CAN/CSA-S501-14
National Standard of Canada

Moderating the effects of permafrost degradation on existing building foundations

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National Standard of Canada

CAN/CSA-S501-14
Moderating the effects of permafrost degradation on existing building foundations

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Preface

This is the first edition of CAN/CSA-S501, *Moderating the effects of permafrost degradation on existing building foundations*.

This Standard has been developed through the collaboration of representatives from territorial governments, the federal government, universities, the private sector, and northern community government organizations.

Photographs and figures without sources in the document were supplied by Steven Kokelj, Antoni Lewkowicz, Richard Trimble, John Watson, and Stephen Wolfe.

CSA Group received funding for the development of this Standard from Standards Council of Canada, as part of the Northern Infrastructure Standardization Initiative, supported by the Government of Canada's Clean Air Agenda.

This Standard was prepared by the Working Group on Permafrost Degradation, under the jurisdiction of the Technical Committee on Northern Built Infrastructure and the Strategic Steering Committee on Construction and Civil Infrastructure, and has formally been approved by the Technical Committee.

This Standard has been approved as a National Standard of Canada by the Standards Council of Canada.

Notes:

1) *Use of the singular does not exclude the plural (and vice versa) when the sense allows.*

2) *Although the intended primary application of this Standard is stated in its Scope, it is important to note that it remains the responsibility of the users of the Standard to judge its suitability for their particular purpose.*

3) *This Standard was developed by consensus, which is defined by CSA Policy governing standardization — Code of good practice for standardization as "substantial agreement. Consensus implies much more than a simple majority, but not necessarily unanimity". It is consistent with this definition that a member may be included in the Technical Committee list and yet not be in full agreement with all clauses of this Standard.*

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b) *provide an explanation of circumstances surrounding the actual field condition; and*

c) *where possible, phrase the request in such a way that a specific "yes" or "no" answer will address the issue.*

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a) *Standard designation (number);*

b) *relevant clause, table, and/or figure number;*

c) *wording of the proposed change; and*

d) *rationale for the change.*

CAN/CSA-S501-14 *Moderating the effects of permafrost degradation on existing building foundations*

0 Introduction

Permafrost degradation can be caused by many factors. When degradation occurs, buildings or structures constructed on permafrost can suffer distress or damage.

This Standard is organized according to the progression of steps that should be undertaken in order to moderate the effects of permafrost degradation on existing buildings or structures:

a) pre-emptive and proactive measures to maintain permafrost beneath and adjacent to existing buildings or structures;
b) assessment of structures impacted by changing permafrost conditions. This includes the following steps:
    i) distinguishing the symptoms of building or structure distress related to permafrost degradation from those related to seasonal frost movements;
    ii) investigating the site and structure conditions;
    iii) establishing a monitoring program; and
    iv) producing a final evaluation report that outlines alternative mitigative measures for the structure, recommendations for implementation of the appropriate mitigative measures; and the development of an implementation plan;
c) mitigating permafrost degradation and its effects on existing buildings and structures, as appropriate; and
d) undertaking long-term maintenance and monitoring.

The strategies available to moderate the effects of permafrost degradation on existing buildings or structures depend on site-specific conditions. The use of this Standard therefore requires a flexible approach.

1 Scope

1.1 Mitigation techniques and other actions

This Standard covers the following mitigation techniques to maintain permafrost or remediate permafrost degradation around existing buildings or structures:

a) site techniques that consist of
    i) shading;
    ii) drainage and grading; and
    iii) ground cover and snow management;
b) foundation techniques that consist of
    i) ventilation;
    ii) insulation;
    iii) mechanized refrigeration;

   iv) thermosyphons; and
   v) foundation replacement;

The Standard also covers site abandonment or structure demolition in response to permafrost degradation.

1.2 Applicable foundation types

This Standard covers the following foundation types typically constructed in permafrost terrain:

a) shallow foundations:
   i) footings supported at the ground surface, with a ventilated air space under the building or structure;
   ii) buried footings, with a ventilated air space under the building or structure; and
   iii) slab-on-grade with no air space under the building or structure.
b) deep foundations:
   i) adfreeze piles, with a ventilated air space under the building or structure; or
   ii) rock socket or end-bearing piles, which may or may not have a ventilated air space under the building or structure.

Note: *Further information on these foundation types is presented in Annex A.*

1.3 Application

This Standard is intended to be used by the following:

a) the owners and operators of buildings or structures that can be affected by the degradation of permafrost;
b) the owners and operators of other community infrastructure (e.g., drainage systems) for which the maintenance of permafrost or remediation of permafrost degradation is important;
c) building contractors who implement engineering-based interventions;
d) design professionals and reviewers (consulting engineers, architects, and territorial or regional technical services staff) who design, assess and approve, and oversee the implementation of engineering-based interventions;
e) educators, for the purposes of knowledge transfer; and
f) regulators, such as building inspectors.

1.4 Terminology

In this Standard, “shall” is used to express a requirement, i.e., a provision that the user is obliged to satisfy in order to comply with the standard; “should” is used to express a recommendation or that which is advised but not required; and “may” is used to express an option or that which is permissible within the limits of the standard.

Notes accompanying clauses do not include requirements or alternative requirements; the purpose of a note accompanying a clause is to separate from the text explanatory or informative material.

Notes to tables and figures are considered part of the table or figure and may be written as requirements.

Annexes are designated normative (mandatory) or informative (non-mandatory) to define their application.

2 Reference publications

This Standard refers to the following publications, and where such reference is made, it shall be to the edition listed below, including all amendments published thereto.

CSA Group

Plus 4011-10
Technical guide – Infrastructure in permafrost: A guideline for climate change adaptation

CAN/CSA-S500-14
Thermosyphon foundations for buildings in permafrost regions

CAN/CSA-S502-14
Changing snow loads in the North

CAN/CSA-S503-15
Community drainage plans in a changing environment

Other publications

Burn, C.R., 2004. "The thermal regime of cryosols." In *Cryosols: Permafrost-Affected Soils*, ed. J.M. Kimble. Springer-Verlag, Germany, 391–413.

Heginbottom, J. A., Dubreuil, M. A., and Harker, P. T., 1995. "Canada – Permafrost." In *National Atlas of Canada*, 5th edition, MCR 4177. Ottawa: National Atlas Information Service, Natural Resources Canada, Plate 2.1.

Pihlainen, J. A. and Johnston, G. H., 1963. *Guide to a field description of permafrost for engineering purposes*. National Research Council of Canada, Associate Committee on Soil and Snow Mechanics, Technical Memorandum 79.

Smith, S.L., Lewkowicz, A.G., Burn, C.R., Allard, M., Throop, J. 2010. "The thermal state of permafrost in Canada — Results from the International Polar Year." In: *GEO2010, 63rd Canadian Geotechnical Conference & 6th Canadian Permafrost Conference*, September 12–16, 2010, Richmond, B.C., Canadian Geotechnical Society, 2010, pp. 1214–1221.

van Everdingen, Robert, ed. 1998 (revised May 2005). *Multi-language glossary of permafrost and related ground-ice terms*. Boulder, CO: National Snow and Ice Data Center.

3 Definitions

The following definitions shall apply in this Standard:

Active layer — the top layer of ground that is subject to annual freezing and thawing in areas underlain by permafrost.
Note: *See Clause B.2.3.*

Adfreeze piles — piles that derive their support from the bond between the pile surface and the frozen soils.
Note: *See Clause A.2.2.2.*

Condenser — the upper part (above ground) of a thermosyphon where gas, such as CO_2, flowing from below the ground surface is cooled in winter and condenses into a liquid.

Note: *See also* ***Evaporator****.*

Construction designs — drawings indicating the scope of the proposed work activity that have been approved and issued for construction.

Continuous permafrost — permafrost that occurs everywhere beneath the exposed land surface.

Note: *See Clause B.1.*

Discontinuous permafrost — permafrost occurring in some areas beneath the exposed land surface. Discontinuous permafrost is extensive near its boundary with continuous permafrost and occurs in isolated patches or islands, commonly referred to as "sporadic permafrost", near its southern boundary.

Note: *See Clause B.1.*

Engineer — a professional engineer experienced with design of building foundations on permafrost sites and registered with the Association of Professional Engineers in the jurisdiction where the project is located.

Evaporator — the underground part of a thermosyphon in which a liquid, such as CO_2, evaporates by extracting heat from the surrounding soil.

Excess ice — the volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions.

Note: *See Clause B.2.4.*

Frost heave — the upward or outward movement of the ground surface (or objects on, or in, the ground) caused by the formation of ice in the soil.

Note: *See Clause B.5.*

Frost jacking — incremental upward movement of objects embedded in the ground, caused by frost heave.

Frost-susceptible — ground in which ice lenses will form under specific conditions of moisture supply and temperature.

General circulation model (GCM) — a global, three-dimensional computer model of the climate system that can be used to simulate human-induced climate change through time.

Note: *GCMs are highly complex and represent the effects of such factors as reflective and absorptive properties of atmospheric water vapour, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures, and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and the land surface.*

Ice lens — a predominantly horizontal, lens-shaped body of ice.

Note: *See Clause B.2.4.*

Ice-rich permafrost — permafrost containing excess ice.

Lifecycle — includes the phases of planning, design, construction, operations, maintenance, and decommissioning of a structure.

Non-frost-susceptible (NFS) — ground that is not subject to ice lens formation and frost heave during freezing, and/or to settlement during thawing.

Note: *For example, gravel containing less than 10% by mass passing the 0.08 mm sieve (silt and clay-sized particles; "fines") is NFS.*

Permafrost — ground (soil or rock and included ice and organic material) that remains at or below a temperature of 0 °C for at least two consecutive years.

Note: *See Clause B.1.*

Piles — long slender columns installed into the ground to provide support for buildings.

Note: *This deep foundation type is used where soft, sensitive or otherwise unsuitable ground is underlain by competent strata at depth.*

Qualified professional — a person who through training, qualification, and experience has acquired the knowledge and skills necessary for undertaking the specific tasks assigned to him or her.

Subgrade — the natural undisturbed soil below a building or foundation, generally below any engineered fill that can comprise part of the foundation structure.

Talik — a perennially unfrozen zone or body of earth materials associated with permafrost.

Note: *In relation to foundations, the presence of a talik between the active layer and the top of permafrost generally indicates that the pre-existing permafrost has partially thawed due to thermal disturbance associated with building construction or operation.*

Thaw stable materials — perennially frozen soil or rock that does not typically experience either significant thaw settlement or loss of strength upon thawing.

Thaw sensitive permafrost — perennially frozen ground that typically experiences significant thaw settlement or loss of strength, or both, upon thawing.

Thermosyphon — a two-phase passive refrigeration device charged with a working fluid that transfers heat from the ground to the air when appropriate temperature differentials prevail. [Based upon van Everdingen (1998)]

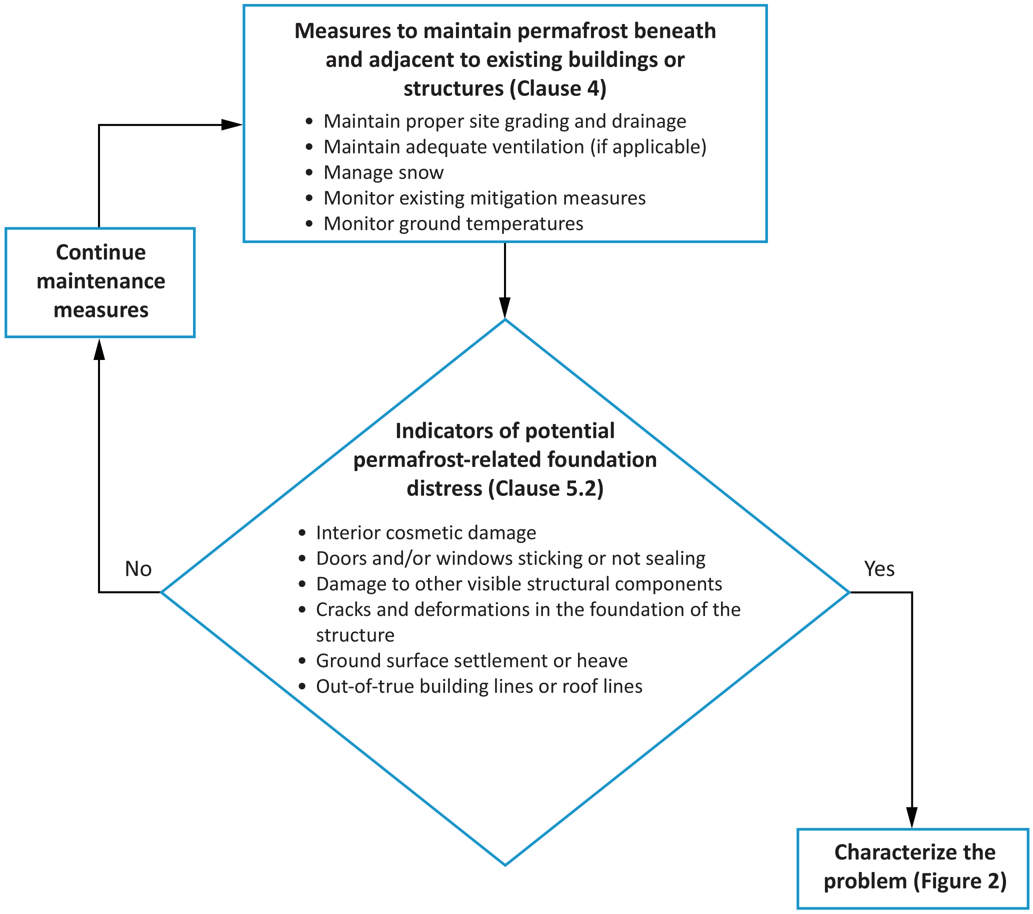
Note: *See also **Condenser** and **Evaporator**.*

4 Measures to maintain permafrost beneath and adjacent to existing buildings or structures

4.1 General

It is essential to undertake regular measures on a proactive basis to preserve permafrost beneath and adjacent to a building or structure whose foundation relies on permafrost. This is because, once it starts, it is usually difficult and/or expensive to halt permafrost thaw. Furthermore, as thaw progresses and the building or structure deforms, additional problems can develop, such as leaking from a water supply or sewage lines. This could saturate soils and cause ponding of water in depressions as the ground surface settles, increasing the rate of permafrost degradation. Maintenance measures can play a significant role in preventing the initiation of thaw and shall be undertaken on an ongoing basis through the entire lifecycle of the building or structure. The following elements should be considered in order to accomplish this (see Figure 1).

