A review of design and adaptation of embankment infrastructure built on permafrost under a changing climate

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ABSTRACT
Arctic regions are sensitive to climate warming, where increasing climatic temperatures and alterations in weather impact permafrost stability and place both existing and future infrastructure at risk. Permafrost thaw impacts industrial and residential infrastructure from unacceptable settlement to complete failure, where linear infrastructure is susceptible to damage. This paper summarizes the current knowledge about adapting and designing infrastructure built on permafrost, focusing on the railway embankments. First, a review of permafrost degradation effects on infrastructure and some examples are presented. The state-of-the-art reliability analysis in permafrost regions is summarized, emphasizing railway embankments design and maintenance. In addition, this paper notes the knowledge gaps regarding the reliability of embankment infrastructure in permafrost regions, which shows that the long-term effects of climate change on infrastructure are not considered. At the end, suggestions for future research ideas are presented.

RÉSUMÉ
Les régions arctiques sont sensibles au changement climatique, où l'augmentation des températures climatiques et les modifications du temps ont un impact sur la stabilité du pergélisol et mettent en danger les infrastructures existantes et futures. Le dégel du pergélisol a des répercussions sur les infrastructures industrielles et résidentielles, allant d'un tassement inacceptable à une défaillance complète, les infrastructures linéaires étant susceptibles d'être endommagées. Cet article résume les connaissances actuelles sur l'adaptation et la conception des infrastructures construites sur le pergélisol, en se concentrant sur les remblais ferroviaires. Tout d'abord, un examen des effets de la dégradation du pergélisol sur les infrastructures et quelques exemples sont présentés. L'état de l'art de l'analyse de la fiabilité dans les régions de pergélisol est résumé, en mettant l'accent sur la conception et la maintenance des remblais ferroviaires. En outre, cet article relève les lacunes dans les connaissances concernant la fiabilité des infrastructures de remblais dans les régions de pergélisol, ce qui montre que les effets à long terme du changement climatique sur les infrastructures ne sont pas pris en compte. Pour finir, des suggestions de recherches futures sont présentées.

1. INTRODUCTION

Permafrost thaw and alteration, as a result of climate warming, is impacting the Arctic landscape altering the way of life for northern communities, their infrastructure, safety, and prosperity. A large amount of data is currently being collected by researchers worldwide to characterize these permafrost changes due to climate change effects (Hjort et al., 2022). Based on current air temperature prediction models (Masson-Delmotte et al., 2021), the GMAT (ground mean annual temperature) continues to rise about 1-3.7˚C across the Arctic by 2100 (Bush & Lemmen, 2019), which results in permafrost thawing, active layer thickening, and the potential for widespread thaw settlement. Yokohata et al. (2020) predicted that the permafrost regions' extent will be reduced by about 20-50% by 2100 due to climate changes. Infrastructure built on permafrost relies on the strength and stiffness of the frozen ground, and as it settles and shifts, this infrastructure becomes very vulnerable to damage, even collapse (Vahdani et al., 2022).

The communities and industrial developments in permafrost regions require transportation infrastructure (roadways, airports, railways), and, in these regions, transportation is of vital social, economic, and political importance (Regehr et al., 2013). However, warming climate conditions leads to the failure of existing and future transportation infrastructure; for example, in Alaska, infrastructure damage caused by permafrost thaw is expected to cost $97 to $200 million depending on future emission scenarios by 2099 (Melvin et al., 2016). Reliability studies are critical to enabling sustainable design and maintenance of the existing and future infrastructure to reduce thaw-induced damage's economic and social impacts. However, there is limited information published about reliability studies for infrastructure in permafrost regions for prioritizing infrastructure maintenance, construction, and replacement. Owners and managers of northern infrastructure make less informed decisions due to a lack of available information.

This paper aims to summarize current knowledge about adapting and designing infrastructure built on permafrost, focusing on the railway embankments and discuses about where further research is required.

