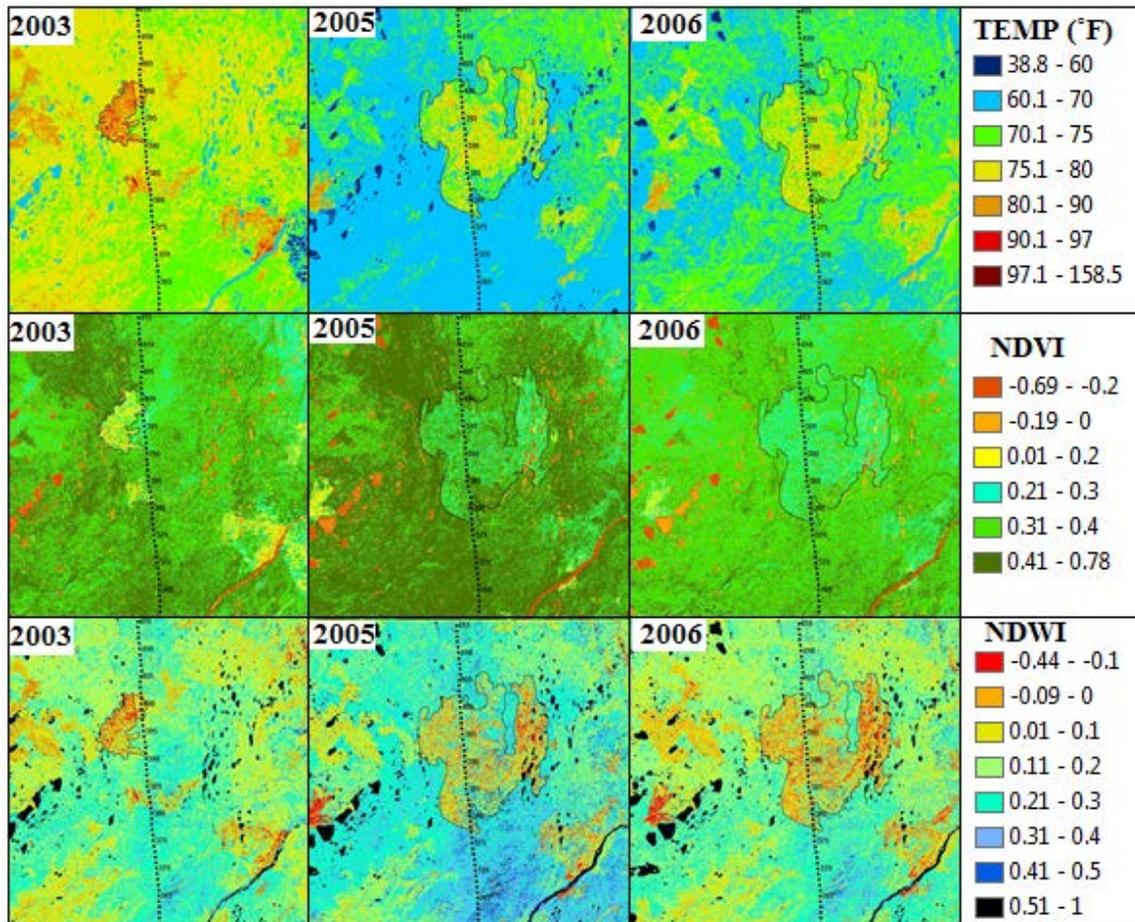


Figure 2. LST, NDWI, and NDVI images from the July 2003 wildfire.

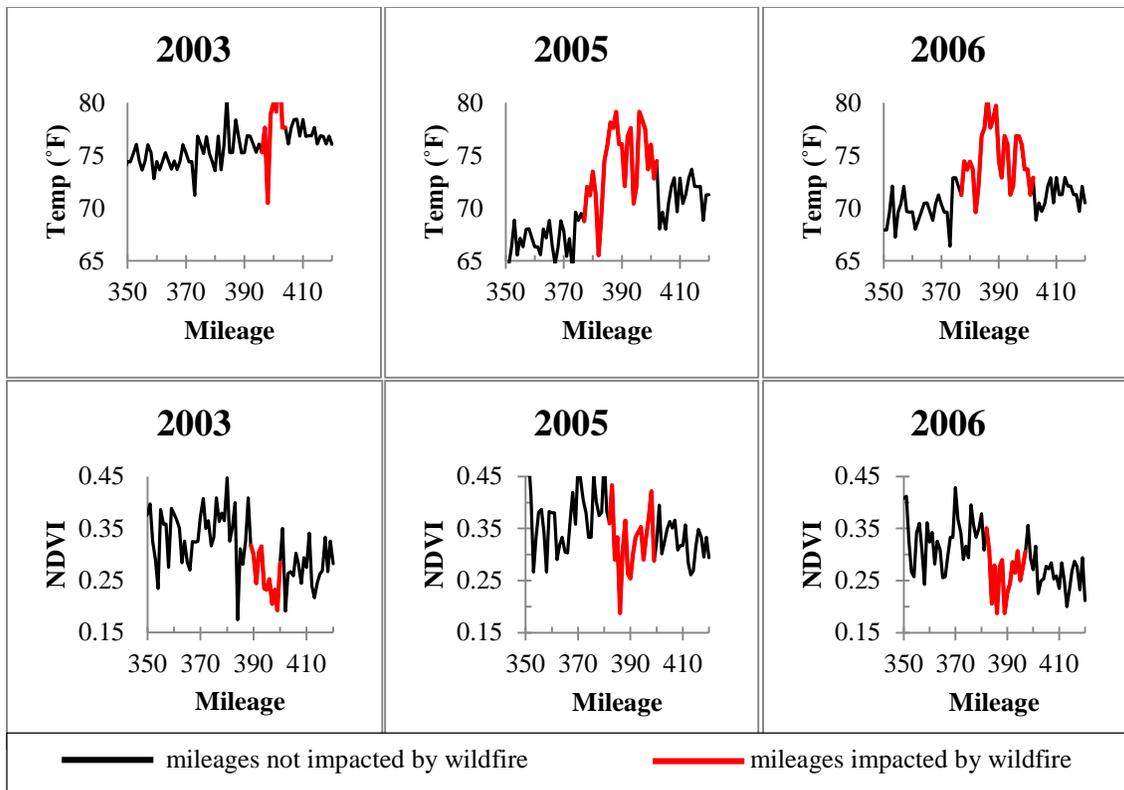


Figure 3. Cross-sectional profiles of LST (top) and NDVI (bottom).

Previous studies have documented potential consequences of wildfires to permafrost regions. For example, tree canopies are known to protect the ground from thick snow cover and provide shade from solar radiation. The initial reduction of the NDVI reflects the destruction of large populations of black spruce dominant at the study site. With the removal of this vegetation the ground becomes exposed and can therefore accumulate thicker snow cover resulting in possible insulation in the winter months, increased runoff in the spring months and increased exposure to the sun in the summer months leading to permafrost degradation (Chasmer et al. 2011 and Zhang et al. 2004).

In addition, vegetation is known to decrease soil temperatures through evapotranspiration and by shielding the ground from the direct radiant heat of sunlight. The persistence of higher LSTs even after NDVI recovery can be explained by the fact that soil thermal conductivity increases with the removal of the insulating organic layer which is associated with severe wildfires. This causes the surface albedo to decrease and the soil to conduct more heat. Significant removal of the organic layer can therefore lead to permafrost degradation (Yoshikawa et al. 2003). Yoshikawa also reported that soil moisture after a wildfire decreases with time which explains why the NDVI values remain low for a period of time.

The dNBR (Figure 4) for the 2003 fire was computed using a July 2001 scene as the pre-burn image since that was the closest available cloud-free image in July from previous years. From the summary of the severity classes in Table 2 it can be seen that >60% of the

area experienced moderate to high burn severity in July 2003. Studies have shown that severe wildfires could result in permafrost degradation causing an increase in the active layer depth when at least 30% of the insulating organic layer thickness is removed (Jafarov et al. 2013). When fire removes the organic layer in a region where climate does not favor permafrost, which is characteristic of many discontinuous permafrost regions, it is likely the permafrost will undergo widespread degradation and will not recover even after vegetation regrowth (Shur and Jorgenson 2007). Based on this information, it is possible that any permafrost degradation that has occurred within the study area might be naturally irreversible.

