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Infrastructure in permafrost: A guideline for climate change adaptation

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Infrastructure in permafrost: A guideline for climate change adaptation

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Dr. Neil Comer of Environment Canada's Adaptation and Impacts Research Section produced original analysis for Chapter 5 of this Guideline. Sharon Fernandez coordinated the scientific contributions of Environment Canada throughout the development of the Guideline.

More than 60 people (Appendix 4) provided input on a preliminary version of this Guideline at three outreach sessions, in Whitehorse, YT, Iqaluit, NU, and Inuvik, NT.

EXECUTIVE SUMMARY

Introduction to the Guideline

Infrastructure in the North commonly depends on permafrost for its foundation material. Such infrastructure should be designed with full consideration for the potential of climate change, particularly increases in air temperature, to cause permafrost warming and/or thawing and create *significantly different foundation environments in the future*.

This Guideline is for decision makers with a role in planning, purchasing, developing, or operating community infrastructure in permafrost regions. It will assist people who are not experts in permafrost and/or climate change, by providing: (i) a better understanding of critical permafrost- and climate change-related issues; (ii) a means for locating key information sources on these topics; and, (iii) the ability to ask "the right questions" of those they hire to ensure appropriate planning, assessment, design, and construction of community infrastructure projects. The Guideline provides contextual material and guidance on the following:

1. Permafrost as an environmental variable, and its response to climate and other environmental change (Chapters 2 and 3);

2. Foundation types for community infrastructure in permafrost (Chapter 4);

3. Trends in climate and permafrost conditions across northern Canada (Chapters 5 and 6); and

4. A process for ensuring that climate change is incorporated into (a) the siting, and (b) the design of foundation systems in permafrost terrain (Chapter 7).

This Guideline is focused on *new* infrastructure projects rather than on maintenance of existing structures. It addresses how to estimate and account for the effects of future climate on permafrost and on foundations at sites where permafrost may be a factor.

Most information in this Guideline is of relevance to the majority of community infrastructure types.

Introduction to permafrost

Permafrost is ground (soil or rock) that remains below 0 °C for two or more consecutive years. Permafrost is fundamentally a product of climate, so it is found at high altitude as well as high latitude. While the majority of permafrost in Canada is found in the territories, there is also considerable permafrost in the mountains of Alberta and British Columbia, and in the northern portions of the provinces from Alberta eastwards to Newfoundland and Labrador.

The ice content of permafrost is, together with temperature, a key determinant of permafrost's strength and behaviour as a foundation material. The ice content commonly varies with soil type and other local conditions. Fine-grained soils such as fine sands, silts and, clays are particularly susceptible to the development of ground ice in permafrost, especially in the uppermost few metres at a site. Many northern communities are located close to the ocean, rivers, or lakes at sites with silt and clay-rich marine and floodplain soils containing significant amounts of ground ice.

An increase in temperature at the surface of the ground, whether due to a disturbance of the ground or to a change in climate, will lead to gradual and generalized increases in temperature throughout the permafrost. Permafrost at temperatures very close to 0 °C will respond more slowly to the effects of surface warming than permafrost below about –4 °C, since in the "warm" permafrost a significant amount of the energy that is introduced by surface warming is absorbed by melting of ice rather than in raising the ground temperature.

Changes to the characteristics and occurrence of permafrost due to construction activities and climate change

Climate is the principal factor controlling the formation and persistence of permafrost. There are general relations between air and ground temperatures, permafrost thicknesses, and summer thaw depths, but local factors are important in determining specific permafrost conditions at a site. A change in air temperatures and other climate variables will result in a change of ground temperature, but this will vary depending on site conditions, so the design, construction, and management of infrastructure foundations must always recognize the importance of site-specific conditions.

During site preparation and infrastructure construction, activities such as vegetation clearance, surface grading, and removal or compression of the organic layer will occur, usually raising ground temperatures. Where the structure is a building, the most significant impact on permafrost normally occurs immediately beneath the building, as heat generated through its use is conducted downwards into the foundation.