2. EFFECTS OF PERMAFROST DEGRADATION ON INFRASTRUCTURE

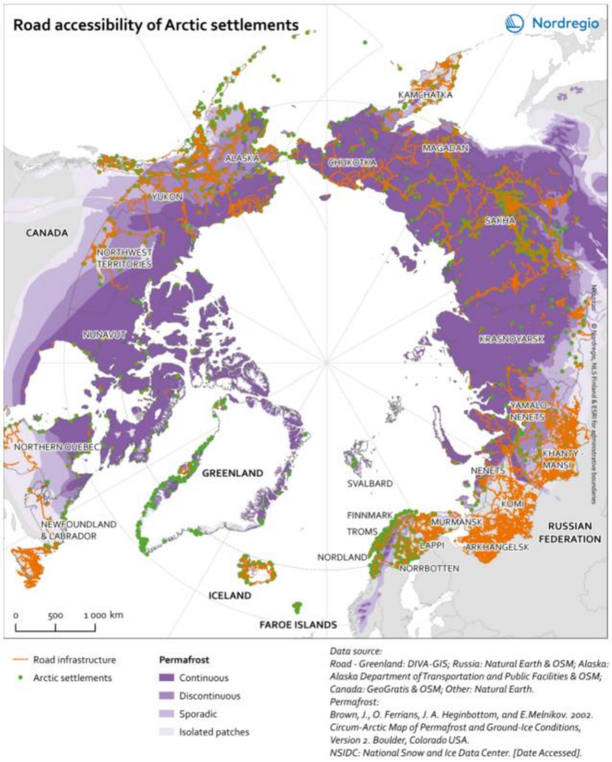
Figure 1 illustrates the intersection of roadways and permafrost; the north is connected by road and rail embankment that traverse continuous to discontinuous permafrost zones. The transportation infrastructure consists of regional granular fill roadways, railways, and airports. Major roadways/highways include the Northwest Territories (NWT) Highway 3, which connects Yellowknife, NWT, to the Canadian Highway network; the Dempster Highway, which connects Inuvik, NWT to Dawson City, Yukon Territory (YT); the Alaska Highway, which is the only year-round ground transportation link between Alaska and the lower forty-eight states of the United States; and the more recent Inuvik Tuktoyaktuk Highway which opened in 2017. In addition, the Dalton Highway connecting Fairbanks and Prudhoe Bay, Alaska, is in permafrost regions (Longo Eder et al., 2007).

Railway infrastructure has been developed over permafrost in Canada, the United States, China, and Russia. Compared to other Arctic countries, Russia has the most developed rail network on permafrost, with at least 5,000 km of railway track. In China, the Qinghai-Tibet Railway (QTR) crosses about 550 km of the continuous permafrost region and 82 km of the discontinuous permafrost region. Railways built in North America include the Alaska Railroad connecting Seward to Fairbanks, a small section of the Quebec North Shore and Labrador Railway, and the Hudson Bay Railway, connecting Canadian National (CN) railways to the Hudson Bay Port in Churchill, Manitoba.

Climate warming was not anticipated at the time of design for most existing infrastructures, and the magnitude of warming was underestimated by others. The major design consideration for road and railway construction was to limit fill embankment to just enough material to avoid thaw. Therefore, many embankments were constructed with insufficient thickness to adequately protect the underlying permafrost against climate warming (Roghani, 2021; Sadollahzadeh, 2021). The impact of neglecting climate change, particularly permafrost degradation, has been increased maintenance and embankment failures across the north (Hajitaheriha et al., 2021). According to some studies, under the SSP5-8.5 scenario defined by the IPCC (Masson-Delmotte et al., 2021), the geographic area underlain by permafrost is expected to decline by 20-50% by 2100 (Yokohata et al., 2020); thus, the need for climate adaptation becomes increasingly urgent.