Figure 1
Measures to maintain permafrost and indications of potential permafrost-related foundation distress
(See Clauses 4.1 and 5.2 and Figure 1.)



4.2 Site grading and drainage

Proper surface water drainage is essential for preserving permafrost stability. The following are recommendations and requirements for helping ensure proper drainage:

a) Drainage ditches should not be excavated in ice-rich permafrost.
b) The area under and within approximately 4 m of the perimeter of the structure should be graded so as to facilitate rapid drainage of surface water away from the structure.
c) During spring thaw, water shall be kept from ponding under or adjacent to the structure or foundation. Additional fill should be placed at select locations as needed to promote positive drainage.
d) Downspouts from buildings or structures shall be directed onto splash pads that discharge to natural ground at least 4 m away from all structures. Where no eaves troughs are installed, areas surrounding the building perimeter should be sloped away from structures at no less than 4% slope.
e) New construction around existing buildings or structures that negatively impacts the permafrost thermal regime should be avoided.

Note: *Drainage considerations are presented in more detail within the CAN/CSA-S503.*

4.3 Ventilation

Ventilation permits winter air flow under the building or structure and promotes ground freezing and maintenance of permafrost. If a building or structure is equipped with a ventilated air space or a duct ventilated pad, periodic checks shall be made to ensure that the space or ducts are not obstructed. For example, shipping containers or sheds, placed right beside a building or structure, and any vegetation that might be restricting the foundation ventilation, should be removed. Mesh such as chicken wire or chain link fence should be installed to protect air spaces or ducts from the accumulation of debris and other items that might restrict winter airflow. If mesh is not used, alternative materials shall be installed that maintain adequate airflow capacity.

4.4 Snow management

Snow banks and snow drifts around structures reduce ventilation and insulate the ground, impeding cooling of the active layer and the underlying permafrost in winter.

Snow should be cleared away from all structures to allow frost penetration and cooling of permafrost in winter. A maintenance program should be implemented to keep snow cleared all winter and stored in a designated location; however, snow may be left in place in the spring provided that melt water will not be an issue. Snow banks should be managed so that melt water in the spring does not pond within 4 m of the building or structure.

If it is not practical to remove the snow drifts, a snow study should be undertaken to determine if a snow fence or other mitigation measures can be implemented.

4.5 Monitoring the effectiveness of existing mitigation measures

Where measures have been employed in the building or structure design to maintain permafrost or provide building heat interception, such as thermosyphons or mechanical cooling, the effectiveness of these measures shall be monitored appropriately to ensure performance as intended.

4.6 Ground temperature monitoring

Ground temperature monitoring over time can provide an early indication of changes in the permafrost thermal regime. Temperature sensors should be installed under the building or structure and in undisturbed terrain to allow for trends in ground temperatures to be monitored.

5 Assessment of structures impacted by changing permafrost conditions

5.1 General

The assessment of structures for suspected permafrost related foundation distress should include a number of distinct steps, each of which has a series of requirements. These are detailed below.

5.2 Indicators of potential permafrost related foundation distress

A number of indicators can provide evidence of potential permafrost degradation beneath a structure (see Figure 1). These include

a) interior cosmetic damage, such as cracks in drywall;
b) doors and/or windows sticking or not sealing;
c) damage to other visible structural components;
d) cracks and deformations in the foundation of the structure;
e) ground surface settlement or heave; and

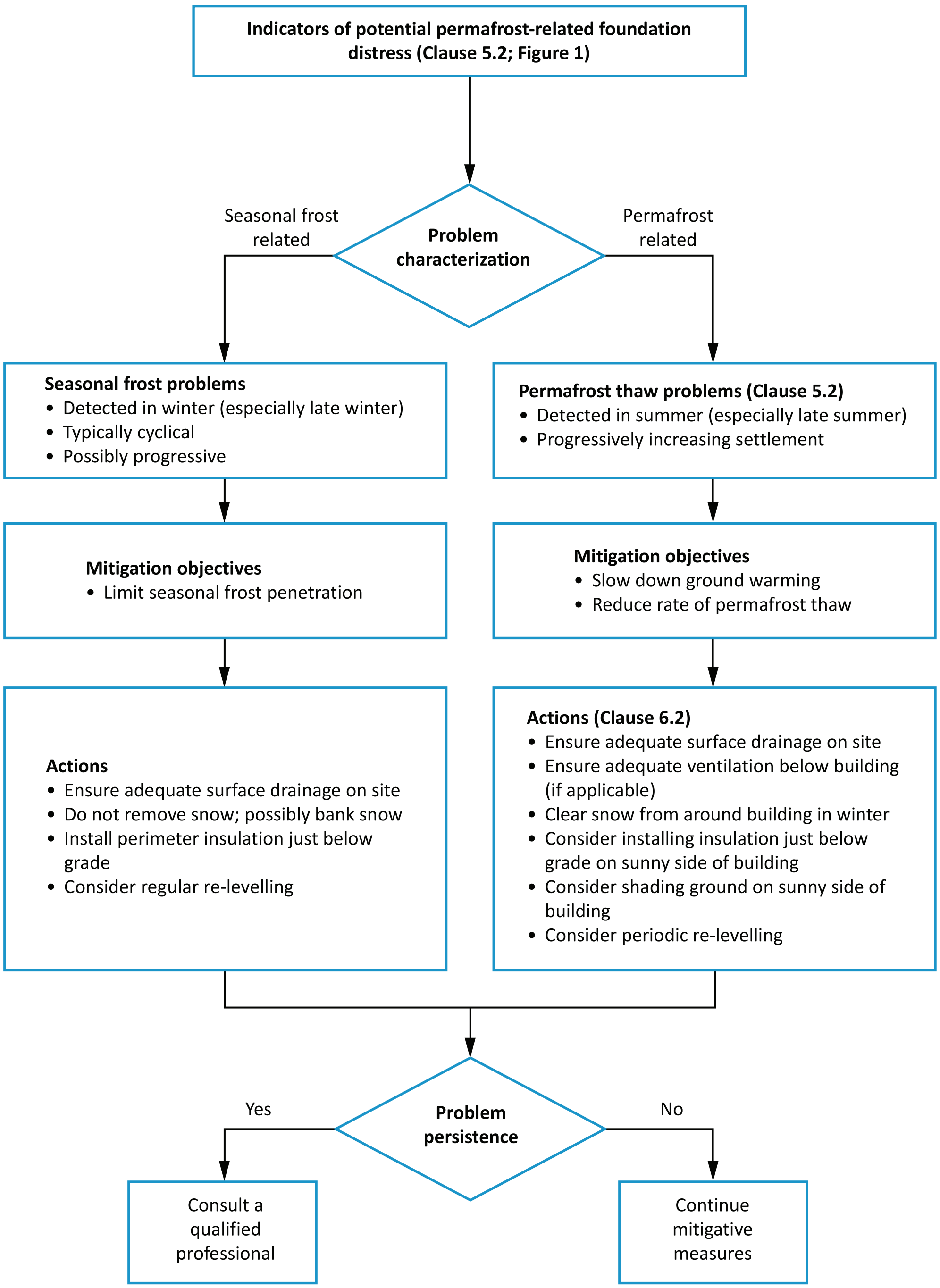
f) out-of-true building lines or roof lines

Figure 2 presents a flowchart of the steps in a typical investigation and mitigation program using site techniques. Seasonal frost related movements within the active layer shall be differentiated from permafrost related degradation issues.

Note: *Figure 2 provides indicators to assist in this task.*

Figure 2
Steps in a typical investigation to characterize the causes of potential permafrost-related foundation distress and mitigation measures that can be applied to the site

(See Clause 5.2 and Figure 2.)



5.3 Initial site investigation

5.3.1 General

The first step in the assessment of existing structures for suspected permafrost related surface displacement is the initial site investigation. This investigation should be undertaken by a qualified professional and should include three phases:

a) collection and documentation of existing background information;
b) inspection of the structure, foundation, and site; and
c) collection of site-specific subsurface data.

Note: *The direction and work plan of each phase will depend on the results of previous phases.*

5.3.2 Types of background information to collect

5.3.2.1 General

The following information should be collected during the initial site investigation:

a) original design information or design values used;
b) a history of the structural problems, including anecdotal information from previous or existing owners, neighbours, and contractors related to when the foundation movements were first noted;
c) documentation of the magnitude and nature of seasonal ground deformation or surface displacement;
d) a history of building maintenance and site management, including consideration of problems concerning water supply or distribution, or sewage systems (e.g. tanks, septic fields, etc.);
e) a history of development that has occurred on adjacent lots that can affect permafrost conditions;
f) an assessment of drainage, including ice damming or water dripping from roof, ponding, snow accumulation, and vegetation conditions at the building or structure; and
g) an assessment of any extreme short-term weather events, and long-term climate change effects such as outlined in CSA Plus 4011.

5.3.2.2 Potential data sources

The following data sources should be used to provide background and baseline data for any investigation:

a) original design documents;
b) maps;
c) stereo air photo pairs;
d) aerial or satellite imagery;
e) previous site-specific geotechnical reports;
f) climate and ground temperature information; and
g) construction reports.

5.3.3 Inspection of structure and site

A complete inspection to assess damage should be undertaken. This inspection should document the following:

a) deviations from issued for construction design;
b) interior cosmetic damage;
c) cracks and deformations in the foundation of the structure;
d) out-of-true building lines or roof lines;
e) ground-surface settlement or heave;
f) any damage to structural components;

g) damage to any water supply/distribution or sewage systems (e.g., tanks, septic fields, etc.) that could lead to permafrost degradation;
h) surface drainage characteristics around the site, including any ice damming or water dripping from the roof;
i) observed changes in adjacent development, vegetation or similar conditions around the site;
j) review of maintenance and operations procedures and records of the facility, including interviews with facility operators and maintenance staff; and
k) monitoring of any in-situ instrumentation present on the site.

5.3.4 Collection of site-specific subsurface data

5.3.4.1 General

If considered necessary based on the available data and initial data review, a geotechnical investigation program should be undertaken to determine and document
a) soil lithology;
b) depth to permafrost and ground temperatures; and
c) ground ice content.

Note: *While this type of information is typically collected by undertaking a drilling program, other methods such as geophysical or remote sensing techniques may provide valuable insights. In addition, the site-specific subsurface data does not necessarily have to include all three types listed above.*

5.3.4.2 Soil lithology

Soil samples should be collected and laboratory testing undertaken to determine
a) moisture content;
b) salinity;
c) particle size distribution; and
d) plasticity.

5.3.4.3 Depth to permafrost and ground temperatures

Ground temperature cable(s) should be installed to monitor temporal changes in ground temperature to the depth of zero annual amplitude (see Clause B.2.2) and to determine the active-layer thickness. Thermistor cables should be installed under the building or structure where practicable as well as in undisturbed terrain. Multiple measurement sites might be required depending on the size of the building or structure and lateral variations in conditions.

5.3.4.4 Ground ice content

The presence of ground ice might represent a threat to the structure due to thaw settlement if the ice were to melt. The ice content with depth shall be characterized so that estimates of thaw settlement might be made. Ground ice should be characterized in accordance with Philainen and Johnston (1963) (see Clause B.2.4). Samples of the soil-ice matrix should be collected so that the total gravimetric ice content can be determined in the laboratory.

5.3.5 Preparation of an investigation report

A report should be prepared that describes and documents the following:
a) the work completed as part of the initial site investigation;
b) the existing conditions based upon the results of the initial site investigation;
c) an interpretation of the cause and severity of permafrost degradation; and

d) detailed recommendations for future monitoring or options for remedial structural work, or both. This should include the minimum monitoring period required to obtain reliable results. The minimum monitoring period is site-specific and structure-specific, but should include at least one annual freeze/thaw cycle.

5.4 Establishing a monitoring program

5.4.1 General

A monitoring program shall be established to verify the structural integrity of the building or structure, and if any changes in the thermal condition of the underlying foundation materials have occurred, as directed by an engineer.

5.4.2 Observations and documentation to be included

The monitoring program should include observations and documentation of the following building and site features:

a) progression of cracks and deformations in the foundation of the structure;
b) progression of ground surface deformation;
c) progression of doors and/or windows sticking or not sealing;
d) progression of interior cosmetic damage;
e) progression of any other damage to other visible structural components;
f) climatic data;
g) depth to permafrost; and
h) ground temperature.

