

An approach for evaluating permafrost thaw settlement potential

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ABSTRACT

Permafrost covers approximately 40% of Canadian lands and provides support for infrastructure built in this region. As climate warming continues to occur across the Canadian Arctic, thawing of the sensitive permafrost has the potential to negatively impact overlying infrastructure. Permafrost thaw induces ground instability with a potential loss of bearing capacity, severe subsidence, and/or slope instability. Identifying regions of Canada at risk of problematic thaw-settlement is essential for hazard and risk assessment, as well as for taking proactive measures during the design and construction phase to assure structural safety and serviceability. This study aims to develop a systematic approach for qualitatively identifying thaw settlement hazard, at a general location, by compiling existing literature, resources, and experimental data. This approach can be used for a desk study evaluation of thaw-settlement sensitivity on a regional scale with minimal effort. To develop the approach, influential factors defining the physical response of the ground to thawing, along with potential resources for obtaining Canada-wide data on these parameters are identified. These factors are prioritized based on their importance in defining the final settlement and using a decision-making process. Ground ice content, surficial deposit type, and bedrock type are influential variables used in this study, which are obtained from resources such as ground ice, surficial geology, and bedrock maps of Canada. Thus, the proposed approach instructs end-users on how to obtain the necessary data from identified resources and guides them through evaluation of permafrost thaw sensitivity of a specific location.

RÉSUMÉ

Le pergélisol couvre environ 40 % des terres canadiennes et sert de support aux infrastructures construites dans cette région. Avec le réchauffement climatique qui se poursuit dans l'Arctique canadien, le dégel du pergélisol sensible peut avoir des répercussions négatives sur les infrastructures sus-jacentes. Le dégel du pergélisol induit une instabilité du sol avec une perte potentielle de la capacité portante, un affaissement important et/ou une instabilité des pentes. L'identification des régions du Canada qui risquent de subir un dégel problématique est essentielle pour l'évaluation des dangers et des risques, ainsi que pour prendre des mesures proactives pendant la phase de conception et de construction afin d'assurer la sécurité et la viabilité des structures. Cette étude vise à développer une approche systématique pour identifier qualitativement le risque de tassement dû au dégel, à un endroit général, en compilant la littérature, les ressources et les données expérimentales existantes. Cette approche peut être utilisée pour une évaluation théorique de la sensibilité au tassement dû au dégel à l'échelle régionale avec un effort minimal. Pour élaborer cette approche, on identifie les facteurs influents qui définissent la réponse physique du sol au dégel, ainsi que les ressources potentielles pour obtenir des données pancanadiennes sur ces paramètres. Ces facteurs sont classés par ordre de priorité en fonction de leur importance dans la définition du règlement final et à l'aide d'un processus décisionnel. La teneur en glace de sol, le type de dépôt superficiel et le type de substratum rocheux sont des variables influentes utilisées dans cette étude, qui sont obtenues à partir de ressources telles que les cartes de la glace de sol, de la géologie superficielle et du substratum rocheux du Canada. Ainsi, l'approche proposée indique aux utilisateurs finaux comment obtenir les données nécessaires à partir des ressources identifiées et les guide dans l'évaluation de la sensibilité au dégel du pergélisol d'un emplacement spécifique.

1 INTRODUCTION

Covering 40% of Canadian lands, permafrost provides support for overlying infrastructure in Arctic regions. In recent decades, global warming has impacted permafrost and projections, based on different emission scenarios, show that a significant decrease in near-surface permafrost might be expected by the end of the 21st century (Pachauri et al., 2014). Thawing induces undesirable changes in the mechanical properties of permafrost such as loss of strength and increase in permeability. Moreover, if excess ground ice is present within the permafrost sediments, these changes are also accompanied by substantial volume changes. Thus, permafrost thaw may induce instabilities in the natural and built environment, such as loss of bearing capacity, slope instability and severe subsidence.