2.1 Common failure modes

Due to permafrost degradation, infrastructure can fail in different ways. Brooks (2019) provided a summary of common failures associated with infrastructure built on permafrost. Based on her study, for 89% of these infrastructures, failure due to thaw settlement was the most common failure mode. For railway embankments either only thaw settlement failure was observed (Alaska Railway) or combined with sudden collapse (Hudson Bay Railway) compared to the other failure modes like thermal cracking and lateral embankment spreading, sudden collapse, etc, as observed in other infrastructures listed.



Data source:
Road - Greenland: DIVA-GIS; Russia: Natural Earth & OSM; Alaska: Alaska Department of Transportation and Public Facilities & OSM; Canada: GeoGratis & OSM; Other: Natural Earth.
Permafrost:
Brown, J., O. Ferrians, J. A. Heginbottom, and E.Melnikov. 2002. Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2. Boulder, Colorado USA.
NSIDC: National Snow and Ice Data Center. [Date Accessed].

Figure 1. Permafrost regions and road infrastructure showing the extensive usage of roads on permafrost (Photo credit: Nordregio Group).

2.2 Canadian examples

The permafrost areas of Alaska and Canada have the most reliable transportation infrastructure for moving goods and people via roads and railways, and airports (McGregor et al., 2008). For example, despite huge spending in maintenance costs, the Alaska Highway's ride quality and safety standards have been deteriorating in recent years (Dore & Fortier, 2010).

Some examples of infrastructure built in permafrost regions damaged by permafrost thawing help illustrate the impacts of climate change.

2.2.1 A provincial road section in Northern Manitoba (PR391)

The #391 provincial road section in Northern Manitoba near Thompson, built in the 1960s, is another case study of documented permafrost degradation located in sporadic permafrost zone. During its operation, it experienced differential deformation (Batenipour et al., 2014). The former asphalt pavement was replaced by gravel surface in the 1990s to reduce the rate of permafrost degradation because the black asphalt surface absorbs more solar radiation than gravel. Although the initial height of the embankment was around 2 metres, approximately 4 metres of extra gravel material has been placed on the embankment over ten years to keep the roadway operational. Drilling and ground temperature measurements revealed evidence of permafrost degradation beneath the embankment's toe and side slopes.

2.2.2 Hudson Bay Railway

The Hudson Bay Railway (HBR) is a 510-mile railway constructed on permafrost in the Hudson Bay lowland. Its construction began in 1914 and was not completed until 1929. Construction was suspended during 1917 and 1926 and by a re-elevation of the terminal site resulting in a substantial shift northward to the Port of Churchill, and during this time, little or no maintenance was done (Addison, 2015).

The results of studies on the effect of climate change on Hudson Bay lowland show that the mean annual ground temperature has risen between 0.3–1.0°C in the last 25 years, leading to permafrost degradation. In particular, the discontinuous permafrost under the mid-section of the HBR has experienced significant thaw settlement since construction of the railway, given rise to sinkholes, was as much as 15cm settlement in the railway track has been recorded. In 1976, already dealing with sinkhole issues, the rail owner at the time, Canadian National Railway (CN), contracted an Arctic geotechnical consulting firm to better understand the sinkhole development, and some studies were conducted from March 1977 to August 1991. These studies provide important information on the railway and historical records of engineering projects completed on it. The site investigations revealed a clear linkage between the location of sinkholes and transitions from permafrost to non-permafrost terrain, which ultimately resulted in using two stabilization methods for the rail line (Addison, 2017).

One method utilized heat pipes as an active method to remove the heat from the ground during the summer, and proved to be effective (Addison, 2015). Thermosyphons are also known as heat pipes categorized in the heat convection methods. The heat convection method works by transferring heat through the movement of air. In 1987 a prototype installation was completed to test the effectiveness of heat pipes (Hayley, 1989). The results showed a positive performance, and then four hundred heat pipes were installed at two 3-mile sites (Addison, 2015). Ground temperature measurements showed heat pipes were effective in lowering the temperature and resulting to ground freezing in some areas; They were effective at about 90% at the Charlebois and 60% at the Sipiwesk site; also, infrared and pressure testing was used to confirm the effectiveness of thermosyphons (Addison, 2015).

