



**BNQ**

**Bureau de normalisation  
du Québec**

# **CAN/BNQ 2501-500/2025**

**Geotechnical Site Investigations for Foundations  
of Building or Structure in Permafrost Zones**

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**STANDARD**



CAN/BNQ 2501-500/2025

Geotechnical Site Investigations for Foundations  
of Building or Structure in Permafrost Zones

*Études géotechniques pour les fondations de bâtiments  
et d'ouvrages d'art dans les zones de pergélisol*



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This new edition supersedes the edition dated February 20, 2017.

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## **INTRODUCTION**

Geotechnical site investigations are essential to select the appropriate design, construction and maintenance of buildings or structures. In permafrost zones, these investigations have an added level of complexity due to the following factors:

- a) potential presence of ice within the soil or bedrock whose properties are dependent on several parameters, including, but not limited to temperature and salinity;
- b) influence of climate change, which is modifying the ground thermal regime thereby changing the properties of the permafrost;
- c) presence of saline soils.

This standard was developed to establish a consistent methodology for geotechnical site investigations, including data collection as well as the evaluation and reporting of site conditions while accounting for seasonal, and interannual climate conditions and projected climate conditions over the service life of the foundations of buildings or structures. In the long term, as improper site evaluation can lead to permanent damage, this standard will help lessen persistent maintenance issues.

The level of detail of a geotechnical site investigation to obtain adequate site information to select and design appropriate foundations for a building or a structure in permafrost zones depends on many factors. This also applies for rehabilitation plans of existing foundations of buildings or structures located in permafrost zones.

This standard was developed taking into account the specific constraints of the North and the diverse nature of projects.

This standard also ensures that each project is carried out within a risk management framework for assessing impacts of climate change according to the document CSA PLUS 4011. Therefore, each project is assigned a risk level based on the sensitivity of the site to climate change and the consequence of potential failure of the foundations of buildings or structures. For moderate/high-risk projects, the level of detail of geotechnical site investigations will be substantially higher than for low/negligible-risk projects. This standard allows for some flexibility throughout the geotechnical site investigations, as the findings may influence the extent of work to be undertaken at the next stage. Additional, hazards and risks related to considerations other than climate change may be included in the geotechnical site investigation program but are not part of this standard.

More specifically, this standard defines a consistent methodology for performing a geotechnical site investigation, but since the level of detail required to obtain adequate site information depends on many factors, it relies on the geotechnical consultant's judgement to make the appropriate recommendations to the client. It also requires that the geotechnical consultant and the client take the appropriate steps to have a common understanding of all work to be

undertaken throughout the project. This two-way communication will ensure that the client is able to take risk-informed decisions in consultation with the geotechnical consultant.

This standard is the fifth in a suite of innovative National Standards of Canada (NSCs), aiming to foster the long-term sustainability and resiliency of Canada's Northern infrastructure. The four other NSCs, that were developed as part of the Northern Infrastructure Standardization Initiative (NISI), are:

- a) CSA S500 — *Thermosyphon Foundations for Buildings in Permafrost Regions;*
- b) CSA S501 — *Moderating the Effects of Permafrost Degradation on Existing Building Foundations;*
- c) CSA S502 — *Managing Changing Snow Load Risks for Buildings in Canada's North;*
- d) CSA S503 — *Community Drainage System Planning, Design, and Maintenance in Northern Communities.*

All of these NSCs are complementary and contribute towards achieving the same objective of helping Canada's North build a resilient infrastructure despite the uncertainties of a changing climate.

This is also true of the document CSA PLUS 4011 *Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation*. It is a key document that was first published in 2010 and reedited in 2019 for a better understanding of how climate change may affect Canada's Northern infrastructure.

## **1**            **PURPOSE**

This standard combines guidance and requirements in order for activities (planning, conducting and reporting) included in geotechnical site investigations for foundations of buildings or structures in permafrost zones to be carried out in a proper and consistent way.

The purpose of this standard is to define a rigorous methodology for performing geotechnical site investigations aimed at obtaining adequate site information to select or rehabilitate foundations for a building or a structure with due consideration, in a climatic risk management framework, of the conditions prevailing on site, including:

- a) the distinctive characteristics of permafrost;
- b) the seasonal and interannual climate conditions as well as the projected climate conditions that affect the thermal regime of soils over the service life of the foundations of buildings or structures.

## **2**        **SCOPE**

This standard applies to geotechnical site investigations performed in permafrost zones to provide essential information to the design, construction, and maintenance or rehabilitation for new foundations of all types of buildings or structures and existing foundations of buildings or structures.

NOTE — The principles laid out in this standard may apply to other types of infrastructure located in permafrost zones. However, it is the user’s responsibility to judge whether this standard is suitable for its needs.

It also applies to the assessment of site-specific conditions as part of the geotechnical site investigation.

This standard applies only to hazards and risks related to climate change and other environmental considerations.

It does not apply to post-construction monitoring of the building or structure site.

NOTE — Users of this standard requiring information on other aspects related to the conditions, design, monitoring and remediation planning not identified in this standard may refer to other documents, namely the document CSA S501.

All considerations outside the geotechnical aspects are not covered in this standard.

This standard is primarily aimed at geotechnical consultants, but it may also be used by the owners, designers of buildings or structures, contractors, and regulatory bodies.

## **3**        **NORMATIVE REFERENCES**

### **3.1**       **GENERAL**

The references below (including any amendment or errata) are normative references, and are therefore considered mandatory. They are essential to the understanding and use of this standard, and are cited in appropriate places in the text.

It should be noted that a dated (normative and informative) reference refers to that specific edition of the reference, while a non-dated reference refers to the latest edition of the reference in question.

NOTE — This standard also cites informative references, which are listed in an annex. A bibliography of references on topics covered in this standard is also annexed.

### 3.2 DOCUMENTS FROM STANDARDS BODIES

#### BNQ (Bureau de normalisation du Québec) [<https://www.bnq.gc.ca>]

CAN/BNQ 2501-090	<i>Soils — Determination of Liquid Limit by the Casagrande Apparatus and Determination of Plastic Limit.</i> (Sols — Détermination de la limite de liquidité à l'aide de l'appareil de Casagrande et de la limite de plasticité.)
CAN/BNQ 2501-092	<i>Soils — Determination of Liquid Limit by a Fall Cone Penetrometer and Determination of Plastic Limit.</i> (Sols — Détermination de la limite de liquidité à l'aide d'un pénétromètre à cône et de la limite de plasticité.)
CAN/BNQ 2501-170	<i>Soils — Determination of Water Content.</i> (Sols — Détermination de la teneur en eau.)
CAN/BNQ 2501-250	<i>Soils — Determination of the Water Content-Dry Density Relation — Standard Compaction Effort Test (600 kN m/m<sup>3</sup>).</i> [Sols — Détermination de la relation teneur en eau-masse volumique sèche — Essai avec énergie de compactage normale (600 kN m/m <sup>3</sup> ).]

#### ASTM International [<https://www.astm.org>]

ASTM D698	<i>Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft<sup>3</sup> [600 kN-m/m<sup>3</sup>]).</i>
ASTM D2216	<i>Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.</i>
ASTM D4083	<i>Standard Practice for Description of Frozen Soils (Visual-Manual Procedure).</i>
ASTM D4318	<i>Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.</i>
ASTM D4542	<i>Standard Test Methods for Pore Water Extraction and Determination of the Soluble Salt Content of Soils by Refractometer.</i>
ASTM D4611	<i>Standard Test Method for Specific Heat of Rock and Soil.</i>

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ASTM D5334	<i>Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure.</i>
ASTM D5520	<i>Standard Test Method for Laboratory Determination of Creep Properties of Frozen Soil Samples by Uniaxial Compression.</i>
ASTM D6032	<i>Standard Test Method for Determining Rock Quality Designation (RQD) of Rock Core.</i>
ASTM D6913	<i>Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis.</i>
ASTM D7012	<i>Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures.</i>
ASTM D7263	<i>Standard Test Methods for Laboratory Determination of Density and Unit Weight of Soil Specimens.</i>
<b>CSA Group</b> [ <a href="https://www.csagroup.org">https://www.csagroup.org</a> ]	
CSA PLUS 4011	<i>Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation.</i> (Guide technique : Infrastructure dans le pergélisol : lignes directrices pour l'adaptation au changement climatique.)
<b>ISO (International Organization for Standardization)</b> [ <a href="https://www.iso.org">https://www.iso.org</a> ]	
ISO 14689	<i>Geotechnical Investigation and Testing — Identification, Description and Classification of Rock.</i> (Reconnaissance et essais géotechniques — Identification, description et classification des roches.)
ISO 17892-1	<i>Geotechnical Investigation and Testing — Laboratory Testing of Soil — Part 1: Determination of Water Content.</i> (Reconnaissance et essais géotechniques — Essais de laboratoire sur les sols — Partie 1 : Détermination de la teneur en eau.)

ISO 17892-2

*Geotechnical Investigation and Testing — Laboratory Testing of Soil — Part 2: Determination of Bulk Density.*

(Reconnaissance et essais géotechniques — Essais de laboratoire sur les sols — Partie 2 : Détermination de la masse volumique d'un sol fin.)

### 3.3 OTHER DOCUMENT

CANADIAN GEOTECHNICAL SOCIETY (CGS). *Canadian Foundation Engineering Manual*, 5th Edition, Vancouver, B.C., 2023, 888 p.

## 4 DEFINITIONS

For the purpose of this standard, the following terms are defined as follows:

**active layer**, n. Layer of ground that is subject to annual thawing and freezing, and underlain by permafrost. French: *couche active*.

**active layer thickness** (abbrev.: **ALT**), n. Thickness of the surface layer of the ground that is subject to annual thawing and freezing, and underlain by permafrost. French: *épaisseur de la couche active* (abbrev.: *ECA*).

**air freezing index** (abbrev.: **AFI**), n. Cumulative number of degree-days below 0 °C for the air temperature during a given time period. French: *indice de gel de l'air* (abbrev.: *IGA*).

**air thawing index** (abbrev.: **ATI**), n. Cumulative number of degree days above 0 °C for the air temperature during a given period. French: *indice de dégel de l'air* (abbrev.: *IDA*).

**borehole**, n. A hole drilled in the ground, typically to observe and sample the substrate, and in permafrost areas, often to permit installation of a ground temperature cable. French: *forage*.

**borrow pit**, n. Excavated area where soil, gravel, sand or another material has been excavated for use as construction material. French: *banc d'emprunt*.

**building**, n. Any structure used or intended for supporting or sheltering any use or occupancy (reference: *National Building Code of Canada* [adapted wording]). French: *bâtiment*.

**client**, n. Person or organization, including its designated representatives that appoint the geotechnical consultant. French: *client*.

**continuous permafrost**, n. Permafrost occurring beneath all of the exposed land surface of a geographic region with the exception of widely scattered sites, such as newly deposited or newly

exposed unconsolidated sediments, where the climate has just begun to impose its influence on the ground thermal regime. French: *pergélisol continu*.

NOTE — In the continuous permafrost zones, permafrost occurs beneath 90% or more of the exposed land surface.

**creep of frozen soil**, n. Slow deformation that results from long-term application of a stress too small to produce immediate failure in the frozen soil. French: *déformation lente du gélisol*.

**cryopeg**, n. Perennially cryotic solute-rich groundwater. French: *cryopeg*.

NOTES —

- 1 Three types of cryopeg may be distinguished based on their position with respect to permafrost:
  - a) a basal cryopeg occurs in the basal portion of the permafrost;
  - b) an isolated cryopeg is entirely surrounded by perennially frozen ground;
  - c) a marine cryopeg, which may be basal and/or isolated, is found in coastal or subsea permafrost.
- 2 Cryopegs may be under pressure, up to and including artesian.
- 3 In North America, the term *cryopeg* has been used to denote an unfrozen zone in the permafrost (i.e., a talik) in which cryotic solute-rich groundwater is present.

**cryostratigraphy**, n. Field of study that examines rock and sediment bodies presently or previously frozen, and organizes them into distinctive, identifiable and mappable units called cryofacies based on their inherent ground-ice properties, with the objectives of establishing the distribution and spatial relationships of these units, analyzing their succession in time, and interpreting the history of permafrost. French: *cryostratigraphie*.

**degree-day**, n. Derived unit of measurement defined as the departure of the mean temperature for one day from a given reference or base temperature. French: *degré-jour*.

**depth of zero annual amplitude**, n. Distance from the ground surface to the level beneath which the annual fluctuation in ground temperature is negligible. French: *profondeur d'amplitude annuelle nulle*.

NOTE — A change of no more than 0.1 °C throughout the year is considered as practically no annual fluctuation.

**designer**, n. Professional engineer responsible for the design and preparation and/or issuing of drawings or specifications for a construction project (reference: CSA S500 [adapted wording]). French: *concepteur*.

**discontinuous permafrost**, n. Permafrost occurring beneath some parts of the exposed land surface of a geographic region while adjacent areas are free of permafrost. French: *pergélisol discontinu*.

NOTE — Depending on the scale, several zones where permafrost is discontinuous can be distinguished based on the percentage of the land surface underlain by permafrost. In Canada, these are termed the extensive discontinuous permafrost zone (percentage from 50% to 90%), the sporadic discontinuous permafrost zone (percentage from 10% to less than 50%) and the isolated patches of permafrost zone (percentage of less than 10%).

**disturbed sample**, n. Sample in which the structure of the soil has been changed in such a way that the structural properties are not representative of in situ conditions, but only properties of the soil particle such as particle size distribution, Atterberg limits, and possibly water content can be accurately determined. French: *échantillon remanié*.

**foundation**, n. Structures at or below the surface of the ground that transfer loads from the building to the ground. French: *fondation*.

NOTE — Foundations of a building or a structure are generally regrouped into two broad categories (shallow or deep) depending on where the loads are transferred to the ground (surface/near-surface of the soil or farther down to a subsurface layer or a range of depths). The most common shallow foundations include post and pad, strip footing and slab-on-grade foundations. Deep foundations consist essentially of piles made of different materials, of different sizes, in various shapes and configurations depending on the application.

**geotechnical consultant**, n. The engineer responsible for carrying out the geotechnical site investigation for the client. French: *expert-conseil en géotechnique*.

**ground ice**, n. All types of ice contained in the ground, including buried ice. French: *glace de sol*.

**ground temperature cable**, n. A cable, typically installed in a borehole and equipped with sensors that measure temperature at multiple depths. French: *câble de température du sol*.

**mean annual air temperature** (abbrev.: **MAAT**), n. Average of daily or monthly mean temperatures for a site for a given calendar year. French: *température moyenne annuelle de l'air* (abbrev.: *TMAA*).

NOTE — The mean annual air temperature is available from Environment and Climate Change Canada for specific locations.

**mean annual ground temperature** (abbrev.: **MAGT**), n. The mean annual temperature of the ground at a particular depth. French: *température moyenne annuelle du sol* (abbrev.: *TMAS*).

NOTE — The mean annual ground temperature at the depth of zero annual amplitude is often used to assess the thermal regime of the ground at various locations.

**n-factor**, n. Ratio of the surface freezing or thawing index to the air freezing or thawing index. French: *facteur n*.

**permafrost**, n. Soil or bedrock, including ice and organic material that remains at or below a temperature of 0 °C for at least two consecutive years. French: *pergélisol*.

**permafrost region**, n. A geographic region in which permafrost is present beneath some or all of the ground surface. French: *région pergélisolée*.

NOTES —

- 1 Permafrost is defined as perennially cryotic ground based on the most easily monitored parameter: ground temperature. Permafrost is not necessarily frozen, because included water may freeze or thaw over a range of temperatures below 0 °C and in some substrates, moisture may be absent altogether.
- 2 Permafrost includes perennial ground ice, but not glacier ice or icing, or bodies of surface water with temperatures perennially below 0 °C.
- 3 The non-uniformity of the criteria used to define permafrost and the active layer can lead to operational ambiguity when the depth to the permafrost table is measured by probing or the active layer thickness is calculated from borehole temperatures.

**permafrost zone**, n. Major subdivision of a permafrost region based on estimated permafrost extent. French: *zone de pergélisol*.

NOTE — The International Permafrost Association's circumpolar map identifies four permafrost zones: continuous, discontinuous, sporadic and isolated patches.

**structure**, n. Construction or constructed object that requires stable ground support. French: *ouvrage d'art*.

**talik**, n. A layer or body of perennially unfrozen ground occurring in association with permafrost due to local thermal, hydrological, hydrogeological, or hydrochemical conditions. French: *talik*.

**test pit**, n. Hand or machine excavation used to examine and take samples of the near-surface ground. French: *puits d'exploration*.

**thaw-sensitive permafrost**, n. Permafrost that contains excess ice and which would experience a significant thaw strain or loss of strength, or both, upon thawing. French: *pergélisol sensible au dégel*.

**thermosyphon**, n. Passive heat transfer device, consisting of a sealed tube, with a condenser above ground and an evaporator below ground, both containing liquid and/or gas, installed to remove heat from the ground (reference: CSA S500). French: *thermosiphon*.

NOTE — A thermosyphon:

- a) does not include moving parts;
- b) requires no external power for operation;
- c) functions only when the air temperature is lower than the ground temperature;

- d) is usually a passive cooling system, but may be coupled with an active freezing system via either chilled fluid circulation in the subsurface or cooling of the condenser to activate the passive cooling over longer periods;
- e) may be either a single- or two-phase systems:
  - A single-phase thermosyphon is usually liquid- or gas-filled. During the winter, heat from the soil surrounding the evaporator is absorbed by and thus warms the working fluid, which rises to the above-ground condenser section of the pipe exposed to the cooler air and loses its heat by conduction and natural convection to the air.
  - A two-phase thermosyphon contains a working fluid that can be in either a liquid or vapour phase, depending on its temperature and pressure. When the air temperature falls below the ground temperature, the vapour condenses in the condenser section of the tube, the pressure in the tube is reduced and the liquid in the evaporator starts to boil. The resulting cycle of boiling, vapour movement up the tube, condensation, and return of the condensate by gravity flow is an effective way of transferring heat up the tube, thus cooling the ground.