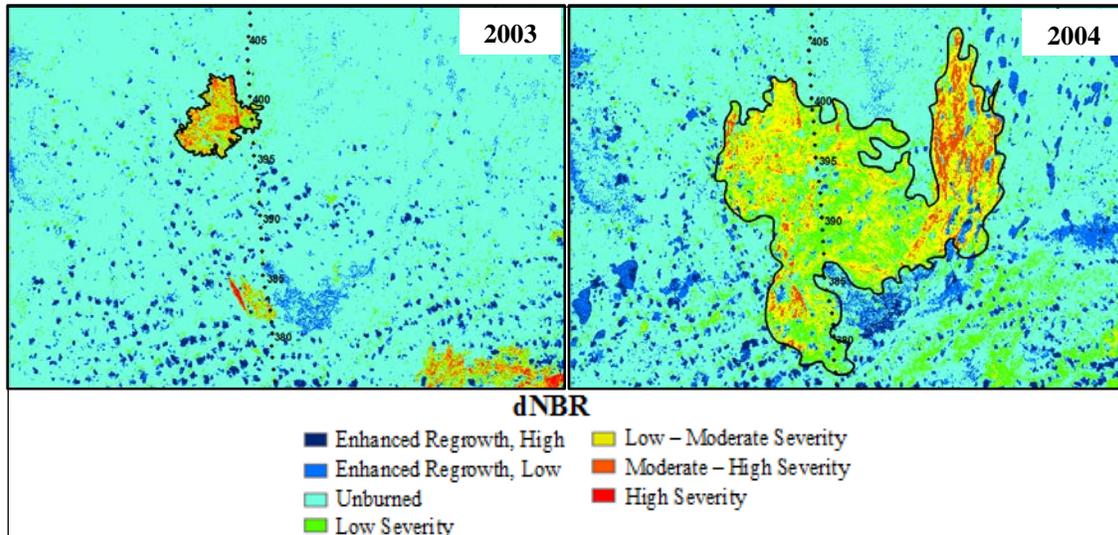


Figure 4. dNBR images of July 2003 and July 2004 indicating the spread of the fire.

Table 2. Percentage Contribution of Burn Severities from the July 2003 Fire

Severity Category	Percentage Contribution	
	2003	2004
Enhanced Regrowth, High (ERH)	0.14%	1.25%
Enhanced Regrowth, Low (ERL)	0.51%	3.01%
Unburned (UB)	11.46%	13.74%
Low Severity (LS)	24.13%	33.15%
Moderate-Low Severity (MLS)	33.26%	37.52%
Moderate-High Severity (MHS)	26.05%	11.18%
High Severity (HS)	4.45%	0.14%

Over the years annual thaw settlements associated with degrading permafrost have been observed at the study site. However, these settlements are not exclusive to regions affected by historic fires, and therefore more data such as maintenance records, ground penetrating radar (GPR) analyses and track geometry survey data interpretation would be needed to validate this relationship. Maintenance data will help correlate the location of these fires

with how much maintenance was associated with the fire affected locations as compared to unburned areas; the GPR will help image the subsurface condition of the underlying permafrost and the active layer depth to observe the effects of the fires, if any; and finally the geometry data will help obtain quantitative settlement data along the stretch of the railroad to observe the response of the fire affected areas as compared to the unburned areas.

4 CONCLUSION AND FUTURE WORK

The depth of snow cover in the winter months, thickness of the organic soil layer, soil moisture content, and the nature of the vegetation canopy are the main variables that are known to control the presence of permafrost in discontinuous zones. Permafrost is impacted more by changes in these variables than fluctuations in climate. Wildfires have been known to affect all four of these surface variables resulting in widespread changes in surface conditions that cause permafrost degradation. Wildfires are also known to result in a decrease in evapotranspiration leading to increased land surface temperature and consequently permafrost degradation.

Our study has shown that many of the fires observed at our study site from 1984 to 2010 typically resulted in moderate to high damage to the organic layer. Temperatures in the burned areas averaged approximately 20°F warmer than the surrounding unburned areas immediately after the fires, and this increase remained for at least three to five years after the burn. Temperatures have, however, been observed to slowly recover as NDVI also recover to pre-burn levels. Fire damage is responsible for major disturbances over potentially unstable permafrost found in the discontinuous permafrost zones, and any permafrost that has degraded over the past few decades is unlikely to recover once thawed (Shur and Jorgenson 2007).

Deepening of the active layer typically results in ground subsidence (Mackay, 1995) which is observed annually at our study site. However, these observed subsidence are not exclusive to regions affected by historic fires so more data such as maintenance records, GPR analyses and track geometry survey data interpretation would be needed to validate this relationship.

ACKNOWLEDGMENTS

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Appendix C

**Embankment Stabilization Techniques for Railroads on Permafrost.
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EMBANKMENT STABILIZATION TECHNIQUES FOR RAILROADS ON PERMAFROST

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ABSTRACT

Degrading permafrost conditions around the world has resulted in stability issues for civil structures founded on top of them. Railway lines have very limited tolerance for differential settlements, making it a priority for railway owners in permafrost regions to consider embankment stabilization measures that ensure smooth and safe operations.

Several passive and active engineered solutions have been developed to address the permafrost stability issues, such as awnings, shading boards, crushed rock embankments, ventiduct embankments, and thermosyphons. Local site conditions, including soil type, soil temperature, ice content, and precipitation determines which method is selected for a particular site and in most cases the best stabilization solution is a combination of two or more alternatives. When potential solution can be identified, it will only be implemented if perceived benefits exceed the implementation and maintenance costs.

This paper aims to provide a brief literature review on some common embankment stabilization solutions with consideration to the Hudson Bay Railway (HBR) in northern Manitoba, Canada which has been witnessing thaw settlements for extensive time period. It will discuss the applicability of the different methods, the advantages and disadvantages of the different methods, as well as the benefits to be derived by utilizing a combination of methods.

INTRODUCTION

Permafrost is defined as “ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years for natural climatic reasons” [1]. It is very sensitive to changes in soil temperature possessing high physical and mechanical strength when it is sufficiently cold, but losing strength quickly with increase in soil temperature [2]. The situation is compounded with ice-rich fine grained soil, because thawing of the ice results in the creation of voids which are subsequently compressed to create differential settlements [3 – 5].

Undisturbed permafrost enters an equilibrium state with its environment with the passage of time, but upon construction of any engineering infrastructure this energy balance is lost. First, the process of clearing the land in preparation of construction removes all vegetation which used to protect the permafrost from thawing. In the case of roads and railways the constructed embankment has a low albedo which transmits more heat to the underlying permafrost. Its added weight also accelerates differential settlements should degradation occur. The constructed infrastructure therefore becomes a thermal magnet that delivers heat to the frozen subsoil, unfettered by the insulating qualities of natural vegetation.

There are three engineering approaches to address the situation; preserving the permafrost from thawing, slowing down permafrost thaw rate after construction, or pre-thawing permafrost before construction. Currently, the first approach, though challenging is the most widely used since by protecting the permafrost from thawing, the frozen ground offers the added

benefit of the high bearing capacity to infrastructure founded on it. This paper therefore only discusses methods geared at achieving the objective of the first approach.

Several passive and active engineered solutions have been developed to address the permafrost stability issues. Local site conditions, including soil type, soil temperature, ice content, precipitation and vegetation determines which method is selected for a particular site and in some cases the best stabilization solution is a combination of two or more alternatives. When potential solution can be identified, it will only be implemented, if perceived benefits exceed the implementation and maintenance costs.

This paper aims to provide a brief literature review on some common existing embankment stabilization solutions with consideration to the Hudson Bay Railway (HBR) in northern Manitoba, Canada which has been witnessing thaw settlements for extensive time period [6 – 8]. It will discuss the applicability of the different methods the advantages and disadvantages of the different methods as well as the benefits to be derived by utilizing a combination of methods.

BRIEF HISTORY OF THE HBR

The Hudson Bay Railway (HBR) is a 510-mile railway built within the permafrost region of Northern Manitoba, Canada. It is a passenger and freight corridor that connects domestic locations in North America with international destinations through the Port of Churchill. Construction of the rail embankment began in the early 1900s and line was opened to revenue service in 1929. The HBR runs north from The Pas (milepost 0) to Churchill (milepost 510), along the route shown in Figure 1.

During construction, isolated permafrost bodies were first encountered in Wabowden (milepost 136). As the line pushed further north, an increase in the size and frequency of permafrost bodies was encountered. From The Pas to Churchill there is gradual northward transition of permafrost condition from non-existent to sporadic discontinuous to extensive discontinuous and finally to continuous permafrost from M’Clintock (milepost 442) to Churchill. Construction of the HBR was temporarily suspended between 1917 and 1926 due to World War I, during which time little or no maintenance work was done. When construction resumed after the war, it was observed that local subsidence or differential settlements had occurred along the embankment in many places which necessitated the placement of large volumes of additional granular fill to restore the embankment to usable condition. This subsidence experienced was a precursor to the long term behavior of this rail corridor which has since required significant and continuous maintenance.

These seasonal differential settlements, termed “sinkholes” by maintenance personnel, have been linked to the degradation of the underlying warm, ice-rich permafrost soils within the subgrade in the discontinuous permafrost zone [9]. Sinkholes consist of short sections of track that may experience as much

as 100mm (4 in) to 150mm (6 in) of settlement during a single summer thawing season [9].