The second approach used on the HBR was installing surface insulation to increase the thermal resistance of the embankment (Addison et al., 2016). In the summer, insulation decreases the heat transition to the embankment, and in the winter, it prevents heat from escaping from the embankment. It should be operated as close as possible to the surface; they were installed at the surface of HBR. They were successful at first, but they lost their effect in the next month hence it was suggested insulation should be used in addition to other methods (Addison et al., 2016). Insulation is suitable for regions that contain cold permafrost and constructed with careful quality control.

These examples are just a few documented cases that demonstrate the impact of permafrost degradation on infrastructures. Several additional incidents are not included here, and more failures occur daily that are not published (Hjort et al., 2021).

3. DESIGN AND ADAPTATION OF PERMAFROST EMBANKMENT TO CLIMATE CHANGE

There are two major concerns related to infrastructure in permafrost regions: design of new infrastructures and maintenance of existing infrastructure. Considering climate change, tools are required to aid decision-makers in prioritizing infrastructure maintenance, replacement, and construction and potentially justifying the use of mitigation strategies for embankments on permafrost. Thus, in recent decades, guidelines and frameworks have been developed to address these concerns at the site scale.

3.1 Standards and guidelines

3.1.1 CSA PLUS 4011:19 Guideline

The CSA PLUS 4011:19 Guideline was developed by the Canadian Standards Association (CSA) group. The guideline describes methodologies for estimating the long-term durability of buildings located on permafrost foundations in northern Canada. This guideline aims to reduce the risk of system failure caused by climate change at the design stage and prepare for the effects of climate change expected in the future. This guideline was first developed in 2010 to aid community decision-makers in considering the effects of climate change on permafrost during the location, design, and maintenance of new infrastructure. The CSA PLUS 4011:19 is a modified version of the first guideline, and it is broader and applies to all new infrastructure in permafrost areas, notably resource development infrastructure.

The guideline covers assessment and design methods to determine the extent of site investigation and engineering design services needed for effective structure adaptation to climate uncertainty and warming. The screening process, described in the guideline, determines and assesses the prospective sensitivity of structures to the impacts of climate change on permafrost. The process requires information about the site's ground temperatures, ground materials, and ground ice content. Screening also includes predicting ground temperatures toward the end of the service life of the infrastructure by extrapolating previous temperature trends and assessing climate forecasts. These data are used to evaluate the vulnerability of permafrost to climate change. To estimate the risk posed by the project, this sensitivity is paired with an assessment of the implication of permafrost degradation on foundation failure.

The following are the key components of the process outlined in this guideline: 1) field analysis of permafrost material properties and temperatures; 2) prediction of foundation ground temperatures over the life span of the structure/embankment; 3) determination of climate-induced risks posed by the project; 4) geothermal modeling of the suggested foundation over its life span, and 5) development of a detailed monitoring and maintenance plan.

The flowchart for adapting infrastructure, located on permafrost, to changes in future climate consists of two stages. In Stage One, the climate change assessment stage, the possible sensitivity of the proposed structure to the impacts of climate change on permafrost is first calculated, and related hazards are assessed. The screening might be done for a single project or the development at the town-site level. The climate change screening defines the design services needed to address risks caused by climatic change and its uncertainty. Stage Two permits the engineers to evaluate the foundation design needed to build a project.

3.1.2 Guidelines for development and management of transportation infrastructure in permafrost regions

McGregor et al. (2010) published the "Guidelines for development and management of transportation infrastructure in permafrost regions" by the Transportation Association of Canada. This guideline is a compilation of best practices for transportation infrastructure planning, design, construction, maintenance, and rehabilitation in northern Canada's permafrost areas. Although the emphasis is on all-season roadways, the information offered is applicable to railways and airports. This report provides case studies and the lessons learned from development of transportation infrastructure on permafrost in Canada. This information is important for designers and engineers when developing future infrastructure on permafrost. Given the increased cost of constructing and managing transportation infrastructure in permafrost regions compared to the non permafrost regions, a methodical planning strategy is essential to optimize costs.

