State-of-practice for synthesizing climate modelling data and risk-based estimation of geotechnical properties within the Canadian context: a literature review

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ABSTRACT
The need for an improved understanding of thawing permafrost behaviour is increasing due to the demand for infrastructure adaptation to climate change in Canada. Thawing permafrost leads to potential hazards such as reduced ground strength, thaw settlement, ground instability, frozen ground creep, increased runoff and flooding, and undesirable impacts on socioeconomic aspects of communities. We review the literature and state-of-practice for geotechnical characterization in permafrost regions considering: 1) current climate models and possible future socioeconomic pathways, 2) geotechnical models for changes to soil properties resulting from changes to ground temperature profile, 3) state-of-practice for incorporating climate impacts into geotechnical design and analysis. We conclude by suggesting key areas of focus for future research and improvement to design practices for sustainable and resilient infrastructure.

RÉSUMÉ
Le besoin d'améliorer la compréhension du comportement du dégel du pergélisol augmente en raison de la demande d'adaptation des infrastructures aux changements climatiques au Canada. Le dégel du pergélisol entraîne des dangers potentiels tels que la résistance réduite du sol, le tassement du dégel, l'instabilité du sol, le fluage du sol gelé, l'augmentation du ruissellement et des inondations, et des impacts indésirables sur les aspects socio-économiques des communautés. Nous passons en revue la littérature et l'état des pratiques pour la caractérisation géotechnique dans les régions de pergélisol en tenant compte de ce qui suit: 1) les modèles climatiques actuels et les voies socioéconomiques futures possibles, 2) des modèles géotechniques pour les changements apportés aux propriétés du sol résultant des changements apportés au profil de température du sol, 3) l'état des pratiques pour l'intégration des impacts climatiques dans la conception et l'analyse géotechniques. Nous concluons en suggérant des domaines d'intérêt clés pour la recherche future et l'amélioration des pratiques de conception pour des infrastructures durables et résilientes.

1 INTRODUCTION

Due to the increasing impacts of climate change in permafrost regions, there is an urgent need to advance the understanding of thawing ground behaviour to develop sustainable and resilient infrastructure and promote socioeconomic climate adaptation in Canada. Permafrost is ground composed of any combination of soil, rock, peat, ice, and water, that remains below 0°C for at least two consecutive years (Harris et al., 1988). Approximately half of Canada is in permafrost regions (Couture et al., 2003) and Northern Canadian communities are the most vulnerable to the impacts of climate change (O'Neill et al., 2020). Permafrost regions in Canada are important socioeconomic zones hosting large northern and Indigenous communities, industry, and tourism (Lemmen et al., 2008) and are connected by a network of highways, railways, airports, and ports (Transport Canada, 2020). Many Northern communities rely on linear infrastructure such as railways as the only source of transportation for work, freight, tourism, and connection to the rest of Canada (Couture et al., 2003).

Over the next half-century, most infrastructure built on permafrost will require engineering solutions to remain operational (Streletskiy, 2021) and will pose challenges to the geotechnical engineering profession. This paper aims to put these challenges in context and provide motivation for a sharpened focus on permafrost and frozen ground engineering within géotechnique. The paper is organized into three main areas: Section 2 focusses on a review of climate data, models, and forward-looking climate projections in the Canadian context; Section 3 summarizes existing understanding of how changes in ground temperature and ice content affect soil properties and the resulting types of geohazards; Section 4 examines the state-of-practice for incorporating climate change information into geotechnical design in permafrost regions. The paper concludes with the authors' thoughts on key areas for future research and practice.