5.4.3 Collection of ground temperature data

The following should be followed if ground temperature data are to be collected:

a) ground temperatures should be recorded on at least a monthly basis;
b) sensors should be installed down a borehole that subsequently should be backfilled with dry sand or other conducting medium for a permanent installation, or within a sealed small diameter casing installed within the backfilled borehole;
c) in the absence of site-specific ground temperatures, records from nearby buildings may be used; and
d) all information collected should be forwarded to a geotechnical engineer or other qualified professional for review.

Notes:

1) *Ground temperature cables consist of either single sensor cables or multi-point cables with sensors at pre-determined spacings along a cable.*
2) *In a multi point sensor cable, closer spacing of sensors (0.5 m or less) should be used in the upper part of the ground in order to define the active layer and to track changes in thaw depth.*
3) *Ground temperatures can be recorded automatically using a data-logger connected to the thermistor cable or manual readings may be taken, typically using a digital multimeter, with thermistor resistances converted to temperatures using a look-up table or formula.*
4) *Regular readings of ground temperature cables can measure the change of ground temperature with time.*

5.5 Producing a final evaluation report

After the monitoring period, the monitoring data, together with the other investigations completed, shall be used to propose the following:

a) alternative mitigative measures for the structure, including estimated costs to implement and maintain each alternative;

b) recommendations for implementation of the appropriate mitigative measures; and
c) development of an implementation plan, including a schedule for implementing the recommendations taking into account the urgency and severity of the problem.

Following implementation of any mitigation or intervention, data from the monitoring program should be used as a baseline against which continued monitoring data can be compared in order to assess the extent to which the implemented mitigations have been successful.

6 Mitigation techniques for structures impacted by changing permafrost conditions

6.1 Applicability of remediation techniques to different foundation types

The techniques available to restore foundation stability of structures impacted by changing permafrost conditions can be divided into those applied to the site or those applied to the structure itself and its foundation. Table 1 summarizes the applicability of the various techniques for each foundation type. Descriptions of these foundation types are given in Clause A.2.

Table 1
Applicability of various techniques for moderating the effects of permafrost degradation
(See Clauses 6.1 and 7.)

Mitigation technique	Shallow foundations			Deep foundations	
	Surface footings	Buried footings	Slab-on-grade	Adfreeze piles	Grouted/End-bearing piles
Shading — see Clause 6.3.1	Yes	Yes	Yes	Yes	Yes
Drainage — see Clause 6.3.2	Yes	Yes	Yes	Yes	Yes
Snow management — see Clause 6.3.3	Yes	Yes	Yes	Yes	Yes
Ventilation — see Clause 6.4.2	Yes	Yes	No	Yes	No[5]
Ground Insulation — see Clause 6.4.3	Yes	Yes	No[1]	Yes	Maybe[2]
Adjustment/levelling of existing foundation — see Clause 6.4.4	Yes	Yes	Maybe[3]	Yes	Yes
Mechanized refrigeration — see Clause 6.4.5	Yes	Yes	Maybe[5]	Yes	Yes
Thermosyphons — see Clause 6.4.5	Yes	Yes	Maybe[5]	Yes	Yes
Foundation replacement — see Clause 6.4.6	Yes	Yes	No[5]	Maybe[4]	Maybe[4]

Notes:
1) *Perimeter insulation might be effective. Insulation under slab likely not feasible, except as per Note 3.*
2) *Perimeter insulation will be feasible. Feasibility of insulation under building will depend on access.*
3) *Relevelling by grout or foam injection may be feasible.*
4) *Replacing piles with adjustable footings could be considered. It might be feasible to replace piles under building with beams and outrigger piles. Less likely would be underpinning with micropiles.*
5) *Might be feasible under rare circumstances.*

6.2 Coordination of remediation work activities

Remediation work on the structure, the building, or the surrounding site should be coordinated with all other work undertaken as part of mitigation activities.

6.3 Site techniques

6.3.1 Shading

Vegetation may be planted around the structure to shade the ground surface in summer and help moderate ground surface temperatures. In regards to shading,

a) any planted vegetation shall not restrict airflow under an elevated structure;
b) vegetation and trees that provide natural shading should not be cut down; and
c) sun screens may be constructed on south facing locations.

Note: *Shading should not be relied upon to resolve permafrost degradation impacts without detailed numerical modelling as conducted by an engineer.*

6.3.2 Drainage

Proper surface water drainage is essential for preserving permafrost. In regards to drainage,

a) drainage ditches or swales should not be excavated in ice-rich permafrost without detailed design and measures to control erosion and prevent progressive permafrost degradation. Berms can be effective to control surface drainage, but should not be constructed without detailed design and measures to control erosion;
b) the area under and within approximately 4 m of the perimeter of the structure should be graded to encourage rapid drainage of surface water away from the structure;
c) water shall not be allowed to pond at any location within approximately 4 m of the structure;
d) during spring thaw, water shall be kept from ponding under or adjacent to any structure. Additional fill should be placed as needed to promote positive drainage; and
e) downspouts from buildings shall be directed onto splash pads that discharge to natural ground at least 4 m away from all structures. Where no eaves troughs are installed, the area surrounding the building perimeter shall be sloped away from the structure at no less than 4% slope.

Note: *Drainage considerations are presented in more detail in CAN/CSA-S503.*

6.3.3 Snow accumulation management

In regards to the mitigation of permafrost degradation for existing buildings or structures,

a) snow should be cleared away in winter from around buildings or structures to promote more rapid frost penetration that will maintain the permafrost; and
b) a maintenance program should be implemented to keep snow cleared all winter.

Notes:

1) *Snow management considerations are presented in more detail in CAN/CSA-S502.*
2) *Snow banks and drifts around structures prevent adequate ventilation, insulate the ground preventing required winter frost penetration, and create significant melt water in the spring that could negatively affect the foundation.*
3) *Where access permits, snow should be cleared within 4 m of the building or structure.*

6.4 Techniques applied to the building or structure

6.4.1 General

If the nature of the foundation is such that techniques applied to the building or structure are to be considered, a qualified professional shall be consulted. The implications of climate change should be considered in the design developed.

Increases in the depth to permafrost, whatever the cause, might require the initiation or enhancement of techniques to minimize the heave and settlement effects of increased active layer thickness on the building or structure foundation. In some circumstances, permafrost thaw is inevitable and the selected remediation technique should take this into account.

Note: *CSA Plus 4011 provides guidance on adaptation to climate change for the design of infrastructure in permafrost.*

6.4.2 Ventilation

Open air spaces under buildings or structures provide a means to isolate building heat from the permafrost, remove heat from under the buildings or structures in winter, and reduce the opportunity for permafrost degradation. In regards to ventilation,

a) the structure shall be elevated to maintain a clear ventilated air space of at least 0.6 m to permit winter air flow under and around the foundation;
b) any vegetation that might be restricting foundation ventilation shall be removed;
c) mesh such as chicken wire or chain link fence should be installed to protect the ventilated air space from the accumulation of debris and other items that might restrict winter airflow. If mesh is not used, alternate materials should be installed that maintain adequate airflow capacity; and
d) shipping containers or sheds shall not be placed immediately adjacent to a building or structure.

6.4.3 Ground insulation

Ground insulation is meant to reduce the rate of heat transfer from a building or water/sewer service components into the ground:

a) in areas where mean annual ground temperatures are below –4 °C [i.e., cold permafrost; see Figure B.3 b)], the placement of insulation on or just below the ground surface should be considered;
b) in areas where mean annual ground temperatures are between –4 °C and 0 °C, ground insulation should be used only on the recommendation of a qualified professional; and

   Note: *In areas where mean annual ground temperatures are between –2 °C and 0 °C [i.e., warm permafrost; see Figure B.3 b)], ground insulation can restrict ground cooling in winter and therefore not be effective;*

c) lawns and flowerbeds should be planted in bare ground surface areas to provide additional natural insulation to the ground surface. Any such landscaping should not obstruct access to the structure and foundations.

6.4.4 Foundation adjustment and levelling

It might be possible to rehabilitate the foundation in a way that would allow for periodic adjustment so that the service life of the structure is increased. This includes the following techniques:

a) screw jacks on wooden cribbing;
b) wedges on wooden cribbing;
c) slotted columns with foundation jacking points; and
d) mud jacking of concrete foundation slabs.

Each technique shall be specifically designed (e.g., range of adjustment) for each structure and each site.

6.4.5 Mechanized refrigeration or thermosyphons

A refrigeration or thermosyphon system may be installed under the slab or shallow foundation, or around deep foundations to chill the foundation soils to a stable thermal condition. In regards to the use of mechanized refrigeration or thermosyphons for the mitigation of permafrost degradation for existing buildings or structures,

a) in all cases, geothermal modelling shall be undertaken; and
b) the refrigeration or thermosyphon system shall be designed and installed by qualified professionals.

Note: *The implementation of either of these techniques might result in frost heave and the implications of this should be considered in design.*

6.4.6 Foundation replacement

It might be possible to replace the foundation on the existing site by

a) placing shallow foundations, such as screw jacks or wedges on wooden cribbing, on engineered granular pads above the surrounding terrain;
b) installing steel piles (or adding to existing piles) or footing around the exterior of structure and then supporting the structure on new beams resting on these new foundations;
c) underpinning of foundation elements using pile jacking; and
d) lifting the structure off its present foundation and moving it to a new foundation specifically designed for the structure and the site.

Each technique shall be specifically designed for each structure and each site.

6.5 Abandonment and demolition

6.5.1 Site abandonment

If the structure is considered to be repairable and/or reusable, but located on ice-rich thaw sensitive permafrost (especially warm permafrost) that cannot be preserved, the site should be abandoned and the structure should be moved to a new location with a foundation designed specifically for site conditions.

6.5.2 Structure demolition

If the structure is considered to be damaged beyond repair or is a public safety hazard, the structure should be demolished.

7 Long term performance of foundation rehabilitation

There are two important issues relative to the long-term performance of any foundation rehabilitation technique used to maintain permafrost or remediate permafrost degradation around existing buildings or structures: the time required for the applied mitigation strategy to become effective; and the need for performance monitoring. These two issues shall be considered.

Table 1 presents a list of potential mitigation techniques to address foundation distress due to permafrost degradation. In selecting an appropriate mitigation technique, both its short-term and long-term performance should be considered. For example, a particular technique can provide long-term mitigation but without addressing the continuing effects of permafrost degradation in the short-term. In some cases it can take five or more years for a new thermal equilibrium to be established in the permafrost under the structure. For this reason, and depending on site-specific conditions, more than one mitigation technique may be applied so that immediate stability requirements and long-term stability requirements are both addressed. If the planned building life exceeds approximately 20 years, the potential for climate change shall be taken into account during the choice of mitigation strategy.

Plans to monitor the performance of the structure, foundation, and mitigation technique should be drawn up and implemented early in the rehabilitation phase. Depending on site-specific conditions, performance monitoring may include
a) routine visual inspections;
b) recording and assessing crack monitoring points;
c) conducting floor elevation and foundation element surveys;
d) thermal monitoring of the subgrade, open air gaps, and floors;
e) leak checks on water supply and sewage disposal systems;
f) surface and groundwater monitoring; and
g) operational monitoring of thermosyphons or other cooling techniques, if present.

The designer, building owner, and maintenance staff should collaboratively develop an appropriate monitoring program, including a schedule and reporting system, that is appropriate for the site-specific conditions.

Annex A (informative)
Background information on foundation types for permafrost areas

Note: *This Annex is not a mandatory part of this Standard.*

A.1 General

Foundations are a structural element to transmit building loads to the supporting ground below the building or structure. Conventional foundation design primarily considers two factors: bearing capacity and settlement. Settlement is usually what governs foundation design because significant settlement can occur before the full strength of the ground is reached. In particular, foundation design attempts to limit differential settlement between supports, because differential settlement results in distortion of the building or structure causing cracking and operational difficulties, such as inoperable doors and windows.

In permafrost, the strength-settlement relationship is temperature dependent:

a) Frozen soil is stronger than unfrozen soil, and cold permafrost is stronger than warm permafrost. Ice-rich permafrost under load will deform over time, like glaciers flow. This time-dependent movement is referred to as creep.
b) If the permafrost thaws, ice in the permafrost will melt. There will be the initial 9% volume change of ice to water upon thaw, and then, if there was excess ice in the permafrost, there will be time-dependent settlement as the excess moisture drains out of the soil.

A third aspect of deformation to be considered is associated with seasonal frost heave and thaw settlement within the active layer. The implications of seasonal frost action are often overlooked and can be more problematic than deformations in the permafrost.

A.2 Foundation types

A.2.1 General

Foundations types are broadly characterized as

a) shallow foundations, which typically comprise some type of footing, at or within about 3 m of the ground surface; or
b) deep foundations, which typically comprise some type of pile and generally extend more than about 6 m below the ground surface and derive their support from the ground (soil or rock) at depth.