**undisturbed permafrost sample**, n. Sample of frozen ground from the permafrost that is preserved in its collected condition. French: *échantillon de pergélisol non remanié*.

## **5 PLANNING OF A GEOTECHNICAL SITE INVESTIGATION**

### **5.1 SCOPE OF A GEOTECHNICAL SITE INVESTIGATION**

The geotechnical consultant and the client shall agree upon the scope and limitations of the geotechnical site investigation. Additionally, the process shall allow for flexibility as findings may necessitate adjustments to the initial scope and reveal additional or different requirements. The scope and limitations of the geotechnical site investigation should be aligned with the project under study.

The scope of the geotechnical site investigation shall consider the proposed concept of the new building or structure or the description of the existing building or structure in order to provide information on the site mentioned hereinafter that are required for the design or rehabilitation of the foundations.

The information shall include, as appropriate:

- a) description of the building or structure: location, size, configuration (number of storeys), whether it is above ground or underground, and a general site plan with the building or structure outline;
- b) proposed functions of the building or structure and its operating conditions (e.g., heated or unheated, envelope heat loss assumptions, requirements for personnel and vehicle access);
- c) magnitude and type of loads, including dynamic loads;

- d) recommended service life of the foundations of the building or structure, recognizing that the building or structure components may be retrofitted several times on the original foundations;
- e) tolerance of building or structure to deformation (both total and differential);
- f) ancillary works (utilities) and infrastructure;
- g) construction schedule limitations.

The scope of the geotechnical site investigation shall include provisions for collecting and analyzing the necessary information related to the building or structure site. This information shall include, as appropriate:

- a) surface conditions prevailing at the building or structure site, including, but not limited to, the topography, vegetation cover, surficial geology, geomorphological landforms and surface water drainage;
- b) subsurface conditions, including, but not limited to, the stratigraphy, properties of the overburden and bedrock, active layer thickness (ALT) and groundwater, presence and characteristics of ground ice, ground thermal regime, and availability of borrow materials;
- c) climate conditions including seasonal and interannual climate variations, as well as the projected climate conditions over the service life of the foundations of a building or a structure;
- d) seismic hazards and anticipated changes in site conditions over the service life of the building or structure.

The scope of the geotechnical site investigation shall include, at minimum, a preliminary site evaluation in accordance with the requirements of Chapter 7. Depending on the building or structure's type and complexity, as well as the site conditions, it may also include a site investigation in accordance with the requirements of Chapter 8.

## **5.2 DEVELOPMENT OF THE GEOTECHNICAL SITE INVESTIGATION PROGRAM**

The geotechnical site investigation program shall be appropriate for the type and complexity of the building or structure, knowledge of the local conditions, the time of the year when the investigation is conducted, and the availability of sampling equipment. For additional guidance, a flow chart outlining the steps to be undertaken (see Annex A) and a checklist of characteristics to consider are provided (see Annex F).

The level of detail of the geotechnical site investigation and the establishment of foundation recommendations depends on many factors and may vary between projects. The geotechnical consultant and the client shall take the appropriate steps to have a common understanding of the

work to be undertaken throughout the project. In all cases, the geotechnical consultant shall inform the client when additional data is required to make adequate recommendations.

When measurement of site-specific conditions over time is appropriate and required as part of the geotechnical site investigation, a measurement program shall be agreed upon between the geotechnical consultant and the client. This program shall define the parameters to be measured as well as the measurement period. Consideration should be given to integrate portions of the measurement program into a long-term performance-monitoring program for the building or structure.

Geotechnical consultants shall plan to minimize disturbance of natural surface cover as well as ground and drainage conditions (e.g., removal or damage of peat or vegetation cover) in order to maintain the thermal regime of the permafrost and the initial conditions of the site.

NOTE — Regulations related to the preservation of the initial site conditions may apply.

## **6 QUALIFICATIONS**

### **6.1 QUALIFICATIONS OF THE GEOTECHNICAL CONSULTANT**

Geotechnical consultants shall be professional engineers licensed to practice by the engineering regulatory body having jurisdiction in the province or territory where the building or structure site is located. Geotechnical consultants and the subcontractors that they select shall have the necessary training, experience and expertise to competently carry out the work in a permafrost environment.

### **6.2 QUALIFICATIONS OF THE SUBSURFACE INVESTIGATION CREW**

The subsurface investigation crew shall have the appropriate equipment and the necessary training, experience, and expertise to competently perform subsurface investigations in a permafrost environment.

This investigation shall be conducted under the direction of the geotechnical consultant.

### **6.3 QUALIFICATIONS OF THE ORGANIZATIONS ENGAGED IN TESTING, ANALYSES, AND/OR INSPECTIONS**

The organizations responsible for field testing and inspection of bedrock as well as frozen and unfrozen soil shall use appropriate equipment, follow adequate procedures, and employ staff with the required training, experience and expertise to competently carry out the required field tests and inspections.

Laboratory testing and analyses on bedrock as well as on frozen and unfrozen soil shall be carried out using appropriate equipment and procedures, by staff with the required training, experience and expertise.

This work shall be conducted under the direction of the geotechnical consultant.

NOTE — The document ASTM D3740 provides guidelines for evaluating the competency of an organization to properly perform designated tests and inspections on soil and bedrock, including the minimum requirements for personnel, facilities, equipment and a quality system.

## **7 PRELIMINARY SITE EVALUATION**

### **7.1 GENERAL**

The purpose of the preliminary site evaluation is to gather available information to characterize the geotechnical, hydrological and climate conditions at the building or structure site and to guide, if necessary, the development of the site investigation program.

The preliminary site evaluation shall include a desktop evaluation based on available information, in accordance with the requirements of Clause 7.2. It may also involve:

- a) a site visit, in accordance with the requirements of Clause 7.3;
- b) an assessment of the project's climate change-related risk level, in accordance with the requirements of Clause 7.4;
- c) a report of the findings, in accordance with the requirements of Clause 7.5.

NOTE — For low and negligible climate change risk projects, it is possible that a desktop evaluation alone is sufficient to gather all the information required to assess the suitability of the building or structure site.

### **7.2 DESKTOP EVALUATION**

#### **7.2.1 General**

The desktop evaluation shall include all items listed in Clauses 7.2.2 to 7.2.13. It shall present available information on the physical characteristics and properties of the ground surface and subsurface at the building or structure site and nearby properties. It shall also summarize all data on local climate conditions and ground thermal conditions and make a preliminary assessment of how these conditions may change over the service life of the foundations of a building or a structure. This work shall establish the need for, and guide the development of specific requirements (e.g., drilling, excavation of test pits, and/or geophysical investigation methods; specific laboratory tests and/or instrumentation; level of climate change analysis required) and assist in interpreting the findings.

The desktop evaluation shall be suited to the foundations of building or structure under consideration and other foundation considerations. For light, flexible structures, it may suffice, while heavier, more rigid structures require more thorough intrusive investigations.

**NOTE** — Annex A, together with the checklist in Annex F, outline the scope and requirements for the Preliminary Site Evaluation described in Chapter 7, compared to the additional requirements for a Site Investigation, as described in Chapter 8. The checklist in Annex F highlights the typical information needs for the Preliminary Site Evaluation compared to the additional information typically needed for a Site Investigation. Figure A.1 recognizes that, for some low climate change risk projects, a desktop evaluation alone may be sufficient.

Resources that may provide relevant information include, but are not limited to:

- a) satellite imagery;
- b) topographic plans;
- c) aerial photographs;
- d) LiDAR (Light Detection and Ranging) data;
- e) Interferometric Synthetic Aperture Radar (InSAR) data;
- f) digital elevation models;
- g) existing surficial geology information;
- h) bedrock mapping;
- i) geotechnical engineering, hydrogeology, and geology-related reports;
- j) community development plans;
- k) information on the historic land use;
- l) georeferenced databases on ground temperatures;
- m) government climate data and models;
- n) regional permafrost and ground ice maps;
- o) related published literature and case histories.

Additional information on surface and subsurface conditions may include vegetation cover, climate, and surface water drainage data.

**NOTE** — Several agencies across Canada collect permafrost data, namely the distribution of various types of massive ice, permafrost conditions in various sediments, ALT, and ground temperatures. In northern Canada, permafrost data are more detailed for regions where extensive geotechnical site investigations have been conducted for major projects but may be incomplete and scattered in regions with little or no industrial development. For any project, Natural Resources Canada (NRCan) databases and maps are suitable first sources of data. Many other government agencies that also collect, receive, or manage permafrost-related data may be contacted. Among these agencies are: provincial and territorial geological survey groups, regulatory agencies, mining regulators, public works departments, northern research institutes, universities, and geotechnical consultants.

## **7.2.2 Initial assessment of climate conditions**

**7.2.2.1 General** — The desktop evaluation shall include an initial assessment of the seasonal and interannual climate conditions as well as the other conditions listed in Clauses 7.2.2.2 to 7.2.2.6 as these factors may have an impact on the suitability of the building or structure site for the proposed building or structure project. It shall report climate data and trends for the area and the building or structure site and shall make a preliminary assessment of how these conditions may impact the service life of the foundations of a building or a structure.

### **NOTES** —

- 1 A variety of climate parameters can influence the thermal state of the underlying permafrost and modify its mechanical properties. Climate and weather data for regions sparsely covered by Environment and Climate Change Canada (ECCC) might be available from other networks such as federal, provincial and territorial databases, road networks, and mine site data.
- 2 Data from nearby or representative meteorological stations may need to be interpreted if the building or structure site is situated near multiple stations. Alternatively, gridded climate datasets might also be used as a first estimate where representative climate stations are not available.

**7.2.2.2 Mean annual air temperature (MAAT)** — The mean annual air temperature (MAAT) shall be determined based on historic or gridded air temperature data. In addition, seasonal averages and trends in seasonal averages shall be calculated.

**7.2.2.3 Air freezing and thawing indexes (ATI and AFI)** — The air freezing index (AFI) and the air thawing index (ATI) shall be calculated from historic or gridded air temperature data.

**7.2.2.4 Precipitation and wind** — Precipitation data, including rainfall and snowfall, shall be reported on a monthly basis.

Wind direction and velocity may be reported. For example, an initial assessment of wind influence on design considerations such as thermosyphon location and performance as well as snow drifting/scouring may be appropriate.

**NOTE** — Snow drifting/scouring, and particularly changes in snow drifting due to construction or topography, is a significant factor in permafrost foundation design. Snowdrifts around foundations insulate the ground and reduce ventilation under elevated buildings, impeding cooling of the active layer and underlying permafrost during winter. Understanding how the proposed building or structure site will alter snow accumulation patterns is critical to the success of the foundation design.

Data or other evidence of extreme precipitation and wind events should also be reported, if available.

**7.2.2.5 Microclimate** — For large and critical infrastructure, an evaluation of the site's microclimate shall be carried out by including a general assessment of how local topography and nearby buildings or structures may influence air temperature, wind direction and velocity, precipitation, snow accumulation and drifting/scouring, and/or solar exposure (aspect).

**NOTE** — Local topography can influence the climatic conditions at a specific site in such a way that the climate data available from a nearby climate station may not be representative for the conditions at the site of the foundations of a building or a structure site. An assessment of the microclimate helps in the evaluation of how representative available climate data are, and if adjustments are needed.

**7.2.2.6 Climate change projections** — Climate change projections shall cover elements relevant to the foundations of a building or a structure site under consideration, for its service life, as well as the effect these elements have on the ground thermal regime and permafrost conditions of the building or structure site.

As part of the desktop evaluation, initial climate change projections shall be made according to the guidelines provided in Chapter 5 of the document CSA PLUS 4011.

**NOTES** —

- 1 Chapter 4 of the document CSA PLUS 4011 provides additional information on climate change projections, their ranges and uncertainties. Tables 5.2 and 5.3 in Chapter 5 provide a discussion of global climate models (GCMs) and offer guidance for making screening-stage projections of climate change.
- 2 According to the document CSA PLUS 4011, permafrost is warming and degrading faster than anticipated in some thaw sensitive regions. Annex B of this document provides further details on the thaw sensitive and more rapid permafrost degradation processes.
- 3 Some Canadian government data on climate change projections are available from the Canadian Centre for Climate Modelling and Analysis (CCCma) and the Canadian Climate Data and Scenarios (CCDS) websites of ECCC.

**7.2.3 Seismicity**

The seismic hazard associated with the building or structure site shall be determined in accordance with the *National Building Code of Canada*.

#### **7.2.4 Surficial geology and geomorphology**

An analysis of the surficial geology and geomorphology of the building or structure site shall be performed. This analysis shall include a detailed description of the overburden, including organic cover, its characteristics such as thaw sensitivity or frost susceptibility, homogeneity, origin, and any previous disturbances.

The types of bedrock, their origin, the probable thickness of overburden as well as the presence of rock outcrops, surface cobbles and boulders, fill areas, and existing borrow pits shall also be described.

The periglacial landforms observed at the building or structure site, especially those related to ground ice such as, massive ice, ice wedge polygons, frost mounds, frost blisters, pingos, icing, palsas and thermokarst features shall be described. These periglacial landforms shall be described using the terminology specified in the document *Glossary of Permafrost and Related Ground-Ice Terms*.

Geomorphological processes that may adversely affect the building or structure site and/or foundations of a building or a structure such as solifluction, active layer, retrogressive thaw slumps, physical and thermal erosion, and avalanches shall be identified.

#### **7.2.5 Surface and groundwater hydrology**

The surface water drainage and anticipated groundwater conditions at the building or structure site shall be evaluated. The evaluation shall address any physical features at the building or structure site that could adversely impact its foundations site such as permafrost degradation due to surface and groundwater movement during the summer, as well as the grading requirements to control this water flow. Items that shall be broached include, but are not limited to: slope and vegetation cover, presence and water level of nearby creeks and open water bodies, springs and icings related to springs, sea levels, location of the nearest drainage courses and ditches, location of nearby culverts, expected icing problems during freeze-up, presence of bogs and fens, likelihood of a high groundwater table in the active layer during the summer, potential for taliks or cryopegs, historic flood events, and any other features noted.

#### NOTES —

- 1 Surface water drainage is present only during the warm part of the year during snow melt, near-surface seasonal thaw, and when it rains. In permafrost the groundwater flow is normally restricted to the near surface annual thaw zone (active layer). However, groundwater flow is more complex in discontinuous permafrost and is not restricted to the active layer. It is recommended to evaluate the expected continuity of permafrost at the site, and the presence and characteristics of taliks, and how this will impact the groundwater evaluation during the site investigation.
- 2 Surface water and groundwater may cause construction problems, erode final grading around the building, and cause the formation of ice lenses and frost heave during the fall freeze-up. It is therefore recommended to identify these in the desktop evaluation so that these features can be considered in the development of the site investigation program, the selection and design of the foundations of a building or a structure site, and the grading and drainage around the building.
- 3 The document CSA S503 is a reference document that provides guidelines on this topic.

### 7.2.6 Vegetation cover

The vegetation cover at the building or structure site, including the types of shrubs, trees, low ground cover, and the thickness of the vegetative mat, shall be documented, i.e., noting, among other things, the thickness of organic soils, the percentage of ground covered by vegetation, and any historic forest fires records in the area. Disturbances to the natural vegetation cover and drainage conditions during site investigation and construction can significantly affect permafrost conditions and should be minimized to preserve the permafrost.

#### NOTES —

- 1 Vegetation types often indicate soil types, hydrology, and the presence of permafrost, especially in discontinuous permafrost zones.
- 2 Vegetation plays a critical role in providing shade during summer and influencing snow distribution patterns, which in turn impacts permafrost distribution in discontinuous permafrost zones and affects ground temperatures and ALT in continuous permafrost zones.
- 3 Moss and peat at ground surface, through latent heat absorption and ground insulation, reduce summer heat transfer between the atmosphere and the ground, strongly influencing ALT and ground temperature.
- 4 At the southernmost fringe of discontinuous permafrost, isolated patches of permafrost may be found in organic terrain.
- 5 In discontinuous permafrost, removing trees and vegetative cover can accelerate permafrost thawing, potentially allowing building and structures foundations to be designed for non-permafrost conditions.

### 7.2.7 Permafrost zones and local distribution

The permafrost zone in which the building or structure site is located shall be determined by referring to the interactive permafrost map of Canada (consult NRCan Website) If not in a continuous permafrost zone, information on the distribution of permafrost specific to the site should be included.

NOTE — Permafrost regions are commonly subdivided into permafrost zones based on the proportion of the ground that is perennially cryotic. The basic subdivision in high latitudes is into zones of continuous permafrost (>90% of areal extent), extensive discontinuous permafrost (from 50% to 90% of areal extent), sporadic discontinuous permafrost (from 10% to less than 50% of areal extent), and isolated patches of permafrost.

## 7.2.8 Permafrost characteristics

**7.2.8.1 Mean annual ground temperature (MAGT)** — At sites where no ground temperature measurements are available for the year the building or structure site is designed, the geotechnical consultant shall estimate the mean annual ground temperature (MAGT).

### NOTES —

- 1 Approximation of MAGT from MAAT is appropriate at a large scale but is less applicable at the building or structure site scale since MAGT may vary considerably from one site to another depending on surficial conditions (vegetation, water, snow, etc.) and subsurface soil conditions. Accurate determination of current MAGT requires in situ measurements (see Clause 8.5.5.2), and projections of ground temperatures over the service life of the foundations of a building or a structure site require statistical and/or numerical modelling (see Clause 8.5.5.2).
- 2 An n-factor applied to the MAAT, as outlined in Clause 7.2.2.2, may be used to obtain a preliminary estimate of the mean annual ground surface temperature in situations such as desktop evaluations. This provides a reasonable approximation that can be used to estimate the MAGT.
- 3 MAGT at a particular depth can be calculated using borehole temperature monitoring data available from national (Nordicana D) and international databases (Global Terrestrial Network for Permafrost).