2 CLIMATE MODELS IN THE CANADIAN CONTEXT

Many climate modelling institutions around the world are developing global or regional scale climate models with Land Surface Models (LSMs) being a key component for understanding the interaction between land and atmosphere (Flato et al., 2013). The latest versions of these models incorporate a wide range of climate impacts and adaptation into an ensemble of models following a standard framework that produces reliable projections, known as the Coupled Model Intercomparison Project (CMIP) (Meehl et al., 2005). The Intergovernmental Panel on Climate Change (IPCC) is the body of the United Nations tasked to produce reports on climate change which are based on peer-reviewed publications supported by the CMIP (Meehl et al., 2005). The two most recent versions of these models are CMIP5 (in IPCC Assessment Report 5, or AR5) and CMIP6 (in AR6) (IPCC, 2019).

Global and regional scale climate models incorporate physical processes of the atmosphere and include future forecasted projections of greenhouse gases (GHGs) and aerosols that follow a specific representative concentration pathway (RCP) for each simulation. CSA (2019) considers two simulations: RCP4.5 (assuming increased effort to reduce current GHG emissions) and RCP8.5 (assuming current emission rates). IPCC (2019) expects that the Arctic annual mean surface air temperature will rise to 3.3-10.0°C above the 1985-2014 average by the end of the century (Figure 1) based on CMIP6 and forecasts widespread near-surface permafrost disappearance by 2-66% (RCP2.6, "very stringent" pathway) and 30-99% (RCP8.5) by 2100.

There are three main sources of uncertainty in climate projection models: future rates of GHG emissions, seasonal and annual level variability, and surface and atmospheric process physics in each model (Charron, 2016). Suter et al. (2019) note that there is significant spatial variability between model results at the circumpolar scale for CMIP5, especially for the Canadian Arctic Archipelago with relatively high uncertainty in air temperature projections and even more uncertainty for precipitation projections. CSA (2019) recommends using CMIP5 since at the time of publication it was the most up-to-date climate model, although the newer CMIP6 has more recent information about climate projections.

The recent IPCC (2022) CMIP6 (in AR6) includes reference to the concept of Shared Socioeconomic Pathway (SSP) scenarios, comprised of 21 modelling projections with components such as land use, carbon cycle, aerosol chemistry, cloud cover, regional phenomena, and ratios of ocean/land/ice standardized by historical simulations (1850-present) known as the Diagnostic, Evaluation, and Characterization of Klima (DECK) experiments (Eyring et al., 2016). The improved climate models of CMIP6 are recommended to enhance confidence in projections for analysis and design (Eyring et al., 2016).

2.1 Socioeconomic pathways and climate projections

The five SSPs represent alternatives for global development through the 21st century and include effects such as population growth, education, urbanization, gross domestic product, and rate of technological development along with a combination of Representative Concentration Pathways (RCPs) for GHGs (O'Neill et al., 2016). The SSP scenarios emphasize social, political, and economic factors as they can have a significant impact on how mitigation and/or adaptation measures to climate change impacts are supported (Riahi et al., 2017). Each SSP relates to one or more forecasts of radiative forcing on climate by GHGs (Figure 2) ranging from

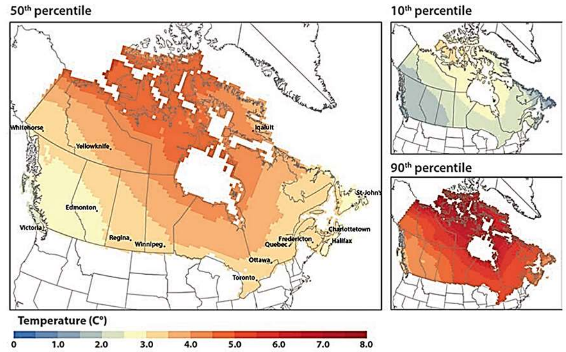


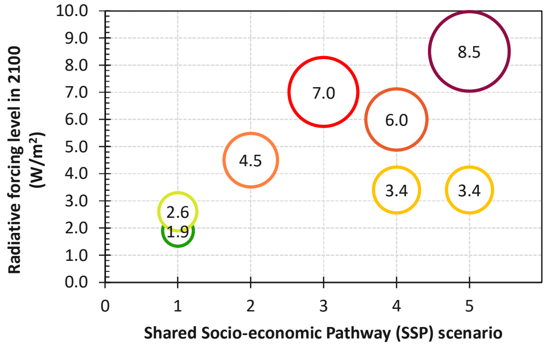
Figure 1. Map of projected changes in temperature (°C) between the reference period 1971-2000 and the 2080 horizon (2071-2100) (adapted from Charron, 2016) (Image Source: T. Logan, Ouranos, with permission from Charron).