Thaw settlement is the most common instability reported in permafrost regions (Brooks, 2019). Thaw settlement is a phenomenon that arises from the degradation of permafrost and subsequent volume change due to expulsion of meltwater and compression of the soil skeleton (Andersland & Ladanyi, 2003). Infrastructure such as airstrips; highways and access roads; railways; and community facilities in Canadian permafrost have already been affected by thaw subsidence, the consequences of which include increased maintenance cost, compromised safety standards, and reduced useful life cycle (Andersland & Ladanyi, 2003; Fortier, LeBlanc & Yu, 2011; Flynn et al., 2015; Hjort et al., 2018; Brooks, 2019; Deimling et al., 2020).

There is a need for a timely and effective response to the changes imposed by climate warming in the permafrost regions, especially given that according to hazard

projection for the mid-century, regardless of the emission scenarios (which RCP), a substantial portion of the northern infrastructure is located in areas with a high potential of near-surface permafrost degradation (Hjort et al., 2018). The ability to evaluate the anticipated thaw settlement and identify thaw-sensitive regions is essential for taking proactive measures and ensuring the safety and serviceability of structures built on permafrost regions. Due to the remoteness and climate condition of permafrost regions, performing detailed site visits and extensive preliminary testing to determine the thaw settlement behaviour at localized sites is often costly and unfeasible. However, a comprehensive and systematic approach that can be used during the desk study phase can alleviate some of these challenges.

This study presents a methodology that can be used by northern practitioners to assess the potential thaw settlement at the feasibility phase of the project. This study makes a connection between available resources provided by non-engineering disciplines such as geography, permafrost science, and geology to their engineering applications. The outcome of the study can assist city planners and federal agencies to identify vulnerable regions and perform a more detailed risk assessment in these areas.

The main objectives of this paper are to (1) develop a systematic methodology for evaluating the thaw settlement potential of permafrost, and (2) introduce useful resources for obtaining the required information for applying the proposed methodology Canada-wide at a regional scale. In this paper, the concept of thaw settlement potential is defined, and previous methods proposed for evaluating thaw settlement potential are recalled. In the next step, the variables that play a key role in evaluating settlement potential at a regional scale are introduced and discussed. Finally, these variables are systematically compared using Analytical Hierarchy Process (AHP) and a weighted factor is assigned to each variable. These weights can be used by final users to estimate the thaw settlement potential index of different regions. An example of the calculation is also provided to walk readers through the application of the proposed methodology.

2 BACKGROUND AND SCOPE OF WORK

2.1 Thaw-settlement potential

Containing different forms and amounts of ground ice and having various soil textures, permafrost sediments may undergo different ranges of settlement upon thawing. Estimating the anticipated settlement is required for evaluating the thaw-related hazards and risks in permafrost regions, and it's a critical component of any study focussing on the impact of thawing on the natural and built environment. The available literature on thaw settlement potential mostly follows the final objective of developing a hazard or risk map at regional or circumpolar scales (Nelson, Anisimov & Shiklomanov, 2002; Daanen et al., 2011; Hong, Perkins & Trainor, 2014; Hjort et al., 2018; Ni et al., 2021). For developing permafrost thaw-related hazard maps, a combination of two sets of factors is required to account for both permafrost settlement potential

(PSP) and permafrost thaw potential (PTP). While PSP indicates the anticipated magnitude of settlement given that permafrost thaws, PTP indicates permafrost degradation and active layer thickening due to climate alterations. Even though PTP is mostly controlled by environmental factors, the final anticipated settlement after completion of thawing (PSP) is controlled by the ground ice content and mechanical properties of the sediments.

Nelson et al. (2002), developed a hazard zonation map at the circumpolar scale based on anticipated changes in the active layer thickness (as PTP) in combination with the volumetric excess ground ice (as PSP). Using a combination of surficial geology data, frost susceptibility of ground material, and ice content to assign a PSP level, and changes in the active layer thickness to assign the PTP level, Daanen et al. (2011) conducted a thaw-related risk assessment for Greenland. Hong, Perkins & Trainor (2014) proposed another approach in which factors controlling PSP and PTP were not differentiated clearly and a combination of ground ice, temperature, soil texture, snow depth, vegetation, and organic soils were used to estimate the permafrost settlement hazard index for Alaska. The high level of uncertainties encountered in providing each of the controlling factors, the complexity of the thawing process and the need for simplification, cause variation in the results obtained by different approaches for a specific location. Therefore, most recent studies have opted for developing hazard maps by means of combining the results obtained by several methods and using an ensemble of the results as a final hazard index (Hjort et al., 2018; Ni et al., 2021).