From 1977 to 1991 a consulting company, EBA Engineering, was tasked to undertake extensive research to understand the geothermal regime of the subsurface, uncover the mechanism of the sinkholes formation, and to propose long term stabilization measures. However, the recommended extensive stabilization measures after the study were not put in place, potentially due to the economic reasons. Consequently, the HBR currently continues to go through its seasonal deteriorations, causing operational concerns to its owner and users as well as financial strain to OmniTRAX Inc. This new study seeks to provide an improved characterization of permafrost challenges along the line and to look at the current stabilization methods available to address the most challenging locations.

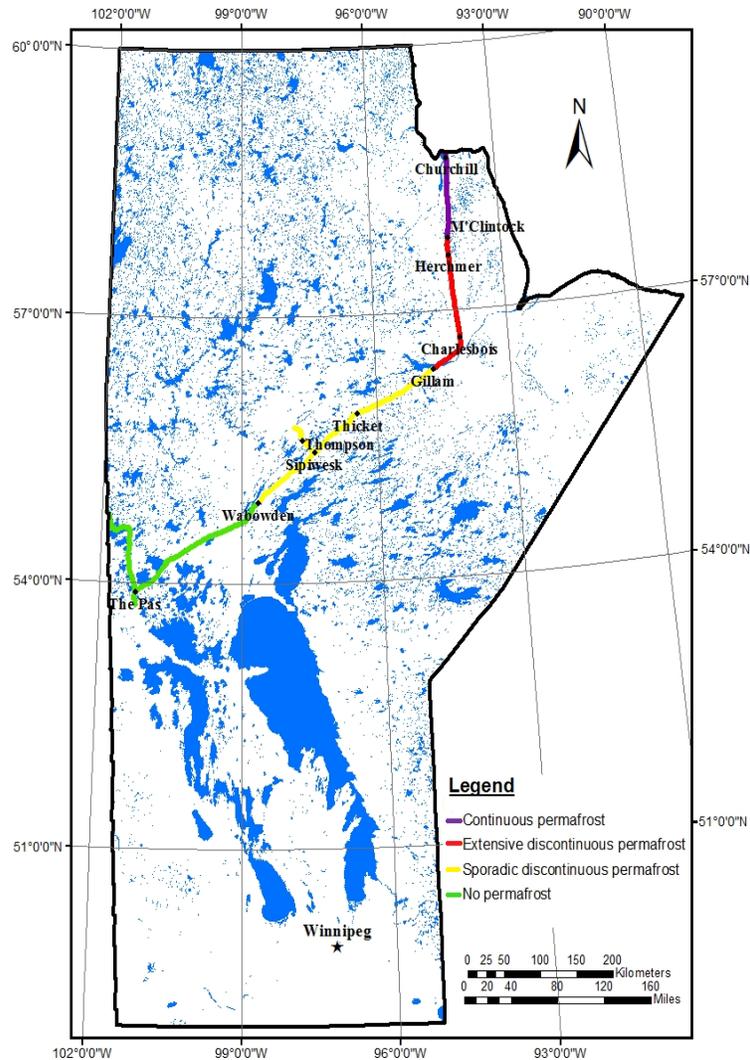


Figure 1. . Location of the Hudson Bay Railway (HBR) from The Pas to Churchill

PERMAFROST STABILIZATION TECHNIQUES

Permafrost stabilization techniques available can fall under these three broad principles:

- Controlling solar radiation
- Controlling heat convection
- Controlling heat conduction

The following sections discuss each of these in detail. There are a few stabilization techniques that do not fall under any of these three areas. These techniques are covered under a general topic of “‘other’ stabilization techniques”.

CONTROLLING SOLAR RADIATION

Embankment protection using this principle seeks to deflect the sun’s radiation, so only a reduced fraction gets to the embankment surface. Past literature has shown that controlling the amount of solar energy that strikes the ground can effectively impact permafrost health [10, 11]. Stabilization methods discussed in the following sections include adjusting the color of the embankment surface, and employing the use of awnings and shading boards

Adjusting Color of Embankment Surface

It is known that an increase in the surface albedo decreases the amount of incident solar radiation that is absorbed. Applying this principle, light colored or white embankment surface can help reduce the amount of heat absorbed by the underlying permafrost and thereby protect it. This can be applied on the shoulders of the embankment [12]. There are currently no known railroads utilizing this technique.

Awnings and shading boards

Awnings and shading boards (Figure 2) both act to reduce the sun’s energy getting to the ground. To investigate the effect of awnings and shading boards on ground temperature, Wenjie et al [13] conducted research on two Qinghai-Tibet Plateau test sites over a one year period; one covered with awnings and the other with shading boards. A control site was also set up which had no solar protection. Results indicated that in comparison to the control site, the awning site recorded an average of 46°F to 59°F lower surface temperatures and the shading board test site recorded 37°F to 41°F lower soil temperatures. Based on the research, awnings have a higher cooling effect, but they are also lightweight, so areas with prevalent strong winds are challenging for implementation.

In addition to reducing solar radiation, awnings and shading boards have been known to reduce water infiltration, minimize snow accumulation and increase convection cooling by utilizing airflow to remove heat from the embankment surface [14].

Shading boards and awnings are best placed in locations with significant solar radiation influence or where water infiltration is expected to be a significant factor for permafrost degradation. Damage due to natural or manmade occurrences,

such as wind damage or vandalism may reduce their effectiveness and increase maintenance costs.



Figure 2. Shading boards installed along the Qinghai–Tibet highway [15]

CONTROLLING HEAT CONVECTION

Stabilization methods utilizing this principle work by transferring heat through the movement of air. When air temperature is significantly higher in the embankment than the atmosphere, the embankment air becomes less dense and rises, carrying the heat with it and being replaced by a denser colder air. Stabilization methods discussed under this are crushed rock embankments, ventiducts, and heat pipes.

Crushed Rock Embankments

Crushed rock embankments function as ‘thermal semi-conductors’- in the winter when the temperature within the embankment is higher than that of the atmosphere, the crushed rocks induce Rayleigh-Bernard convection which causes the warm embankment air to rise and be replaced by the colder atmospheric air. In the summer however, very negligible convection transfer takes place because the air within the embankment is significantly colder and denser than that of the ambient air so it stays put within the embankment [16 – 21].

The only heat transfer to the embankment within the summer is through conduction. Due to the low thermal conductivity of the air and the small contact area of the stones, the rock layers function as a thermal insulating barrier, limiting heat flow into the embankment. This insulating effect causes a larger heat loss in the winter with limited heat gain during the summer. As a result, by employing crushed rock embankments the net heat transfer within a complete year cycle is a loss and therefore aids in preserving permafrost [22].

Qinghai–Tibet railway scientists researched various configurations (Figure 3) of these embankments to investigate their effectiveness:

- Interlayer
- Revetment
- U-shaped
- Protective toe berm

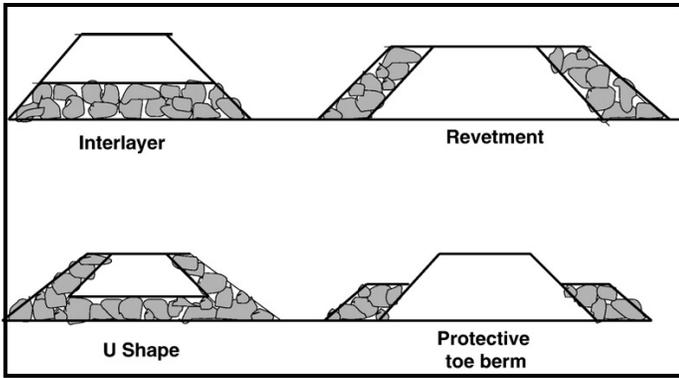


Figure 3. Various embankment configurations [23]

The results indicate that the thicker the overlying fine-grained sand and gravel, the weaker is the cooling effect of the underlying rock layer. When the thickness of the overlying layer is greater than 18ft, sections of the embankment begin to lose their cooling effect [24].

Stone embankments utilize natural wind currents and depend upon reliable air flow to remove accumulated embankment heat. Plugging due to snow or fines as well as the potential for differential settlements should be considered when deciding on this method. Availability of large aggregates close by is also a key factor that needs to be considered when choosing this as a stabilization technique.

A monitoring study conducted by Chen et al. [25] on the Chaidai-Muli Railway shows that in warm permafrost regions these embankments are more effective when they are shaded. The results showed that the embankments had no stabilizing effect on the south facing slopes which received more sunlight.

Another monitoring study conducted by Niu et al [26] on the Qinghai-Tibet railway also showed that crushed rock embankments which were effective in cooling the ground in the short term after their installation lost their thermal stability in the long term. These studies therefore suggest that to crushed rock embankments need to be combined with other stabilization measure to make them more effective.

Ventiducts Embankments

Ventiduct is a contraction of the phrase “ventilation duct”. A ventiduct embankment is basically a traditional embankment that has been fitted with perforated hollow pipes across. The pipes serve as “air culverts” that allows the transfer of air from the core of the embankment to the atmosphere [27 – 29].