1.9 to 8.5 W/m^2 by 2100 (Riahi et al., 2017). The SSPs developed for CMIP6 improve the connection between socioeconomic factors and GHG concentration forecasts from the RCP scenarios alone used in CMIP5 reducing the need for geotechnical engineers to speculate about these factors and reducing variability in approaches to incorporating climate forecasts into engineering design and analysis.

Beyond the IPCC (2019, 2022) reports and CSA (2019) guidelines, several reports can assist in the understanding of climate change in Canada including Charron (2016), Bush and Lemmen (2019), and Environment and Climate Change Canada (ECCC, 2021). Agencies such as CLIMAtlantic (Nova Scotia, New Brunswick, Newfoundland), Ouranos (Québec), Prairie Climate Centre (Manitoba, Saskatchewan, Alberta), Pacific Climate Impacts Consortium (British Columbia), and Risk Sciences International provide customized climate projections at the regional scale.

2.2 Canadian permafrost regions and climate trends

Figure 3 shows an overlay of eleven geographic Northern Canadian zones (CSA, 2019) with permafrost regions. Heginbottom et al. (1995) define four permafrost regions (continuous, discontinuous, sporadic, and isolated), which are dynamic boundaries determined based on mean annual temperature and the probability of permafrost occurrence. Climate change impacts on permafrost is a global phenomenon and beyond the Canadian context Obu et al. (2019) provide permafrost maps for the Northern Hemisphere and Karjalainen et al. (2019) provide circumpolar permafrost maps with associated geohazard indices. IPCC (2019) reports that Canadian permafrost regions are changing rapidly and advises that impacts from climate change are the greatest in northern regions. Arctic and Northern coastal communities are at great risk due to sea level rise and coastal erosion (Larsen et al., 2021). Arctic average annual near-surface air temperature between 1971-2019 increased by 3.1°C, which is three times higher compared to the global average (AMAP, 2021), due to Arctic amplification, which refers to higher near-surface air temperature compared to lower latitudes



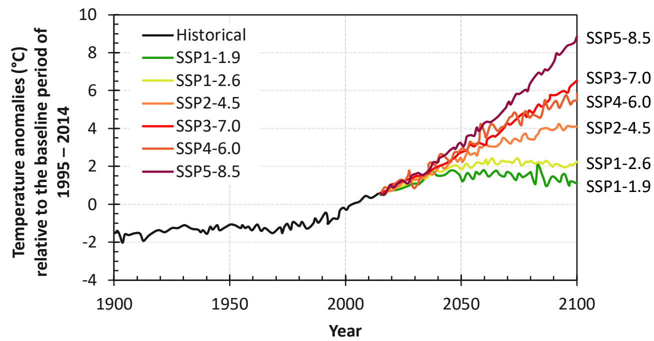


Figure 2. (left) Comparison of Shared Socioeconomic Pathways and year 2100 radiative forcing combinations [adapted from O'Neill et al. (2016)]. The radiative forcing levels signify the Representative Concentration Pathways (RCP) based on the previous scenarios from CMIP5. (right) Temperature anomaly time series relative to the baseline period of 1995-2014 for Canada for each SSP for the period between 1900-2100 (Government of Canada, 2022).

(Previdi et al., 2021). Between 2007-2016 the temperature of continuous permafrost in the Arctic increased by 0.39±0.15°C and for warmer discontinuous permafrost by 0.20±0.10°C (IPCC, 2019). Precipitation shifts are more difficult to detect than temperature trends, but total annual precipitation in the Arctic increased by more than 9% over the same period and rainfall increased by 24% with no net overall trend in snowfall (AMAP, 2021), but the snow cover season is shorter (Derksen et al., 2019).