The main focus of this paper is to propose a systematic way for qualitative assessment of permafrost settlement potential (PSP) induced by the thawing of near-surface permafrost (top 5 meters) at a regional scale. Recognizing that thawing trends may vary, even at site scales, and warm permafrost is at a higher risk of thawing in near future, evaluating the combined impact of PTP and PSP on a site scale is beyond the scope of this paper. Moreover, this paper specifically focuses on the thaw settlement hazard, whereas permafrost degradation can affect the natural and built environment in different ways such as reduced bearing capacity, slope instabilities, and increased creep settlement.

3 CONTROLLING FACTORS

The application of the currently available methodologies for evaluating the thaw-settlement hazard results in large differences in the obtained thaw-settlement risk for a specific region (Hjort et al., 2018; Ni et al., 2021). This can be partially attributed to the diverse factors used in different approaches. To address the variation in the results, a more reliable assessment can be done by combining the results obtained by various methods. Ni et al (2021) applied an ensemble of three different hazard indices, each using various factors, to develop a hazard map for the permafrost regions of the Qinghai-Tibet Plateau. Moreover, they ranked the factors based on their importance in defining the ensemble thaw-settlement hazard index and concluded that volumetric ground ice, bedrock type, and soil texture are the most important factors affecting the thaw-

settlement of permafrost. The same set of factors is employed in this study to assess the settlement potential of near-surface permafrost for the Canadian landscape; however, a different methodology is employed here to evaluate the combined effect of these variables on defining the settlement potential. The importance of the three main controlling factors (ground ice content, surficial geology unit and, bedrock type) on thaw settlement potential along with the available resources for obtaining them, will be discussed in the next section.

3.1 Ground Ice Content

Permafrost may contain ground ice with a wide range of origins and morphologies, from a thick layer of buried glacial ice to a thin layer of ice coatings. Even though other processes such as ice volume change caused by phase change to liquid and soil structure compression due to dissipation of built-up pore pressure in the fine-grained or permeability-capped soils also contribute to the total thaw-settlement, in the presence of considerable excess ice, excess water expulsion is the main contributor to the total settlement. Therefore, volumetric excess ice, which is the ice in excess of soil's natural porosity, plays a key role in defining the final settlement. In combination with other influential factors, or solely on its own, ground ice content has formed the basis for previous approaches proposed for evaluating thaw settlement hazard (Daanen et al., 2011; Hjort et al., 2018; Hong et al., 2014; Nelson et al., 2002; Ni et al., 2021).

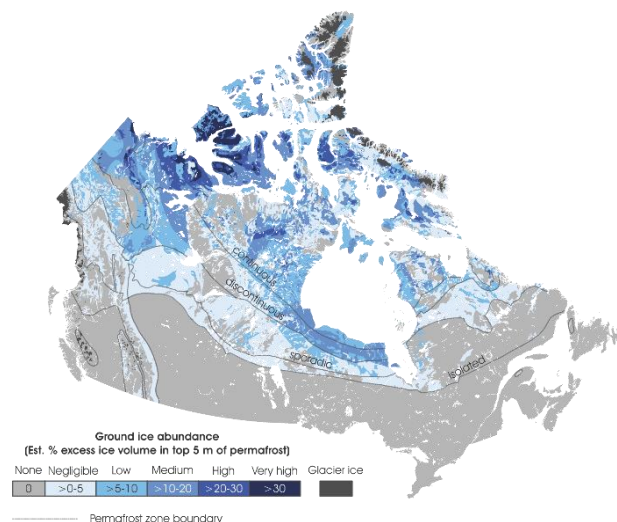


Figure 1- Ground ice map of Canada developed by O'Neill, Wolfe & Duchesne (2019) showing excess volumetric ice ranging from 0 – 30%.