Qinghai-Tibet railway scientists have carried out field ventiduct experiments using PVC and concrete ducts [30-34]. Monitoring efforts showed a net heat loss with embankment temperatures being lowered to below 32°F [35] The results also showed ducts buried flush or below the original ground surface to have greater cooling impact than those buried above the original ground surface.

The scientists also found out that as much as the ventiducts helped in cooling the embankment in the winter, it had a counter

effect of increasing heat gain in the summer since hot air got trapped in the tubes. To curb this they designed a new system with temperature sensor controlled shutters (Figure 4). When the ambient air temperature of the surrounding is higher than a preset value, the shutter get closed, otherwise it is opened [36]. This proved to be effective as temperature measurements over time showed embankments with these new ducts to be 33°F colder than those of the old ones [37, 38].



Figure 4. Temperature-controlled ventiducts [36]

Ventiduct embankments require natural wind currents to remove heat from the embankment. Areas with sufficient drainage and minimal snow accumulation tend to suit these systems best, as such conditions facilitate air flow through the pipes. Differential settlements can reduce air flow and may also increase maintenance requirements and ultimately reduce effectiveness.

Thermosyphons

Thermosyphons (Figure 5), also known as heat pipes were developed on the principle of convective heat exchange. It is a sealed, pressurized tube that is filled with a low boiling point liquid such as Freon, ammonia or carbon dioxide [39]. These are inserted into the embankment with their condensing fins above ground. In the winter when the ambient air temperature is lower than that of the embankment, the liquid gets heated up and evaporates into the fin area where it loses its heat and returns back to the bottom to start the whole process again. In the summer however, when the embankment temperature is lower than the ambient air temperature, the liquid stays put at the bottom of the tube. This prevents any reverse heat transfer and protects the underlying permafrost.

Heat pipes are very effective in cooling permafrost while guarding against heat transfer to the embankment in the summer months. They were first used along the Trans-Alaska Oil pipeline to successfully resolve the problem of transporting hot oil over permafrost. In the rail industry, the first known large scale use was along the Hudson Bay Railway at two 3-mile prototype testing sites. They successfully resolved about 90% of the settlement issues of the worse test site and even resulted in permafrost aggradation in some sections [40 – 42]. Thermosyphons have also been used at some of the most challenging locations along Qinghai-Tibet railway, in many cases together with other stabilization methods.



Figure 5. Thermosyphons [23]

Though effective, thermosyphons are very expensive. Hence, they are best suited for high risk sites with warm ice-rich permafrost. Damage during transport and operation is very detrimental as depressurization or obstruction of the cooling fins will render these devices useless [43].

HEAT CONDUCTION

Conduction is heat transfer between two or more objects that are in contact. The conductivity of water increases four-fold when it is frozen. Yu [20] attempted to use this unique property of water to aid in permafrost stabilization. He built a material with the properties of a thermal semi-conductor that will lower the ground temperature by increasing the heat loss in winter and decreasing the heat gain in summer. The material consists of a water-absorbing material in a sealed container, separated by layers of air. This material absorbs water and upon freezing its thermal conductivity increases about 10-fold from 0.11 to 1.2 W/m·K. The study is yet to be applied in cold regions engineering, but it has the potential of aiding in faster heat loss of embankments in the winter.

“OTHER” STABILIZATION TECHNIQUES

There are other stabilization techniques that could not be fit in any of the three broad areas so they are presented here.

Expanded Polystyrene Insulation

Installing insulation (Figure 6) increases the thermal resistance of the embankment. In the summer months when the embankment is colder than the ambient air, the insulation limits the amount of heat transmitted to the embankment. In the same way in the winter, it again shields the embankment and prevent heat within the embankment from escaping [16]. This acts to more or less keep the temperature of the embankment uniform. This method therefore is better suited to locations where considerably cold permafrost needs to be preserved.

Insulation was also tested on the HBR and it proved successful for the first few months. However, later results indicated that the insulation lost its impact over time [9].

In addition to keeping the temperature of the embankment uniform, polystyrene also resists water absorption and offers good mechanical strength as resistance against cracks and indentations from overlying ballast and trains [44]. However, the long term results indicate that the thermal protection of insulation alone may not be sufficient [9, 39].



Figure 6. Expanded polystyrene insulation [45]

Insulation layers are best used in locations where there is the expectation of high magnitudes of solar absorption by embankments during the summer months. They can also be used to minimize the required construction depth of the embankment. Water absorption issues and mechanical damage can decrease life span and effectiveness so these factors should be designed against if possible [46 – 48].

Dry Bridges

The dry bridge (Figure 7) is the most drastic and effective stabilization technique. It involves digging through the degrading permafrost to found piles on more stable permafrost below the active layer. It can be designed to take heavier loads, since it has a more stable foundation.

Cheng et al [23, 49] reports that a total of 78 mile length along the Qinghai-Tibet railway were fitted with dry bridges due to their very unstable nature (warm ice-rich permafrost). Monitoring efforts after their installation has indicated a maximum deformation height of 5mm so far, showing their effectiveness. It was further noticed that soils underneath them recorded lower temperatures than those without; depicting an added benefit of dry bridges shrouding the ground from direct sunlight and also allowing the free flow of convective winds underneath it which facilitates this cooling [50].



Figure 7. A dry bridge along the Qinghai-Tibet railway [23]

Possible failure modes include differential settlements of the piles if they are not founded on stable enough formations. They can also get damaged by natural disasters such as earthquakes, landslides or derailments. Preliminary research has shown this to be the most expensive of all the previously discussed methods and is therefore recommended to be utilized only in extremely thaw sensitive locations (warm ice-rich permafrost) [23, 49].

APPLICABILITY TO THE HUDSON BAY RAILWAY

As been shown in Figure 1, moving from The Pas (milepost 0) to Churchill encounters four varied subsurface conditions which are approximately:

- No permafrost: 0 mi - 136 mi
- Sporadic discontinuous permafrost: 136 mi – 326 mi
- Extensive discontinuous permafrost: 326 mi – 435mi
- Continuous permafrost: 435 mi – 510 mi

Past work by EBA (Figure 8), compilation of slow order records (Figure 9), track surfacing records and personal conversations with OmniTRAX Inc personnel have revealed the extensive discontinuous permafrost zone along the HBR to be the most problematic [6 – 8] EBA reported permafrost found here to be warm and ice-rich [9], a combination of the “worst kind” of permafrost. Most stabilization efforts in the past were therefore been directed towards this location.

Past literature and applications along the Qinghai-Tibet railway have shown that stabilization measures that combine radiation control, convection control, and conduction control achieve the most beneficial results [49 – 51]. After several years of experimentation and monitoring, Chinese engineers recommended an approach called the “roadbed cooling” which simply involves proactively combining several methods depending on soil temperature and ground ice content. Following their approach, the following sections provide preliminary discussion on possible combinations for the unique sections along the HBR. The sections have been grouped into two main groups according to the intensity of permafrost related problems experienced:

- Section 1: the sporadic discontinuous permafrost and continuous permafrost zones
- Section 2: the extensive discontinuous permafrost zone.

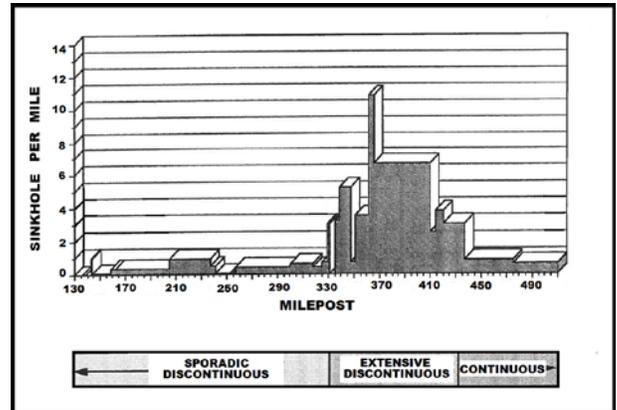


Figure 8. Sinkhole distribution along the HBR [52]

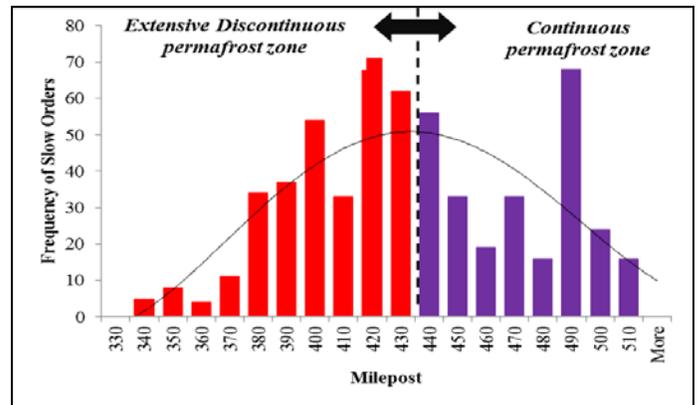


Figure 9. Summary of slow order frequency recorded along the HBR for 2014-2015

Section 1

Zhang et al. [53] studied the combined configuration of insulating boards embedded in a crushed rock embankment. The results indicated these embankments had lower core temperatures than that of crushed rock embankments alone.