Key climate parameters that impact permafrost thaw are air temperature, snow depth, and duration of the warm season, which increase active layer thickness (ALT) and the development of thermokarst systems (Streletskiy, 2021), especially for ice-rich permafrost (French, 2017). Thawing permafrost increases the potential for geohazards such as landslides, rockfalls (Haeberli et al., 2017), thaw settlement, floods (AMAP, 2021), and increased emission of carbon and methane, which accelerates climate change (IPCC, 2019). Climate change also increases the intensity and occurrence of extreme weather (Derksen et al., 2019) and wildfires, negatively impacting the forestry sector and increasing risks of damage to infrastructure (AMAP, 2021) and creating additional ground subsidence and erosion (Gibson et al., 2018). In the following section, we connect climate change to effects on geotechnical properties of frozen ground and the potential for geohazards.

3 CLIMATE CHANGE IMPACTS ON GEOMECHANICAL PROPERTIES

Design and construction in permafrost regions are different from unfrozen soil (CSA, 2019), as they require rigorous investigation of subsurface thermal regime and climate change impacts over the design life. Geotechnical analysis of permafrost strength depends on three key components: ice content, ground temperature profile, and unfrozen soil properties (CSA, 2019). The research literature on this topic is extensive, and an exhaustive review of all available models for geotechnical properties of frozen ground is beyond the scope of the present work. Nonetheless, we provide a summary of geotechnical factors to consider in the design and maintenance of infrastructure in permafrost regions, including how to approach uncertainty using stochastic approaches.

3.1 Impact of changing surface temperature on the ground temperature profile

The subsurface thermal regime is extremely important for the design, analysis, and monitoring of infrastructure in cold regions (CSA, 2019). Ground temperature near the surface varies through the year due to changes in air temperature, creating the thermal "trumpet" of minimum and maximum annual temperatures, which determines the location of the permafrost table and active layer that freezes and thaws annually (Harris et al., 1988) (Figure 4). The amplitude of variation in temperature envelope decreases with depth, and at the depth of zero annual amplitude (DZAA), the effects of air temperature become negligible (Harris et al., 1988). The DZAA varies depending on site conditions such as soil properties and water content which control thermal conductivity and heat capacity of the ground, and ground cover which affects thermal exchange at the ground surface (Andersland and Ladanyi, 2004). An increase in air temperature and precipitation causes warming of permafrost, affecting the ground thermal regime by lowering the permafrost table and increasing ALT which leads to greater variability and reduced confidence in soil property estimates (Derksen et al., 2019). Warm permafrost (near 0°C) responds slowly to increases in surface temperature, due to latent heat and phase change from ice to water, but colder permafrost (below -2°C) responds faster to warming since all energy is going to increase the temperature of permafrost and not to phase change (Andersland and Ladanyi, 2004). The presence of dissolved salts in coastal regions and marine-origin sediments can further reduce the stability of permafrost since the pore water can remain unfrozen below 0°C (Andersland and Ladanyi, 2004).

A complete characterization of soil thermal behaviour requires knowledge of soil conditions (SCs), initial conditions (ICs), and boundary conditions (BCs) (Figure 4). SCs include properties of each layer in the site stratigraphy such as moisture content, ice content, bulk density, specific heat, and latent heat. ICs represent the current state of the ground and are the starting point for a thermal analysis over