**7.2.8.2 Active layer thickness** — The geotechnical consultant shall estimate the expected ALT for the year the building or structure is designed and over the service life of the foundations of a building or a structure. The estimate may be based on published values from representative nearby sites and/or the type of surficial material.

NOTE — The active layer is generally deepest in bedrock and dry granular materials, and shallowest in saturated fine-grained glacial tills and clays. However, numerous other site-specific factors affect ALT, including, but not limited to: vegetation cover, snow cover, surface water and groundwater flow, aspect and elevation, etc.

**7.2.8.3 Other characteristics** — The geotechnical consultant shall determine if additional documents on local permafrost characterization are available for the building or structure site and its surroundings. These may include relevant information on permafrost conditions such as ice content, soil/bedrock types, pore water salinity and ground temperatures from geotechnical site investigations from nearby sites.

NOTE — Pore water salinity data are available in “Distribution of Saline Permafrost in the Northwest Territories, Canada”, in *Canadian Geotechnical Journal*.

## 7.2.9 Site-specific features

The site-specific features shall be documented. This shall include, as applicable:

- a) the site elevation;

- b) the slope gradient and aspect of the ground surface at the building or structure site and of its surroundings reported as accurately as possible referencing the sources used and their limitations;

NOTE — Aspect (north-facing vs. south-facing slopes) affects the presence of permafrost and ground temperature.

- c) the location of steep slopes;
- d) the location of snow stockpiles and details of snow management;
- e) the location and description of adjacent structures, including, but not limited to, buildings, parking lots, roads or utility infrastructure.

#### **7.2.10 Building or structure site access and logistics**

If a site investigation is required as specified in the requirements of Chapter 8, the associated logistics constraints, potential access challenges to the building or structure site, and restrictions related to seasonal operations shall be documented in the preliminary site evaluation report (see Clause 7.5).

#### **7.2.11 Historic land use**

The development history and previous land uses, including any structures that were removed or abandoned, ground subsurface and surface backfilling, and potential presence of contaminants at the building or structure site, shall be documented, if applicable.

The geotechnical engineer should request from the owner all historical records of land use of the building or structure site and provide any environmental site assessment reports.

Recreational use or use as a borrow pits of the building or structure shall also be identified, as well as fill areas such as previous granular pads or stockpiles.

#### **7.2.12 Nearby buildings or structures**

The geotechnical consultant shall evaluate the foundation types of nearby buildings or structures, where available. The performance of these foundations, including any failure, shall be evaluated and documented.

The characteristics of fill materials and the location of borrow pits from which they were obtained and which were used to create infrastructures such as pads or roads shall be documented.

#### **7.2.13 Availability of borrow materials**

The potential borrow pits near the building or structure site shall be assessed as they may impact the type of foundations selected for the proposed building or structure.

### 7.3 BUILDING OR STRUCTURE SITE VISIT

When deemed appropriate by the geotechnical consultant, a building or structure site visit shall be recommended as part of the preliminary site evaluation to validate the information collected during the desktop evaluation and to collect other useful information that cannot be appropriately assessed in the desktop evaluation. The decision to include a building or structure site visit should be made by the client in consultation with the geotechnical consultant within a risk management framework. The geotechnical consultant's recommendation should be based on, but not limited to: building or structure complexity, sensitivity to climate change, tolerance of building or structure to deformation, availability of data from the desktop evaluation, unique micro-climate at the site, uncertainty regarding access, uncertainty regarding the most suitable equipment type for a site investigation, and schedule requirements.

The timing of the building or structure site visit shall be discussed with the client and determined taking into consideration the pros and cons listed in Table 1, in addition to overall schedule requirements.

The building or structure site visit may include interviews with local knowledge holders, or collection of surface condition information through excavation of test pits in the active layer or the drilling of precursory boreholes if necessary for the development of the site investigation program.

**NOTE** — In order to save costs, it is possible that the client prefer to combine the building or structure site visit with the site investigation (see Chapter 8). Should it be the case, the timing of the combined building or structure site visit and site investigation should take into account the scheduling requirements applicable to the site investigation (see Table 1).

### 7.4 RISK LEVEL OF THE PROJECT RELATED TO CLIMATE CHANGE

As part of the preliminary site evaluation, the geotechnical consultant shall determine the risk level of the project related to impacts of climate change. The level of such risk shall be established as specified in the "Stage One: Climate change screening" process presented in Chapter 5 of the document CSA PLUS 4011 using all the information compiled in the preliminary site evaluation. The climate change risk levels are taken from Table 5.1 of the document CSA PLUS 4011:

- D: Low- and negligible-risk project;
- C: Low- and negligible-risk project;
- B: High- and moderate-risk project;
- A: High- and moderate-risk project.

**NOTE** — While not explicitly stated for these four levels (A – D), the risk is only related to the impacts of climate change. Other hazards are not included in the above four levels.

The risk level of the project to climate change shall be used in the development of the site investigation program as illustrated in the flow chart of Annex A.

## **7.5 REPORTING**

The findings of the preliminary site evaluation shall be included in a report. This report shall be presented in a way that enables the client to understand the conditions at the building or structure site and how they may impact the project. The geotechnical consultant shall discuss the report with the client.

The report and the discussion may lead to one of the following options:

- a) Option 1: The findings of the preliminary site evaluation are sufficient to proceed with the design of the foundations for the client's building or structure concept without a site investigation. The report shall be presented as specified in the requirements of Chapter 9.
- b) Option 2: The findings of the preliminary site evaluation are not sufficient to proceed with the design of the foundations for the client's building or structure concept and a site investigation is required, as specified in the requirements of Chapter 8.
- c) Option 3: The findings of the preliminary site evaluation are sufficient to recommend alternative foundations of a building or a structure and determine whether a site investigation is required, as specified in the requirements of Chapter 8.
- d) Option 4: The findings of the preliminary site evaluation are sufficient to recommend that the current building or structure site is not suitable for the client's building or structure concept. The report shall include the justifications as specified in the requirements of Clause 9.13.1.

## **8 SITE INVESTIGATION**

### **8.1 SITE INVESTIGATION PROGRAM**

The geotechnical consultant and the client shall agree upon the scope and limitations of the site investigation program. However, this program should allow for some flexibility throughout the process, as the findings may alter its initial scope and reveal additional or different needs.

The site investigation program may include some or all items described in this chapter. The site investigation program shall be sufficient to determine in detail the occurrence, extent, characteristics and properties of unfrozen and frozen soil and bedrock; the presence of ground ice; the presence of groundwater; and the ground thermal regime at the site under study.

The timing and degree of the site investigation shall be discussed with the client taking into consideration the pros and cons listed in Table 1, in addition to overall schedule requirements.

The site investigation program shall define:

- a) the number of test pits and boreholes required;
- b) their location and depth;
- c) the field sampling method;
- d) the equipment and soil/bedrock sampler to be used;
- e) the inspections and tests to perform to establish the soil and bedrock properties;
- f) the remote sensing technologies and the geophysical investigation methods may be used to support the excavation of test pits or the drilling operations, if applicable.

NOTES —

- 1 The selection of the suitable method and equipment is primarily based on the geotechnical consultant's experience and judgment along with the results of the preliminary assessment of the risks related to climate change on the foundations of a building or a structure over their service life and equipment available within the community.
- 2 The planning of a geotechnical site investigation at remote sites is also a balance between obtaining complete site information and the cost of the methods for obtaining it. The types of samples that may be obtained by the various drilling methods are given in Annex C.

## **8.2 DETAILED CLIMATE CHANGE RISK ASSESSMENT AND OTHER ENVIRONMENTAL CONDITIONS**

### **8.2.1 Climate change projections**

If the risk level of the project to climate change is moderate or high (level A or B, as specified in Clause 7.4), a detailed assessment of these risks may be required at this stage. The results of the tests related to the properties of the soils, carried out as specified in the requirements of Clause 8.5, may also influence the need to carry out further assessment of the impacts of climate change.

More specifically, for moderate- and high-risk projects, the design for foundations in permafrost shall take into consideration a more detailed assessment of the projected climate conditions over the service life of the said foundations.

If changes in geotechnical, physical and thermal properties or soil response due to changes in the soil temperature regime are projected, a range of possible values should be investigated and estimated during the geotechnical site investigation.

The projected climate conditions should be determined by following the guidelines presented in Annex B. Climate expertise should be used to interpret and update regional climate change considerations relevant over the service life of the foundations of a building or a structure.

The assessed climate factors shall include, at minimum, the mean monthly air temperature and precipitation, the AFI, and the ATI from the year the building or structure is designed to the end of its service life.

Factors contributing to accelerated thawing of ice-rich permafrost, such as summer heat or heavy precipitation events, should be considered in the detailed climate change risk assessment. The geotechnical consultant shall document how these climate factors were determined.

Surface water management should take into account mean monthly rainfall and total precipitation. Air temperature and snow depth should be evaluated for their impact on the ground thermal regime.

**NOTE** — For complex foundations with high risk to climate change, the geotechnical consultant and the client may agree to use annual probabilities for the end of the service life of the foundations of a building or a structure to establish the design criteria.

### **8.2.2 Other environmental conditions**

A more detailed assessment of the other environmental conditions that were determined as part of the desktop evaluation (see Clause 7.2) may also be required. These can include the surficial geology and geomorphology, the surface and ground water hydrology, and the vegetation cover as well as site-specific features.

### **8.3 REMOTE SENSING TECHNOLOGIES**

If used, the results of remote sensing technologies shall be recorded in the geotechnical site investigation report as specified in the requirements of Clause 9.12.1. This shall include a description of the methods used and the results obtained.

**NOTE** — The documents *Remote Sensing in Northern Hydrology: Measuring Environmental Change*, *Airphoto Interpretation and the Canadian Landscape*, *Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics: Report of a Workshop*, *Remote Sensing for Geoscientists: Image Analysis and Integration* and *Remote Sensing of the Cryosphere* provide information on remote sensing technologies for permafrost environments.

### **8.4 GEOPHYSICAL SURVEY METHODS**

If used, the results of geophysical surveys shall be recorded in the geotechnical site investigation report as specified in the requirements of Clause 9.12.1. This shall include a description of the methods used and the results obtained.

**NOTE** — Annex D provides information on geophysical survey methods.

## **8.5 PROPERTIES OF THE SOILS**

### **8.5.1 General**

The results of soil property testing are necessary for evaluating foundation options and their detailed geotechnical design. They may also raise the need for specific analyses described in Clause 8.5. Additionally, soil properties could influence the necessity of further assessing the potential impacts of climate change.

### **8.5.2 Field sampling**

The excavation of test pits and drilling of boreholes shall be performed as planned in the site investigation program to secure information on the soil stratigraphy and cryostratigraphy by observation of the test pit and borehole advance and the collecting of samples for laboratory testing.

**NOTE** — Test pits may only reach the top of the permafrost, be restricted in depth, and thus only provide limited meaningful subsurface information.

The number of boreholes per unit area necessary to adequately characterize the building or structure site should be at least one for every 200 m<sup>2</sup> of the building or structure footprint area with a minimum of three boreholes per building or structure site. Additional boreholes shall be drilled if subsurface conditions are heterogeneous. Borehole locations shall be selected based on observed surface features, topography, and any site-specific requirements.

**NOTE** — In northern Canada, drilling contractors often charge by the day rather than by the hour. As a result, it may be beneficial to drill more than the recommended number of boreholes if completing fewer boreholes takes only a small portion of the day.

Exploration at the building or structure site shall extend to a depth of 10 m or to a depth at least equal to the minimum width of the foundations of a building or a structure unless competent bedrock is encountered at shallow depth. In the latter case, boreholes shall be advanced at least 2 m into competent bedrock. Depth of exploration shall increase to a depth greater than the anticipated pile length for buildings or structures to be supported on pile foundations in order to establish the nature of the materials in which the piles will be supported.

Core and other samples shall be collected at least at every one metre of hole depth or less in the case of a change in the stratigraphic unit.

**NOTE** — Smaller sampling intervals in the first four metres of hole depth are recommended due to the high probability of ice-rich material in the transient interface between the active layer and the permafrost table.

The sampling interval shall be modified when changes are observed and/or when engineering sensitive permafrost conditions are encountered such as high ice concentration, unfrozen zones or other similar changes.

Attention shall be paid to evaluating the integrity of every sample (disturbed or undisturbed) and identifying any potential sources of disturbances induced by the drilling operations. Drilling procedures that deliver thermally undisturbed samples shall be favoured in most investigations (e.g., drilling using chilled drilling fluid, or sonic or dry auger drilling).

Disturbed samples shall be sealed to preserve the water content after the samples thaw. Undisturbed samples shall be preserved in frozen condition for additional testing. The samples shall be kept until they are released by the client.

NOTE — The document *Transportation, Preparation, and Storage of Frozen Soil Samples for Laboratory Testing* provides guidance on the transportation, preparation, and storage of frozen soil samples for laboratory testing.

All core and other samples shall be logged as specified in the requirements of Clause 9.12.3 and photographed as they are collected. The geotechnical consultant shall record and photograph the equipment used for the excavation of test pits and drilling work.

### **8.5.3 Stratigraphy and cryostratigraphy**

The excavation of test pits and borehole advance shall be carried out under the supervision of the geotechnical consultant to document soil stratigraphy and cryostratigraphy, its changes, and sample location.

Unfrozen soils shall be described as specified in the *Canadian Foundation Engineering Manual*. If the drilling and sampling equipment permits, ground ice description shall be given at least at each 0.5-m interval along a borehole or if significant changes occur. Frozen soils shall be described as specified in the document ASTM D4083.

#### NOTES —

- 1 Additional description of the cryostratigraphy is provided based in “Cryostructures in Permafrost”, in *Canadian Journal of Earth Sciences* or “Description and Classification of Frozen Soils”, in *Proceedings of the 1<sup>st</sup> International Conference on Permafrost*.
- 2 It is recognized that some drilling and sampling equipment (e.g., air-track drill rigs, auger drill rigs) provides disturbed samples and therefore a less detailed description of the frozen soils is possible.

As part of the description of the cryostratigraphy, the volumetric ice content shall be estimated based on the following:

- a) pure ice (100% volumetric ice content);
- b) soil-poor ice (volumetric ice content higher than 75% and lower than 100%);
- c) soil-rich ice (volumetric ice content higher than 50% and lower than or equal to 75%);

- d) ice-rich soil (volumetric ice content higher than 15% and lower than or equal to 50%);
- e) ice-poor soil (volumetric ice content lower than or equal to 15%).

NOTE — A field indication of the volumetric ice content may be made by thawing a soil sample in a clear container and allowing the supernatant water to accumulate over the soil particles. The ratio of the volume (or height) of supernatant water to the volume (or height) of soil particles represents the approximate excess ice content. Soils with no supernatant water are ice-poor.

#### **8.5.4 Bedrock**

When bedrock is encountered during a geotechnical investigation of overburden soils, the geotechnical consultant shall measure and record the depth to bedrock. Boreholes shall be advanced sufficiently into the bedrock to confirm its presence, determine the thickness of the weathered or fractured zone, and assess its competency in both frozen and thawed conditions.

#### **8.5.5 Ground thermal regime**

**8.5.5.1 Ground temperature measurement** — If recommended by the geotechnical consultant, ground temperatures shall be measured and recorded. Automatic data logging may be used with the logger connected to a ground temperature cable with either a single sensor or multiple sensors at predetermined spacing. Sensors shall have a precision of at least 0.1 °C and the 0-degree offset shall be determined in an ice bath.

Ideally, the ground temperature profile should be measured in 10-m-deep to 20-m-deep boreholes as planned in the site investigation program. The spacing between individual sensors may increase with depth, with closer spacing of sensors used in the upper part of the ground in order to be able to estimate the ALT.

NOTE — Common locations of ground temperature sensors could be at depths of 0.05 m, 0.25 m, 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 4 m, 5 m, 6 m, 8 m, 10 m, 12 m, 15 m and 20 m below ground surface.

The ground temperature cables shall be installed down a borehole subsequently backfilled with dry sand or another conducting medium for a permanent installation. If the ground temperature cables are to be removed, they should be installed within a sealed small-diameter casing placed in the backfilled borehole. In this case, the casing may be filled with a non-freezing, environmentally friendly medium or any other means to prevent vertical convective air currents within the casing.

The ground temperatures should ideally be measured for a year. At a minimum, ground temperatures shall be measured until the thermal condition recovers from the thermal disturbances induced by the drilling.

NOTE — Thermal conditions may take days to several months to recover depending on the soil conditions and the drilling methods.

Ground temperature envelope graphs shall be provided for each instrumented borehole, displaying temperature variations over the measurement period. The graphs shall also indicate the minimum and maximum temperatures recorded during this period.

NOTE — If necessary, the base of the permafrost should be determined using the MAGT, either by direct reading from the temperature curve if permafrost is shallow, or by inference through extrapolation (see Annex E).

**8.5.5.2 Mean annual ground temperature (MAGT)** — The ground temperature measurements recorded as specified in Clause 8.5.5.1 shall be used to confirm the MAGT established during the preliminary site evaluation (see Clause 7.2.8.1).

The MAGT shall be determined at the depth of zero annual amplitude. If the depth of zero annual amplitude is not reached by drilling, as specified in the requirements of Clause 8.5.5.1, it shall be determined by extrapolation and/or by averaging warm and cold ground temperatures to estimate the temperature at the extrapolated depth of zero annual amplitude.

NOTE — The MAGT at the depth of zero annual amplitude is typically used to assess the thermal regime of the ground at various locations.

The MAGT over the service life of the foundations of a building or a structure shall be estimated by taking into consideration the climate change projections determined as specified in the requirements of Clause 8.2.1. The geotechnical consultant shall document how it was established.