A.2.2 Shallow foundations

A.2.2.1 General

The following shallow foundation types can be encountered in permafrost areas:

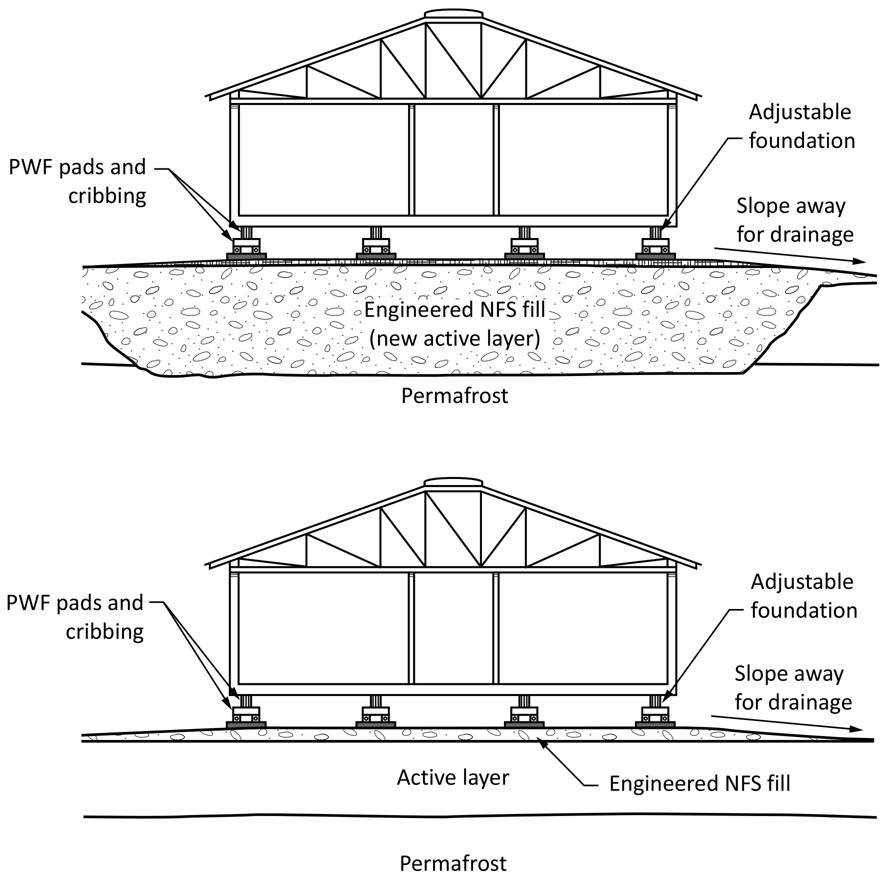
a) footings supported at the ground surface on an engineered granular pad, with a ventilated air space under the building or structure. Variations of this type of foundation include timber or concrete pads or cribs, possibly with wedges for adjustment; timber pads with screw-jacks; or a space frame;

b) buried footings, with a ventilated air space under the building or structure. Buried insulation is typically installed with this foundation type in permafrost areas, so that the footing is set either on or in permafrost; and
c) slab-on-grade with no air space under the building or structure. Often, building structural support is provided by footings that are cast integral with the slab, as thickened zones in the slab. On permafrost that is thaw sensitive, this foundation type would typically be constructed with insulation and some means to maintain permafrost, such as thermosyphons or forced ventilation.

A.2.2.2 Footings at ground surface

This type of footing is normally constructed on a pad of gravel or crushed rock (engineered NFS fill), as shown in Figure A.1. This is a very common foundation type in the north, particularly for residential foundations and for other small buildings or structures.

Figure A.1
Shallow foundations — Footings at ground surface with and without excavation
(See Clause A.2.2.2.)



PWF = preserved wood foundation

Being supported at ground surface (grade), this foundation type is at the top of the active layer and moves with the ground. If the gravel pad is sufficiently thick, the active layer can be contained within the gravel pad and seasonal movements can be negligible. If the active layer extends into the natural soil below the gravel pad, there can be seasonal frost heave and settlement. As shown in Figure A.1, sometimes the active layer is replaced with an engineered fill pad to minimize these seasonal movements.

This foundation type typically allows for some form of adjustment (see Figure A.2) to compensate for the seasonal movements or possible settlement, if desired. Examples are pads and wedges.

Figure A.2
Two photos of adjustable footings at ground surface
(See Clause A.2.2.2.)

Insulation may be used to reduce the thickness of the active layer below the building or structure; however, this is rarely done in practice. If used, an assessment should be made to determine whether the net effect of the insulation is to maintain the permafrost, or inhibit winter cooling that could result in degradation of the permafrost.

A TRIODETIC® foundation, generically referred to as a space frame, uses a three-dimensional network of prefabricated steel trusses to support the building or structure on a rigid plane (see figure A.3).

Figure A.3
A TRIODETIC® foundation
(See Clause A.2.2.2.)

The rigid frame accepts and bridges local differential movements so that the top of the framework moves as a plane and stresses from differential movement are not transmitted to the building or structure. Thus, the need for periodic relevelling is reduced or eliminated.

While the steel plates of the space frame can reportedly rest directly on a gravel pad, experience has shown that supporting the steel plates on timber pads is preferable.

A.2.2.3 Buried spread footings

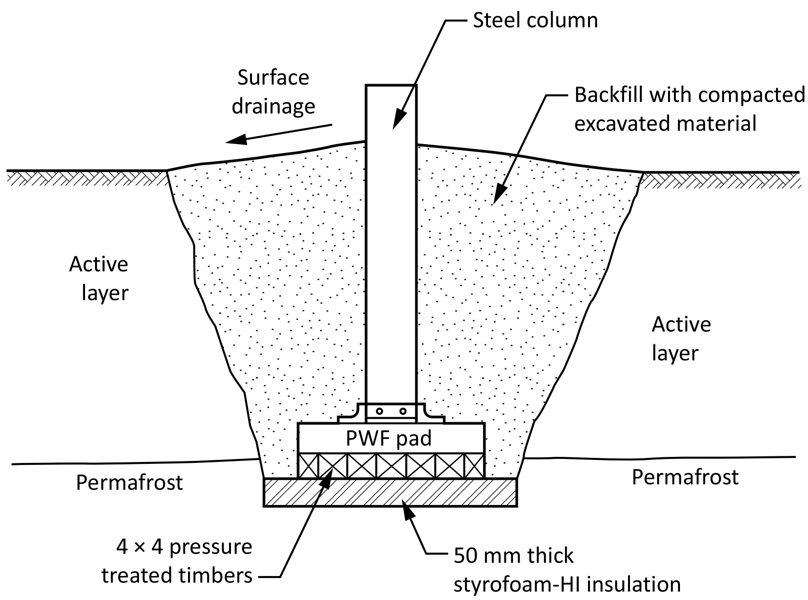
Buried spread footings are set down near, on, or in the permafrost. The objective is to limit seasonal frost heave and settlement of the foundation by setting the footings on a stable base.

Buried insulation is usually installed with this foundation type, usually above the footing as shown in Figure A.4 b). An alternative configuration would be to place the insulation below the footing, as shown in Figure A.4 a). This provides better thermal protection, but limits the bearing pressure to the strength of the insulation. In either case, the objective is to configure the insulation to bring the level of the permafrost up to immediately below or above the footing.

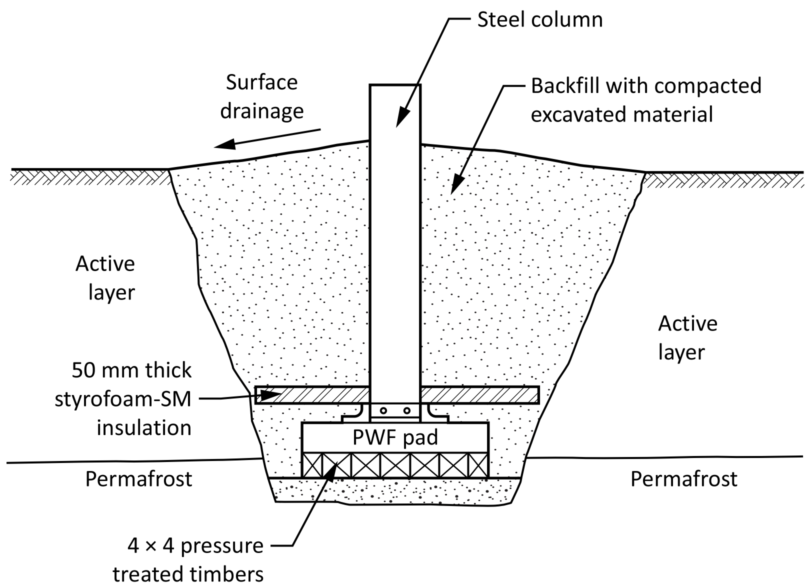
This foundation type can be difficult to construct if there is seepage and sloughing in the active layer. Therefore, this foundation type is less common than surface footings.

Figure A.4
Shallow foundation — Buried spread footing with insulation (a) below the footing (cold permafrost) and (b) above the footing (warm permafrost)
(See Clause A.2.2.3.)

a) Buried spread footing with insulation below the footing (cold permafrost)



b) Buried spread footing with insulation above the footing (warm permafrost)



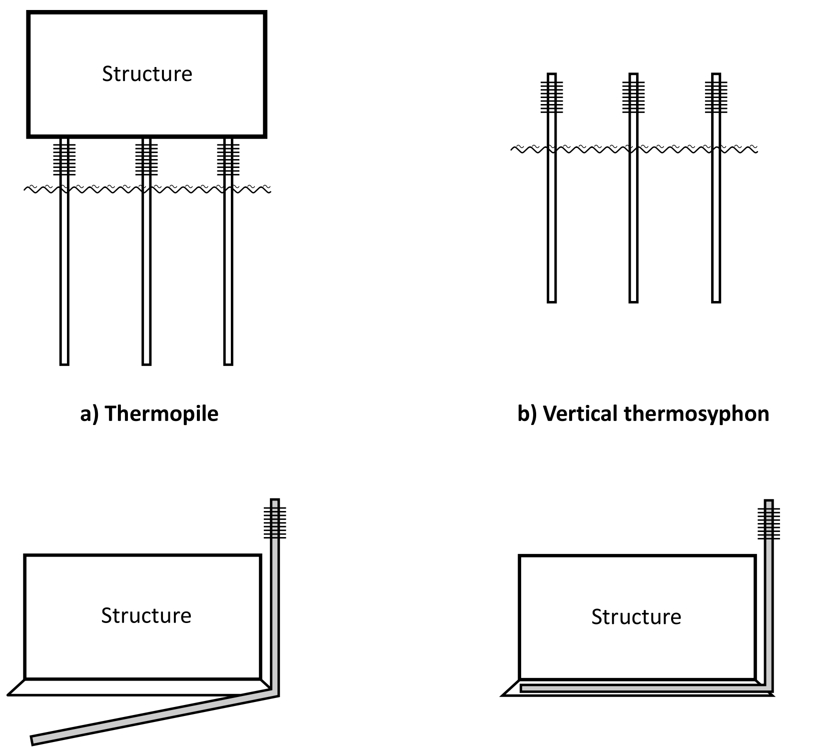
A.2.2.4 Grade-supported foundations

It is desirable to set some buildings or structures on the ground. Examples include equipment garages or hangars, with heavy floor loads, or other institutional buildings where at-grade access is preferred to stairs and ramps.

In permafrost areas, heat from an at-grade building or structure can be expected to thaw the underlying permafrost. A common misconception is that insulation can effectively prevent thaw of the permafrost. Insulation reduces heat flow into the ground, but does not prevent it. Therefore, insulation alone, no matter how thick, will not prevent thaw of permafrost.

The heat transmitted to the ground needs to be extracted in order to maintain the permafrost. Thermosyphons are most commonly used for this purpose in the north. Simply, thermosyphons comprise a network of evaporator pipes below the building or structure, which are connected to radiator pipes outside the building or structure. Thermosyphons extract heat from the ground whenever the air is colder than the ground. In the winter, the thermosyphons cool the permafrost, so that summer thaw is limited to within design values. Typical thermosyphon arrangements are shown in Figure A.5.

Figure A.5
Four thermosyphon foundation design options
(See Clause A.2.2.4.)



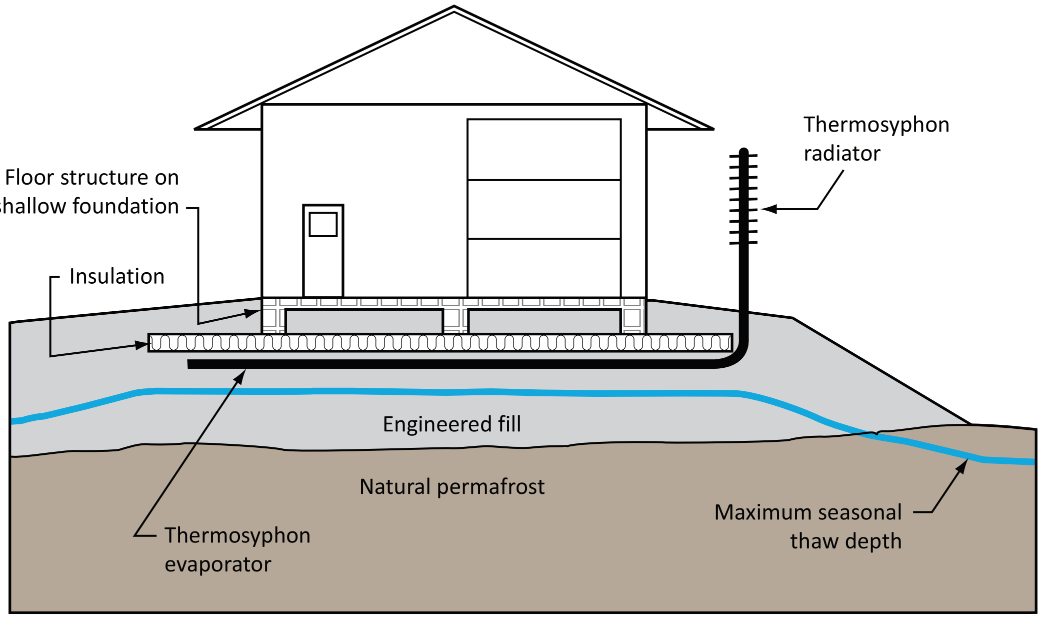
a) Thermopile **b) Vertical thermosyphon**

c) Sloping thermosyphon **d) Flat looped evaporator thermosyphon**

Note: *This Figure is modified from CSA PLUS 4011.*

For at-grade buildings, the flat-looped system depicted in the Figure A.6 is most commonly used. CAN/CSA-S500 provides details on the design, construction, and maintenance of thermosyphon systems.