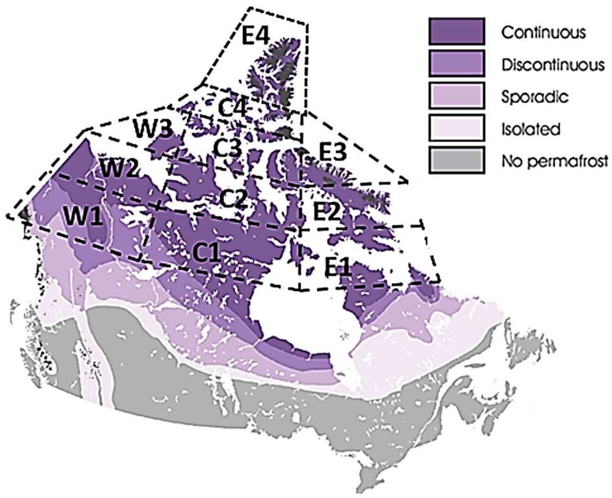


Figure 3. Permafrost distribution map in Canada [adapted from Heginbottom et al. (1995) and CSA (2019)]. Approximate location of eleven zones of northern Canada (the matrix of West, Central, and East sectors).

over the design life. The temperature of the ground can be determined from site investigation using ground temperature sensors such as thermistors in boreholes. CSA (2019) recommends recording data for ground temperature over a complete annual cycle with at least four sets of readings including the maximum and minimum temperatures. BCs represent heat exchange between the soil and the surrounding environment at the spatial limits of the thermal model. CSA (2019) recommends taking these heat exchange locations at the ground surface (heat exchange with the atmosphere) and the lowest layer of the model (heat flow upwards along the geothermal gradient). It is important to begin any thermal modelling with as accurate as possible ICs and BCs as subsequent estimates of soil properties will be influenced by this information.

3.2 Changes to soil properties resulting from changes to the ground temperature profile

Frozen soil has excellent strength, bearing capacity, and low permeability, but as ground temperature increases, thawing soil becomes unstable and loses its strength due to the loss of ice (Buteau et al., 2010; Arenson et al., 2021). The potential for ice lensing in silty and organic soils (Terzaghi, 1952) adds complication since this may lead to inhomogeneities in porosity and degree of saturation. As permafrost temperature increases, the soil may also undergo thaw settlement due to a 9% volume decrease from phase change (CSA, 2019) and thaw consolidation due to excess pore water pressure from melting ice which dissipates over time (Dumais and Konrad, 2018). The impact of thaw could be the greatest in regions such as the Yukon, where ice-rich permafrost has massive ice layers, ice wedges, and ice interspersed with frozen sediment (Strauss et al., 2017). High ice content permafrost can slowly deform under sustained load, a process known as frozen ground creep (Savigny and Morgenstern, 1986) leading to slow developing failure modes after construction.

Thawing permafrost also leads to increased runoff and flooding (Zheng et al., 2019), and soil erosion (McGregor et al., 2010). Claridge and Mirza (1981) developed a soil erosion code table for erosion potential depending on the thermal state conditions, soil description, and general characteristics of the material. Thawing of the active layer can cause a plane of weakness since thawed fine soil above the liquid limit has very low shear strength, which can lead to landslides and detachment of the active layer (McGregor et al., 2010).

3.3 Probabilistic approaches to geotechnical modelling in permafrost terrain with high data uncertainty

Permafrost data is very limited (Streletskiy, 2021) and it is important to use statistical techniques to estimate the current properties of the ground and predict its future behaviour (Baecher & Christian, 2003). McGregor et al. (2010) state that permafrost conditions are highly unpredictable and unforeseen conditions are common during construction, therefore the application of the observational method (Peck, 1969) is very practical since design revisions and adaptation to new conditions can reduce future failure and costs associated with maintenance and reconstruction. A variety of probabilistic land surface models (LSMs) exist for permafrost extent and impacts on soil properties (Schneider von Deimling et al., 2021). Karjalainen et al. (2019) use four statistical techniques (generalized linear model (GLM), generalized additive model (GAM), random forest (RF), and generalized boosted model (GBM)) to develop geohazard maps to predict settlement and risk zonation for permafrost terrain. Daanen et al. (2011) also examine permafrost degradation risk zones using simulation models. Wang et al. (2020) model permafrost spatial distribution and dynamics using physics-based analytical models and the Kudryavtsev et al. (1977) active layer model to develop permafrost temperature and ALT predictions and investigate the sensitivity of ALT using Monte Carlo simulations. It is important to ensure that sufficient local and regional data coupled with engineering expertise and judgment are used to constrain the model to provide accurate and reliable estimates of soil properties.