The guideline divides the planning step in the construction of new transportation infrastructure or the improvement of an existing one into three stages:

- Assessment of transportation requirements and functional needs
- Site investigation and evaluation
- Planning

Analyzing the infrastructure's sensitivity to climate change is critical and must be considered throughout these three stages.

Detailed topics in these guidelines include site investigation, different types of materials for construction in permafrost regions, engineering considerations for designing a transportation system. Also, it provides information about the special protection techniques to preserve permafrost under transportation infrastructure, adequate drainage provided near the infrastructure, and a general guideline for management and maintenance of transportation infrastructure.

3.1.3 CAN/BNQ 2501-500: Geotechnical Site Investigations for Building Foundations in Permafrost Zones

The "Geotechnical site investigation for building foundations in permafrost zones" published by the National Standard of Canada (2017) was aimed at promoting long-term sustainability and resiliency of northern infrastructure in Canada faced with ongoing climate change concerns. The Northern Infrastructure Standardization Initiative (NISI) includes this standard, as well as the other four in the series:

- CAN/CSA-S500-14: Thermosyphon foundations for permafrost constructions.
- CAN/CSA-S501-14: Modifying the impacts of permafrost deterioration on existing building foundations.
- CAN/CSA-S502-14: Addressing changing Snow Load Risks in Canada's North.
- CAN/CSA-S503-15: Planning, designing, and managing community drainage systems in northern settlements.

This standard is intended for geotechnical consultants, although building owners, designers, constructors, and regulators may also use it. It was developed to achieve a consistent methodology for geotechnical site investigations, including data collection, site condition reports and evaluations, and seasonal and annual climate conditions. It predicted future climate conditions that might exist during the service life of building foundations. Implementing this standard would decrease maintenance concerns over time and help to avoid irreversible structural damage caused by climate change or incorrect site evaluations. This standard specifies the requirements for various aspects of a geotechnical investigation, including planning, development of the investigation program, qualifications for geotechnical consultants who perform the investigation, initial site evaluation, site visit, and determining the project's risk level, and detailed reporting.

The desktop evaluation is an essential part of this standard. The desktop evaluation is used to develop the site investigation program (drilling, test pit excavation, laboratory testing, equipment, level of climate change analysis needed, and so on) and to understand the outcome s from the site investigation data. The desktop evaluation is adapted to the type of structure under consideration.

3.1.4 Discussion

The guidelines for infrastructure and design offer a starting point for northern infrastructure, however there are some shortcomings. The CSA PLUS 4011:19 guideline has a highly informative flow chart, however the processes for determining infrastructure risk in this guideline are based on qualitative values. Similarly, the TAC and CAN/BNQ guidelines provide practical advice for maintenance of the permafrost. However, future climate warming trends are not considered specifically in these documents. Some general approaches are presented for designing the infrastructure, but failure modes are not discussed for further considerations.

To move beyond guidelines, some examples of risk assessment of potential hazards in permafrost regions are proposed and discussed in the following section.

3.2 Risk assessment of potential hazard in permafrost regions

Besides guidelines and standards which are useful in site scale, developing risk maps is a practical approach to help the engineers and geologists better understand the hazards may occur to the infrastructure in the future in the regional scale. Another way of assessing the risk potential of a region is performing a reliability analysis as described in the previous section.

It should be noted that “reliability”, “risk”, “hazard”, and “limit state function” are defined as follows in this section:
Reliability: the probability of non-failure of a component or system (Haldar & Mahadevan, 1999).

Risk: the potential for consequences where something of value is threatened but the outcome is uncertain. It is the probability of occurrence (hazard) multiplied by its impacts (Haldar & Mahadevan, 1999).

Hazard: the potential occurrence of events in the natural system that may cause damage to infrastructure, environmental resources, ecosystems and health (CSA, 2019).

Limit state function: define ultimate or serviceability limit state conditions. These are frequently stated in terms of safety factor (resistance divided by load) or safety margin (resistance minus load) (Baecher and Christian 2003a).