**8.5.5.3 Active layer thickness (ALT)** — The geotechnical consultant shall estimate the ALT for the ground beneath and around the building. The depth of the annual thaw may be inferred from the ground temperatures profile determined as specified in Clause 8.5.5.1. Thaw depth measurements may also be made by mechanically probing the active layer or obtained by drilling boreholes or excavating test pits at a number of locations as planned in the site investigation program. The average, maximum, and minimum depths of thaw at the building or structure site shall be recorded.

NOTE — Measurements made from late summer to early fall, depending on the location, will determine the ALT when the depth of seasonal thawing reaches its maximum.

Records of the depth of thaw shall include notes on the dates of observation, vegetation cover, relief, surface water drainage, and a description of the subsurface materials in the various areas probed.

Depth of thaw observations shall be made in areas having different surface covers and then extended to locations within these areas that have noticeable changes in relief, surface water drainage or subsurface materials.

NOTES —

- 1 Differences in the depth of thaw for an area as small as 1.5 m<sup>2</sup> are possible.
- 2 The post-construction ALT may differ from the existing undisturbed condition. Thinner active layer is observed in areas with thick organic materials underlain by fine-grained soils with high water contents. Removal of the organic layer and introducing of groundwater control during the construction of a building or a structure site increase the ALT.

The projected ALT over the service life of the foundations of a building or a structure shall be estimated by taking into consideration the climate change projections determined as specified in the requirements of Clause 8.2.1. The geotechnical consultant shall document how it was established.

## 8.5.6 Index properties of the soils

**8.5.6.1 General** — The site investigation program shall specify which index properties of soils shall be measured as part of the geotechnical site investigation. If included in the site investigation program, the index properties of soils shall be measured as specified in the requirements of Clauses 8.5.6.2 to 8.5.6.8.

The index properties of frozen soils determined in their unfrozen state provide a means to assign the soils to groups with known behaviour and estimate the required design parameters. The index properties of frozen soils in their unfrozen state shall be established using disturbed or undisturbed samples.

**8.5.6.2 Water content** — Water (moisture) content of the soils shall be determined as specified in the requirements of the standard CAN/BNQ 2501-170 or the documents ISO 17892-1 or ASTM D2216.

**8.5.6.3 Particle size** — Particle size of the soils shall be determined as specified in the requirements of the document ASTM D6913.

**8.5.6.4 Liquid and plastic limits** — Liquid and plastic limits of the soils shall be determined as specified in the requirements of the standards CAN/BNQ 2501-090 or CAN/BNQ 2501-092 or the document ASTM D4318.

**8.5.6.5 Classification of the soils** — The soils in their unfrozen state shall be classified as specified in the *Canadian Foundation Engineering Manual*.

**8.5.6.6 Salinity** — Salinity of the soil pore water shall be determined as specified in the requirements of the document ASTM D4542. A minimum of five samples shall be taken from two drill holes for the measurement of salinity.

**8.5.6.7 Density** — Density shall be measured in a laboratory as specified in the requirements of the documents ISO 17892-2 or ASTM D7263. Alternatively, density may be measured in situ as specified in the requirements of the standards CAN/BNQ 2501-052, CAN/BNQ 2501-054, CAN/BNQ 2501-058, CAN/BNQ 2501-060 or the document ASTM D1556/D1556M.

**8.5.6.8 Other index properties** — The maximum dry density and optimum water content of soils to be used in earthwork shall be determined as specified in the requirements of the standard CAN/BNQ 2501-250 or the document ASTM D698.

NOTE — The test method described in the document ASTM D698 was historically referred to as the “Standard Proctor Test”.

## **8.5.7 Properties of frozen soils**

**8.5.7.1 General** — The site investigation program shall specify which properties of frozen soils are to be measured or determined. It shall indicate whether these properties be determined through field or laboratory testing and if engineering design parameters be derived based on a risk-informed decision from correlations of the literature and the index properties established as outlined in the requirements of Clause 8.5.6.

If the properties of frozen soils are to be measured by laboratory or field testing, this shall be carried out as specified in the requirements of Clauses 8.5.7.2 to 8.5.7.7 using undisturbed frozen core samples. The core samples shall be extracted from the appropriate sections of the frozen core under the supervision of the geotechnical consultant. The frozen state of the core samples shall be preserved during transport to the laboratory.

### NOTES —

- 1 Many properties of frozen soils are dependent on temperature. Since the final, long-term ground temperature will not have been established at the time of laboratory testing, it is normal to conduct the laboratory testing at two temperatures that represent the likely range.
- 2 Because of the complexity and cost of measuring the properties of frozen soils in a laboratory or in the field, it is common to derive the engineering design parameters from correlations published in the literature.

**8.5.7.2 Bulk density** — Bulk density shall be measured in a laboratory as specified in the requirements of the documents ISO 17892-2 or ASTM D7263.

**8.5.7.3 Thaw strain and consolidation** — Thaw consolidation shall be measured in a laboratory through thaw-consolidation testing, i.e., the time-dependent compression resulting from the thawing of the frozen soils and subsequent draining of excess water if the foundations of a building or a structure site are considered susceptible to thaw by the geotechnical consultant.

NOTE — Estimates of thaw strain can be made by using correlations developed in the document *Alaska Highway Gas Pipeline (Yukon Section) — Thaw Settlement Design Approach*. Furthermore, the documents “One-Dimensional Consolidation of Thawing Soils”, in *Canadian Geotechnical Journal*, and “Thaw-Consolidation Tests on Remoulded Clays”, also in *Canadian Geotechnical Journal* provide further information on thaw consolidation.

**8.5.7.4 Thaw weakening susceptibility** — Thaw weakening susceptibility shall be determined if the geotechnical consultant considers it is critical for the building or the structure. A minimum of three frozen core samples shall be taken and tested to establish the thaw weakening susceptibility.

NOTE — The document ASTM D5918 specifies how to determine the thaw weakening susceptibility.

**8.5.7.5 Unfrozen water content** — The soil-freezing characteristic, the relationship between unfrozen water content and temperature, should be determined in a laboratory using pulsed nuclear magnetic resonance (NMR) or time-domain reflectometry (TDR). Alternatively, relationships presented in literature may be used.

NOTE — “The Measurement of Unfrozen Water Content by Time Domain Reflectometry: Results from Laboratory Tests”, in *Canadian Geotechnical Journal, Measurement of the Unfrozen Water Content of Soil: Comparison of NMR and TDR Methods*, “The Prediction of Unfrozen Water Contents in Frozen Soils from Liquid Limit Determinations”, in *Monograph 76-8*, and “Measurement of Unfrozen Water Content and Relative Permittivity of Frozen Unsaturated Soil Using NMR and TDR”, in *Cold Regions Science and Technology* provide useful information on the measurement of unfrozen water content.

**8.5.7.6 Creep properties** — The creep of frozen soils properties shall be determined as specified in the document ASTM D5520.

**8.5.7.7 Strength properties** — Where the measured strength of the frozen soil is required, the unconfined compressive strength may be measured using the testing methods specified in the document ASTM D2166/D2166M. During the test, care should be taken to keep the test equipment and sample at an appropriate sub-freezing temperature for the duration of the test. Where feasible, multiple tests at different temperatures and strain rates provide important insights to the rheological behaviour of the frozen soil.

NOTE — Strength properties are strain rate and temperature dependent.

## **8.5.8 Thermal properties**

**8.5.8.1 General** — The site investigation program shall specify which thermal properties of the soils shall be measured or determined as part of the geotechnical site investigation. The site investigation program shall also specify if the thermal properties of the soils shall be determined from frozen or unfrozen, undisturbed or disturbed samples, or calculated based on material properties including proportion of constituents, or from values available in literature. If included in the site investigation program, the thermal properties of soils shall be measured as specified in the requirements of Clauses 8.5.8.2 to 8.5.8.4.

NOTE — Thermal properties of selected materials can be estimated based on typical values available from literature, for example “Thermal Properties of Soils”, in *Bulletin 28*, “Thermal Properties of Soil”, in *W. R. van WIJK (ed.), Physics of Plant Environment*, “Water Supply in Cold Regions”, in *Monograph 111-C5a, Permafrost: Engineering Design and Construction*, *Heat Transfer in Cold Climates* and “Thermal Properties of Soils”, in *Monograph 81-1*.

**8.5.8.2 Thermal conductivity** — Thermal conductivity of permafrost soils in their frozen or unfrozen conditions shall be measured as specified in the document ASTM D5334. Frozen and unfrozen soil thermal conductivity may also be evaluated on the basis of soil type, dry density, water content, and degree of water saturation by using charts available from Chapter 3 “Ground Thermal Regime”, in *Geotechnical Engineering for Cold Regions*.

NOTE — Natural soils will vary in composition over relatively short distances; hence average thermal conductivities are appropriate for many thermal problems. Various methods for calculating the thermal conductivity of soils have been reviewed in the documents “Thermal Properties of Soils”, in *Monograph 81-1* and *Thermal Conductivity of Soils*. These methods generally give the best results for unfrozen and frozen soils, coarse or fine, at degrees of saturation above 0.1. Computed thermal conductivity values are expected to differ from measured values by less than 25%.

**8.5.8.3 Specific heat** — The specific heat of soils shall be determined as specified in the requirements of the document ASTM D4611 or calculated based on correlations available in literature.

**8.5.8.4 Latent heat of fusion** — The latent heat of fusion of water shall be calculated based on available literature.

NOTE — The reference value for water is typically 334 J/g.

## **8.6 PROPERTIES OF THE BEDROCK**

### **8.6.1 General**

The site investigation program shall specify which properties of the bedrock shall be measured as part of the geotechnical site investigation. If included in the site investigation program, core sampling shall be carried out as specified in the requirements of Clause 8.6.2 and the properties of the bedrock shall be examined as specified in the requirements of Clauses 8.6.3 to 8.6.7.

### **8.6.2 Core sampling**

When specified in the geotechnical investigation program, coring of bedrock should be performed to obtain good to high-quality, intact samples. This process involves coring the bedrock using drilling equipment equipped with double- or triple-tube core barrels, with core runs of 1.5 metres in length. If thermally undisturbed samples are needed, the drilling shall be performed using chilled drilling fluid.

NOTE — Triple-tube core barrels are preferred since they minimize the disturbance of fractured bedrock cores.

All samples shall be logged as specified in the requirements of Clause 9.12.3 and photographed as they are collected. The geotechnical consultant shall record and photograph the equipment used for the bedrock investigation.

### **8.6.3 Stratigraphy and cryostratigraphy**

The progress of borehole advance shall be carried out under the supervision of the geotechnical consultant to document bedrock stratigraphy and cryostratigraphy, its changes and sample location.

The bedrock shall be examined by the geotechnical consultant to establish, as applicable:

- a) the rock types;
- b) the size and shape of rock blocks;
- c) the degree of weathering;
- d) the fracture frequency;
- e) the filling, type, spacing, inclination, aperture, and roughness of discontinuities;
- f) the cryogenic textures (ice distribution).

### **8.6.4 Rock quality designation (RQD)**

Rock quality designation (RQD) shall be established as specified in the requirements of the document ISO 14689 or ASTM D6032.

### **8.6.5 Bedrock temperature**

The temperature of the bedrock shall be measured in situ as specified in the requirements of Clause 8.5.5.1.

### **8.6.6 Compressive strength**

The compressive strength of intact bedrock samples shall be determined as specified in the requirements of the document ASTM D7012.

NOTE — When extensive testing or prompt information is required for reconnaissance activities, alternative tests performed as specified in the requirements of the document ASTM D5731 may be used to reduce the time and cost of compressive strength tests. Such data may be used to make prompt, risk-informed decisions during the exploration phases and a more efficient and cost-effective selection of samples for more precise and expensive laboratory tests. The test results should not be used for design or analytical purposes.

### **8.6.7 Groundwater salinity**

In presence of groundwater in the bedrock, the salinity shall be determined as specified in the requirements of the document ASTM D4542. A minimum of five samples shall be collected from at least two boreholes for the measurement of salinity.

NOTE — Groundwater salinity impacts the freezing point and therefore the unfrozen water content and the hydraulic conductivity of the bedrock.

## **8.7 GROUNDWATER CHEMISTRY**

Sampling of groundwater shall be performed for water quality and chemistry testing following respective standards and guidelines, if considered necessary by the geotechnical consultant.

NOTE — Information on water quality and/or chemistry may be required for the fabrication of the concrete mixture or when soil contamination is assumed.

## **9 REPORTING AND RECOMMENDATIONS**

### **9.1 GENERAL**

The findings of the geotechnical site investigation shall be included in a report. The geotechnical site investigation report will depend on the scope, magnitude and complexity of the project and the building or structure site-specific conditions.

### **9.2 SCOPE OF THE REPORT**

The geotechnical site investigation report shall include a description of the scope of the geotechnical site investigation agreed upon between the geotechnical consultant and the client at the outset of the investigation as defined in Clause 5.1, and any modifications that were necessary during the course of the project.

The report shall also include the conceptual design of the building or structure that is under consideration or the description of the building or the structure for which a foundation rehabilitation plan is required as specified in Clause 5.1.

The client's intended use of the report (e.g., for preliminary/schematic design, cost estimating, detailed design, limitations) shall also be documented.

### **9.3 CLIMATE CONDITIONS**

The geotechnical site investigation report shall include a description of the climate conditions influencing the building or structure site, namely the seasonal and interannual climate conditions, the MAAT, the ATI, the AFI, precipitations and winds, and microclimate considerations as well as the climate change projections over the service life of the foundations of a building or a structure. This information shall address the requirements specified in the requirements of Clauses 7.2.2 and 8.2.1. The report shall also include the references for the sources of the climate and weather data and the rationale for selecting these sources of data.

The report shall include a historical review of the climate and address the issue of differences between past climate conditions and those that were observed at the time of the geotechnical site investigation.

The report shall include an evaluation of how the projected climate conditions are expected to impact the ground conditions throughout the service life of the foundations of a building or a structure.

NOTE — Particular emphasis is needed regarding temperature, but perhaps even more significantly the impact of changes in precipitation patterns, for both snow and rain.

#### **9.4 SEISMICITY**

As specified in Clause 7.2.3, the geotechnical site investigation report shall identify the seismic hazard associated with the building or structure site.

#### **9.5 SURFICIAL GEOLOGY AND GEOMORPHOLOGY**

The geotechnical site investigation report shall include a description of the surficial geology and geomorphology of the building or structure site area. This part of the report shall address the items specified in Clause 7.2.4.

#### **9.6 SURFACE AND GROUNDWATER HYDROLOGY**

The geotechnical site investigation report shall include a description of the surface water drainage and anticipated groundwater conditions at the building or structure site. This part of the report shall address the items specified in Clause 7.2.5.

#### **9.7 VEGETATION COVER**

The geotechnical site investigation report shall include a description of the vegetation cover at the building or structure site. This part of the report shall address the items specified in Clause 7.2.6.

#### **9.8 PERMAFROST ZONES AND LOCAL DISTRIBUTION**

The geotechnical site investigation report shall identify the permafrost zone of the building or structure site and, if applicable, the site-specific distribution of permafrost. This part of the report shall address the items specified in Clause 7.2.7.

#### **9.9 SITE-SPECIFIC FEATURES**

The geotechnical site investigation report shall identify the site-specific features of the building or structure site. This part of the report shall address the items specified in Clause 7.2.9.

#### **9.10 HISTORIC LAND USE**

The geotechnical site investigation report shall identify the historic land use of the building or structure site. This part of the report shall address the items specified in Clause 7.2.11.

## **9.11 NEARBY BUILDINGS OR STRUCTURES**

The geotechnical site investigation report shall include relevant information on nearby buildings or structures. This part of the report shall address the items specified in Clause 7.2.12.

## **9.12 SUBSURFACE CONDITIONS**

### **9.12.1 Characterization of subsurface conditions**

The geotechnical site investigation report shall include a summary of the site investigation program conducted to characterize the subsurface conditions at the building or structure site including the time of year when the geotechnical site investigation was carried out.

The summary of the site investigation program shall detail the methods used to assess the subsurface conditions, which may include earlier desktop evaluations (see Clause 7.2), remote sensing technologies (see Clause 8.3), and geophysical survey methods (see Clause 8.4), as well as field testing and inspection combined with laboratory tests (see Clauses 8.5 and 8.6).

### **9.12.2 Subsurface properties**

The geotechnical site investigation report shall specify the properties of the subsurface at the building or structure site and their variability. The report shall also specify if the properties were measured by field or laboratory tests, or describe how the properties were estimated. The level of accuracy and precision of the measurements shall be mentioned in the report.

The geotechnical site investigation report shall include a description of the major soil and bedrock formations observed and identify any localized anomalies that could affect the design of the foundations of a building or a structure.

The geotechnical site investigation report shall provide, as applicable and as defined in the scope:

- a) the stratigraphy and cryostratigraphy of the soils and bedrock (see Clauses 8.5.3 and 8.6.3);
- b) the ground thermal regime (see Clauses 7.2.8 and 8.5.5);
- c) the index properties of the soils (see Clause 8.5.6);
- d) the properties of the frozen soils (see Clause 8.5.7);
- e) the properties of the bedrock (see Clauses 8.6.4, 8.6.5, 8.6.6 and 8.6.7).

If required for the design, the thermal properties of the soils determined as specified in the requirements of Clause 8.5.8 shall be included in the report.

### 9.12.3 Field testing, inspection and laboratory tests

If subsurface properties were established using a combination of field testing, inspection and laboratory tests, the geotechnical site investigation report shall contain the list of the various equipment used; the number and location of test pits and boreholes, including execution dates; and the field and laboratory tests conducted.

The geotechnical site investigation report shall include the results of all tests and investigations carried out, including a copy of the test reports.