4 INCORPORATION OF CLIMATE CHANGE INTO GEOTECHNICAL PRACTICE

Geotechnical engineers working in permafrost terrain must understand the climate and local factors impacting permafrost such as snow, vegetation, surface organic layer, and water bodies (Streletskiy, 2021). Linear infrastructure from design phase to end of life requires reduction of damage associated with permafrost degradation (exposure, vulnerability) by planning and evaluating risks at every phase of the project (Haeberli et al., 2017), and mitigation of hazards due to effects from climate change through monitoring permafrost to better understand the changes and prevent negative consequences (Streletskiy, 2021).

Mitigation of climate change impacts on permafrost refers to engineering interventions through design and

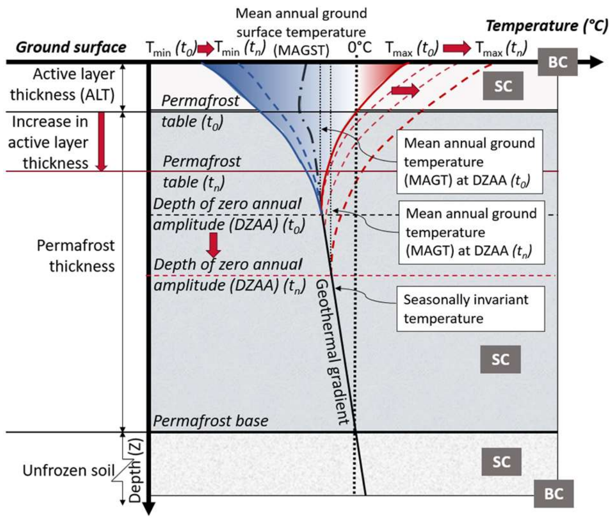


Figure 4. Schematic representation of permafrost thermal regime (adapted from Osterkamp and Burn, 2003) showing factors of soil conditions (SCs), initial conditions (ICs), and boundary conditions (BCs).

technology to reduce the negative impacts of climate change on permafrost regions (CSA, 2019). Adaptation to climate change is the process of evaluating all impacts that a climate scenario may cause to individuals, communities, and organizations and implementing strategies, actions, and policies to reduce risks and utilize opportunities, adjust to changing conditions, and reduce the vulnerability of natural and human systems (Smit and Wandel, 2006). CSA (2019) and McGregor et al. (2010) outline the process of designing or evaluating infrastructure in permafrost terrain and the following subsections highlight important aspects of this process.

4.1 Desktop study for site investigation

Site investigation begins with collecting existing information about the site including historical documentation, satellite imagery, aerial photography, and existing geological and geotechnical information (McGregor et al., 2010). The analysis of the site should include expert judgment to investigate corridor location, the impacts on existing terrain, environments, and socioeconomic factors of the region (McGregor et al., 2010). The use of aerial photography and satellite images are cost-effective techniques for preliminary analysis of linear infrastructure alignment (Doré & Zubeck, 2008).

4.2 Risk assessment and screening process

In-depth risk analysis with design alternatives and climate pathways may assist decision-makers to take the most appropriate actions over the life of the infrastructure (McGregor et al., 2010). The design should incorporate long-term maintenance and monitoring programs and suggest active or passive systems to increase the stability of permafrost, such as thermosyphons (Hayley and Horne, 2008). Monitoring should include ground and air temperature, soil deformation, and groundwater (where applicable) and data should be analysed regularly to support the health of infrastructure (CSA, 2019; McGregor et al., 2010).