Li et al. [54] also studied a combination of shading boards with crushed rock embankments. The combined advantage to be derived from this is the shading boards reduces the sun’s radiation getting to the embankment and crushed rocks make use of convection to lower the ground temperature. The shading boards can also reduce the amount of fine-grained soil and snow getting into the openings of crushed rocks. With optimal configuration depending on local factors this method was shown to be effective, but it did not show to any indication of

aggrading permafrost. This can be a possible economical approach of for the sporadic discontinuous and continuous permafrost zones, combining the passive methods to keep permafrost from thawing. A possible variation could be combining these with insulation boards, but there is no known literature of such implementations, so there is a need to first investigate the effectiveness of this configuration before its adoption.

Section 2

While the dry bridges would be the most effective engineering measure for the extensive discontinuous permafrost zone, it might not be the most economical approach.

Wen et al. [55] investigated a less expensive approach of combining insulating boards with thermosyphons. A numerical model was analyzed for four scenarios: just the embankments alone, embankments installed with only thermosyphons, embankments installed with only insulation boards, and embankments with both insulation boards and thermosyphons.

The model assumed a mean annual air temperature of 26°F on the Qinghai-Tibet plateau; this was further modelled to increase to 29°F over the course of 50 years. Results showed the stability of the first three configurations to be compromised without exception; the fourth was the most effective in maintaining the embankment integrity with the simulated warming trend.

Along HBR, test sites set up EBA proved heat pipes to be effective in stabilizing permafrost in the extensive discontinuous zone and sometimes even resulted in permafrost aggradation [40, 56]. The preliminary findings suggest that thermosyphons, perhaps complimented by insulation boards, may have potential as main stabilization method along the most challenging locations of HBR

CONCLUSIONS AND FUTURE WORK

The paper has provided a brief literature review on existing embankment stabilization solutions with consideration to the HBR. As has been seen no single stabilization technique is without disadvantages- either economical or engineering effectiveness. Mostly, combinations of two or more methods yields better results than a standalone method. Some preliminary suggestions of combinations have been made for the unique case of the HBR, but these have been made without thorough tests on the unique local factors of the different sections. Further studies are under way to quantify and optimize various configurations and come up with the most effective combinations for the HBR.

ACKNOWLEDGEMENTS

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Appendix D

**Utilizing Vegetation Index as a Proxy to Characterize the Stability
of Railway Embankment in a Permafrost Region. AIMS
Geosciences, 2 (4): pp. 329-344.**



Research article

Utilizing Vegetation Indices as a Proxy to Characterize the Stability of a Railway Embankment in a Permafrost Region

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Abstract: Degrading permafrost conditions around the world are posing stability issues for infrastructure constructed on them. Railway lines have exceptionally low tolerances for differential settlements associated with permafrost degradation due to the potential for train derailments. Railway owners with tracks in permafrost regions therefore make it a priority to identify potential settlement locations so that proper maintenance or embankment stabilization measures can be applied to ensure smooth and safe operations. The extensive discontinuous permafrost zone along the Hudson Bay Railway (HBR) in Northern Manitoba, Canada, has been experiencing accelerated deterioration, resulting in differential settlements that necessitate continuous annual maintenance to avoid slow orders and operational interruptions. This paper seeks to characterize the different permafrost degradation susceptibilities present at the study site. Track geometry exceptions were compared against remotely sensed vegetation indices to establish a relationship between track quality and vegetation density. This relationship was used as a proxy for subsurface condition verified by electrical resistivity tomography. The established relationship was then used to develop a three-level degradation susceptibility chart to indicate low, moderate and high susceptibility regions. The defined susceptibility regions can be used to better allocate the limited maintenance resources and also help inform potentially long-term stabilization measures for the severely affected sections.

Keywords: Site characterization; permafrost; remote sensing; track geometry; electrical resistivity; degradation susceptibility; NDVI

1. Introduction

Statistics gathered from the Federal Railway Administration (FRA) showed that 70% of all train accidents in 2015 in the U.S. were caused by derailments [1]. One of the most significant derailment causes include defects in track geometry, as trains have very low tolerances to vertical and horizontal imperfections [2]. Railway embankments located in permafrost regions globally are becoming more vulnerable to such occurrences due to accelerated permafrost degradation [3–7]. Permafrost degradation results in the formation of differential settlements, which can then potentially cause track geometry defects resulting in derailments.

Permafrost is defined as “ground that remains at or below 0 °C for at least two consecutive years for natural climatic reasons” [8]. Depending on the extent of the subsurface that is underlain by permafrost, three different permafrost types can be defined:

- *Continuous Permafrost:* 90 to 100% of the subsurface is underlain by permafrost, with the permafrost being only absent under deep bodies of water which do not fully freeze to the bottom in winter [8];
- *Extensive Discontinuous Permafrost:* 50 to 90% of the subsurface is underlain by permafrost [8]; and
- *Sporadic Discontinuous Permafrost:* Less than 50% of the subsurface is underlain by permafrost [8].

This study focused on the Hudson Bay Railway (HBR), a 510-mile track constructed within the permafrost region of northern Manitoba, Canada. The HBR, owned by OmniTRAX Inc. at the time of this study, serves as a critical linkage for passengers and freight from The Pas (milepost 0) to Churchill (milepost 510), connecting locations in North America to international destinations through the Port of Churchill. All three permafrost types occur along the HBR route. From The Pas to Churchill, there is a gradual northward transition from no permafrost zone, to sporadic discontinuous, to extensive discontinuous, and finally to continuous permafrost (Figure 1).

In response to an increasingly warming climate, the HBR has been experiencing differential settlements within its discontinuous permafrost zones during thawing summer seasons since the completion of the line in 1929. These differential settlements, termed “sinkholes,” have been found to develop in response to thawing of the underlying warm, ice-rich permafrost soils within the subgrade. Sinkholes mainly form in the discontinuous permafrost zones at transitions between no permafrost (fen) to permafrost ground (peat plateau), as the relatively warm fen loses its heat to the adjacent relatively cold peat plateau. Short sections of track that overlay these activated sinkholes may experience as much as 15 cm (five inches) of settlement during a single summer thawing season [9].