Figure A.6
Typical sloping thermosyphon design sketch showing insulation placement and evaporator pipes in an engineered foundation pad
(See Clause A.2.2.4.)



Note: *This Figure is from CSA PLUS 4011.*

Other forms of heat exchangers that have been used include

a) Air ducts through a gravel pad under a structure (see Figure A.7). These are commonly employed but while natural ventilation through ducts has been successfully used for unheated structures, ducts under heated structures require some form of mechanical ventilation to achieve sufficient cooling.

b) Active refrigeration systems and heat pumps. These have been used in the past, but have not gained popularity because of high operating cost and complex maintenance requirements.

Figure A.7
Photo of a ventilated gravel pad beneath a storage tank, Inuvik, NWT
(See Clause A.2.2.4.)

A.2.3 Deep foundations

A.2.3.1 General

The following deep foundation types might be encountered in permafrost areas:

a) Adfreeze piles, with a ventilated air space under the building or structure. These piles are typically steel pipes and derive their support from the bond between the steel and the frozen soil.

b) Rock socket or end-bearing piles, which might or might not have a ventilated air space under the building or structure. These piles are typically founded on thaw stable materials, so are not intended to rely directly on permafrost stability for support. However, problems can occur if the piles pass through ice-rich permafrost because lateral support to the piles may be compromised if the permafrost thaws.

c) Driven piles are typically steel pipe or H-sections, as timber is not sufficiently durable to withstand the hard-driving that would be associated with permafrost. This pile type might or might not have a ventilated air space, depending on whether the capacity is derived from friction in the permafrost or from end-bearing in thaw stable materials at depth.

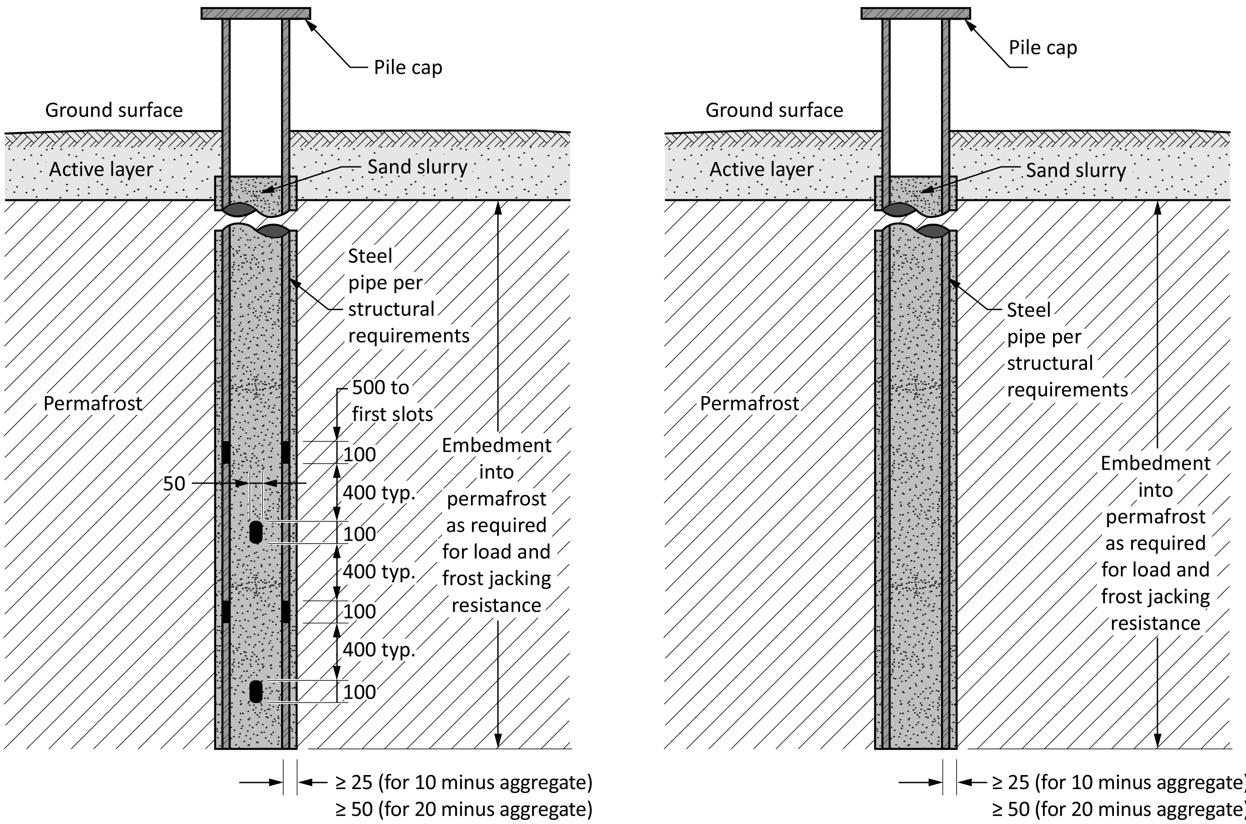
A.2.3.2 Adfreeze piles

Adfreeze piles are the most common deep foundation type in permafrost areas. They are widely applicable and relatively simple to install. Some degree of seepage or sloughing may be accepted without compromising the successful installation of this pile type.

Design capacity is based on determining an allowable creep settlement over the life of the structure. As such, adfreeze in warm permafrost can have relatively low capacities, sometimes making other foundation types preferable. The design should consider not only present ground temperatures, but also ground temperature response to climate warming.

Adfreeze piles are installed into drilled, oversize holes, which are then backfilled with a mixture of water and sand or fine gravel, as shown in Figure A.8.

Figure A.8
Example of adfreeze piles in permafrost, with and without slots
(See Clause A.2.3.2.)



Some methods have been used to increase the bond between the pipe and the soil, such as cutting holes in the piles or welding rings on the piles. But it is typically more economical to install additional pile length than to introduce complexities into the piles.

The performance experience with adfreeze piles is good. However, adfreeze piles must be designed with sufficient embedment to resist frost jacking, as experience indicates that frost jacking has been the most significant performance problem.

A.2.3.3 Rock socket piles

If bedrock is present within a depth that is practical to reach with pile installation, it is normally preferable to set the piles in the bedrock, rather than the overlying permafrost. Normally, bedrock does not contain excess ice, although the upper portion of the bedrock can be weathered or fractured and contain some ice.

In its simplest form, a rock socket pile consists of a steel pipe grouted into an oversized hole drilled into the rock. This concept is shown in Figure A.9 a). As this pile is seated on competent bedrock, a ventilated air space might not be required to protect the overlying permafrost.

Design capacity is based on some combination of bond (friction) in the grouted rock socket and end-bearing of the pipe on the bottom of the rock socket. Rock socket piles will typically be able to develop much higher capacities than adfreeze piles.

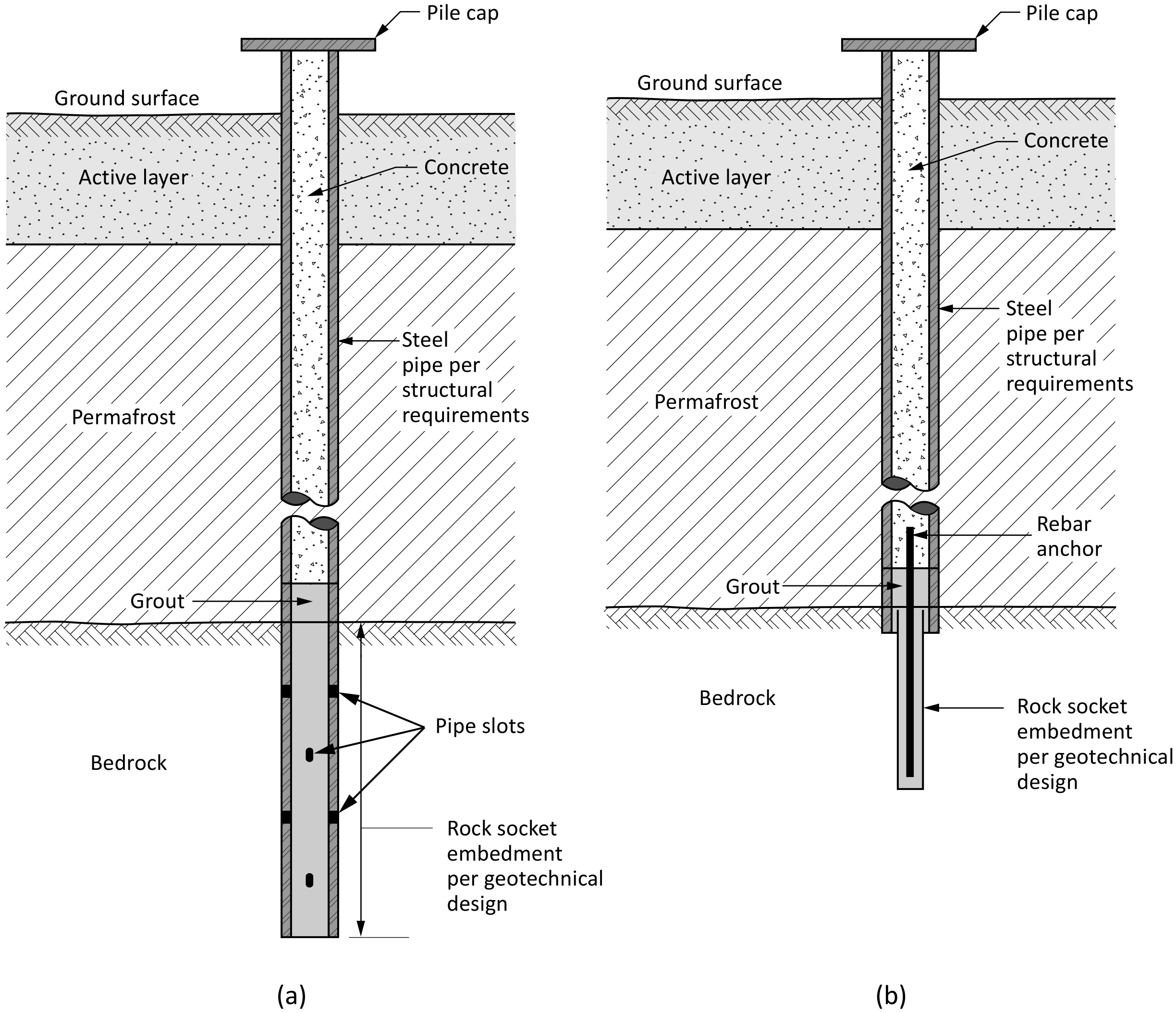
Successful installation of rock socket piles is dependent on the rock socket being able to be kept reasonably clean and dry after drilling and before placement of the grout. Thus timing of construction becomes a consideration, with drilling while the ground is frozen being preferable to drilling when the active layer is fully developed. If difficult drilling conditions are anticipated, specialized drilling systems can be employed to advance casing into the rock in an effort to improve the seal against seepage and sloughing. An example of a pile that had the casing installed with a specialized drilling system is shown in Figure A.9 b).

In permafrost, specialized grout mixes are required to ensure adequate hydration before the grout freezes.

While this pile type has advantages over adfreeze piles in terms of pile capacity and the limitations the foundation imposes on the building or structure, construction is more challenging and attention to quality control becomes more important.

Recently, there have been installations of what has been termed an “end-bearing adfreeze pile”. The ends of these piles are set in a drilled rock socket but the pile hole is filled with aggregate and water, rather than grout. This pile type is able to take advantage of the end-bearing in the rock, but avoids the expense of grout. This hybrid between an adfreeze and rock socket pile has not yet been used widely, and requires careful oversight by an engineer.

Figures A.9
Examples of rock socket piles in permafrost
(See Clause A.2.3.3.)



A.2.3.4 Driven piles

Driven piles, although rare in permafrost areas, have been used. When used, it has generally been in warm permafrost, where the soil has a high proportion of unfrozen moisture content, so that it remains somewhat pliable. If used, they require the drilling of a slightly undersized pilot hole to the minimum desired embedment depth.

If the end of the pile is seated in bedrock, it becomes potentially more economical to install than rock socket piles. If the pile is embedded entirely in permafrost soil, it offers no advantage to a conventionally installed adfreeze pile.