A risk management framework is an important component of infrastructure analysis in permafrost terrain (CSA, 2019), and should include the likelihood and severity of permafrost degradation due to climate change and construction disruption of natural terrain and the consequences on the performance of the linear infrastructure and the degradation of the adjacent environment (McGregor et al., 2010). Negative consequences on infrastructure that is built on climate-sensitive permafrost may be high unless appropriate mitigation to reduce the negative impacts is implemented (Hayley and Horne, 2008). CSA (2019) provides a screening matrix for risk assessment adapted from Environment Canada (1998). Based on the temperature of permafrost and soil type, Etkin (1998) proposes the Designation of Material Sensitivity by Zone and Soil Type matrix for North America, which is implemented in McGregor et al. (2010). PIEVC Engineering Protocol for Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate is a structured qualitative process to assess the risks and vulnerabilities of infrastructure to climate change and current and future extreme weather events (Sandink and Lapp, 2021). Hjort et al. (2018) developed a hazard-risk index map to assess the impact of permafrost degradation on infrastructure at the circumpolar scale. From these frameworks, the risk category can be identified, and the level of thermal analysis could be prescribed accordingly.

4.3 Site investigation in permafrost terrain

McGregor et al. (2010) recommend a level of investigation based on the type of infrastructure and risk tolerance and advise that construction or rehabilitation is the most successful when extensive planning was performed during the preliminary phase of the project. Any site work performed in permafrost terrain should minimize ground surface disturbance that would negatively impact the thermal regime of permafrost (CSA, 2019). Site investigation should not be limited to the infrastructure corridor but extend beyond right-of-way where possible to better understand the future behaviour of the permafrost in the region (McGregor et al., 2010). With critical infrastructure, McGregor et al. (2010) advise using geophysical surveys (e.g. electrical resistivity tomography (ERT), electromagnetic ground penetrating radar (GPR), seismic reflection/refraction, natural gamma logging), geotechnical tests (e.g. static cone penetration test, dynamic cone penetration test, standard penetration test, vane shear strength test, light weight deflectometer (LWD), pressuremeter test), and monitoring of thermal regime in thaw sensitive soils. Geophysics surveys showed successful performance in frozen ground terrain investigation, however, should be used as a complement to geotechnical data (McGregor et al., 2010). ERT showed excellent performance for mapping underlying sediment layers, permafrost table, and ground ice for investigation and monitoring (Hauck, 2013). Pavement and road profiling testing are described in detail by Doré and Zubeck (2008).

Various techniques are available for measuring ground temperature in permafrost terrain such as thermocouples and single or multi-bead thermistor cables placed in boreholes (McGregor et al., 2010) where the desired accuracy for engineering work is ±0.2°C (Andersland and Ladanyi, 2004).

4.4 Thermal modelling and analysis

Thermal analysis of linear infrastructure is typically two-dimensional and must be performed perpendicular to the alignment to see the response under the centre of the embankment, shoulder, and toe (McGregor et al., 2010). Downscaling climate models can be achieved by layering local-level data for the specific site with larger-scale climate models (Cooney, 2012), and using this information as climatic forcing input for thermal modelling. The geothermal design could include numerical models to predict the future ground temperature by solving the heat flow equation in the ground or fully coupled transient thermo-hydro-mechanical analysis using commercial or open-source software packages including applications such as TEMP/W (e.g. highway embankment on degrading permafrost in Manitoba (Flynn et al., 2016)), PLAXIS (e.g. modelling of thermosyphon foundation system (Bui and Brinkgreve, 2017)), Python toolkit packages (e.g. site-level permafrost simulation in Northwest Territories (Cao et al., 2019)), SVHEAT (e.g. shoulder air convection embankments (Kong et al., 2021)), and THERM2 (e.g. geothermal regime of drilling-mud sumps in the Mackenzie Delta region (Kokelj et al., 2010)). These packages can aid in providing numerical solutions to the heat equation and in some cases phase changes (Stefan problem) by predicting the temperature profile (Alekseev et al., 2018).