For construction design, a main difference between unfrozen soils and permafrost is the strength presented by pore ice which binds the soil particles together in permafrost. However, frozen soils weaken as they warm, and, when they thaw, lose all strength conferred by their ice content. The *long-term* strength of frozen ground depends on the soil or rock of which the ground is composed, and the amount of ice in the ground. Ground ice may deform (or bend) under sustained loads over time, a process known as "creep". The potential for creep increases rapidly as ice approaches its melting point.

Where ground is covered by sediments, the upper parts of permafrost commonly contain "excess" ice — ice content greater than the pore space of the thawed soil. Soils with excess ice undergo considerable transformation when they thaw. Initially, the excess water content reduces the strength of the soil. As excess water from thawing permafrost drains, the soil settles and the ground subsides. Spatial variation in excess ice contents and soil drainage can result in differential thaw settlement. This is a design factor for larger structures which may cover patches of different materials, as differential settlement may lead to deformation of the structure.

Northern infrastructure foundations

Conventional foundation design primarily considers two related factors: bearing capacity and settlement. Settlement is both the total and any differential settlement beneath a structure, resulting from one or several of the support elements. Foundation design in permafrost imposes several challenges for control of differential settlement and the resulting deformation of structures. First, the bearing capacity of permafrost is largely a function of the amount and temperature of ground ice. As the amount of ground ice commonly varies across the area of a construction site, bearing capacity may differ across a foundation, causing different portions of the structure to experience settlement at different rates. Second, since ice-rich soils consolidate and discharge excess water as they thaw, variably distributed ground ice can result in the settlement of portions of the ground, causing distortion in the structure above. Third, if the "active layer" of ground above the permafrost that thaws and freezes each year deepens, foundation systems that rely on piles may experience accentuated frost heaving. Less of the piles' surface will be frozen year-round to the surrounding soil, while more will be exposed to the lifting force exerted through soil expansion when the water in the active layer re-freezes in the autumn and winter.

It is important that long-lasting community infrastructure in permafrost regions accommodate the potential instability of the ground. Foundations that rely directly on frozen ground must be designed to ensure the ground does not thaw following construction, and all foundations must accommodate changes that are anticipated throughout the service life of the structure.

Three principal foundation types are commonly used in permafrost terrain:

Surface pads: The construction of a surface pad to preserve the temperature of the underlying permafrost is common in northern Canada. One of the primary advantages of using surface footings on a granular pad with a cold crawl space below is the ability to compensate for any differential settlement through jacking or shimming. Unheated structures may be built directly on a pad, but only if they are well ventilated, have insulation inserted between the structure and the pad, and remain unheated throughout their service life.

Deep foundations: There are two fundamental pile types in use in the Canadian North: adfreeze piles and rock-socketed piles. Their designs and applications are fundamentally different. *Adfreeze piles* are commonly installed where permafrost soils extend to substantial depths without encountering bedrock. These piles rely on the bond with the surrounding ground for their load-bearing capacity. The ground can be ice-rich but should be below –3 °C, and colder still if the soil is saline. *Rock-socketed piles* are used where bedrock occurs within a practical depth below the surface. These piles are designed to transfer the full load of a structure to the underlying bedrock.

Foundations with heat exchangers: Foundations enhanced with heat exchangers are now widespread in Canada's North. They are generally used where heated crawl spaces and warm first floors at finished grade are required. For such structures, systems are built to intercept heat that would otherwise flow to the ground and affect the permafrost. Thermosyphons are the most widely used heat exchangers. When designs with thermosyphons are being considered, detailed geothermal analyses are required. The inclusion of climate warming in the design process requires careful consideration of the conditions chosen for the design, in particular, the winter monthly temperatures that drive heat removal through the thermosyphons. Thermosyphons are an example of a foundation system that requires significant expertise to design, install, maintain, and monitor.