Because permafrost presents a difficult driving condition, driving shoes are required on the ends of the piles. Potential for damage to the pile during driving is high. Therefore, care must be taken to match the pile driving hammer energy to the steel section being used. Pile installations must be carefully monitored to verify that the piles are not damaged during driving.

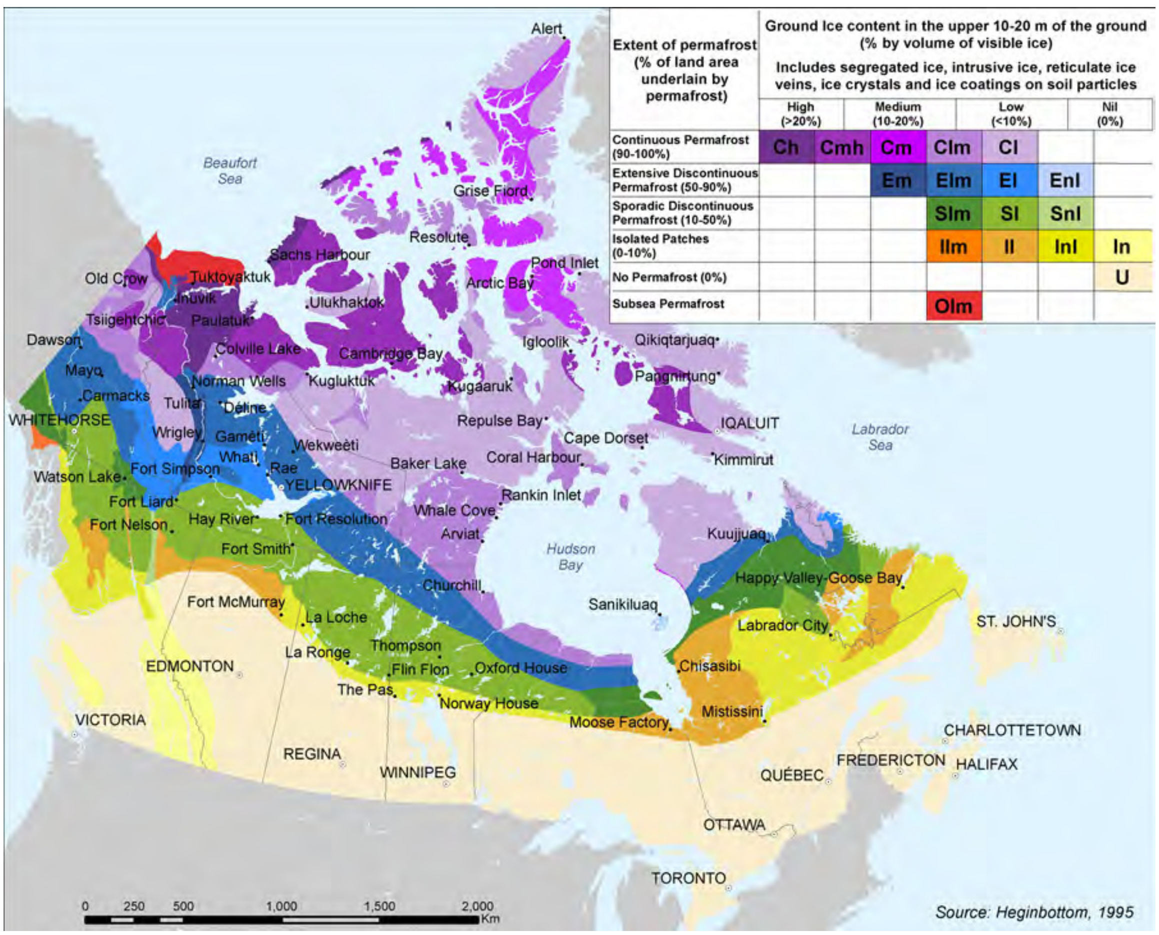
Annex B (informative)
Background information on permafrost

Note: *This Annex is not a mandatory part of this Standard.*

B.1 What is permafrost

Permafrost is ground (soil or rock) that remains at or below a temperature of 0 °C for two or more consecutive years. The layer of material above the permafrost that thaws and refreezes annually is called the active layer. Figure B.1 shows that the permafrost region covers about half of Canada.

Figure B.1
Permafrost zones of Canada
(See Clause B.1.)



Note: *Adapted from Heginbottom et al. (1995), with permission from Natural Resources Canada.*

North of the treeline (or above it in most mountains north of 62°N), permafrost underlies almost all of the land area and is spatially continuous, whereas south of the treeline (or below it in the mountains) there is a broad zone of discontinuous permafrost. The latter is subdivided into the extensive discontinuous permafrost zone to the north where 50 to 90% of the landscape is underlain by permafrost and the sporadic permafrost zone farther south where 10 to 50% of the land area is underlain by permafrost. The proportion of the land area underlain by permafrost decreases still further southward to less than 10%. In this zone of isolated patches, permafrost is present only in some parts of the landscape, such as peat plateaus in the lowlands or beneath the highest peaks in the mountains.

Throughout the permafrost zone, lakes that exceed the depth of maximum winter ice-thickness and large rivers are underlain by perennially unfrozen ground referred to as a talik. Taliks can also be caused by construction activities or natural disturbances such as forest fire. Taliks can partially penetrate into or completely through the permafrost.

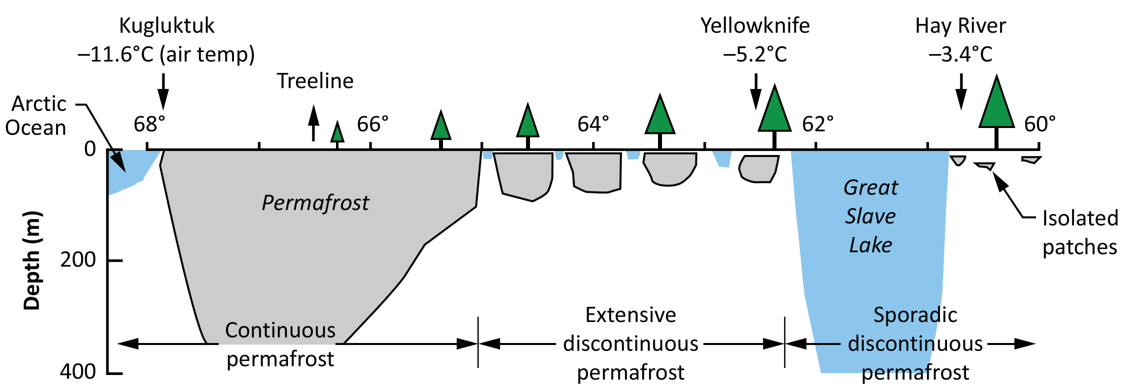
The definition of permafrost is significant in relation to the stability of foundations, as it is based on temperature as opposed to the phase change between water and ice. Not all water in the soil changes to ice at 0 °C and this is particularly the case if the soil is fine-grained (such as silts and clays) or if the pore water is saline (such as in sediments of marine origin). In the Arctic coastal areas and other regions containing marine sediments, permafrost might not be solidly frozen. In engineering applications, frozen strength in permafrost does not develop until the phase change to ice has occurred and, prior to this, strength properties for unfrozen soil should be used. After phase change, there is a considerable increase in strength and foundation bearing pressure is not usually an issue. In saline permafrost, the strength can be significantly less than freshwater permafrost at any given frozen temperature.

B.2 Characteristics of permafrost

B.2.1 Geographical variation of permafrost thickness

The thickness of permafrost relates to air temperature, the thermal properties of the earth materials, geological history, and local site conditions such as surface drainage, soils, vegetation, and snow conditions, as well as the geothermal gradient. On Ellesmere Island, where mean annual air temperatures are as low as –19 °C, permafrost can be greater than 700 m thick. On the mainland Arctic Coast, permafrost is about 400 m thick and its thickness decreases southward as mean annual air temperature rises (Figure B.2). Where present within the southern zone of isolated patches, permafrost will be just below 0 °C and might be only a few metres thick.

Figure B.2
Permafrost thicknesses across a latitudinal gradient from north to south
(See Clause B.2.1.)

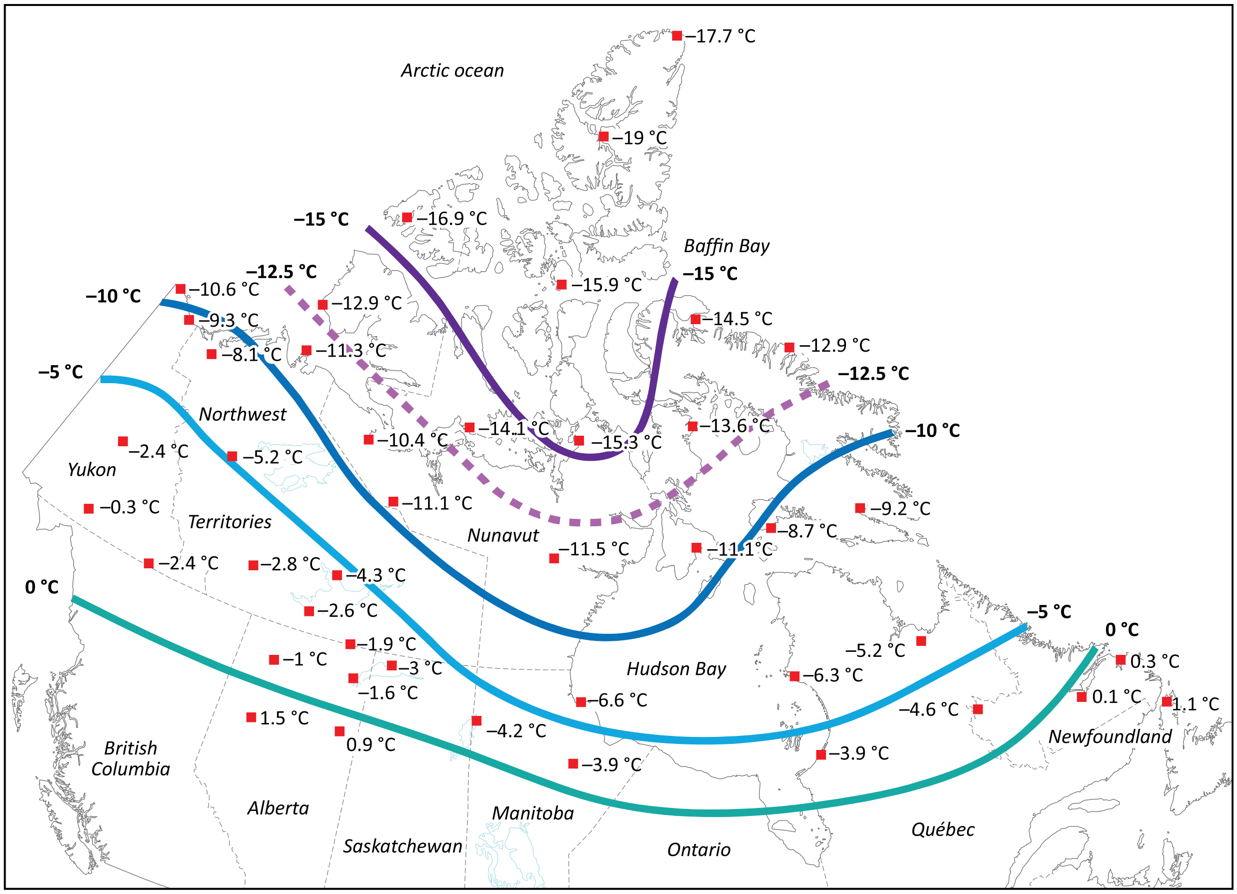


B.2.2 Ground temperatures

Permafrost is the geological manifestation of climate, so there is typically an association between the variation in air temperature and the distribution and temperatures of permafrost [Figure B.3 a)]. The term mean annual ground temperature (MAGT) is often used to characterize permafrost temperature.

In the High Arctic, MAGT can be as cold as –15 °C. Temperatures are much warmer in the zone of discontinuous permafrost where MAGT is typically above –3 °C [Figure B.3 b)].