It shall also include a detailed borehole/test pit log including, at a minimum, the following information:

- a) coordinates for the borehole collar location with the following precision: max.  $\pm 5$  m for the x, y coordinates and max.  $\pm 0.5$  m for relative site elevation. If boreholes are inclined, the dip and azimuth of the borehole shall be included. The coordinates system and datum shall be reported;
- b) detailed soil/bedrock stratigraphy determined from recovered samples, visual logging, drilling difficulties/behaviour and drillers' comments where appropriate;
- c) sample location and sampling technique including degree of disturbance as well as the field or laboratory tests carried out on each sample;
- d) drilling methods;
- e) cryostratigraphy including volumetric ice content;
- f) instrumentation installed in the borehole, if any;
- g) groundwater conditions, including characteristics and extent of cryopegs, if present, if any, and the presence of any water inflow including details from where the water is originating or where it was encountered;
- h) any notes pertaining to instability of the borehole/test pit.

If instruments were installed, their measurements shall be included in the report, in particular, if the site is visited multiple times, ground temperatures obtained during the investigation as well as follow-up readings shall be provided. Profiles showing seasonal variations at different times of the year should also be included if available.

The report shall include comments regarding the stability of the instrument readings. Additionally, details of the installed instruments shall be provided, including but not limited to, the cable and sensor manufacturer, calibration information, data logger setup (if applicable), performance, maintenance requirements, and download frequency. The temperature thermistor sensors shall have the accuracy of at least  $\pm 0.1$  °C and a resolution of 0.01 °C with a range from +30 °C to -30 °C, and the 0-degree offset should be determined in an ice bath.

## 9.13 RECOMMENDATIONS

Where recommendations are to be included in the geotechnical investigation report, the aspects described in Clauses 9.13.1 to 9.13.5 shall be included.

NOTE — Some clients may request a Data Report, where the geotechnical consultant is responsible only for data collection, with the interpretation and recommendations to be carried out by other parties.

### 9.13.1 Suitability of the building or structure

The geotechnical site investigation report shall provide recommendations on the suitability of the current or proposed building or structure site. If the recommendations indicate that the current or proposed site is not suitable for the client's concept, the report shall include justifications.

### 9.13.2 Foundation recommendations and alternatives

The geotechnical site investigation report shall provide recommendations on the suitable foundation types based on the identified permafrost conditions and the structural requirements of the building or structure. The foundation recommendations shall consider the impact of projected climate conditions on their ability to support the building or the structure throughout its service life. The report should also consider existing and potential changes in snow drifting/scouring (see Clause 7.2.2.4), as these factors can significantly affect the thermal behaviour of the supporting foundation soils or bedrock.

Foundation recommendations for the building or structure should be based on the assessment and characterization of the site, and on the uncertainties related to the projected ground conditions, which are linked to the uncertainties in the projected climate conditions.

The report may suggest alternative foundation types for the building or structure as well as the advantages and disadvantages (pros and cons) of the foundations, and foundation alternatives.

NOTE — Guidance and technical support to assist in the design of foundations in permafrost and in foundation selection, monitoring and performance assessment is presented, but not limited to, in the following documents:

- a) CSA PLUS 4011 outlines methods to estimate the sustainability of engineered structures on permafrost foundations over their service lives in northern Canada, with the objective to mitigate climate-change-induced risk of foundation systems failure at the design stage and to accommodate climate change effects.
- b) CSA PLUS 4011.1 is a companion document to CSA PLUS 4011 providing technical information on the attributes of the various foundation systems, selection criteria, ground conditions, and related issues intended to assist the general selection process and choices for permafrost foundation systems and their limitations.
- c) *Canadian Foundation Engineering Manual* presents a chapter (Chapter 13) discussing foundations in permafrost, including site investigations in permafrost, classification of permafrost, ground temperature monitoring, deep and shallow foundation design, effects of ground disturbance, climate warming effects, thaw settlement and creep of foundations, and a discussion on adaptive design methods to address a changing geothermal regime in the ground.

In a case where a deep foundation is recommended, recommendations for adfreeze strength properties of permafrost frozen soils shall be provided by the geotechnical consultant. The average permafrost temperature may be used to estimate the average adfreeze bond for preliminary design. For final design, in situ subsurface temperature distributions shall be obtained and the adfreeze strengths calculated along the ground profile as a function of temperature.

NOTE — The adfreeze strength used for the design of foundations of a building or a structure may be calculated as illustrated in “Pile Design in Permafrost”, in Canadian Geotechnical Journal, “A Study of Some Factors Affecting the Adfreeze Bond of Piles in Permafrost”, in *Proceedings of the 5<sup>th</sup> Canadian Permafrost Conference* or in *Canadian Foundation Engineering Manual*.

In a case where a geotechnical site investigation is performed for developing a rehabilitation plan for existing foundations of a building or a structure, the geotechnical site investigation report shall provide recommendations to moderate the effect of permafrost degradation on the foundations of a building or a structure.

NOTE — Guidance for moderating the effects of permafrost degradation on existing foundations of a building or a structure can be found in the document CSA S501.

If the proposed design requires the installation of instruments to monitor the performance of the foundations over time, such requirements shall be documented in the geotechnical site investigation report. Likewise, other tasks related to monitoring, such as thermosyphon operation checks, settlement surveys, visual inspections, etc., should be clearly outlined in the report.

### **9.13.3 Site preparation**

When required by the scope for the geotechnical site investigation, the report shall summarize the required site preparation to construct the foundations of a building or a structure as well as the optimal site preparation schedule considering potential limitations in site access (e.g., winter clearing and grubbing).

When applicable, the geotechnical site investigation report shall also identify potential borrow pits (see Clause 7.2.13) and provide the likely quantities available.

### **9.13.4 Surface water management**

When required by the scope for the geotechnical site investigation, the report shall provide guidance for surface and groundwater management. The impact on the local surface and groundwater flow patterns caused by the construction of the proposed building or structure and any earthworks shall be considered and recommendations for any required drainage measures (ditching, berms, snow management, etc.) shall be provided.

### **9.13.5 Construction aspects and schedule**

When required by the scope for the geotechnical investigation, the report shall provide comments and guidance on onsite issues that may impact the selection and design of the foundations of a building or a structure, such as: excavation of peat and shallow ice-rich soils, need for dewatering of the excavation, re-use of the excavated inorganic thawed ground for backfill, predrilling for pile

installation, fill pad construction timing, construction sequence, timing of thermosyphon installation and/or other issues.

When required by the scope for the geotechnical investigation, the report shall also identify the months of greatest thaw depth for ease of excavation, if required, and the month by which the earthwork should be completed. If excavation requires drilling and blast operations, this shall also be noted. Similarly, the report shall indicate when construction or foundation installation shall not be carried out because of the potential for non-reversible thaw or the inability to undertake construction. The approaches to be employed during construction and the restrictions on construction activities (e.g., no operation of equipment on the natural ground surface) shall be identified.

**9.14 SCHEDULING OF THE GEOTECHNICAL SITE INVESTIGATION**

The report shall document the time of year when the geotechnical site investigation was carried out as well as the impact of the timing on the near-surface characteristics observed (e.g., ALT, ground temperatures, water flow in the active layer, surface water flow, and snow cover).

**9.15 LIMITATIONS OF THE GEOTECHNICAL SITE INVESTIGATION**

The geotechnical consultant shall state in the geotechnical site investigation report the practical and legal limitations of the geotechnical site investigation and the derived information. This typically contains a limitation in use to the client for whom the report was prepared.



**Table 1**

**Scheduling of building or structure site visits and site investigations**  
(Clauses 7.3 and 8.1)

Seasonal timing	Pros	Cons
Spring — early summer	<ul style="list-style-type: none"> <li>• Frozen ground permits easier drill rig access and better cores in the active layer.</li> <li>• Air temperatures are higher, requiring fewer cold temperature interventions.</li> <li>• Surface water sources may be available for use during drilling.</li> <li>• Evidence of snowdrifts or snowbanks may still be present.</li> <li>• Evidence of some periglacial features occurring in winter such as frost blisters or icing is discernible.</li> <li>• Surface drainage conditions may be most discernible.</li> <li>• Daylight hours are longer.</li> <li>• A building or structure site visit in spring or early summer may provide sufficient time for site investigation later in summer/fall.</li> </ul>	<ul style="list-style-type: none"> <li>• Active layer is not fully thawed to maximum depth.</li> <li>• Summer groundwater conditions are not fully developed.</li> <li>• Test pits are limited to depth of frost in active layer.</li> <li>• Lingering snow cover may conceal topography, vegetation, or other important surface features.</li> <li>• Freshet may impact the site investigation.</li> </ul>
Mid-summer — autumn	<ul style="list-style-type: none"> <li>• Active layer is at or near maximum depth and best suited for test pits and measurement.</li> <li>• Surface water and groundwater conditions are most developed.</li> <li>• Surface features are easily discernible.</li> </ul>	<ul style="list-style-type: none"> <li>• Softer ground may complicate rig access and is more sensitive to disturbance.</li> <li>• Caving or sloughing of the active layer soils may complicate drilling methods.</li> <li>• A building or structure site visit in late summer or autumn may not provide sufficient time to develop and execute a site investigation during the same summer.</li> </ul>
Winter	<ul style="list-style-type: none"> <li>• If they are not hidden by snow, periglacial features occurring in winter such as frost blisters or icing are discernible.</li> <li>• Snowdrifts are discernible.</li> <li>• There is potential of less disturbance to the natural ground surface.</li> <li>• Access to drill sites is often easier over snow than across rough tundra.</li> <li>• Recovery of undisturbed frozen samples is easier if drilling is proposed.</li> <li>• A building or structure site visit in winter can facilitate site investigation in spring and possibly same-year summer construction.</li> </ul>	<ul style="list-style-type: none"> <li>• Limited daylight hours and frigid temperatures reduce efficiency and are hard on equipment.</li> <li>• Snow cover conceals micro-topography, vegetation and other surface features.</li> <li>• ALT cannot be determined.</li> <li>• Surface drainage and groundwater conditions cannot be observed.</li> <li>• Finding a source of water for drilling may be more difficult.</li> <li>• Delays to work and travel due to weather may greatly increase costs.</li> </ul>
<p><b>NOTES —</b></p> <ol style="list-style-type: none"> <li>1 The time of year selected for conducting a site investigation may impact on sampling methods and cost.</li> <li>2 In the Western Arctic, access by road in winter or barge in summer may factor into the timing of a site investigation.</li> <li>3 In the Eastern Arctic, the annual sea lift schedule does not allow mobilizing drilling equipment, so air becomes the only option. However, if a drilling crew happens to be present in a community, it becomes a significant consideration in the timing (and cost) of a site investigation.</li> </ol>		

**ANNEX A**  
(informative)

**Geotechnical site investigation program**  
(Clauses 5.2 and 7.4 and Annex F)

Figure A.1 provides some guidelines on the development of the geotechnical site investigation program based on the climate change-related risk level of the project (see Clause 7.4). These levels, which follow the document CSA PLUS 4011, determine the level of climate change analysis and additional associated geotechnical investigative measures that are required to adequately characterize the building or structure site.

The checklist available in Annex F may be used in support of the flow chart shown in Figure A.1.

**Continued on next page**

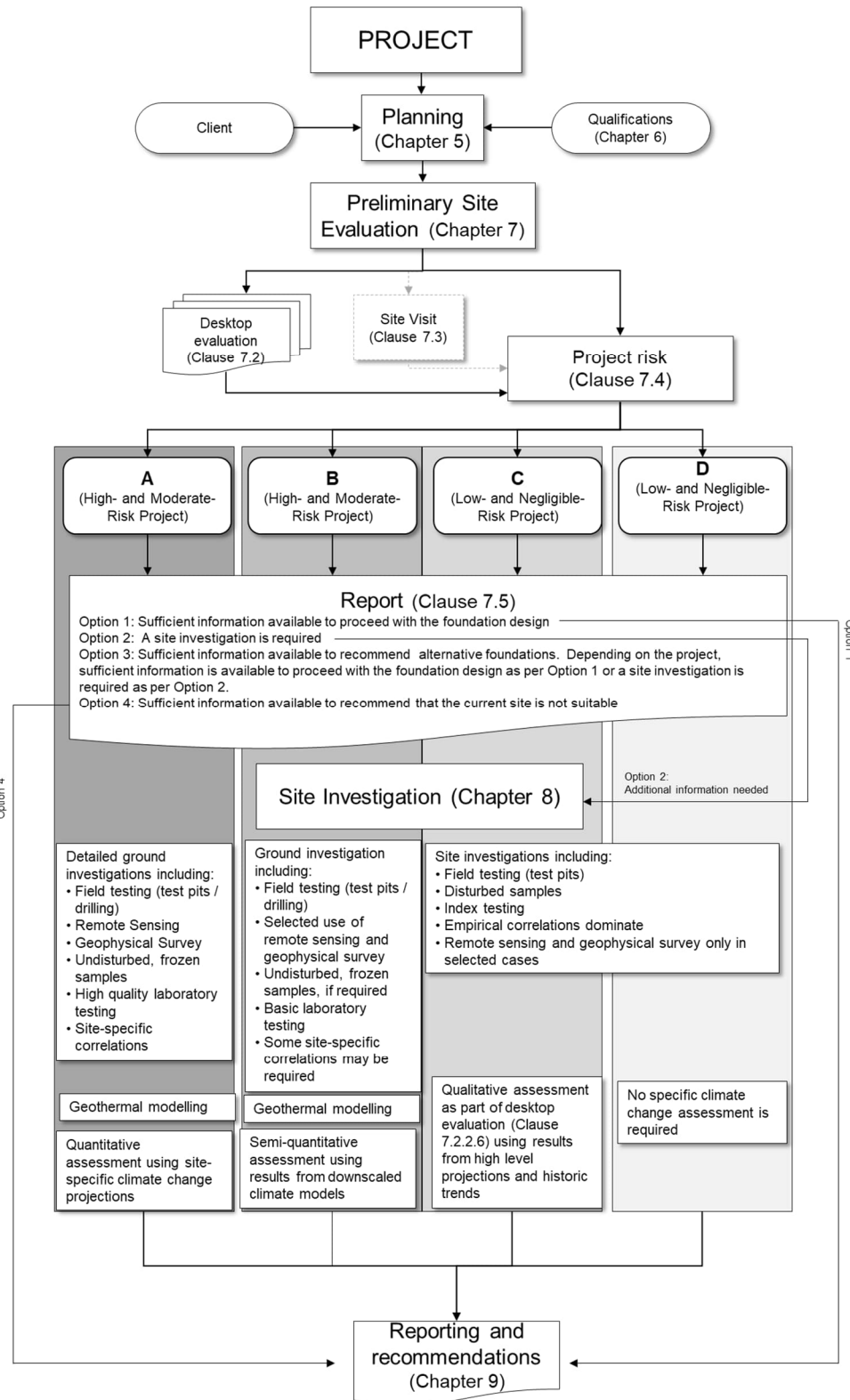


Figure A.1 — Geotechnical site investigation program components

**ANNEX B**  
(informative)

**Climate change and permafrost degradation**  
(Clauses 7.2.2.6 and 8.2.1)

**B.1 INTRODUCTION**

Air temperatures in the Arctic have warmed much faster than in the rest of the world (Rantanen et al., 2022). This warming has contributed to the thawing and degrading of permafrost across parts of Arctic and sub-Arctic regions, with the degradation often exacerbated by wildfire, extremes in rainfall and snowfall, snowpack changes and from construction itself (Biskaborn et al., 2019).

The state of permafrost thawing and degradation varies widely in space and time. Unfortunately, data reflecting the changes in deeper permafrost (i.e. > 1 m) are limited in time and space. Recognizing the limitations of the available monitoring data and permafrost modelling, this standard provides recommended practices for assessing and managing the various risks to permafrost foundation sites under a changing climate.

**B.2 ARCTIC RISKS UNDER CLIMATE CHANGE**

For decades, community, economic and industrial development in the Arctic was based on the assumption that permafrost would serve as a permanent and stable platform for foundations. However, the construction itself as well as air temperature warming and other changes in the climate are resulting in increased permafrost thaw, which in turn threatens both existing infrastructure and future construction projects.

A recent study estimated that as much as 30% to 50% of crucial infrastructure on permafrost regions could become at risk under projected climatic warming by mid-century (Hjort et al., 2022).

**NOTE** — It should be noted that the study used circumpolar scale permafrost maps, did not consider the design criteria used for local and regional infrastructure and subsequently, was not intended to reflect regional or local scale conditions and risks.

The study advises that engineering and geological conditions, including evaluation of thaw sensitivity, need to be accurately explored and spatially referenced to guide engineering design and construction in permafrost areas under a changing climate.

Another study using the latest climate change models and a permafrost-geotechnical model to investigate changes in bearing capacity and ground subsidence risks for circumpolar Arctic infrastructure estimated that roughly 17% to 33% of roads and other linear infrastructure were likely at risk of significant damage in future due to climate-induced thaw subsidence (Streletskiy

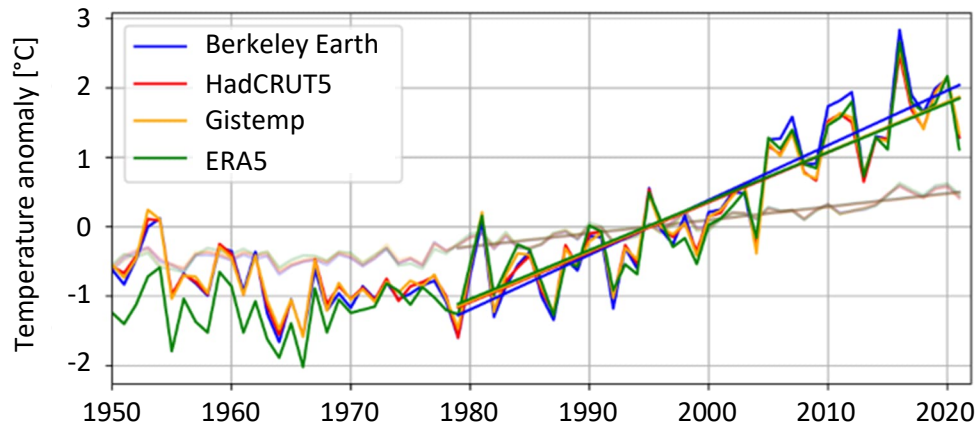
et al., 2023). Higher global greenhouse gas (GHG) emissions were associated with the higher percentages of at-risk roads.