Thermal modelling of real conditions presents a variety of challenges including lack of data, heterogeneity and uncertainty of thermal properties at large scales and issues with modelling phase change (Flynn et al. 2016). For example, thermal conductivities vary with soil type, density, water content, degree of saturation, and temperature (Harlan and Nixon 1978). Other challenges include providing appropriate ICs (e.g. initial subsurface temperature distribution), BCs (e.g. geothermal gradient, surface temperature time series), heat sources/sinks, vegetation effects, hydrological factors, and weather extremes such as prolonged cold spells, heat waves, forest fires, or droughts (Flynn et al. 2016).

4.5 Economic considerations

Life-cycle replacement cost of infrastructure on permafrost in Canada is expected to increase by 33.6%, with a baseline lifecycle replacement cost by 2059 of US$12.9 billion and the cost with climate forcing is US$17.2 billion (Suter et al., 2019). Yukon and Northwest Territory are likely to experience the greatest impact in terms of the cost of infrastructure damage (Figure 5), costing the region the equivalent of a third of the total highest economic inputs (mining) (Suter et al., 2019).

There has been much advancement in mitigation techniques to reduce the impacts of climate change on infrastructure due to permafrost degradation. Beaulac et al.

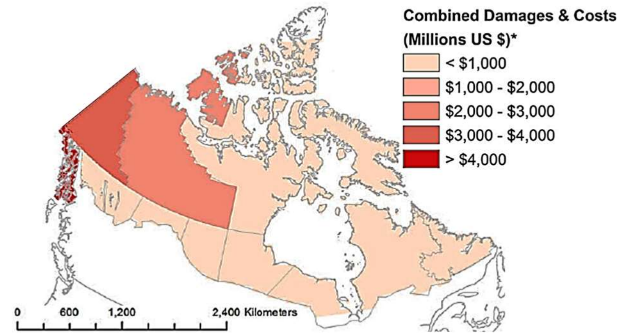


Figure 5. Total lifecycle costs & damages to infrastructure by 2060, by region (modified from Suter et al., 2019). *USD 2017.

(2004) developed a table with applicability and relative cost of mitigation techniques in permafrost terrain that is implemented by McGregor et al. (2010). Continued development of such design tools should aid in the improvement and consistency of design approaches for geotechnical engineering works in permafrost terrain.

5 CONCLUSION AND NEXT STEPS

This paper reviewed the state-of-practice for incorporating climate impacts into geotechnical design and analysis to assist in developing mitigation and adaptation solutions. This included a summary of current climate models, impacts on Canadian permafrost regions, the influence of climate change on soil properties, and an overview of key steps in the planning process for geotechnical engineering works. Going forward, AMAP (2021) among others urge the importance of a holistic approach to assessing the impacts of climate effects in the Arctic and Northern regions to better understand all the risks and hazards and provide climate adaptation and mitigation strategies. It will be important to create consistent schemes for translating between large-scale, long-term LSMs and small-scale, short-term geotechnical models (Schneider von Deimling et al., 2021). AMAP (2021) advise expanding monitoring and investigation of permafrost including site conditions and extreme events using satellites, autonomous vehicles, and other emerging technologies along with community-based monitoring to better understand and adapt to more sustainable approaches.

The authors plan to advance on bridging the gap between coarse LSMs and short-term transient geotechnical models incorporating infrastructure and climatic forces to develop systematic risk maps with failure prediction over the design life of infrastructure. One of the key components of the observational approach is to make estimates of the most probable and most unfavourable conceivable estimates of soil conditions, and plan how the project will adapt as knowledge of conditions improves or changes over time (Peck, 1969). The next steps are to advance modelling of climate impacts coupled with the observational approach to aid in providing systematic updates to mitigation and/or adaptation strategies for infrastructure as knowledge of climate change impacts on soil conditions at the regional and local scale evolve.

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