This study uses the recent Canada-wide Ground Ice Map developed by O'Neill, Wolfe & Duchesne (2019) as the main resource to determine the state of ground ice. This map is drawn by an expert system approach in conjunction with paleogeographic modelling technique to determine the ground ice aggradation and degradation over time. The qualitative abundance of three major forms of ground ice including relict ice, segregated ice and wedge ice in the top 5 meters of Canadian permafrost is

presented. Even though this map provides a high spatial resolution with an area of 1km² per map unit, the low spatial resolution of underlying maps used in modelling restricts its application at fine scales. The ground ice map is available in KML format ([link to download](#)), showing the abundance and spatial distribution of each ground ice form, as well as the total abundance. Figure 1 shows the total ground ice abundance reported in six levels from “none” to “very high”.

3.2 Soil texture

Soil texture is another controlling factor commonly used in defining the thaw settlement risk of permafrost sediments. Fine-grained soils (such as silt, clayey silt, and peat) are generally more compressible and undergo high volume changes due to the thaw consolidation process. Moreover, soil texture strongly affects the aggradation of ground ice and frost susceptibility of sediments. Therefore, soil texture, not only regulates the settlement behaviour of sediments, but also the ground ice formation and preservation.

As this study aims to provide a tool for preliminary assessment of settlement potential, without any need for site investigation and borehole data, surficial deposit and bedrock types are used as the basis for incorporating soil texture in the assessment. The approach used here builds on that of O'Neill, Wolfe & Duchesne (2019) in terms of using a combination of surficial geology units and bedrock types to represent soil texture. However, in this study, surficial geology units are evaluated from an engineering perspective and thus based on the anticipated range of settlement magnitude according to their particle size and deposition process. While the ground ice content accounts for the initial settlement component induced due to expulsion of excess water from soil structure, soil texture accounts for settlement caused by compression of the soil structure due to dissipation of excess pore pressure generated during the thawing process.

3.1.1 Surficial geology map

The 1:5 000 000 scale Surficial Geology of Canada, which consists of 10325 polygons with an average area of about 880 km² can be used as the main resource for obtaining the deposit type at each location (Geological Survey of Canada, 2014). This map classifies the surficial geology units into 25 groups as shown in Table 1.

The thaw settlement potential level of each surficial geology unit is assessed based on the grain size, deposition process, and overburden thickness. For example, fine-grained sediments and organics deposited as blankets are expected to experience larger settlements caused by soil structure compression compared to dominantly coarse-grained sediments deposited as veneers. Five levels, from “extremely high” (XH) to “extremely low” (XL), are assigned to each map unit as shown in Table 1. Glacial ice, and deposits settled at the bottom of a body of water, such as lacustrine and marine sediments, are excluded from thaw settlement evaluation due to their substantially different volume change behaviour upon thawing.

Table 1-Classification of surficial geology units from Surficial Geology of Canada with the level of settlement potential assigned to each unit based on its description. Refer to the Geological Survey of Canada (2014) for a detailed description of each unit.

Symbol	Unit name	Level
I	Glacier ice	Excl.
O	Organic deposits, undifferentiated	XH
Gmo	Glaciomarine and marine sediments; offshore sediments	XH
Glo	Glaciolacustrine and lacustrine sediments; offshore sediments	XH
Gln	Glaciolacustrine and lacustrine sediments; littoral and nearshore sediments	H
Tb	Till blanket	H
Th	Hummocky till	H
Tm	Till moraine complex	H
E	Eolian sediments, undifferentiated	H
A	Alluvial sediments, undifferentiated	M
Lo	Lacustrine sediments; offshore sediments	Excl.
Gmv	Glaciomarine and marine sediments; veneer	M
Tv	Till veneer	M
W	Weathered bedrock or regolith; regolith, undifferentiated	M
C	Colluvial deposits, undifferentiated	L
Ln	Lacustrine sediments; littoral and nearshore sediments	Excl.
Gmn	Glaciomarine and marine sediments; littoral and nearshore sediments	L
Gfp	Glaciofluvial sediments; outwash plain sediments	L
Gfc	Glaciofluvial sediments; ice-contact sediments	L
Wv	Weathered bedrock or regolith; regolith veneer	L
Cv	Colluvial veneer	XL
V	Bedrock; quaternary volcanic rocks and deposits, undifferentiated.	XL
R	Bedrock, undifferentiated	XL
Mn	marine sediments; littoral and nearshore sediments	Excl.
Mo	marine sediments; offshore sediments	Excl.