Due to the location of infrastructure and permafrost types, (Streletskiy et al., 2023) estimated that both Alaska and northern Canada included a higher percentage of at-risk roads on discontinuous permafrost as compared to continuous permafrost. The total cost of replacing damaged sections of roads was estimated \$12 billion in Canada, while it was projected that some 13% to 17% of buildings would be affected by the loss of permafrost bearing capacity in future, depending on the rate of increase in GHGs. It should be noted that new technologies can help to reduce permafrost thawing risks to structures over their planned lifespans, as highlighted in the other northern permafrost documents of this suite (e.g., CSA S500, CSA S501) and in ongoing research (e.g., Oswell and Coutts, 2024). Overall, the higher risks for infrastructure in North American permafrost zones are for low-lying coastal areas and ice-rich permafrost.

In addition to permafrost thaw risks, infrastructure in permafrost regions will be subject to additional risks from rapid coastal erosion, new flooding hazards, new and accelerated landslides, drainage of ridge-top lakes and potential snow-dam outbursts. As the Arctic warms at rates faster than other regions, the thawing permafrost will also have impacts globally through carbon release. Since the Arctic is the Earth's biggest climate-sensitive carbon pool or carbon storage source and is warming faster than other regions, there are concerns that significant permafrost thaw could also potentially release additional GHG emissions, thereby amplifying climate change globally (Meredith et al., 2019; Nitzbon et al., 2024; Canadell et al., 2021).

### B.3 CHANGING CLIMATE AND PERMAFROST THAWING

Under a climate phenomenon long known as Arctic amplification, recent climate studies indicated that many parts of the Arctic have warmed at rates ranging from twice and up to four times the global average (Rantanen et al., 2022), as illustrated in Figure B.1.



Source: “The Arctic has Warmed Nearly Four Times Faster than the Globe since 1979”, in *Communications Earth and Environment*.

**Figure B.1 — Annual mean temperature evolution in the Arctic**

**NOTE** — Annual mean surface air temperature anomalies in the circumpolar Arctic (66.5° to 90° N) [shown in dark or bold colours] compared to global mean temperature anomalies (shown in light or faint brown colours) during the period ranging from 1950 to 2021 derived from the various observational datasets. Temperature anomalies have been calculated relative to the standard 30-year period from 1981 to 2010. Shown as straight lines are the Arctic and global linear temperature anomaly trends for the 1979 to 2021 period, indicating that circumpolar Arctic air temperatures have warmed as much as four times that of the global average since 1981.

Trends in ground temperatures in Arctic regions are broadly consistent with those in air temperature. For example, widespread warming of permafrost at the depth of the zero annual amplitude (DZAA) has generally been observed across the Canadian Arctic over the past three to four decades, but with spatial and temporal variability in the magnitude of the changes (Smith Duchesne et O’Neill, 2024). Relationships between air and permafrost soil temperatures are not straightforward due to variable buffering layers at a site, including vegetation, active layer soils and snow cover, and monitoring and data challenges (Derksen et al., 2019; Biskaborn et al., 2019; Smith et al., 2022). Longer-term permafrost measurements at or near the DZAA identify increases in ground permafrost temperatures in the continuous permafrost zones of Nunavut and the northern Mackenzie region ranging from 0.4 °C to 1 °C per decade, while warming rates of about 0.1 °C per decade have been measured in the central Mackenzie Valley (Derksen et al., 2019; Smith, Duchesne and O’Neill, 2024). In the coldest and continuous permafrost zones, warming at the DZAA of up to about 1 °C per decade has been noted in the high Arctic.

Active layer thicknesses have also increased by approximately 10% since 2000 in the Mackenzie Valley (Derksen et al., 2019). Thaw tube measurements and ground surface observations in this

valley indicate that ice-rich permafrost degradation is occurring at many sites, resulting in substantial surface subsidence and widespread formation of thermokarst landforms (Derksen et al., 2019; O'Neill et al., 2023; Smith, Duchesne et O'Neill, 2024). These changes in permafrost are consistent with changes observed in Russia, Alaska, and other Arctic regions.

#### **B.4 VARYING RATES OF PERMAFROST DEGRADATION**

While mean air temperature warming can lead to more widespread and uniform top-down permafrost thaw, many studies have shown that the gradual thawing may also be accompanied by more rapid thermokarst, thermal erosion and mass wasting processes that operate on different and varying spatial and temporal scales than the gradual thawing (Burn, 2021; Kokelj et al., 2023). This more rapid thawing leading to thermokarst landscapes can be expected in ice-rich permafrost regions (Lewkowicz and Way, 2019; Farquharson et al., 2019; Rodenhizer et al., 2022). Various thermokarst features include ground slumping or subsidence, erosion gullies, retrogressive thaw slumps or landslides, talik formation, new lakes, the enlargement and even occasional draining of lakes and other disturbances (Hjort et al., 2022).

The more rapid thaw and the initiation of spatially and temporally variable thermokarst processes often follow climate triggering events from weather extremes or disturbances (Rodenhizer et al., 2022). These weather extremes can include unusually warm temperatures during the thaw season (Lewkowicz and Way, 2019; Farquharson et al., 2019), wildfires (Smith, Riseborough and Bonnaventure, 2015; Turetsky et al., 2020; Young et al., 2022), excess precipitations and extreme rainfall events (Kokelj and Jorgenson, 2013; Douglas, Turetsky and Koven, 2020; Magnússon et al., 2022; Kokelj et al., 2015; Hamm et al., 2023), surface water or coastal inundation (Zheng et al., 2019; Guimond et al., 2021) and anomalously snowy winters (Jorgenson et al., 2020; Parmentier et al., 2024). The construction itself also can trigger or accelerate thermokarst processes (Schnabel, Goering and Dotson, 2020; Kanevskiy et al., 2022). Thermokarst features vary widely, depending on site-specific factors such as topography, soil characteristics, soil ice content, erosion, and thermo-erosion processes.

A multi-partner thermokarst mapping collective for the Northwest Territories has estimated that much of western Arctic Canada's permafrost soils are broadly thaw-sensitive (Kokelj et al., 2021). Other studies in the Canadian high Arctic indicate that, despite very cold permafrost temperatures (< -10 °C), zones of cold permafrost with massive ground ice close to the surface are highly vulnerable to rapid permafrost degradation and thermokarst development (Farquharson et al., 2019; Nitzbon et al., 2020).

With ongoing climate change, it is projected that permafrost thawing processes across the Canadian Arctic will continue to impact large areas by mid-century, resulting in increasing risks for foundations (Derksen et al., 2019; Kokelj et al., 2021). In their report, the Intergovernmental Panel on Climate Change (IPCC) [Meredith et al., 2019] estimates that about 80% of the permafrost across the circumpolar Arctic will thaw gradually under climate change but that some 20% of Arctic regions with relatively ice-rich permafrost may be susceptible to rapid thaw and subsidence.

## **B.5 PERMAFROST DEGRADATION, RISKS AND CANADIAN STANDARDS**

The CSA PLUS 4011 permafrost document and the various Canadian permafrost standards recommend that engineering design be based upon projected climate change for the next few decades or for the projected service life of the foundation structure, where the future rate of climate change will depend on the global greenhouse gas scenarios. The guide and standards also recommend that these estimates be accompanied by effective permafrost monitoring to inform owners about performance of the infrastructure during its service life.

Canadian guidelines and standards for infrastructure risks in permafrost zones have historically assumed gradual and widespread thawing in response to projected air temperature increases (CSA Group, 2019). But permafrost in some more thaw-sensitive communities may be degrading at locally rapid rate or in coastal regions, at unprecedented rates (Lewkowicz and Way, 2019). While the gradual top-down thaw can affect the landscape surface by centimetres over decades, the more rapid landscape changes can affect the near-surface by meters over much shorter periods of time (e.g., weeks to many years) [Lewkowicz and Way, 2019; Burn, 2021; Anthony, 2023]. In such cases, engineering practices that only consider gradual air warming and top-down permafrost thawing could underestimate the rate of permafrost degradation, emphasizing the importance of undertaking more detailed permafrost site risk assessments and investigations, including the requirements and recommendations of this standard.



Source: Government of NWT, ENR-Forest Management.

**Photo B.1 — Permafrost thaw slumps captured in an aerial shot near Fort Simpson, N.W.T.**

## **B.6 NOTE ON CSA PLUS 4011 AND GRADUAL PERMAFROST DEGRADATION**

While the document CSA PLUS 4011 outlines climate change risks broadly due to gradual top-down thawing of permafrost, future updates could include additional risks from more rapid permafrost degradation. It also identifies four slow onset permafrost foundation risk zones (1 to 4) as a function of local MAGTs. For simplicity, the document uses MAAT as a surrogate for

MAGTs. This allows the updated document to make use of future projected mean MAATs (for MAGTs) and to support “best climate change practices” to use multiple climate change projections and different GHG assumptions over the design service life of building and structure foundations.

**ANNEX C**  
(informative)

**Drilling and sampling**  
(Clause 8.1)

**C.1 EXCAVATION OF TEST PITS**

Wheeled and tracked hydraulic hammer-equipped excavators have been used to excavate weak bedrock. Provided that there is adequate access to permit the use of excavators, these machines offer great versatility and excellent capability for assessing shallow subsurface conditions in frozen soils and weak bedrock. Without hydraulic hammers or excavator buckets equipped with ripper teeth, subsurface investigations using common excavators in cold permafrost ( $\leq -2$  °C) are ordinarily prohibitively slow unless ground temperatures are just slightly below 0 °C. Critical to the success of excavation using hydraulic hammers is matching the hammer size and excavator configuration to the expected unconfined compressive strength of the material to be excavated. This can be done using the manufacturer's literature when the likely ranges of soil strengths are known.

Dozers with ripper teeth are available in some northern communities; therefore, granular borrow material investigations are sometimes carried out with these machines.

One of the primary factors that could interfere with the use of excavators and dozers is the rehabilitation of test excavation sites to the satisfaction of the landowners and government authorities. Excavation should be kept water free as much as possible and backfilled as soon as possible after the observation/sampling/installation is completed or at any sign of instability. Unlike most test excavations in temperate zones, a test pit in permafrost, if not properly backfilled and monitored, can cause permanent and destructive site alterations that are dangerous to large game and other wildlife. The excavation of test pits at the preliminary and early design stages therefore presents a greater liability than drilling boreholes.

**C.2 DRILLING**

**C.2.1 GENERAL**

Small portable rigs can be moved by mounting them on small vehicles or with construction equipment such as a loader/forklift or, if skid mounted, towed with a truck loader or dozer. Many small rigs may also be heliportable. Portable drill rigs mounted on the back of a "Nodwell" or other tracked vehicle offer substantial opportunity to drill in remote locations in winter conditions without using helicopters.

Some of the types of drill rigs that have been used on Arctic and sub-Arctic geotechnical investigations in the past include:

- a) hand-held drilling equipment;
- b) air-track percussion hammer drill rigs;
- c) auger drill rigs — solid- and hollow-stem drilling;
- d) sonic drill rigs — high frequency vibratory drilling;
- e) diamond drill rigs — diamond drilling.

Drilling in permafrost and sampling undisturbed frozen cores can be extremely challenging and should therefore only be carried out by experienced drillers.

### **C.2.2 HAND-HELD DRILLING EQUIPMENT**

Sometimes, a small, lightweight, portable drilling equipment, operated by one or two people, may be sufficient. The Geological Survey of Canada (GSC) developed a modified Cold Regions Research and Engineering Laboratory (CRREL) barrel. The CRREL barrel is a hollow steel barrel with welded double helix flight configuration. Attached to a power head, the CRREL barrel can retrieve a high-quality, continuous core in snow, ice, and fine-grained organic and mineral soils. The disadvantage of the CRREL barrel is that it does not work well in coarse gravelly ground, unfrozen soils or soils with a significant unfrozen water content. In addition, the drilling process can be slow due to insufficient storage for the cuttings on the outside of the barrel limiting the length of core recoverable in a single run.

A second method used by the GSC is diamond drilling, which uses a core barrel with a diamond impregnated carbide drill bit. Also attached to a power head, this method can cut through fine-grained soil with ice, sand, gravel, and boulders up to 200 mm in diameter. This off-the-shelf equipment produces a high-quality continuous core. The disadvantages with this drilling method are that in pure ice the core tends to break into smaller segments, slowing drilling, and in warmer permafrost conditions ( $> -2$  °C), the core tends to disintegrate due to the uncemented materials and frictional heat.

This type of equipment allows for total-length recovery of cores 100 mm in diameter without almost any alteration, and works in a larger variety of frozen soil types. Drilling depths between 4 m and 5 m are typical, but up to 7 m is possible in optimal soil conditions using a two- to three-person operating crew. Drilling in fine-grained soils, such as clay, which contain little ice may lead to the mud clogging the core barrel and slowing down drilling. Practically, a volumetric ice content of 5%-10% in fine soils is sufficient to provide good sampling conditions. The drilling equipment can use different core barrel diameters and lengths along with various drill bit configurations and materials (diamond or carbide).

A small, two-person, hand-held drilling equipment is shown in Photo C.1. In this case the gasoline-powered drill head is advancing a CRREL barrel into frozen fine-grained soils.



Source: unknown.

**Photo C.1 — Hand-held portable drilling equipment using a CRREL barrel sampler**

### **C.2.3 AIR-TRACK PERCUSSION HAMMER DRILL RIGS**

In the Eastern Arctic, one of the only drills available locally in many of the communities is the “air-track” drill rig. These drills, which are designed to rapidly bore a hole into rock for blasting purposes, are often used to provide some information on the characteristics of the permafrost soils because of the excessive costs that would be incurred to mobilize another type of drill rig to these remote communities. Although less than ideal, they do allow an estimate of the moisture content of the soil/bedrock to be reasonably measured. These drills only provide small chips of the soil/rock, which are blown back to the surface by the drill rig. The recovered material is often thawed or partially thawed. Thus, they only allow an estimate of the soil type and ice content and the thickness of the overburden if bedrock is within the penetration depth. These drills are track-

mounted and often tow the large air compressor that powers the hammer behind them. A photo of an air-track drill rig is shown in Photo C.2.



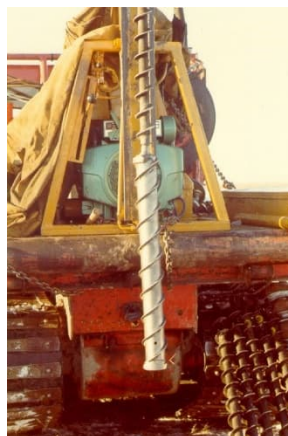
Source: unknown.

**Photo C.2 — Typical air-track drill rig**

#### **C.2.4 AUGER DRILL RIGS**

Truck-mounted, track-mounted and helitransportable auger drills have seen relatively widespread use in permafrost regions where the soils are primarily fine-grained.

The Ranger drill rig was one of the first small drills developed by Mobile Augers and Research Ltd. of Edmonton. This drill rig has been used on numerous projects for subsurface investigations along pipeline routes in Yukon, the Northwest Territories and Nunavut, and was used for some of the investigations carried out for the Norman Wells oil pipeline. The Ranger drill rig is shown in Photo C.3.



Source: unknown.

**Photo C.3 — Small auger drill rig mounted on a tracked carrier, set up to drill with solid augers and a CRREL core barrel (the ranger drill rig)**

The Ranger drill rig weighs about 500 kg and can be mounted on a truck or tracked carrier. Due to its light weight, it can also be transported in a single trip by a Bell 206 Jet Ranger helicopter or equivalent.

The Ranger drill rig is normally equipped with a 100-mm-diameter or 150-mm-diameter solid-stem auger. The maximum depth of drilling depends on subsurface conditions; however, in most materials the practical limit is 5 m to 10 m. The Ranger drill rig does not have the weight or power to penetrate gravelly deposits efficiently. Its use is therefore generally limited to silts, clays and clay-rich tills.

In unfrozen soils and poorly ice-bonded soils, disturbed samples can be taken off the augers or collected with Shelby tubes. The drill rig can be configured to carry out Standard Penetration Tests. With modifications, the Ranger drill rig can be used to drill with hollow-stem augers and used to core bedrock.



Source: unknown.

**Photo C.4 —      ATV-transportable small auger drill rig**

One type of auger drill rig that has seen relatively extensive use in the northwestern part of the Northwest Territories is what is commonly referred to as a rat-hole drill rig. A typical rat-hole auger drill rig is shown in Photo C.5. These large drill rigs are often locally available in the Mackenzie Valley and Mackenzie Delta area where they are used to drill surface casing or well cellar holes for oil and gas exploration rigs. They are also sometimes used to drill installation holes for adfreeze pile foundations. These drill rigs are only capable of retrieving disturbed soil samples but this can sometimes be sufficient to be able to establish at least the amount of ground ice found within the permafrost. Because of their local availability in the Western Arctic, the high costs associated with mobilization of a more ideal drill rig can be avoided if simple foundation systems are suitable for the building or structure site being considered.



Source: unknown.

**Photo C.5 — Rat-hole auger drill rig**

Larger auger drill rigs are heavier and more powerful than the Ranger drill rig or other small auger drill rigs and are therefore more likely to penetrate some tills and granular deposits. These larger auger drill rigs can also be mounted on trucks or tracked carriers or moved about in a community by a loader/forklift or towed by a dozer. The borehole is typically advanced using 150-mm-diameter solid-stem or hollow-stem augers. The maximum depth of drilling depends on subsurface conditions; however, in frozen fine-grained materials the practical limit is about 15 m. Some of these drill rigs can be reconfigured to core bedrock.

Larger auger drills are often mounted on trucks or tracked carriers such as shown in Photo C.6.



Source: unknown.

**Photo C.6 — Typical track-mounted auger drill rig**

In unfrozen soils, samples can be obtained using conventional sampling techniques, including Standard Penetration Tests and sampling with Shelby tubes. Grab samples of disturbed frozen soils can be obtained from the auger flights or using conventional unfrozen soil samplers if the permafrost is warm ( $> -2$  °C).