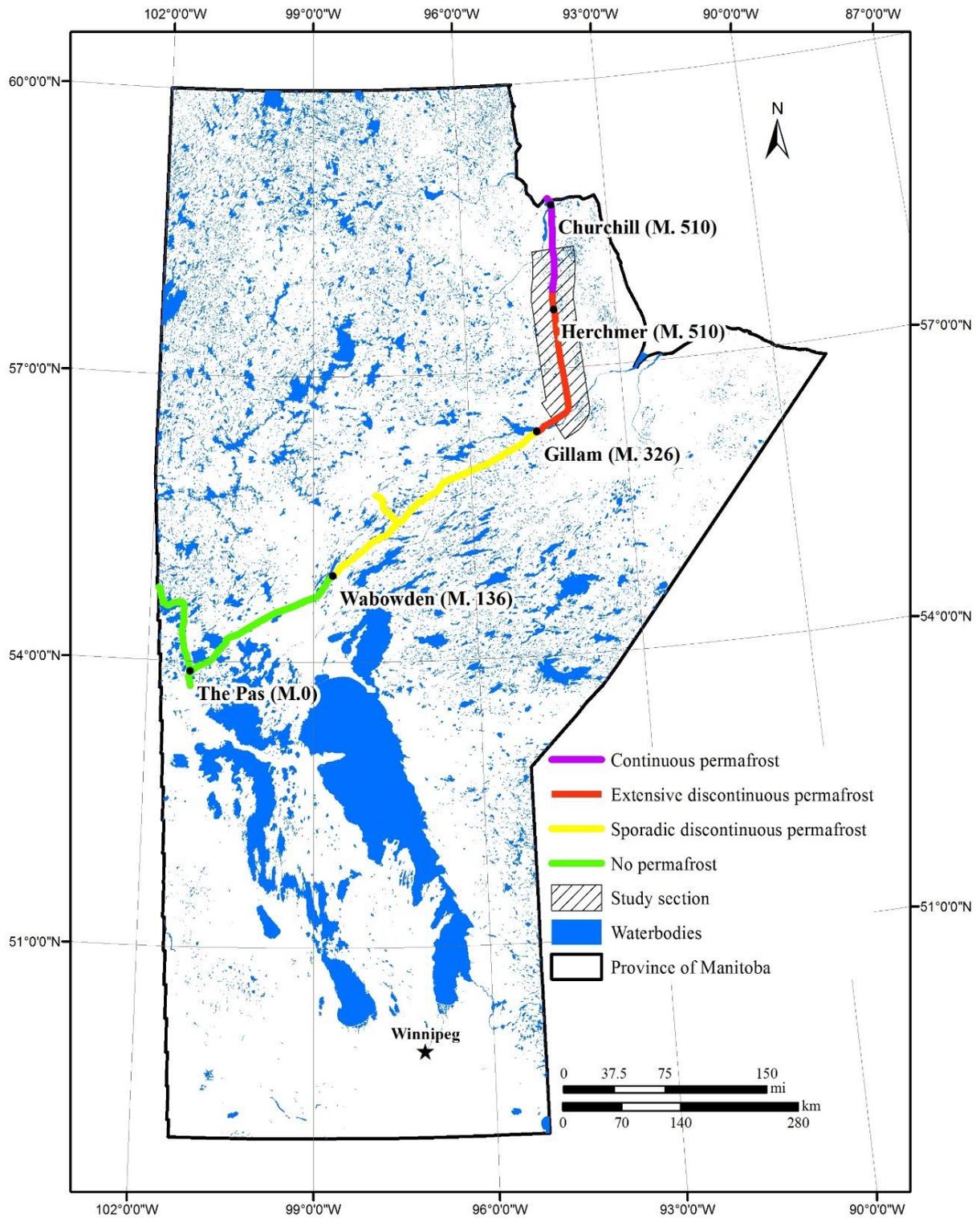


Figure 1. Location of the HBR from The Pas to Churchill showing the varying permafrost conditions.

To subvert the effect of sinkholes and keep the track safe and operational, extensive and frequent resurfacing with ballast is performed annually. Currently, maintenance is performed on as-needed basis. However, railway owners are interested in developing a data-driven understanding of the corridor conditions that can be used to effectively allocate limited maintenance resources and plan for long-term stabilization measures for severely affected sections. In a bid to address this challenge, this paper offers a first step toward a solution by characterizing the railway embankment and identifying different permafrost degradation severities along the HBR. Rather than using the traditional method of borehole drilling for characterization, which is time consuming and costly, this research proposes an integration of three technologies as a more rapid and economic method.

The proposed methodology involves employing an integration of track geometry analyses, remote sensing techniques, and geophysical profiling as investigative tools. More specifically, records of track geometry exceptions data were compared against remotely-sensed vegetation indices to establish a relationship between track quality and vegetation density, as past studies have shown vegetation pattern to have a strong influence on the relative intactness of permafrost [10,11]. Electrical resistivity tomography was then used to validate that the vegetation density and track quality indeed provided an accurate picture of the subsurface permafrost conditions.

2. Methodology

2.1. Study Area

Since the completion of the HBR in 1929, sinkhole formation has been an increasingly recurrent phenomenon during the summer thawing season. From 1976–1991, an engineering consulting company, EBA Engineering Consultants Limited (from here onwards referred to as EBA), was tasked to undertake extensive research along the rail corridor to understand the geothermal regime of the subsurface and to uncover the mechanism of sinkholes formation [9]. The reports produced by EBA indicate that the extensive discontinuous permafrost region between mileposts 330 and 430 is the most problematic segment of the HBR [12,13]. Recent track surfacing records, increases in slow orders (speed restrictions placed on a section of track to limit train speeds below regular limits due to unfavourable track conditions) [14], and interviews with OmniTRAX personnel confirmed that this section remains the most problematic, depicting increasing structural instability. Hence this section of the HBR, as well as an overlap in the continuous permafrost region to milepost 473, was chosen as the focus of the study (Figure 1).

2.2. *Data Analyses*

The following sections give brief backgrounds on the three individual techniques used—track geometry analyses, geophysical exploration, and remote sensing analyses. The last section describes how all three techniques were integrated for the route characterization study.

2.3. *Track Geometry Analyses*

The term *track geometry* refers to the measured relative positions of the different geometrical elements—profile, gauge, alignment, crosslevel, warp, etc. [15]—along a railway track in space and time [16]. Transportation authorities in different countries set maximum permissible thresholds for each of these different elements for a given set of traffic and operating conditions. All railway tracks across the country have to conform to such standards to be considered safe for operations. The HBR follows the standards set by Transport Canada.

Track geometry measurements may be obtained either through manual inspections or automated data collection by specialized vehicles. Manual inspections involve trained personnel using approved methods to take measurements of the various geometry elements of the track. This is time consuming and is usually only conducted at locations with noticeable deviations from track standards. Automated data collection, on the other hand, is a technique where a vehicle operating on rails, uses either laser or mechanical gauges, to take uniform and continuous measurements of the different geometry parameters as it travels along the corridor. The measurements also indicate locations where geometry deviations exceed or approach the limits allowed in approved standards. These tagged locations are known as *track exceptions* or *track defects*. In this paper, they are referred to as *track exceptions*.

The automated vehicle acquisition is the method used along the HBR to collect continuous data at one-foot intervals. Three complete sets of geometry survey data, one each, from 2012, 2013 and 2014, were obtained and used to extract track exception data with Andian Technologies' GeoPrint 3.30 software [17] for further analyses.

2.4. *Geophysical Investigation*

Electrical resistivity tomography (ERT) is the geophysical method that was adopted for the research. This method is known to work particularly well in permafrost areas [18–21]. ERT functions on the principle that different materials offer varying resistance to the flow of current, a property known as the material's resistivity. Water resistivity increases strongly at the freezing point due to the phase change from electrically conductive water to electrically non-conductive ice [22]. This intrinsic quality is what makes it easy to differentiate frozen permafrost table (high resistivity) from thawed saturated active layer lying on top of it (low resistivity).

Two sets of ERT field data collections were taken: one during October 2014 and a second during September 2015. The collections were scheduled during the fall season, when the top layer of soil was fully thawed, to allow for a clear delineation of the permafrost profile. A total of 10 sites were selected, mainly to match locations with borehole and geophysical data from EBA's past work, as it facilitated comparison between current and previous results. The SuperSting 2D multi-electrode system [23] was the instrumentation used for the ERT survey. At each test location, 28 electrodes were inserted into the ground at equal distances. Current was injected into the ground and a set of apparent resistivity values were measured by the electrodes, producing a 2D dataset along the profile. Acquired data was analyzed with Advanced Geosciences, Inc.'s EarthImager 2D inversion and modelling software [24] using a smooth model inversion. Results from this study were compared to spatially corresponding track exception data for the 10 sites to assess the trends between the two datasets. The objective was to infer subsurface conditions delineated by the ERT with the surficial data of the track geometry exceptions.

2.5. Remote Sensing of Vegetation Pattern

Vegetation has been identified as one of the key factors that influences the relative intactness of permafrost [25,26]; thus, changes in vegetation density have greater effect on the degradation or aggradation of permafrost than fluctuations in climatic regime [27]. A typical permafrost ecosystem has a thick and spongy mossy vegetation on top of it. The moss layer acts as an insulating mat that traps stagnant air to reduce the thermal contact between air and ground during the summer months. In addition to its insulating properties, the organic mat also cools the ground through the process of evaporation. Lastly, typical tree cover found within permafrost regions, such as *Picea mariana* (black spruce) and *Picea glauca* (white spruce), shroud the ground from the radiant heat of direct sunlight and thereby retard/prevent permafrost thaw. Since higher vegetation density was believed to depict a more protected/intact permafrost, it was also expected to correlate with higher level of track quality, i.e. locations that record lower track exceptions within the study area. Vegetation density was therefore used as a proxy for the relative intactness of permafrost.

Satellite remote sensing was employed in this analysis as it offers a cost-effective quantitative approach to analyse the entire study area. The investigative period was limited to 2012–2014 to correspond to the available track geometry data. Data from only Landsat 8 (commissioned in 2013) was used since data from Landsat 7 was unusable due to its scan line corrector failure since May 2003 [28]. Pre-requisites for scenes used for the investigation were that they had to be from the summer season since the vegetation is at the peak of the growing season and the ground is snow-free. The scenes also had to be cloud-free to prevent erroneous estimations from cloud contamination. Landsat 8's scene from row 31, path 20 acquired in July 29, 2014 is the only one that met these selection criteria. Although this data is from a single time stamp, the authors believe it is still representative of site conditions because in the relatively short investigative period of 2012–2014, no

extreme environment-altering phenomena such as wildfires occurred, leading to the hypothesis that the plant communities within the study site remained the same throughout the three-year investigative period. The data was downloaded as a geometrically and radiometrically corrected Level 1 product. It was first converted to radiance and then to top-of-atmosphere (TOA) reflectance, using the steps outlined by Chander et al. [29]. To analyze vegetation condition (i.e., differentiate between “normal” growing conditions and stressed), Normalized Differenced Vegetation Index (NDVI) was calculated using the TOA image after Rouse et al. [30].