Summary of past and future climate change in northern Canada

Environmental impacts linked to climate change have now been documented throughout the polar regions. Measured temperature trends indicate that the western Canadian Arctic is warming at a rate unprecedented in the last 400 years (ACIA, 2005), while over the past several years, mean annual air temperatures have risen more rapidly in the eastern Arctic than anywhere else in Canada. Precipitation patterns have also changed significantly in many parts of the North. Mean annual precipitation has increased by as much as 25 to 35% in the High Arctic since the 1950s, with some regions receiving more snow. The duration of the snow season, and the onset and rate of snowmelt have also been affected by the changing climate.

Climate projections must be used to predict future permafrost conditions when planning community infrastructure projects. Given *moderate* greenhouse gas emission scenarios, over the next 100 years average annual temperatures in the Arctic are projected to rise further by 4 to 5 °C over land, and winter temperatures by 4 to 7 °C.

For this Guideline, Environment Canada used a number of internationally accepted climate model ensembles to project future temperature changes over periods of 30 years across nine arctic zones. Twenty-four models were initially tested for their ability to duplicate historical mean annual temperatures across each of the zones. Of these, four were selected based upon their ability to reproduce historical trends. Summary results from these models are provided in Tables 5.2 and 5.3 for each Arctic zone.

Trends in permafrost conditions

Many sites in northern Canada show changes in permafrost temperature as a result of recent climate warming. Since the relatively small climate change of the 20th century has had a noticeable impact on the temperature and physical condition of permafrost, we must expect these impacts to develop further under the climate change scenarios discussed in Chapter 5 of the Guideline.

Addressing climate change in the planning and design of foundations for community infrastructure

Incorporation of climate change into the design of foundations for structures on permafrost is presented as a two-stage process. The *first stage* involves use of a screening tool to assess the level of climate change-related risk posed to a project. Application of the screening tool will allow a Project Manager to determine the scope of design services required to manage the climate change-related risks through the siting and design process. The screening assesses both the climate-change sensitivity of the permafrost at the proposed site and the consequences associated with an eventual failure of the project. In principle, the screening process may also be used in the planning of proposed sites for community expansion during the first stages of any development, when terrain suitability for zoning is being assessed.

If the screening process suggests a need for rigorous climate change-related analysis for a particular structure, the *second stage* presents, among other things, steps required to ensure that a more detailed evaluation of climate characteristics at the end of structure life is conducted. The second stage protocol involves quantitative analysis of the ground thermal regime, critical evaluation of design limitations, development of a monitoring and maintenance plan, and establishment of design and construction documentation. This second stage will require the help of experts in various fields.

Table of Contents

1 INTRODUCTION TO THE GUIDELINE

CHAPTER AT A GLANCE

This Chapter introduces the Guideline. This Guideline is for community decision makers with roles in planning, developing, or managing community infrastructure in permafrost regions. It concerns structures that require foundations. It is not a design text book for building in permafrost regions. It is intended to equip community decision makers with the ability to ensure that the impacts of climate change on permafrost are considered during the siting, design, and management of new community infrastructure.

1.1 Need for this Guideline

Engineering projects in the North often encounter permafrost in their foundation environment. The ability of frozen ground to support these structures depends mostly on local climatic conditions, ground temperatures, soil/rock material properties, and ground ice conditions.

Geographic range of permafrost in Canada

This Guideline is relevant to communities in the territories and the northern portions of most provinces, where permafrost also occurs (see Figure 2.1).

Since significant climate warming is anticipated in northern Canada, community infrastructure in permafrost terrain should also be sited and foundations designed considering the potential for *significantly different foundation environments in the future* as permafrost warms and thaws. The analyses required to address permafrost and climate change-related factors will vary between projects, depending upon the type of infrastructure in question, its design, location, design life, and purpose.