3.2.1 Risk map of the northern hemisphere

Hjort et al. (2018) was the first to produce a high spatial resolution map of infrastructure hazard areas of permafrost regions in the Northern Hemisphere using predicted changes in climate for the region. The map was compiled using geographic and environmental data, as well as in-situ observations of ground temperature and thaw depth to estimate the current and future ground thermal regime. The authors also developed a settlement index, analytic hierarchy process (AHP) based index, a consensus of the AHP based index, and risk zonation index. The settlement index is dependent on the relative increase of the active layer and volumetric proportion of excess ground ice.

Four factors were taken into account while developing the AHP analysis: relative ALT analysis, ground temperature, slope gradient, and fine-grained sediment content in the ground. The risk zonation index (Ir) was created by combining surface properties (sediment/bedrock), ground-ice (high/low), ground material frost susceptibility (high/low), and permafrost thaw potential (high/low). From calculating the indices, the geohazard map of the northern hemisphere was created (Figure 2).

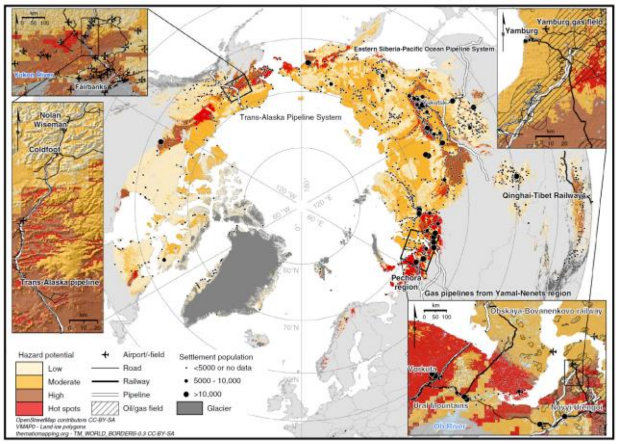


Figure 2. Pan-Arctic infrastructure geohazard map (Hjort et al., 2018).

3.2.2 Risk map of Qinghai-Tibet Plateau

Ni et al. (2021) investigated the potential thaw settlement hazard in Qinghai-Tibet Plateau utilizing the three settlement indices of Is, I_r, and I_a for the years 2061-2080. Also, a combination of the indices (I_c) was calculated as the fourth index to estimate the thaw settlement hazard and create the map risk (Figure 3).

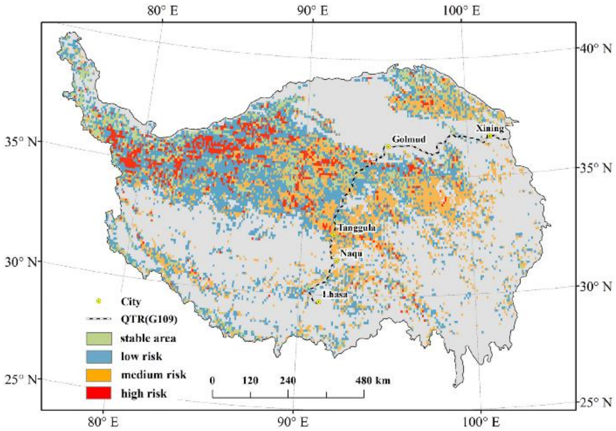


Figure 3. The risk maps of the Qinghai-Tibet Plateau for the years 2061-2080 based on I_c (Ni et al., 2021).

3.2.3 Reliability and risk analysis of linear infrastructure on permafrost

Brooks (2019) Ph.D. thesis "Quantitative risk analysis for linear infrastructure supported by permafrost: methodology and computer program" developed a methodology, and developed a tool, for quantitative reliability and risk assessment of the linear infrastructure in permafrost regions. By investigating the hazards and failure modes of permafrost embankment and establishing each failure mode's corresponding limit state functions to determine the probability of non-failure (reliability analysis), then, based on the reliability study, she developed a methodology for assessing the implications of infrastructure failures.