2.6. Integration of Methods

Results from the ERT surveys at the 10 sites were compared against the track exception data to identify trends between these datasets. The objective was to infer subsurface conditions delineated by the ERT from the surficial data of the track exceptions. After establishing this relationship, the NDVI from the remote sensing analyses was compared against their corresponding average number of track exceptions recorded. This analysis was modelled after Roghani et al.’s approach [31] by dividing the study section into 22-mile sections, resulting in six subsections from milepost 341 (southern end) to milepost 473 (northern end). The process is summarized in Figure 2. The corresponding track exceptions per mile of track were calculated by combining the recorded yearly average exceptions per section and dividing them by the segment length (22-miles).



Figure 2. Process for determining relation between NDVI and track geometry exceptions.

3. Results and Discussion

3.1. Relationship between Track Geometry Exceptions and Subsurface Profile

A plot of the six subsections against their recorded average geometry exceptions indicated a general increasing trend in exceptions from subsection 1 to 6 (Figure 3) which confirms worsening track conditions from south to north.

Results of the subsurface profiles from the ERT investigation are displayed along a plot of the study section in Figure 4. The legend at the bottom right of the figure provides an explanation of the color scheme from blue to red, representing low to high resistivities. Palacky and West [32] found that the average resistivity for permafrost materials is 10,000 ohm. Figure 4 shows that several

locations recorded a resistivity of 10,000 ohm indicating the presence of permafrost (indicated by the red color).

From Figure 4, it can be seen that the only site underlain by well-defined continuous permafrost is milepost 382. For all other sites, various degrees of permafrost degradation were observed. Particularly noteworthy is that excluding the subsurface profile of milepost 363, the southern sections of the study area were found to be almost devoid of permafrost. The lack of permafrost in the southern sections correlate with lower records of track exceptions in the south as observed in Figure 3. The northern sections, which recorded higher track exceptions, have permafrost present but they seem to be actively thawing, as indicated by the profusion of thawing transition zones. These subsurface profiles suggest that permafrost zones classification by EBA (shown in Figure 1) is changing, as permafrost degradation appears to be moving northward. It is likely that the southern boundary of the extensive discontinuous permafrost zone is transitioning into a sporadic discontinuous zone, whereas the southern boundary of the continuous permafrost zone may also be converting into extensive discontinuous zone. The results also confirm EBA's hypothesis that sinkholes develop at the permafrost transition zones, as thawing northern sections with the most transition zones also recorded the high occurrences of track exceptions.

Based on these analyses, it can be concluded that locations with high track geometry exceptions are likely underlain by thawing permafrost and locations with few or no track exceptions are mostly devoid of permafrost. With this relationship established, the next step was to discern the relationship between track exceptions and vegetation trends.

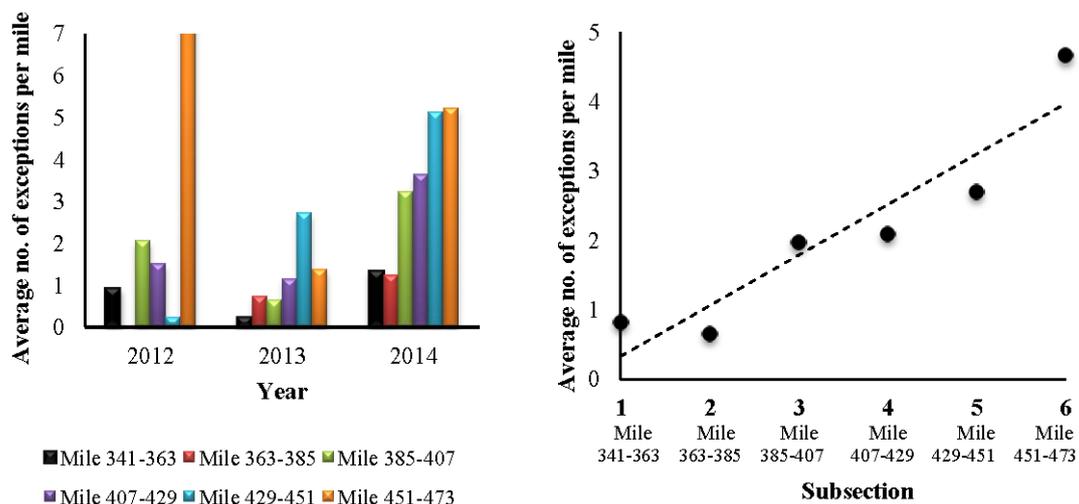


Figure 3. A plot of track exceptions recorded for the six subsections in 2012–2014 (left); and a plot of the average track exception recorded for the investigative period for each subsection (right).

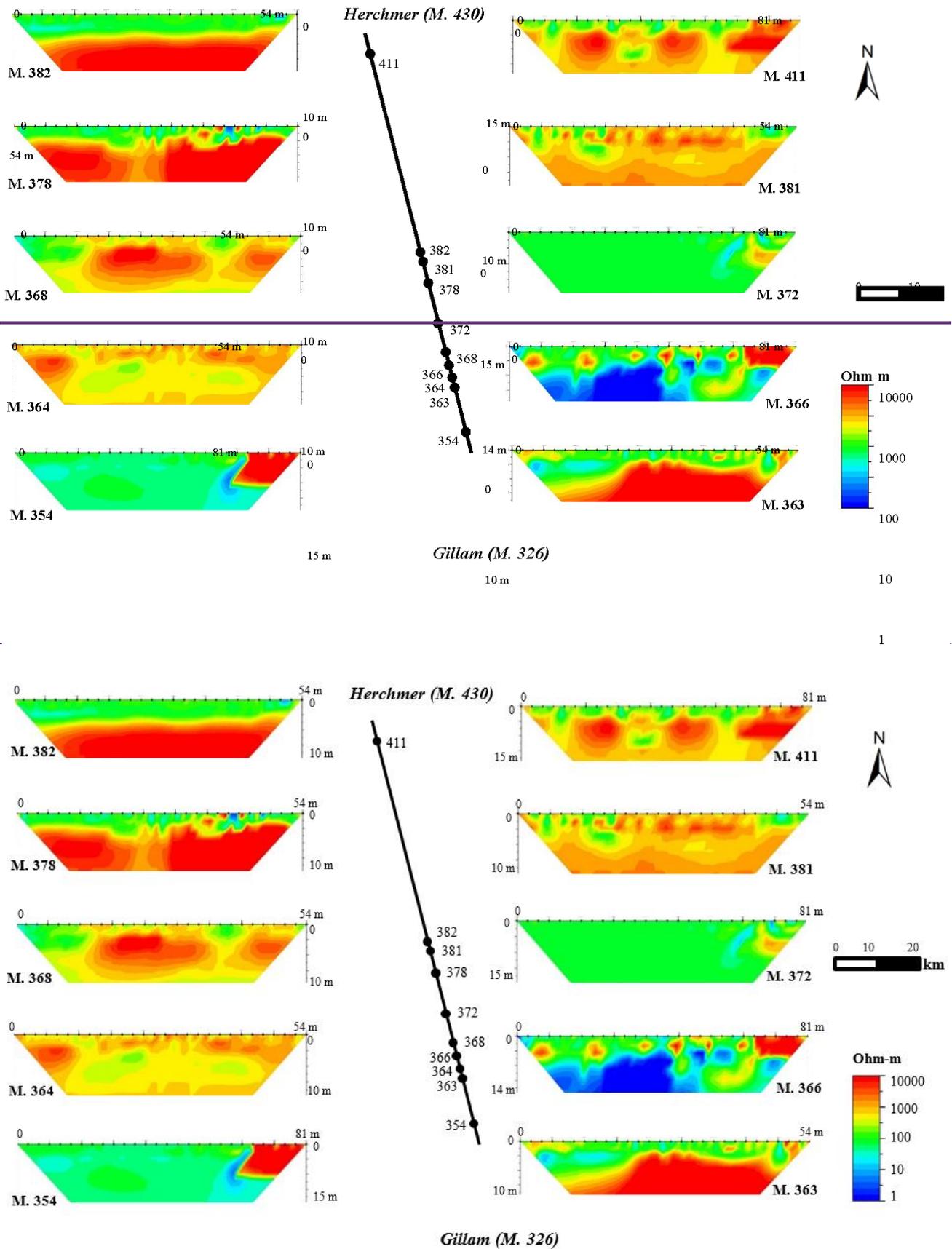


Figure 4. Subsurface profiles from the ERT investigation displayed along the track route of the study section, showing ground resistivities from low resistive thawed soils in blue to highly resistive permafrost layers in red color.

3.2. Relationship between Vegetation and Exceptions

NDVI was compared against the corresponding average number of track exceptions recorded for each of the six subsections. A plot of the NDVI against subsection shows a general negative correlation from section 1 to 6 (Figure 5A), which indicates a decrease in the vegetation density as one moves northward. A plot of the NDVI versus the track exception also shows a negative correlation indicating that as vegetation decreases, the number of track exceptions increases and vice versa (Figure 5B).