In gravel-free frozen soils, the hole can be bored using a CRREL barrel. Photo C.7 shows a CRREL barrel and recovered undisturbed permafrost sample of frozen fine-grained soil.



Source: unknown.

**Photo C.7 — CRREL core barrel and undisturbed permafrost sample of frozen fine-grained soil**

### C.2.5 DIAMOND DRILL RIGS

The BBS-1 drill rig one of the first helitransportable diamond drills, was developed by Midwest Drilling of Winnipeg (now Major Drilling Ltd.).

The BBS-1 drill rig was used extensively for subsurface investigations along many proposed pipeline routes throughout the Canadian Arctic in the 1970s and 1980s. Because they see widespread use of these drills for mineral exploration, many different companies have similar diamond drills that can be used for geotechnical investigations. Today there are many types and sizes of diamond drill rigs available in the Canadian Arctic, particularly in areas where lots of mineral exploration is ongoing. It is therefore sometimes feasible to mobilize these drills and transport them relatively short distances for site investigations in municipalities. Diamond drills allow geotechnical investigations to be conducted in granular tills and glaciofluvial deposits that are derived from igneous and metamorphic rocks. Boulders and cobbles are common in these materials and present significant drilling difficulties for most other types of drill rigs. The diamond drills also allow bedrock found underlying the overburden to be sampled. A refrigeration unit can be used with the drill rig and chilled fluids or air can be used as the drilling fluid to prevent thawing of the frozen core. Photo C.8 shows a typical diamond drill rig with chilled drilling fluid system. The use of chilled salt brine drilling fluid was common until recently. Due to environmental restrictions, alternative environmentally friendly freezing point depressed drilling fluids (including glycol-based fluids and even a beet juice-based drilling fluid) have seen recent use.



Source: unknown.

**Photo C.8 — Typical diamond drill rig with refrigerated brine system**

Diamond drill rigs work effectively where frozen coarse- or fine-grained soils are present; however, they are not suitable for drilling and sampling unfrozen overburden or obtaining samples within the active layer unless the drilling operations are conducted in winter. Photo C.9 shows the high quality of undisturbed samples that can be obtained by diamond drilling with chilled brine in very challenging frozen granular till materials.



Source: unknown.

**Photo C.9 — High quality frozen undisturbed sample of granular till recovered using chilled brine diamond drilling**

### **C.2.6 SONIC DRILL RIGS**

The original sonic drill rig was developed by Midwest Drilling of Winnipeg (now Major Drilling Ltd.). This helitransportable drill rig was used extensively for subsurface investigations along the portion of the proposed route for the Polar Gas Pipeline located in the Arctic Islands where subsurface conditions range from high-plastic clays to competent sandstone and limestone bedrock.

Several drilling companies now operate sonic drill rigs of various sizes. The sonic drills continue to use a hydraulically powered oscillator to produce an axial force and high-frequency vibration that is transmitted along a hollow drill steel to the drill bit. The drill steel is advanced 1 m to 3 m, and then withdrawn from the hole. The soil core inside the drill steel is then vibrated out and collected. A relatively small sonic drill rig on a tracked carrier is shown in Photo C.10.



Source: unknown.

**Photo C.10 — Small track-mounted sonic drill rig**

Sonic drills provide continuous core samples in many frozen and unfrozen overburden soils, including coarse ice-rich frozen till. The rate of advance of the drill bit and the maximum depth of drilling depends primarily on the density of the subsurface soils. In overburden soils, particularly those with excess ice, the rate of drilling is relatively rapid. Sonic drills pulverize large rocks rather than coring through them and they do not penetrate most bedrock formations efficiently. Maximum penetration in overburden is typically 30 m.

The core recovered during drilling provides a continuous record of subsurface stratigraphy; however, depending on the soil structure, the frozen core may be broken up and disturbed.

**C.2.7 HELIPORTABLE DRILLS**

In some cases, where sites may only be accessible by helicopter, the drilling equipment is limited to weights and dimensions that can be transported by helicopter. Heliportable geotechnical drilling rigs and associated tools are designed to be transported by helicopter.

While heliportable systems offer advantages in terms of accessibility and mobility, there are limitations associated with this type of equipment:

- a) **Weight Restrictions:** Helicopters have limited payload capacities, so heliportable drilling equipment is lightweight and compact. This can restrict the size and capabilities of the drilling rig and the equipment it can carry.
- b) **Setup and Teardown Time:** Heliportable drilling equipment often requires more time for setup and teardown compared to larger, more stationary rigs. This can impact the overall efficiency of the drilling operation, especially in situations where rapid deployment is crucial.
- c) **Limited Depth and Power:** Heliportable rigs may be limited in terms of drilling depth and power compared to larger, ground-based drilling rigs.
- d) **Weather Dependence:** Helicopter operations are highly dependent on weather conditions. Adverse weather, such as strong winds or low visibility, can limit the ability to transport drilling equipment to and from remote locations, leading to delays in operations.
- e) **Cost Considerations:** Heliportable drilling operations can be expensive due to the cost of helicopter transport. The cost per drilling project may be higher compared to using ground-based equipment, which could impact the overall feasibility of heliportable solutions.

Despite these limitations, heliportable geotechnical drilling equipment remains a valuable solution for reaching remote or challenging locations where other forms of transportation may be impractical. The decision to use heliportable equipment should be based on a careful assessment of the specific project requirements and constraints.

### **C.3 BOREHOLE DRILLING METHODS FOR SOILS**

Table C.1 outlines typical drilling techniques and sampling techniques considerations for geotechnical investigations and describes the advantages and limitations for use in both frozen and unfrozen ground conditions. The most appropriate equipment and drilling technique for any project depends on:

- a) the specific objectives of the investigation (stage of design, depth of investigation);
- b) the sample requirements;
- c) the site location and access;

- d) the expected subsurface conditions;
- e) economic considerations.

Where sufficient access is available, conventional multifunctional drill rigs mounted on either rubber-tired or tracked vehicles are preferred. However, during preliminary design and early design stages these drill rigs may be prohibitively expensive. Smaller portable drill rigs that have less utility but are more easily moved may be adequate for a limited range of data.

**Table C.1**  
**Comparison of drilling methods and equipment**  
(pane 1 of 4)

Drill rig	Application	Drilling method	Sampling type & quality	Advantages	Limitations
Rotary drill rigs	To procure all types of soil and bedrock samples. To make holes for many types of field testing and coring. To drill inclined holes in soil or bedrock.	Drill bit on end of power-driven rotating drill rod to which pressure is applied hydraulically. Drillhole is normally retained by mud slurry although in some soils, water, or air (air rotary) may be feasible.	Sampling methods typically include split- spoon or Shelby tubes in weakly bonded (warm) frozen soils. Good quality core can be retrieved in warm, ice-rich frozen soils and weak bedrock when equipped with a core barrel.	Drilling is relatively rapid. Most types of materials can be penetrated. Boulders and cobbles can be delineated based on the "operator's feel of drill bit progress" or refusal of drill.	These drills are difficult to use in swampy or rugged terrain. Truck-mounted drills require trail or road and require a level platform for drilling. Drill cuttings are very disturbed and can be difficult to log. Drill bit wear can be expensive. Penetration in strong soils to significant depths or through gravel layers is difficult, and not possible through boulders and bedrock. Drill refusal is possible in competent bedrock. These drills are generally not suitable for sampling cold, well-bonded frozen soils.
Auger drill rigs (solid-stem flight auger)	To drill small to moderate-sized holes for continuous but disturbed sampling. Normally used in cohesive soils with adequate strength to prevent open borehole collapse. A heavy and powerful drill is used to auger into frozen and permafrost soils.	Rotating continuous flights of helical augers. Remove all flights from the drill hole to allow for the examination of soil cuttings along the auger flights. Can add a dry auger CRREL core barrel to the end of the flight auger for undisturbed soil sampling.	Sampling methods typically include retrieving disturbed grab samples of frozen and unfrozen soil from the flight augers or using a split-spoon sampler. Disturbed grab samples are suitable for evaluating soil type, visible ice volume, and soil sampling for lab index testing. A dry auger core barrel (i.e., CRREL core barrel) can be attached to the end of the solid-stem auger to retrieve quality core in fine-grained, ice-rich frozen soils. Shelby tube sampling is possible in fine-grained, warm frozen soils.	This method provides a rapid procedure for exploratory boring in strong cohesive soils and soft bedrock. Standard Penetration Test (SPT) sampling is possible in warm, poorly bonded frozen soils when borehole remains open after auger removal. It is possible to advance a CRREL barrel into fine-grained frozen soils without using a drilling fluid. Relatively inexpensive and fast allowing soil classifications. CRREL Core Barrel — High quality undisturbed frozen core samples.	Hole collapses when auger is withdrawn from weakly bonded (warm frozen) cohesive or cohesionless granular soils. Auger samples are disturbed. Penetration is difficult through gravel layers, and not possible through cobbles, boulders and rock. Auger advance is slow in well-bonded frozen soils and augering produces heat that will warm and may thaw warm permafrost and melt the pore ice. Soil descriptions and samples obtained from the auger cuttings cannot be used for appropriate evaluation of permafrost structure and associated properties. CRREL can only be used in fine-grained overburden soils.

**Table C.1**  
**Comparison of drilling methods and equipment**  
(pane 2 of 4)

Drill rig	Application	Drilling method	Sampling type & quality	Advantages	Limitations
Hollow-stem auger drill rigs	To drill small to moderate-sized holes for soil sampling.	Similar to continuous-flight auger except hollow-stem auger casing is advanced into the ground rather than a solid-stem flight auger.	Allows for continuous sampling as the auger advances into the subsurface. Can provide a more representative profile of the soil conditions compared to some other drilling methods.	Method is rapid in weak to moderately strong soils. SPT and undisturbed sampling are possible in poorly bonded (warm) frozen soils. They can handle a range of subsurface conditions including sloughing soils and groundwater.	Method affords slow progress in most frozen soils. Sampling with hollow-stem augers should be used with caution because the auger may become frozen in the hole. Penetration in strong soils to significant depths or through gravel layers is difficult, and not possible through boulders and bedrock. Considerable disturbance may occur from auger bit.
Large-diameter auger drill rigs (bucket, helical, piling, caisson drills)	To drill large-diameter holes to recover disturbed samples and for soil strata examination in cohesive soils where the hole remains open.	Rotating large-diameter auger cuts soil to form hole.	Samples from flights are disturbed. Collecting undisturbed frozen soil samples is difficult. May be possible to lower other sampling equipment downhole but this requires more equipment and can be cumbersome.	Method is rapid and suitable in frozen and permafrost conditions. Examination of subsurface soil conditions is possible by observing larger volume of auger cuttings.	Depth is limited by groundwater and bedrock conditions. Method is not suitable in sloughing conditions including cohesionless soils, soft clays, or organic soils. Large machine requires easy access to site. Drill refusal is possible in boulders and bedrock.
Hammer drill rigs (including Becker Hammer drill)	To drill water wells. To drill exploratory holes through cobbles and boulders.	Pile-driving-type hammer used to drive double-wall casing while circulating air through annulus to blow cuttings from inner barrel.	Non-applicable	Penetration is relatively rapid through cobbles and boulders. Method is well suited for exploratory holes in non-plastic frozen tills. Obtaining a relative measure of resistance is possible by recording hammer blows per unit length of penetration.	Limitations are similar to those of percussion drills, except progress is more rapid. Progress is slow in cohesive/plastic soils. SPT sampling is only feasible in relatively warm, fine-grained permafrost. Adapting to CRREL barrel is not possible.
Pneumatic percussion drill rigs (including air-track drills and seismic drills)	To drill holes for blasting or bedrock anchors.	Percussion bedrock bit chips and crushes rock with hammer blows as bit rotates; chips removed by air pressure.	Highly disturbed samples are small chips that have been blown to surface. Cannot ordinarily be used for sampling or testing.	Procedure is rapid for making small-diameter holes in hard bedrock. Determining overburden thickness above bedrock is possible. Method is best for hard massive bedrock.	Losing entire drill stem is possible in overburden with cobbles and boulders, loose fractured rock, clay seams, wet shale, etc. Undisturbed sampling is not possible.

**Table C.1**  
**Comparison of drilling methods and equipment**  
(pane 3 of 4)

Drill rig	Application	Drilling method	Sampling type & quality	Advantages	Limitations
Diamond drill rigs	To carry out continuous coring of rock and frozen overburden for geotechnical site investigations.	Continuous coring by setting one or more casings and advancing a triple or double tube core barrel through casing to drill and sample in increments of 1.5 m to 3 m. Drill system uses mud, fluid, or air to remove cuttings from hole; mud, brine or air can be chilled to preserve samples at required temperatures.	High-quality sample recovery. Preservation of ground ice in frozen core is effective. SPT testing can be conducted.	This is the most efficient method of recovering frozen core samples with the least amount of mechanical and thermal disturbance if chilled drilling fluid is used. Method provides a near-continuous core. Many diamond drills are helitransportable.	Drilling fluid and a cooling system are required. Mobilization and operation are costly. Progress is slow — efficiency of drilling varies with drill rig size. Recovering samples in unfrozen overburden (active layer) is difficult. SPT testing typically requires drill rig modification.
Sonic drill rigs	To advance cased 150-mm-diameter (to 300-mm-diameter) holes to depths as great as 150 m using a fast and versatile system.	High-frequency mechanical oscillations developed in a special head transmit resonant vibrations and rotary power through the drill tooling to the drill. High drilling rates are achieved without the need for drilling fluids or air.	Continuous core samples are retrieved. Stratigraphically intact but samples can be undisturbed or disturbed depending on the difficulty of drilling and experience of the driller. Due to the vibrations and repeated cyclic loading, soil and rock samples are likely to be disturbed and may not be suitable for some specialized lab testing.	Sonic drills are successful in permafrost regions. Provides drill penetration through all overburden soil types including cobbles and boulders. Some rigs are capable of push sampling using Shelby tubes, hydraulic piston sampling, and split spoon samples. Waste is reduced by up to 80% relative to conventional methods, reducing the expensive disposal of contaminated waste. Some sonic drills are helitransportable.	Drill system produces substantial; therefore, continuous core samples are often thermally disturbed. Although capable of penetrating boulders and bedrock, this method is slow and expensive. Sonic drilling pulverizes cobbles, rock fragments, and boulders, altering the grain-size distribution of the samples. Caution therefore should be used when assessing gravel size and angularity. For practical purposes, coring capability using the same drill rig is required for bedrock and boulders. Large truck-mounted drills require trail or road and a level platform for drilling. Vibrations make drill rigs susceptible to mechanical problems. Sonic drilling often generates considerable heat, so the water content of recovered samples will likely be less than the formation in situ content.

**Table C.1**  
**Comparison of drilling methods and equipment**  
(pane 4 of 4)

Drill rig	Application	Drilling method	Sampling type & quality	Advantages	Limitations
Heliportable drill rigs	Sites that are only accessible by air, no ground access.	Various drilling methods (auger, diamond drill, sonic drill) may be used provided that the equipment can be transported by helicopter. Helicopters have limited payload capacities, so heliportable drilling equipment must be lightweight and compact. This can restrict the size and capabilities of the drilling rig and the equipment it can carry.	The drilling method dictates and available sampling techniques which influence sample types and sample quality.	Heliportable geotechnical drilling equipment remains a valuable solution for reaching remote or challenging locations where other forms of transportation may be impractical. The decision to use heliportable equipment should be based on a careful assessment of the specific project requirements and constraints.	Setup and teardown time: drilling equipment often requires more time for setup and teardown compared to larger, more stationary rigs. This can impact the overall efficiency of the drilling operation, especially in situations where rapid deployment is crucial. Weather dependence: operations are highly dependent on weather conditions. Adverse weather, such as strong winds or low visibility, can limit the ability to transport drilling equipment to and from remote locations, leading to delays in operations. Reduced drilling speed: might have lower drilling speeds compared to larger rigs due to their smaller size and weight restrictions. Cost considerations: heliportable drilling operations can be expensive due to the cost of helicopter transport. The cost per drilling project may be higher compared to using ground-based equipment, which could impact the overall feasibility of heliportable solutions.
Hand-held/Portable drills	To rapidly and economically advance shallow, small-diameter drill holes without using heavy equipment and within minimal ground disturbance.	Various hand-held/portable drills are available, and the market is always coming up with new ideas. Drills are typically gas powered but some electric and battery-powered equipment options are available. Examples: Window sampler, Backpack coring drill, Talon drill system. Backpack coring drill is gas powered and requires a large heavy battery to run the water pump.	Core fine-grained permafrost to 5 m depth using a 50 mm core system and auger-drill fine-grained permafrost to 7 m depth using the 25 mm auger.	A low-impact, compact, and effective equipment. It is light enough to be carried by one person and make a hole through many different types of permafrost rock, ice and soil. Mobile and versatile equipment.	Drill depths typically less than 5 m but some equipment can advance to 10 m in ideal soil conditions with sufficient length of drill equipment. Disturbed sample recovery does not work well in coarse gravelly ground or soils with a significant unfrozen water content. Drill rods and fasteners tend to fatigue and break. Disadvantages with this drilling method are that in pure ice the core tends to break into smaller segments, slowing drilling, and in warmer permafrost conditions (> -2 °C), the core tends to disintegrate due to the uncemented materials and frictional heat. Depending on the drilling method and location sourcing a water supply or hauling a water tank may be difficult.

**C.4 BOREHOLE DRILLING METHODS FOR BEDROCK**

The strength of intact sedimentary bedrock can increase by as much as 80% from an unfrozen to frozen condition. Fractured and weathered frozen rock masses also have higher strengths in the frozen condition than in an unfrozen condition. Therefore, the presumption of suitable bedrock in permafrost can be risky in all but the weakest of bedrock formations. “Suitable bedrock” should therefore be determined based on good ground temperature measurements, observations made of favourable structure, and sufficient data on unconfined compressive strength based on both indirect and direct measurements. This requires block samples from test pits or undisturbed core samples from diamond drill, or sonic drill methods. Ground temperatures are best determined in bedrock from borehole ground temperature cable installations. Table C.2 lists the drilling equipment that can be used for investigation in bedrock.