The hazard is calculated by applying the Modified Berggren equation to calculate the depth of active layer, and empirical estimates of thaw strain to calculate the thaw depth and settlement. The Modified Berggren equation is an analytical analysis which considers the surface thawing index, the average unfrozen thermal conductivity, the average latent heat, the N-factor of the site, the heat capacity and permafrost temperature changes for calculating the depth of thaw. The thaw depth and settlement are then utilized as inputs to other risks' limit state functions. The hazard is calculated by dividing the number of failed simulations by the total number of simulations selected by the user.

A program for analyzing the risk and hazards of infrastructure in permafrost zones, Arquluk-RISK, was developed. It has some limitations and assumptions, notably the need for a large amount of input data, however it has an advantage of providing a cost/benefit analysis.

Brooks (2019) chose the Airport Access Road in Salluit, QC, as a case study to analyze its reliability and risk, and cost/benefit analyses were performed using the Arquluk-RISK program for the Iqaluit International Airport, NU. The greater hazard risk reported in the Salluit analysis corresponded well with infrastructure assessments obtained from the access road infrastructure damage. The cost/benefit calculations resulting from the hazard and risk study at Iqaluit International Airport indicated that adding insulation to the embankment section near the ice-wedge sites is less expensive than leaving these sites uninsulated.

The Arquluk-RISK program is a significant addition to permafrost engineering in calculation of risk and reliability; however, it does not consider future climate change. As described previously, the impact of climate warming on permafrost cannot be neglected.

3.2.4 Discussion

Risk assessment methods inform decision makers with the goal of reducing the consequences of permafrost degradation on infrastructure serviceability and failure. Risk maps that apply hazard indices to address the hazards of permafrost-based infrastructure, such as the northern hemisphere and Qinghai-Tibet maps, enables engineers to forecast infrastructure hazards and make informed design and maintenance decisions. Despite the excellent work of Hjort et al. (2018), no validation was conducted to confirm the risk map. Furthermore, qualitative risk classification makes it difficult for decision-makers to forecast the hazards and costs of construction in specific regions, such as sensitive regions, because they tend to be produced at a global, national or very large regional scale.

In addition to the risk-based approach, Brooks (2019) created an Excel-based program for risk analysis of six modes of failure of permafrost-based infrastructure design. However, no validation was performed for the developed program. Calculating thaw settlement through a computer-based program and risk assessment of existing infrastructure is an innovation in permafrost-related science. However, risk assessment was based on thaw settlement predicted using analytical methods for current climatic conditions and did not take into consideration future climate change scenarios. As such, predicting future subsidence for a given area is not available.

The development of infrastructure in permafrost environments is difficult because any activity including climate change, alters the ground temperature regime of the embankment and subsequently influences the mechanical characteristics of the sensitive ground. The design, building, and maintenance of northern infrastructure have become more difficult and uncertain due to climate change. The uncertainties of how the permafrost responds to climate change, thereby changing the hazards on infrastructure, are likely the most significant gaps in current knowledge regarding the design, construction, and maintenance of infrastructure in permafrost regions.

4. DISCUSSION AND RECOMMENDATIONS

The stability of infrastructure in permafrost regions is directly reliant on the thermal stability of the ground and requires the preservation of frozen ground conditions. Therefore, present and future climate conditions must be investigated to assure thermal stability (Dore et al., 2016).

Design and maintenance of infrastructure built on permafrost are two major concerns for engineers and decision-makers in arctic regions. Guidelines and standards have been developed to reduce the consequences and costs to address these concerns. Three of these documents are mentioned and summarized in this literature review: 1) CSA PLUS 4011:19 Guideline, mainly about adapting the infrastructure to climate changes. This guideline provided a flow chart containing 2 stages to address the sensitivity of structure to climate changes and evaluate the foundation design to build the project. 2) the Guidelines for development and management of Transportation Infrastructure in Permafrost Regions by McGregor et al. (2010), which includes the assessment of infrastructure needs, site investigation, and planning for railways. Moreover, 3) CAN/BNQ 2501-500: Geotechnical site investigations for building foundations in permafrost zones (National Standard of Canada) (2017) which is developed for creating a consistent methodology for geotechnical site investigations.