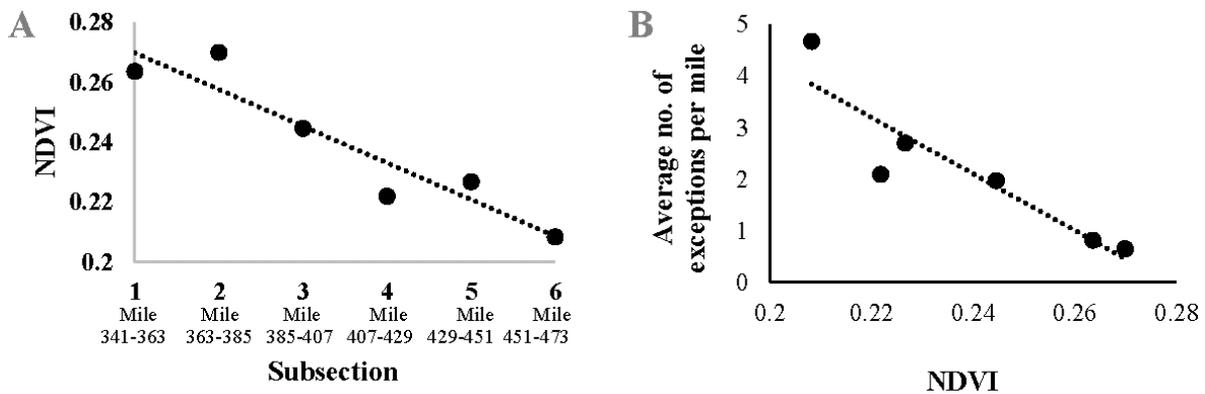


Figure 5. A plot of track sections versus NDVI showing the tendency to find less vegetation as you move northwards (left); and NDVI versus track exceptions showing that it is more likely to find track exceptions in locations with little vegetation and vice versa (right).

Photo images were taken in 10-second intervals while traversing the entire study area by a hi-rail truck. A comparison between the photos and research findings revealed that the northernmost sections with the lowest NDVIs (Subsections 5 and 6) are generally devoid of tree cover. This is intuitive; however, a more noteworthy finding was that these sections had substantial amounts of ponded surface water close to the embankment shoulders. Figure 6 shows two such typical images for milepost 468 (Subsection 5) and milepost 448 (Subsection 6). Conversely, the southernmost sections, which recorded the highest NDVIs, had denser vegetation with no surface water close to the embankment shoulders (Figure 7). From these photos, it was realized that the low NDVIs obtained for this particular study site translate not only to low vegetation densities but also to high percentage of ponded surface water.



Figure 6. Photos of milepost 468 (left) and milepost 448 (right) showing no tree cover and ponded water close to embankment shoulders.



Figure 7. Photos of milepost 349 (left) and milepost 377 (right) showing population of trees and no surface water ponded close to the embankment shoulders.

These photos also reinforced the perceived relationship between the NDVI and track exceptions, as past literature have shown collected waterbodies in the form of ponds and lakes have deleterious effects on underlying permafrost. Ponded water absorbs the sun's heat and transfers it to the permafrost table [33], which explains why the northernmost sections recorded higher frequencies of track exceptions, indicative of permafrost degradation.

3.3. *Degradation Susceptibility Chart*

As the fundamental aim of this study was to characterize the permafrost degradation susceptibility along the HBR, the established relationship between the NDVI and track exceptions

was used to develop a degradation susceptibility chart. The chart was developed to delineate sections in the extensive discontinuous permafrost zone that will require additional maintenance attention and those that will not. It should be noted that the defined classifications are empirical and are based on parameters specific to the extensive discontinuous permafrost zone of the HBR. Any adaptation of the methodology to other sites requires site specific analyses.

The average number of exceptions recorded was used as the basis of the chart. Locations that developed a maximum of one exception per year were generally considered stable and within acceptable performance levels, whereas locations that developed more than 2.5 exceptions are of concern and need to be mitigated [31]. Using these two track exception limits, a three-level severity chart was developed. The results are summarized in Figure 8 and Table 1.

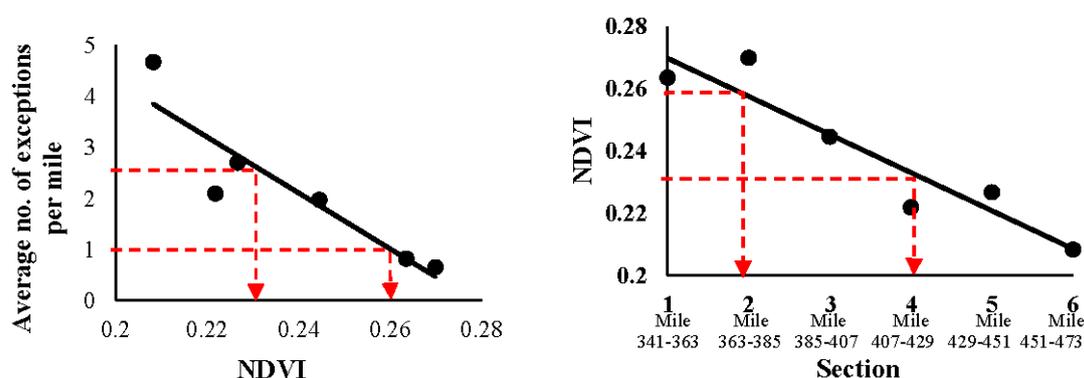


Figure 8. Defining percentiles for developing severity chart.

Table 1. Permafrost degradation susceptibility chart developed for study section along the HBR.

Rating	Degradation Susceptibility	Vegetation	Exceptions	Mileposts
1	Low	$\text{NDVI} > 0.26$	$E < 1$	341–363
2	Moderate	$0.23 \leq \text{NDVI} \leq 0.26$	$2.7 \leq E \leq 1$	363–407
3	High	$\text{NDVI} < 0.23$	$E > 2.7$	407–473

A rating of 1 represents a low degradation susceptibility region, located between mileposts 341 and 363. This region is predicted to develop no more than one track exception per mile annually and is characterized by having continuous vegetation and no ponded surface water, with an NDVI of 0.26 or higher. The region can be inferred as being the least susceptible to permafrost degradation due to the fact that it is likely underlain by a thawed subsurface or a stable intact permafrost.

A rating of 2 represents a medium degradation susceptibility region, located between mileposts 363 and 407. This region is predicted to develop between 1 to 2.5 track exceptions per mile annually, with an NDVI between 0.23 and 0.26.

A rating of 3 represents the northernmost extent of high degradation susceptibility, located between mileposts 407 and 473. This region is predicted to develop at least 2.5 track exceptions per mile every year and is characterized by having sparse vegetation with water ponded close to the embankment shoulders, and an NDVI of 0.23 or lower. The region can be inferred as being most susceptible to permafrost degradation due to the fact that it is likely underlain by an actively thawing permafrost table with many transition zones.

4. Conclusions and Future Work

This study looked into using innovative methods to characterize permafrost degradation susceptibility along the deteriorating railway embankment of the Hudson Bay Railway (HBR) in northern Manitoba, Canada. A combination of track geometry analyses, geophysical explorations, and remote sensing techniques was used to locate and delineate the severity of the different stability challenges found along the HBR.

The analyses revealed that locations with high records of track geometry exceptions are likely underlain by thawing permafrost, whereas locations with low geometry exceptions tend to be devoid of permafrost. A comparison of the track exceptions against NDVI confirmed that locations with low NDVI have high records of track exceptions, which is indicative of permafrost degradation. The converse was found to also hold true.

Photo surveys taken at the study site revealed that for the HBR corridor, low NDVI does not only translate to the typical interpretation of low vegetation density, but more importantly, to an accumulation of ponded water close to the embankment shoulders. These photos also reinforced the perceived relationship between NDVI and track exceptions, as past literature concluded surface water to have a detrimental effect on the underlying permafrost. This study confirmed that ponded water is an important contributor to the permafrost degradation found along the HBR.

The established relationships were used to develop a three-level permafrost degradation susceptibility chart with ratings of 1, 2, and 3 representing low, moderate and high susceptibility regions, respectively. The chart was developed to delineate sections in the study area that need more frequent maintenance attention and represents a first step towards developing a data-based approach to maintenance activities for the HBR. The defined susceptibility regions can be used to more strategically allocate limited maintenance resources and narrow down the consideration of long-term stabilization measures for segments that are more severely affected.

The study also illustrated that earlier permafrost zone classifications by EBA may be shifting, as permafrost degradation was seen to be moving northward. It is likely that lower boundary of the extensive discontinuous permafrost zone is evolving into a sporadic discontinuous zone, and the lower boundary of the continuous permafrost zone may also be transitioning into an extensive discontinuous zone. Future work should refine these current boundaries.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

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