**Table C.2**

**Drilling equipment for investigations in bedrock**

<b>Truck- or track-mounted drilling equipments</b>	<b>Comments</b>
Sonic drill	Sample disturbance may be significant; drilling is slow.
Becker drill	Not suitable for sampling.
Rotary drill	Assessment is by feel of drill reported by driller; most rotary drills are converted to diamond drilling.
Diamond drill	Used commonly for high-quality bedrock samples.
Solid-stem	Not adequate for sampling; may probe some weathered rocks.
Hollow-stem	Not adequate for sampling; may probe some weathered rocks.
Excavator with hammer	Feasible although not used commonly for this purpose.
Large auger (Texoma)	Not adequate for sampling; may probe some weathered rocks.
Percussion hammer (seismic or air-track)	Not adequate for coring; may delineate weathered vs. competent bedrock.

**ANNEX D**  
(informative)

**Ground-based geophysical survey methods**  
(Clause 8.4)

Ground-based geophysical surveys, if conducted in the right setting, can offer substantial added value to a drilling/test pit investigation by providing the means to improve interpolation of the ground conditions between boreholes/test pits and by helping to identify subsurface anomalies. Geophysical surveys may be conducted prior to a drilling/test-pit program for guidance purposes.

**NOTE** — Aerial geophysical survey methods are also available and could be used for large linear infrastructure or dams. For buildings, a better resolution is achieved when using ground-based geophysical survey methods.

In a permafrost environment, geophysical surveys are commonly used to establish the presence or absence and the distribution (horizontally and vertically) of permafrost, massive ground ice, ice-rich permafrost and taliks. Geophysical survey methods are also used to measure the physical and mechanical properties of frozen and unfrozen material and other miscellaneous environmental and engineering problems such as location of groundwater flows, voids, and fractures. In a permafrost environment, many physical and mechanical properties are temperature dependent due to the influence of the water component state (frozen or unfrozen). For that reason, analysis of geophysical data requires the geotechnical consultant to have a general understanding of the environmental setting of the site (stratigraphy, and general ground characteristics [gradation, porosity, water content, temperature, salinity, etc.]) otherwise it may lead to erroneous interpretations. Therefore, geophysical surveys generally play a complementary role to drilling and test pit investigations and are rarely used in isolation.

Table D.1 provides an overview of the most important geophysical survey methods, their characteristics and potential applications in permafrost environments. Table D.1 was taken from the document “Advances in Geophysical Methods for Permafrost Investigations”, in *Permafrost and Periglacial Processes*. The document “Geophysics in the Study of Permafrost”, in *Geotechnical and Environmental Geophysics* is another reference that can be consulted for further information.



Source: BGC Engineering.

**Photo D.1 — Electrical resistivity tomography (ERT) survey equipment**



Source: BGC Engineering.

**Photo D.2 — Installation of electrodes for electrical resistivity tomography (ERT) survey**



Source: BGC Engineering.

**Photo D.3 — Ground penetrating radar (GPR) survey equipment – 12.5 MHz antenna**



Source: BGC Engineering.

**Photo D.4 — Ground penetrating radar (GPR) survey equipment – 80 MHz inline antenna**

**Table D.1**  
**Characteristics of geophysical survey methods**  
(pane 1 of 2)

Geophysical survey method	Penetration depth	Data processing	Applications	Comments
Electrical resistivity tomography (ERT)	0.15-0.20 times current electrode spacing (Wenner array).	Software packages available (e.g., RES2DINV).	<ul style="list-style-type: none"> <li>Detecting massive ice, e.g., in rock glaciers, ice-rich frozen till, moraines and other periglacial phenomena.</li> <li>Mapping isolated ice occurrences.</li> <li>Monitoring change of permafrost properties over time, and evolution of the active layer.</li> <li>Mapping frozen ground distribution.</li> <li>Analyzing the ice origin in rock glaciers.</li> <li>Quantifying/comparing ice contents.</li> </ul>	<ul style="list-style-type: none"> <li>Obtaining good electrical contact between the electrodes and the ground is essential. This requires even more care in specific ground types (e.g., till, bedrock, compacted gravel fill or asphalt).</li> <li>Experience in data inversion is needed for data processing.</li> <li>Differentiation between ice, air and specific rock types can sometimes be difficult.</li> <li>ERT is insensitive to manmade electromagnetic noise.</li> </ul>
Capacitively coupled ERT	Depends on instrument geometry and upper layer resistivity. Typical depths of investigation are 10 m to 20 m. Skin depth effects on electromagnetic measurements often determine the practical limit of the depth of investigation in highly conductive areas. The approximation of skin depth is the following: $SD = 500 \sqrt{\frac{\rho}{f}}$ where $SD$ : skin depth, in metres; $\rho$ : resistivity, in ohms; $f$ : frequency, in hertz.	Software packages available (e.g., RES2DINV).	<ul style="list-style-type: none"> <li>Detecting permafrost bodies and taliks in the discontinuous permafrost zone.</li> <li>Monitoring change of permafrost properties over time, and evolution of the active layer.</li> <li>Mapping frozen ground distribution.</li> <li>Quantifying/comparing ice contents.</li> </ul>	<ul style="list-style-type: none"> <li>There is no need for galvanic contact.</li> <li>Method offers rapid deployment and fast data acquisition.</li> <li>Method is suitable for electrical resistivity surveys on roads.</li> <li>Surveys over a terrain characterized by a rugged topography or a dense vegetation may be challenging.</li> <li>Method is best for highly resistive areas.</li> <li>Experience in data inversion is needed for data processing.</li> </ul>
Frequency-domain electromagnetic (FEM) induction mapping	Depends on instrument geometry and frequency (skin depth, often restricted to < 10 m).	Often direct conductivity reading from the instrument.	<ul style="list-style-type: none"> <li>Mapping isolated ground ice occurrences</li> <li>Mapping the boundaries of ice-rich zones and other periglacial phenomena.</li> <li>Mapping horizontal differences in the ALT.</li> <li>Determining the degree of heterogeneity to assess the representativeness of single point measurements.</li> </ul>	<ul style="list-style-type: none"> <li>Equipment is lightweight.</li> <li>Different surface conditions may greatly influence the survey results.</li> <li>Instrument drift may lead to erroneous results due to small measurement values.</li> <li>Data processing is simple.</li> <li>Results can be frequency dependent.</li> <li>Equipment is sensitive to manmade electromagnetic noise (power lines, etc.).</li> </ul>

**Table D.1**  
**Characteristics of geophysical survey methods**  
(pane 2 of 2)

Geophysical survey method	Penetration depth	Data processing	Applications	Comments
Seismic refraction tomography	1/3 to 1/5 of the offset distance (maximum shot-receiver distance); depends also on shot energy and velocity distribution.	First arrival picking; software packages available (e.g., REFLEXW, SeisImager) — some experience needed.	<ul style="list-style-type: none"> <li>Detecting massive ice in ice-rich till, rock glaciers, moraines and other periglacial phenomena.</li> <li>Mapping isolated ice occurrences.</li> <li>Differentiating between ice, air and specific rock types, each exhibiting anomalously high resistivity values.</li> <li>Mapping the ALT.</li> </ul>	<ul style="list-style-type: none"> <li>Number of receivers should be at least twelve, with shots between every receiver or every second receiver location.</li> <li>A sledgehammer can be used as a source for most applications.</li> <li>Geophones are sensitive to weather (wind and rain) and construction activities (drilling and trucking), leading to noisy data sets.</li> <li>Experience in data inversion is needed for data processing.</li> </ul>
Ground penetrating radar (GPR)	Difficult to predict — depends on attenuation and frequency. Typical depths are generally from 2 m-5 m with a frequency of 200 MHz, 5 m-10 m with a frequency of 100 MHz and 10 m-20 m with a frequency of 50 MHz.	Software packages available (e.g., REFLEXW, EKKO_Project) — experience needed.	<ul style="list-style-type: none"> <li>Carrying out stratigraphic investigations.</li> <li>Delineating the boundaries of massive ice in ice-rich till, rock glaciers and other periglacial phenomena (e.g., ice wedges).</li> <li>Mapping ALT.</li> <li>Mapping subglacial topography.</li> <li>Monitoring seasonal hydrothermal changes in glaciers.</li> <li>Mapping ice and snow thickness.</li> </ul>	<ul style="list-style-type: none"> <li>Penetration depth is small in the case of conductive near-surface layers (e.g., fine-grained material, poorly drained terrain, water bodies, etc.).</li> <li>Application is difficult in very heterogeneous media.</li> <li>Survey speeds are fast for ice, snow, and linear infrastructures (e.g., roads and runways).</li> <li>Choice of suitable antenna frequency is important as it will influence the resolution and depth of the survey.</li> <li>The depth scale of the radargram (velocity-depth conversion) is difficult to determine.</li> <li>Experience in data processing is needed.</li> <li>Equipment is sensitive to manmade electromagnetic noise (power lines, etc.) and reflectors above ground (rock wall, cables, etc.).</li> </ul>

**ANNEX E**  
(informative)

**Temperature trumpet curve**  
(Clause 8.5.5.1)

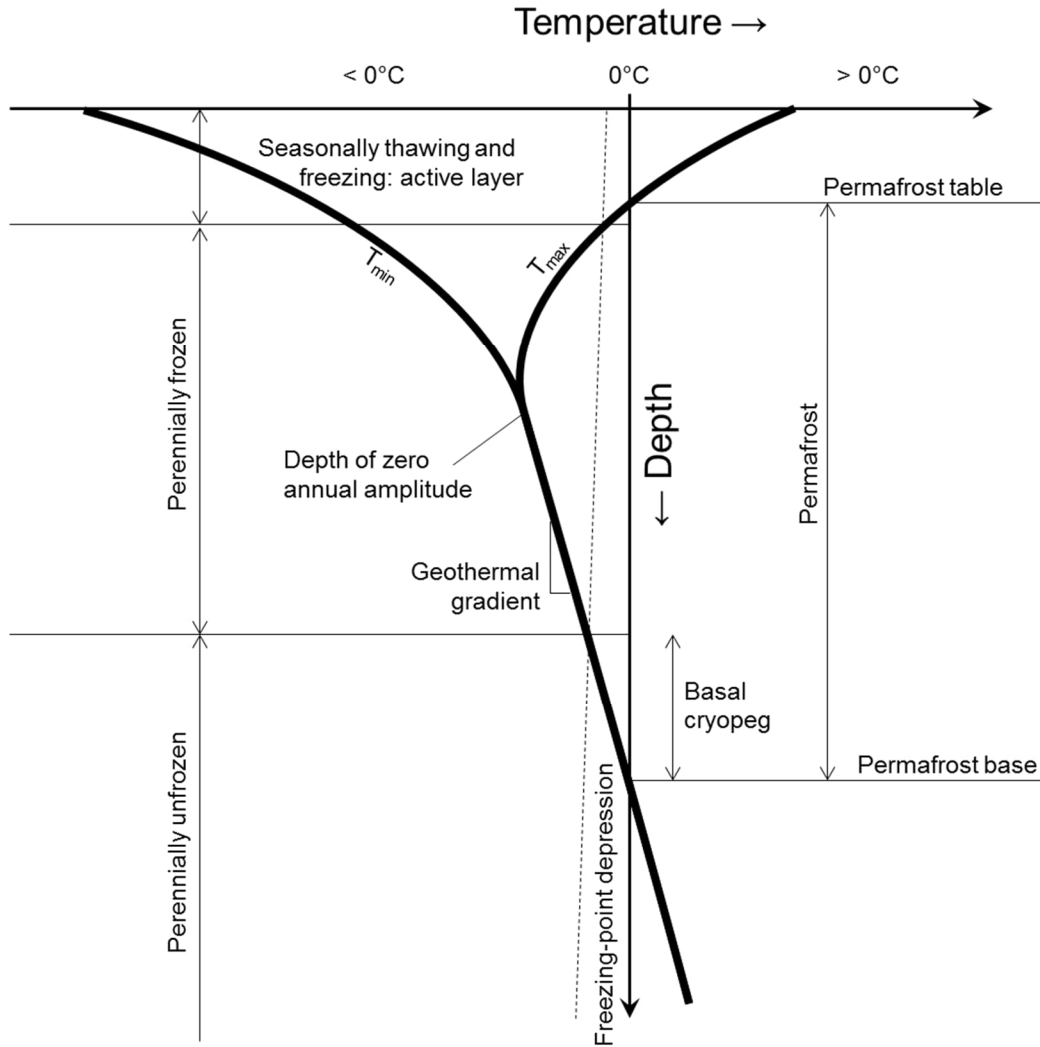


Figure E.1 — Example of a temperature trumpet curve

**ANNEX F**  
(informative)

**Checklist**  
(Clause 5.2 and Annex A)

This checklist, which may be used in combination with the flow chart presented in Annex A, provides a comprehensive guidance on all steps that should be considered as part of a geotechnical site investigation program in permafrost zones. Depending on the climate change-related risk level of the project (A – D), more or less of the elements listed in the checklist may apply.

**GENERAL**

- Scope
- Qualified geotechnical consultant
- Qualified subsurface investigation crew
- Qualified testing laboratory

**PRELIMINARY SITE EVALUATION**

**DESKTOP EVALUATION**

- Initial assessment of climate conditions
- Seismicity
- Surficial geology and geomorphology
- Surface and groundwater hydrology
- Vegetation cover
- Permafrost zones and local distribution
- Permafrost characteristics

**SITE-SPECIFIC FEATURES**

- Building or structure site access and logistics
- Historic land use

- Nearby buildings or structures
- Availability of borrow materials
- Site visit
- Climate change-related risk level of the project
- Preliminary site evaluation report

#### SITE INVESTIGATION

#### DETAILED CLIMATE CHANGE RISK ASSESSMENT AND OTHER ENVIRONMENTAL CONDITIONS

- Climate change projections
- Other environmental conditions
- Remote sensing technologies
- Geophysical surveys

#### PROPERTIES OF THE SOILS

- Stratigraphy and cryostratigraphy
- Ground thermal regime
- Index properties of the soils
- Properties of frozen soils
- Thermal properties

#### PROPERTIES OF THE BEDROCK

- Stratigraphy and cryostratigraphy
- Rock quality designation (RQD)
- Bedrock temperature
- Depth to bedrock
- Compressive strength

- Salinity
- Groundwater Chemistry

#### REPORTING

- Scope
- Climate conditions
- Seismicity
- Surficial geology and geomorphology
- Surface and groundwater hydrology
- Vegetation cover
- Permafrost zones and local distribution
- Site-specific features
- Historic land use
- Nearby buildings or structures

#### SUBSURFACE CONDITIONS

- Summary of the site investigation program
- Subsurface properties
- Field testing, inspections and laboratory tests

#### RECOMMENDATIONS

- Suitability of the building or structure
- Foundation recommendations and alternatives
- Site preparation
- Surface water management
- Construction aspects and schedule
- Limitations of the geotechnical site investigation

**ANNEX G**  
(informative)

**Informative references**

**G.1**      **GENERAL**

The references below are cited for information purposes in this standard.

**G.2**      **DOCUMENTS FROM STANDARDS BODIES**

**BNQ (Bureau de normalisation du Québec)** [<https://www.bnq.qc.ca>]

CAN/BNQ 2501-052      *Soils — Determination of In-Place Density of Soil Using an Elastic Membrane — Washington Type Apparatus.*  
(Sols — Détermination de la masse volumique du sol en place à l'aide d'une membrane élastique — Appareil de type Washington).

CAN/BNQ 2501-054      *Soils — Determination of In-Place Density of Soil Using an Elastic Membrane.*  
(Sols — Détermination de la masse volumique du sol en place à l'aide d'une membrane élastique).

CAN/BNQ 2501-058      *Soils — Determination of In-Place Density of Soil Using a Flexible Membrane (Water Volume).*  
[Sols — Détermination de la masse volumique du sol en place à l'aide d'une membrane flexible (volume d'eau).]

CAN/BNQ 2501-060      *Soils — Determination of In-Place Density of Soil Using the Sand-Cone Method.*  
(Sols — Détermination de la masse volumique du sol en place selon la méthode du cône de sable.)

**ASTM International** [<https://www.astm.org>]

ASTM D1556/D1556M      *Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method.*

ASTM D2166/D2166M      *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.*

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ASTM D3740	<i>Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction.</i>
ASTM D5731	<i>Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications.</i>
ASTM D5918 <sup>1</sup>	<i>Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils.</i>
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<b>CSA Group</b> [ <a href="https://www.csagroup.org">https://www.csagroup.org</a> ]	
CSA S500	<i>Thermosyphon Foundations for Buildings in Permafrost Regions.</i> (Fondations à thermosiphon de bâtiments construits dans des régions pergélisolées.)
CSA S501	<i>Moderating the Effects of Permafrost Degradation on Existing Building Foundations.</i> (Modérer les effets de la dégradation du pergélisol sur les fondations de bâtiments existants.)
CSA S502	<i>Managing Changing Snow Load Risks for Buildings in Canada's North.</i> (Gestion des risques liés aux charges de neige sur les infrastructures du Grand Nord canadien.)
CSA S503	<i>Community Drainage System Planning, Design, and Maintenance in Northern Communities.</i> (Planification, conception et maintenance de systèmes de drainage dans les communautés du Nord.)
CSA PLUS 4011.1	<i>Technical Guide: Design and construction considerations for foundations in permafrost regions.</i> (Guide technique : considérations relatives à la conception et à la construction des fondations dans les régions de pergélisol.)

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1 This document was withdrawn in 2022, and there is no replacement for its content yet.

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**ANNEX H**  
(informative)

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**ANNEX I**  
(informative)

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