3.1.2 Bedrock rock map

As the overburdened cover of sedimentary bedrocks tends to be more fine-grained than other types of bedrocks, in addition to surficial geology datasets, bedrock maps can also be used to refine the approximation of the soil texture at a regional scale (O'Neill, Wolfe & Duchesne, 2019).

Atlas of Canada (6th Edition, available at [Natural Resources Canada](https://www.naturalresources.ca)) provides a Canada-wide map of major rock categories, that can be used to differentiate areas underlain by igneous, metamorphic, and volcanic bedrock from those underlain by sedimentary bedrock for a specific location (Atlas of Canada, 1997). Using this map, a high and low level of settlement potential can be assigned to areas with deposits derived from sedimentary and non-sedimentary rocks, respectively (see Figure 2).

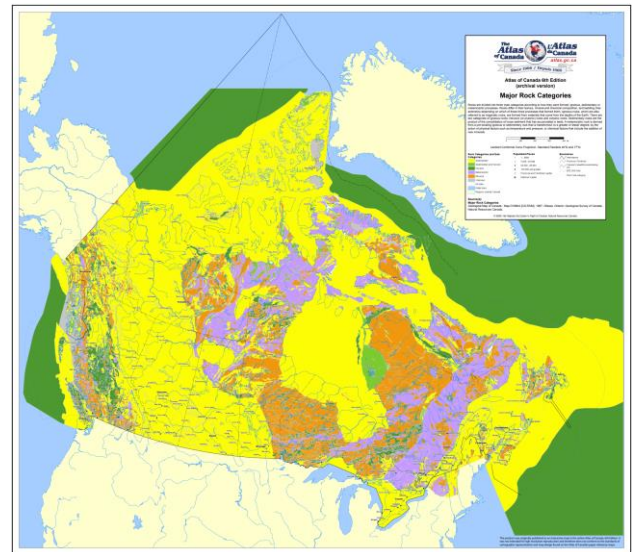


Figure 2- Map of major rock categories showing rocks formed by igneous (green and orange), sedimentary (yellow) or metamorphic (purple) processes. For an enlarged version see [this link](https://www.naturalresources.ca) (Atlas of Canada, 1997). Deposits underlain by sedimentary bedrock have higher settlement potential due to finer particle size.

4 THAW-SETTLEMENT POTENTIAL INDEX

Using the three factors introduced above, the thaw-settlement potential index (TSPI), which provides a qualitative assessment of anticipated settlement after thawing, is calculated. This is done by comparing the relative importance of each factor through Analytic Hierarchy Process (AHP). The methodology presented here has been adapted from and built on that of Hong et al. (2014), which is the method also adopted by Hjort et al. (2018).

4.1 Analytic hierarchy process

The AHP is a structured approach for organizing and comparing various factors involved in decision-making. Here it is used to systematically obtain a relative weight for each controlling factor introduced earlier. To do this, the

three factors are compared using expert judgment and based on their relative importance in defining the settlement magnitude. To obtain weights for each variable, all the variables are entered into a comparison matrix and assigned relative importance by pairwise comparison of row variables with column variables using a nine-point rating scale (Table 2). Then, column elements were normalized by dividing each value by the sum of all column elements. After obtaining the normalized values, the average of each row is calculated and considered as the weight for the row variable (Hong, Perkins & Trainor, 2014). Thus, the weights are determined to be 0.78, 0.15, and 0.07 for ground ice abundance, surficial geology unit, and bedrock type, respectively.

Table 2- Pairwise comparison of all three factors and allocated relative importance to each pair. Relative importance for B vs A can be obtained as the inverse of the values assigned to A vs B. For more details on the rating scale refer to Hong, Perkins & Trainor (2014) and Saaty (2008).