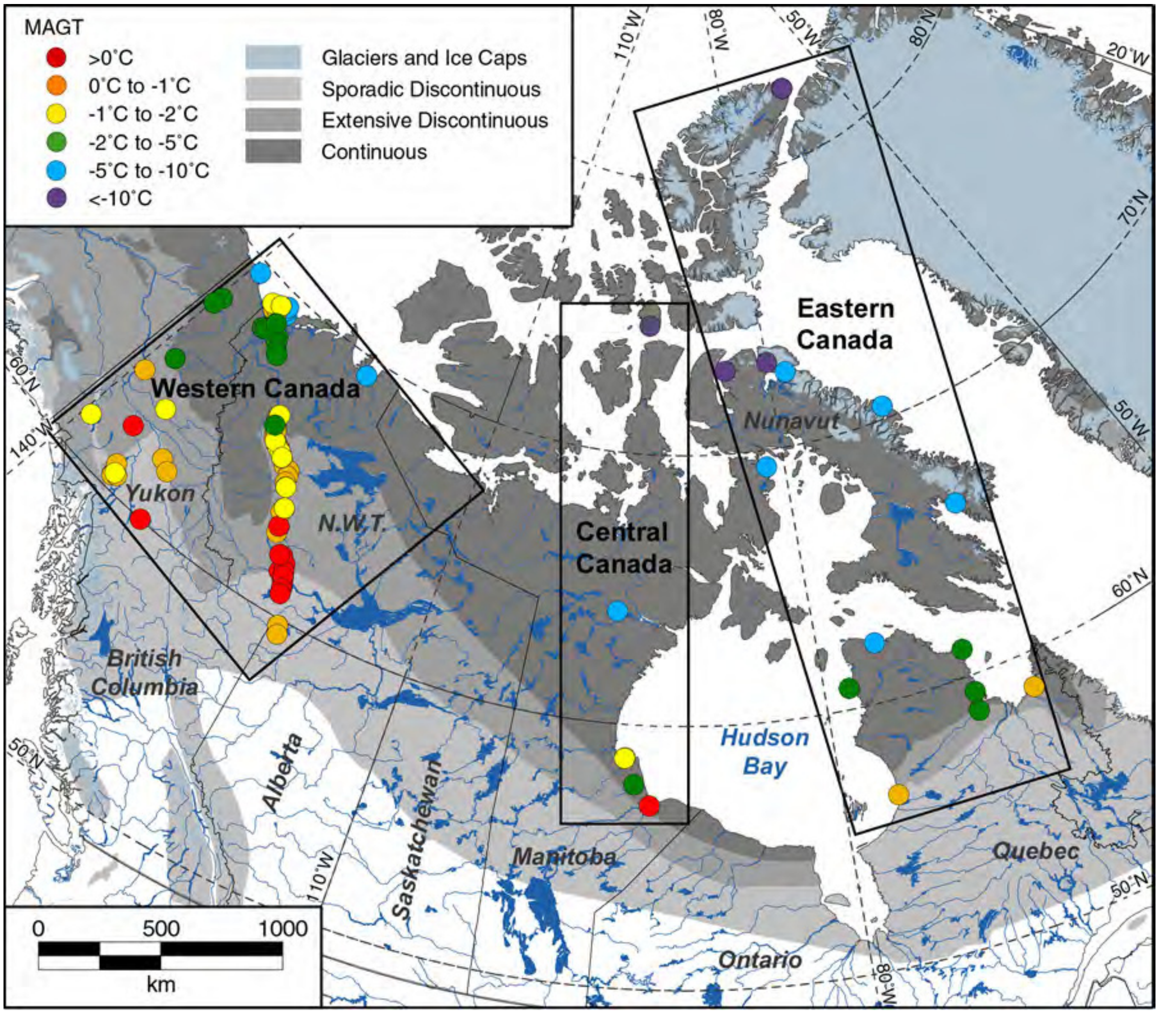
Figure B.3 a)
Mean annual air temperature (MAAT) isotherms (1979–2008)
(See Clauses 6.4.3 and B.2.2.)



Legend:
■ Environment Canada homogenized climate station data

Source: *Environment Canada*.

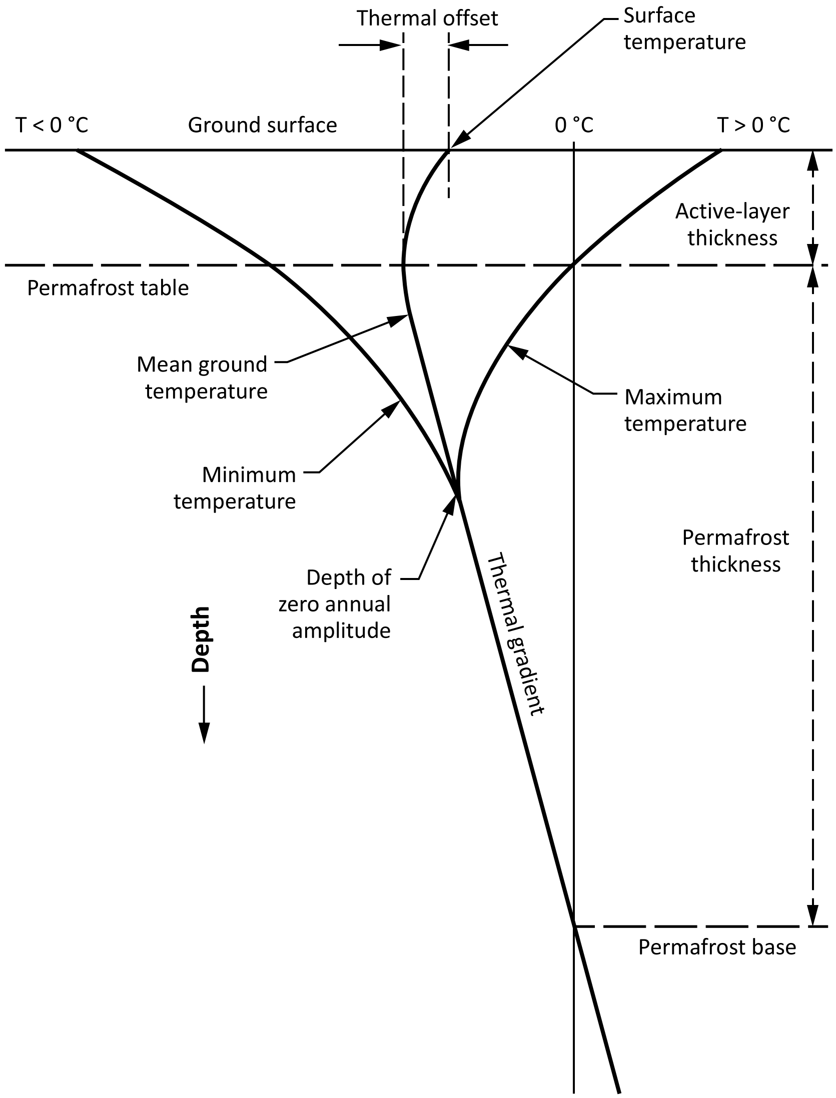
Figure B.3 b)
Mean annual ground temperatures (MAGT) in Northern Canada
(See Clause B.2.2.)



Source: *Smith et al. (2010).*

Figure B.4
Typical ground temperature profile in a permafrost area

(See Clauses B.2.2 and B.2.3)



Source: *Burn (2004)*.

The near surface experiences cold ground temperatures in winter and temperatures above 0 °C in summer. The active layer extends to the depth where the maximum temperature is 0 °C. The amplitude of seasonal temperature variation decreases with depth to the point of zero annual amplitude, where the ground temperature remains constant throughout the year. The depth of zero annual amplitude at a site depends on surface conditions, soil properties, and the range of the ground-surface temperatures. In discontinuous permafrost, latent heat effects in warm, fine-grained permafrost soils might restrict the depth of zero annual amplitude to between 2 and 5 m below the ground surface. In cold, continuous permafrost or in bedrock, ground temperatures can vary annually to depths exceeding 15 m. Under equilibrium conditions, ground temperatures increase below the depth of zero annual amplitude to the base of permafrost.

An increase in temperature at the ground surface due to disturbance or climate change can lead to a rise in the temperature of permafrost. Permafrost that is near 0 °C will respond more slowly to the effects of surface warming, than colder permafrost. This is due to the absorption of latent heat by melting ice as permafrost temperatures approach 0 °C. In contrast, ground ice in colder permafrost is farther from its melting point so that progressive heating of the ground surface is only used to raise the ground temperature. This point is significant when monitoring ground temperatures because warm permafrost might not appear to be warming rapidly, but the geotechnical properties might be changing significantly as pore ice is converted to water at temperatures near 0 °C.

B.2.3 Active layer

The active layer is defined as the upper layer of earth materials that freezes and thaws on an annual basis. Figure B.5 illustrates an active layer exposed in a soil pit.

Figure B.5
The active layer exposed in a soil pit on Ellesmere Island
(See Clause B.2.3.)

Note: *The active layer thaws to a depth of 50–60 cm in summer and refreezes in the winter, and at this location overlies perennially frozen ground at the base of the pit which extends to depths of hundreds of metres.*

The main factors that influence the thickness of the active layer are summer air temperature, soil composition, moisture content, vegetative cover, slope aspect, and elevation. Active layer thicknesses in the zone of continuous permafrost vary between 0.3 m in organic soils to more than 1.0 m in dry sandy soils. Active layers in bedrock can be several metres in thickness.

The active layer generally increases in thickness with decreasing latitude. This general trend relates to summer air temperature, but factors such as vegetation cover, soil moisture content, slope aspect (north- versus south-facing), and elevation give rise to significant local variation that can locally invert this trend. For example, in the discontinuous permafrost, subarctic spruce forests with thick organic soils can be characterized by active layer thicknesses of less than 60 cm. In contrast, barren terrain in the southern Canadian Arctic Archipelago may thaw to a depth of 2.0 m, especially in coarse-grained soils or shallow bedrock areas with a southern exposure.

Disturbance or removal of the surface organic layer can cause active layer thicknesses to increase and near-surface permafrost to thaw. This can have a profound effect on surface stability in ice-rich terrain.

B.2.4 Ground ice

Permafrost derives its environmental and geotechnical significance from the occurrence and characteristics of the ice within it. The presence of ground ice in permafrost contributes significantly to a site's sensitivity to disturbance. Melting of ground ice associated with permafrost thaw can lead to subsidence of flat terrain or landsliding on slopes.

Excess ice is the volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions. When permafrost containing excess ice thaws this water is released, the ground surface typically subsides and ponding can occur.

Ground ice can be classified by its appearance into pore ice, which occurs in the pores of soils and rocks and acts to bond these materials, and larger horizontal or vertical bodies of essentially pure ice (Figure B.6). The latter can range from thin segregated ice lenses several mm to several cm in thickness, to pure massive ice several metres thick.

Figure B.6
Canadian system for describing ground ice
(See Clause B.2.4.)

GROUND ICE DESCRIPTION

ICE NOT VISIBLE

GROUP SYMBOL	SYMBOL	SUBGROUP DESCRIPTION	
N	Nf	Poorly-bonded or friable	
	Nbn	No excess ice, well-bonded	
	Nbe	Excess ice, well-bonded	

VISIBLE ICE LESS THAN 50% BY VOLUME

GROUP SYMBOL	SYMBOL	SUBGROUP DESCRIPTION	
V	Vx	Individual ice crystals or inclusions	
	Vc	Ice coatings on particles	
	Vr	Random or irregularly oriented ice formations	
	Vs	Stratified or distinctly oriented ice formations	

VISIBLE ICE GREATER THAN 50% BY VOLUME

GROUP SYMBOL	SYMBOL	SUBGROUP DESCRIPTION	
ICE	ICE + Soil type	Ice with soil inclusions	
	ICE	Ice without soil inclusions (greater than 25 mm thick)	

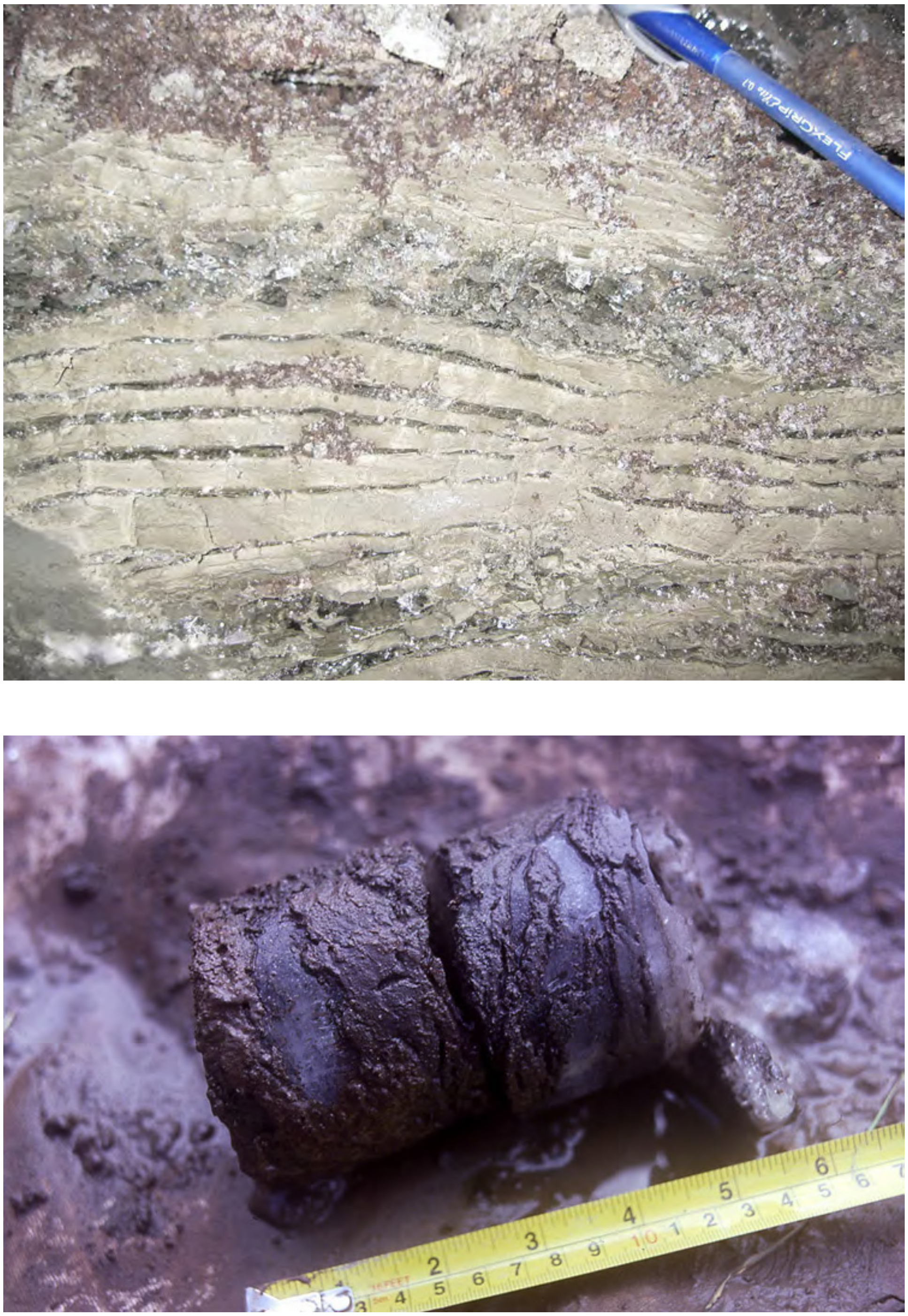
Notes:
1) *Dual symbols are used to indicate borderline or mixed ice classifications.*
2) *Visual estimates of ice contents indicated on borehole logs ± 5%.*
3) *This system of ground ice description has been modified from NRC Technical Memo 79, Guide to the Field Description of Permafrost for Engineering Purposes.*

Legend:
☐ Soil ■ Ice

Source: *Pihlainen and Johnston (1963).*

In general, permafrost in coarse-grained sands and gravels has low to moderate ground ice contents with most of the ground ice occurring as pore ice which is often not visible to the naked eye. Ice lenses encountered in near-surface permafrost form because water can be drawn along a thermally-induced gradient into freezing ground. Fine-grained soils such as silts or clays that contain unfrozen water at temperatures below 0 °C are considered frost-susceptible and excess ice contents of 30% or more are common in these soils, particularly in the top few metres of permafrost (see Figure B.7).