Risk assessment of potential hazards in permafrost regions is another approach to reduce the costs of permafrost degradation. Risk maps, such as the northern hemisphere and Qinghai-Tibet maps, which apply hazard indices to address the hazards of permafrost-based infrastructure enables engineers to forecast infrastructure hazards and make informed design and maintenance decisions. The pan-arctic infrastructure geohazard map (Hjort et al., 2018) and the risk maps of the Qinghai-Tibet Plateau (Ni et al., 2021) make excellent contributions, however these qualitative risk classifications make it difficult for decision-makers to forecast the hazards and costs of construction in specific regions, such as sensitive regions, because they tend to be produced at a global, national, or very large regional scale.

In addition to the risk-based approach, Brooks (2019) created an Excel-based program for risk analysis of six modes of failure of permafrost-based infrastructure design. Calculating thaw settlement through a computer-based program and risk assessment of present existing infrastructure is an innovation in permafrost-related science; nevertheless, this study predicts thaw settlement using analytical methods and uses it as the foundation for risk assessment. As a result, considering climate change for predicting the future subsidence of an area is the gap in this study.

The development of infrastructure in permafrost environments is difficult because any activity including climate change, alters the ground temperature regime of the embankment and subsequently influences the mechanical characteristics of the sensitive ground. The design, building, and maintenance of northern infrastructure have become more difficult and uncertain due to climate change. The uncertainties of how the permafrost responds to climate change, thereby changing the hazards on infrastructure, are likely the most significant gaps in current knowledge regarding the design, construction, and maintenance of infrastructure in permafrost regions.

The consequences of permafrost degradation on infrastructure are happening fast, not predicted at the time of design, it has resulted in millions to billions of dollars spent on maintenance, repair and replacement of transportation infrastructure. Attempts to change this trend and reduce costs, such as standards and risk maps, have been mainly qualitative and do not consider future climate changes.

The major goal of this project is to provide a quantitative framework to analyze permafrost degradation on infrastructure embankment that incorporates realistic climate change scenarios. The Hudson Bay Railway will be used for the site-specific development of the methodology, which will then be generalized to other linear infrastructure embankment projects.

The results of the thesis work will provide a much-needed tool for decision makers to assess current infrastructure embankment and predict embankment performance under realistic future climate change scenarios.

5. CONCLUSIONS AND FUTURE WORK

Global warming trends have become one of the most critical issues worldwide. Arctic regions are particularly sensitive to global warming trends, with preferential warming in the arctic at rates two times higher than the rest of the world. Predictions indicate up to 5oC long-term warming which could result in a decline in the extent of permafrost regions of 20-50% by 2100.

Thaw degradation is a complex process that occurs in various stages and depends on ground surface conditions and soil thermal properties. This phenomenon requires simulation methods, and the results depend on soil parametrization, representation of latent heat, and unfrozen water content (Zhang et al., 2008). If air temperature continues to rise, active layer thickening and potentially complete thaw degradation of permafrost could occur based on the climate changes.

From unacceptable settlement to complete failure, the impact of permafrost thaw on transportation infrastructure must be considered. Despite having one of the most dependable transportation infrastructure systems for transferring products and people via roads, railroads, and airports (McGregor et al., 2008), the overall future economic implications of the SSP scenarios range from $4.2 to $5.5 billion, excluding normal replacement and maintenance costs. To decrease the costs of maintenance and replacement, qualitative and quantitate guidelines and frameworks have developed in recent decades. However, there is a lack of information regarding considering the long-term climate change effects on infrastructure; thus, the major goal of this project is to provide a framework for analyzing the reliability of infrastructure built on permafrost embankment, with an emphasis on railways, for future climate scenarios.

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