Factors		Relative importance of A against B
A	B	
Ground ice	Surficial geology units	7
Ground ice	Bedrock type	9
Surficial Geology unit	Bedrock type	3

As presented in Section 3, ground ice abundance, surficial geology units, and bedrock types were classified into five, five and two classes, respectively. Each of the classes is converted to numeric values as shown in Table 3. Having the relative weight of each factor, and the class of each variable, the TSPI can be calculated as shown below:

$$\text{TSPI} = (\text{class of ground ice abundance} \times 0.78) + (\text{class of surficial geology units} \times 0.15) + (\text{class of bedrock type} \times 0.07)$$

Table 3- The numeric values corresponding to classes assigned to each factor used in calculating TSPI

Variable	Assigned level: Corresponding numeric value				
Ground ice	Very high: 9	high: 7	Medium: 5	Low: 3	Negligible : 1
Surficial geology unit	XH: 9	H:7	M:5	L:3	XL:1
Bedrock type	Sedimentary bedrock: 9		Non-sedimentary bedrock:1		

The obtained results are ranked numerical values ranging from 1 to 9 and are conservatively converted into three settlement potential levels of “high” for [5 to 9],

“medium” for [2.5 to 5), and “low” for [1 to 2.5). As an example, for a location with a surficial deposit with XH class (numeric 9) and non-sedimentary bedrock (numeric 1) and a medium ground ice abundance (numeric 5), the TSPI is 5.32, which corresponds to a settlement potential of medium level.

$$\text{TSPI} = 0.78 \times 5 + 0.15 \times 9 + 0.07 \times 1 = 5.32$$

5 RESULTS AND DISCUSSION

A methodology to evaluate the thaw-settlement potential in Canada is proposed here. This evaluation can be done at the feasibility phase of construction projects to obtain a preliminary assessment of settlement potential at a regional scale and identify areas with high sensitivity to thaw with minimal effort.

The thaw settlement potential index (TSPI) for all combinations of the three factors is shown in Figure 3. In general, the high TSPI represents areas with high and very high ground ice content and/or fine-grained deposits with medium ground ice. These results are compatible with the fact that ice-poor permafrost with fine-grained sediment may experience noticeable settlement due to the consolidation process. Medium TSPI, represents areas of low ground ice, and fine-grained sediments with negligible ground ice. Finally, coarse-grained sediments with negligible ground ice are classified as regions with low settlement potential.

(a)						(b)							
Sedimentary Bedrock : 9		Ground ice					Non-sedimentary Bedrock : 1		Ground ice				
		9	7	5	3	1			9	7	5	3	1
Surficial Geology Unit	9	H	H	H	M	M	Surficial Geology Unit	9	H	H	H	M	L
	7	H	H	H	M	L		7	H	H	H	M	L
	5	H	H	H	M	L		5	H	H	M	M	L
	3	H	H	M	M	L		3	H	H	M	M	L
	1	H	H	M	M	L		1	H	H	M	M	L

Figure 3-Calculated TSPI for all possible combinations of ground ice abundance and surficial geology unit classes for (a) sedimentary bedrock and (b) non-sedimentary bedrock

The result of this study could be used by community planners and for general decision-making about future development in the north. Even though this study doesn't provide a tool to obtain settlement potential at site scales, due to the coarse-scale of resources identified for obtaining required inputs, the approach presented can be used with finer-scale resources such as regional surficial geology maps to perform an evaluation on a narrower scale.

6 GEOTECHNICAL RECOMMENDATION

Infrastructures and buildings located in areas with high settlement potential will experience substantial settlement upon permafrost degradation and impose high maintenance costs. The approach proposed here could be used by local municipalities, communities and practitioners to evaluate the suitability of various regions for future development. While regions with low TSPI are the most appropriate selection for future construction, regions with moderate settlement potential may also be considered as

potential choices, given that a thorough site investigation is conducted to capture variability at the site scale and decide on geotechnical recommendations. Construction in areas with high TSPI should be avoided, if possible, or adaptive design should be implemented to mitigate the impact of anticipated settlement during the life cycle of structures.

7 FUTURE WORK

We seek to combine the result of this study with factors defining thaw potential, to develop a thaw-settlement hazard map for Canadian permafrost regions. Moreover, by overlaying this map with the location of current infrastructure and their sensitivity, the permafrost risk map can be developed and used to identify sensitive regions for hazard planning and adopting mitigation measures.

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