Figure B.7
Segregated ice developed in fine-grained soils. Top: Ice layers in a pit excavated in central Yukon. Bottom: lenses in a core from a permafrost-cored mound (palsa) in the southern Yukon
(See Clause B.2.4.)



The presence of this near-surface ice-rich zone makes many areas of permafrost terrain sensitive to deepening of the active layer. Ice can be found not only in surficial deposits but also in pores and cracks/bedding planes of sedimentary bedrock (Figure B.8) or in cracks and fissures within igneous and metamorphic bedrock. Massive ice, on the order of several metres thick, is common in numerous areas of Northern Canada (Figure B.9). Some bodies of massive ice may be buried glacier ice, but many are the result of ice segregation, as in pingos and some ice-cored ridges.

Figure B.8
Massive segregated ice in bedrock (coal layers), Ellesmere Island
(See Clause B.2.4.)

Note: *The ice is immediately behind the scale.*

Figure B.9
Massive segregated ice exposed in a thaw slump in the Peel Plateau
(See Clause B.2.4.)

Notes:

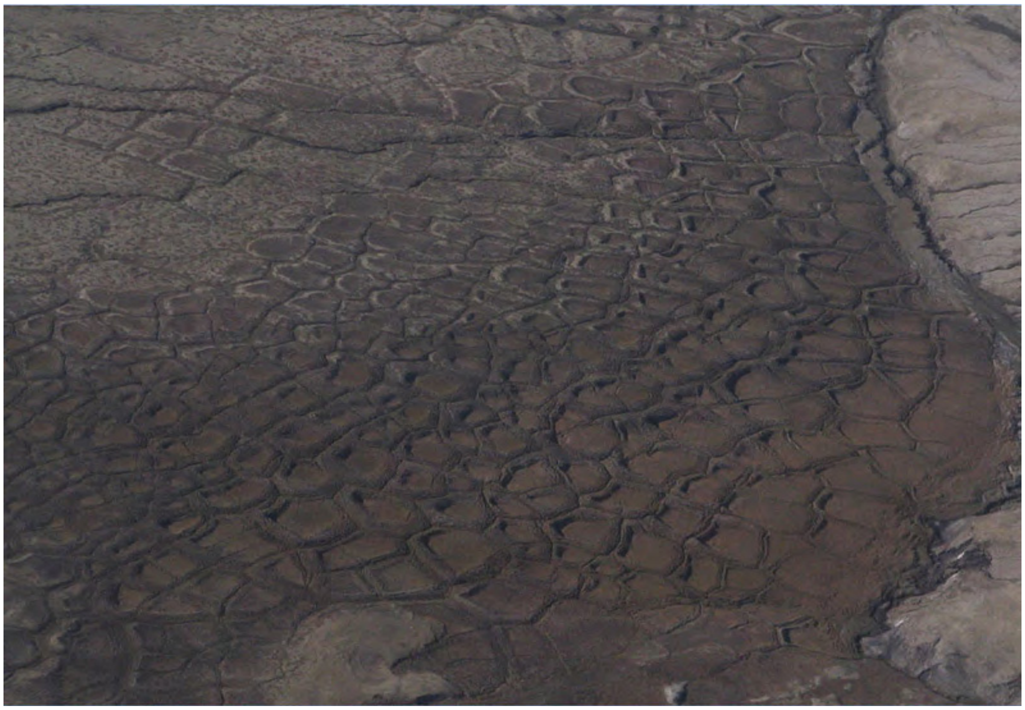
1) *The sediment layers in the ice constitute less than 30% of the total volume of the permafrost.*

2) *Ice wedges are a common type of ground ice in the continuous permafrost zone (Figure B.10).*

Figure B.10
Wedge ice exposed in a thaw slump, Mackenzie Delta
(See Clause B.2.4 and Figure B.9.)

These bodies of massive ice develop in permafrost where winter ground temperatures are sufficiently low to cause cracking due to thermal contraction. Infiltration of snowmelt and refreezing of water in the crack forms a vertical vein of ice and, with repetition, an ice wedge. Polygonal terrain common throughout tundra environments is the surface expression of an ice-wedge network (Figure B.11).

Figure B.11
Polygonal terrain caused by thermal contraction cracking, Ellesmere Island
(See Clause B.2.4 and Figure B.10.)



Note: *An ice wedge is present beneath the margin of each of these polygons.*

B.3 Effects of climate change on permafrost in Canada

There are numerous general circulation models (GCMs) in use, and most project an initial, global averaged air temperature warming for the near future (to 2030) of 0.6 to 0.7 °C relative to the 1980–1999 period. This increase in air temperature is largely due to the greenhouse gases that have been emitted into the atmosphere.

In the future, the atmosphere's composition will continue to change, but the rate of increase or decrease of greenhouse gases over the next several decades is unknown. By the end of the 21st century, only about 20% of the projected warming will be due to the greenhouse gases that are now in the atmosphere, while 80% of the climate change will be associated with greenhouse gases that will be emitted in the future. All GCMs indicate that climate change will be greater in the Arctic than in other regions of Canada, and will become more pronounced over time. Given moderate emissions scenarios, mean annual air temperatures in the Arctic over the next 100 years are expected to increase by an average of 5 °C over land. Winter temperatures are affected the most, with significantly warmer winters and only slightly warmer summers.

Monitoring data from the Canadian North demonstrates that permafrost temperatures have responded to recent climate warming. Since the 1970s, permafrost in the lower Mackenzie Valley has warmed by about 2 °C, but the rate of temperature increase has been slower in discontinuous permafrost further to the south where much of the excess heat entering the ground has been consumed by the gradual conversion of ice to water, rather than by an increase in ground temperature. It is anticipated that climate warming will cause ground temperatures to continue to increase and that thin permafrost in the isolated patches and sporadic discontinuous zone will eventually disappear. An increase in active layer thicknesses will lead to thawing of near-surface ground ice and surface subsidence. In areas with infrastructure, settlement of roads and foundations can accelerate. An increase in active layer thickness may also create greater seasonal frost heave effects at sites where frost-susceptible soils and water are present.

B.4 Effects of permafrost thaw on structures

Thaw settlement occurs due to melting of excess ice within the soils or bedrock, resulting in consolidation of the materials and surface settlement. There can also be additional settlement after the excess water dissipates in the foundation soils.

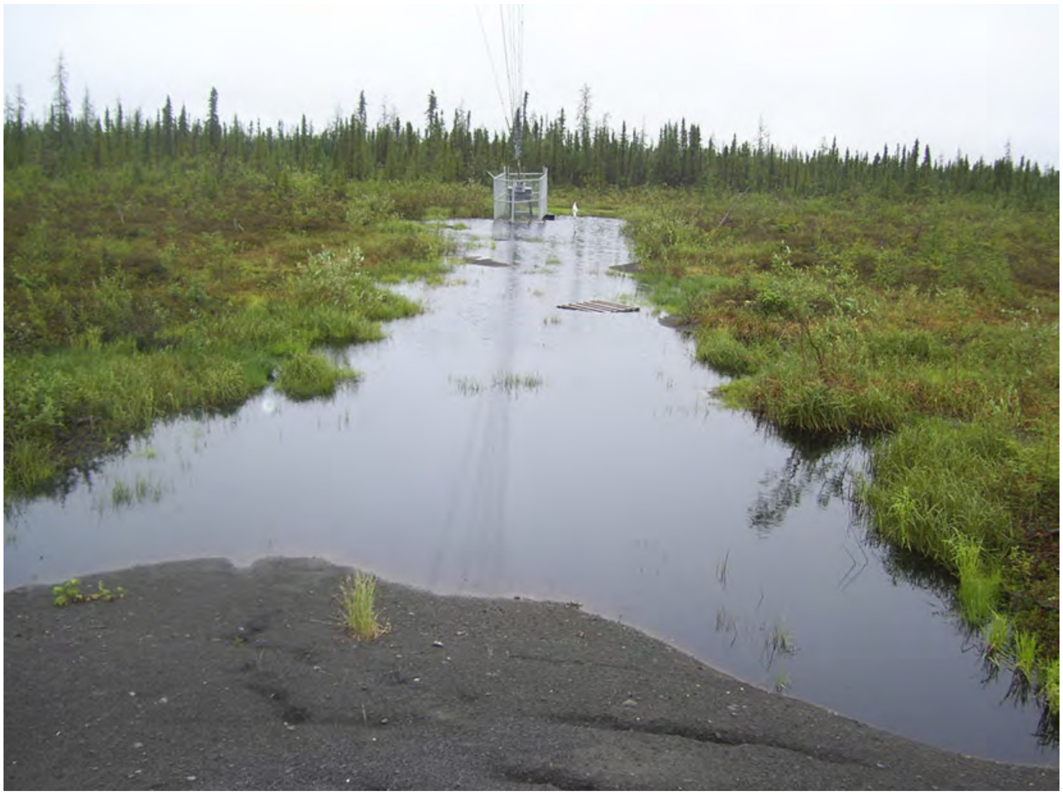
Movements of a structure built on permafrost can occur for a variety of reasons. Before deciding on mitigation methods, it is necessary to verify if thaw settlement is responsible. Among the characteristics of thaw settlement is that its effects will continue to get worse all year round, but the rate of settlement may slow down in the winter months. There will be increasing permanent deformations throughout the structure that will continue to get worse with time. There can also be surface depressions around structures, which can accumulate surface water and might require additional fill.

The magnitude of thaw settlement depends upon the ice content of the thawing permafrost. Long-term thaw settlement on the order of several metres is not uncommon. Thaw settlement effects on structures can include cracks in brittle finishes, while doors and cupboards on interior walls can jam and be difficult to open and close. There can also be diagonal cracks above window and door openings, and drywall seams can open up. Thaw settlement under heated structures usually results in a bowl-like depression under the building or structure, with the centre of the building or area of greatest heat transfer settling more than the exterior walls (Figure B.12).

Figure B.12
Cracks above interior window of school in central Yukon
(See Clause B.4.)

For towers, guy anchors will lose tension as tower base settles, or guy anchors may gain tension due to guy anchor settlement (Figure B.13).

Figure B.13
Thaw settlement and increased guy anchor tension due to permafrost thaw
(See Clause B.4.)



The ground has settled allowing the pond to form and the anchor in the background has also settled, increasing tension on the wires.

B.5 Frost heave

Frost heave occurs during seasonal freezing of the active layer over permafrost in the late fall, or during the annual frost penetration in an area of seasonally frozen ground within (or outside) the zone of discontinuous permafrost. It is the result of the expansion of water by about 9% during the freezing process, as well as the movement of water from unfrozen soil into freezing ground and subsequent formation of ice lenses. Frost heave is greatest in fine-grained sediments such as silts, which contain unfrozen water at temperatures below 0 °C and possess a sufficiently high hydraulic conductivity to permit the movement of water towards a freezing front. Frost heave can result in differential movement of foundation systems. The magnitude of frost heave depends on many factors, but annual ground surface heave in the order of 0.3 m has been observed.

Some of the effects of frost heave can resemble those produced by thaw settlement. These include cracks in brittle finishes, as well as building doors and cupboards on exterior walls that may jam and be difficult to open and close. In addition, there can be diagonal cracks above window and door openings, and drywall seams can open up. Guy wires on towers can lose tension due to heave of guy anchors and no movement of the tower base or guy wires on towers can gain tension due to heave of the tower foundation.

An important diagnostic feature for frost heave is that its effects will be most noticeable in approximately April of every year, at the time of coldest ground temperature and greatest frost penetration. The structure will return to near-normal conditions when seasonal frost has thawed (usually in June or July). However, there will usually be some permanent deformation as the structure never returns completely to its original condition.