NATIONAL STANDARD OF CANADA
CAN/BNQ 2501-500/2017

Geotechnical Site Investigations for Building Foundations in Permafrost Zones
NATIONAL STANDARD OF CANADA
CAN/BNQ 2501-500/2017

Geotechnical Site Investigations for Building Foundations in Permafrost Zones

Études géotechniques pour les fondations de bâtiments construites dans les zones de pergélisol

ICS: 91.080.01; 93.020
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STANDARD
OF CANADA

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BUILDING FOUNDATIONS IN PERMAFROST ZONES
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* At the time of publication of this standard, the aforementioned person no longer worked for this organization.
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GEOTECHNICAL SITE INVESTIGATIONS FOR BUILDING FOUNDATIONS IN PERMAFROST ZONES

INTRODUCTION

Geotechnical site investigations are essential for the appropriate design, construction and maintenance of buildings. 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 the collection of data, and evaluation and reporting of site conditions while accounting for seasonal, and interannual climate conditions as well as the projected climate conditions over the service life of the building foundations. In the long term, it is expected that the application of this standard will help lessen persistent maintenance issues, which, as a result of climate change or improper site evaluation, can cause permanent damage to structures.

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

This standard was developed with the view that the geotechnical site investigation should provide the information that will allow for the design and maintenance of a building within a reasonable timeframe and cost while taking into account the specific constraints of the North and the diverse nature of building projects.
This standard also ensures that each project is carried out within a risk management framework. Each project is assigned a risk level based on the sensitivity of the permafrost to climate change and the consequence of failure of the building foundations. For moderate/high-risk projects, the level of detail of geotechnical site investigations will be much higher than for low/negligible-risk projects. This standard therefore allows for some flexibility throughout the process of carrying out geotechnical site investigations, as the findings will influence the extent of work to be undertaken.

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 proper 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 in a position 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 National Standards of Canada that were developed as part of the Northern Infrastructure Standardization Initiative (NISI) include:

**CAN/CSA-S500 [11]** *Thermosyphon foundations for buildings in permafrost regions.*

**CAN/CSA-S501 [12]** *Moderating the effects of permafrost degradation on existing building foundations.*


**CAN/CSA-S503 [14]** *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 published in 2010 for a better understanding of how climate change may affect Canada’s Northern infrastructure.

* The reference numbers in square brackets indicate documents whose full references are provided in Annex F.
1 PURPOSE

This standard specifies the minimum requirements applicable to the planning, conducting and reporting of geotechnical site investigations for building foundations in permafrost zones.

The purpose of this standard is to define a consistent methodology for performing geotechnical site investigations so that the results can be used to design building foundations with due consideration, in a risk management framework, of the conditions prevailing at the building site, including:

- the distinctive characteristics of permafrost;
- the seasonal and interannual climate conditions as well as the projected climate conditions over the service life of the building foundations;
- the other conditions that may have an impact on the design of the building foundations.

2 SCOPE

This standard applies to geotechnical site investigations performed in permafrost zones to provide essential information for the design of:

- foundations for all types of buildings;
- rehabilitation plans for existing building foundations.

It also applies to the measuring of site-specific conditions in the process of performing geotechnical site investigations. It does not apply to post-construction monitoring of the building site conditions, which is covered in the document CAN/CSA-S501 [12].

NOTE — The principles laid out in this standard are specific to geotechnical site investigations performed to support the design of building foundations. They may apply to other types of infrastructure located in permafrost zones. It is the user’s responsibility to judge the suitability of this document in these cases.

This standard is primarily aimed at geotechnical consultants. It is also intended to be used by the owners of buildings, designers of buildings, contractors and regulators.
3 NORMATIVE REFERENCES

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 document, and are cited in appropriate places in the text.

NOTE — This document also cites informative references that are of a non-mandatory nature. A list of these references is provided in the appendix.

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

3.1 DOCUMENTS FROM STANDARDS BODIES

BNQ (Bureau de normalisation du Québec) [www.bnq.qc.ca]

CAN/BNQ 2501-090  Soils — Determination of Liquid Limit by the Casagrande Apparatus and Determination of Plastic Limit.
(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  Soils — Determination of Liquid Limit by a Fall Cone Penetrometer and Determination of Plastic Limit.
(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  Soils — Determination of Water Content.
(Sols — Détermination de la teneur en eau.)

CAN/BNQ 2501-250  Soils — Determination of the Water Content-Dry Density Relation — Standard Compaction Effort Test (600 kN·m/m³).
[Sols — Détermination de la relation teneur en eau-masse volumique sèche — Essai avec énergie de compactage normale (600 kN·m/m³).]

ASTM International [www.astm.org]

ASTM D698  Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN·m/m³)).


ASTM D4318  

ASTM D4542  
Standard Test Method for Pore Water Extraction and Determination of the Soluble Salt Content of Soils by Refractometer.

ASTM D4611  

ASTM D5520  

ASTM D5918  

ASTM D6032  

ASTM D6913  
Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis.

ASTM D7012  

ASTM D7263  
Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens.

CSA Group [www.csagroup.org]

CSA PLUS 4011  
Technical guide: Infrastructure in permafrost: A guideline for climate change adaptation.

ISO (International Organization for Standardization) [www.iso.org/iso/home.html]

ISO 14689-1  
(Reconnaissance et essais géotechniques — Dénomination, description et classification des roches — Partie 1: Dénomination et description.)
ISO 17892-1  Geotechnical investigation and testing — Laboratory testing of soil — Part 1: Determination of water content.
(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.)

3.2 GOVERNMENT DOCUMENTS


3.3 OTHER DOCUMENT


4 DEFINITIONS

For the purpose of this document, the following definitions shall apply:

**active layer**, n. The top layer of ground that is subject to annual freezing and thawing in permafrost zones. (Reference: CAN/CSA-S501 [12] (adapted wording).) French: *couche active*.

**active layer thickness** (abbrev.: ALT), n. The maximum ground depth of thawing and freezing. French: *épaisseur de la couche active* (abbrev.: ECA).

**air freezing index** (abbrev.: AFI), n. The cumulative number of degree-days below 0°C for the air temperature during a given time period. (Reference: R.O. Van Everdingen, *Multi-language glossary of permafrost and related ground-ice terms* [70].) French: *indice de gel dans l’air* (abbrev.: IGA).
air thawing index (abbrev.: ATI), n. The cumulative number of degree days above 0°C for the air temperature during a given period. (Reference: R.O. Van Everdingen, Multi-language glossary of permafrost and related ground-ice terms [70].) French: indice de dégel dans l'air (abbrev.: IDA).

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


building site, n. The area on which a building stands, which includes the building footprint and its surroundings. French: site.

client, n. The person or the organization and its designated representatives that appoint the geotechnical consultant to carry out the geotechnical site investigation. French: client.

climate normal, n. The mean value of the observed climate variables for a given location over a thirty-year period of consecutive records. French: normale climatique.

NOTE — In the case of air temperature, the climate normal represents the arithmetic means for each month of the year calculated from daily data. For further information, the website of Environment and Climate Change Canada (ECCC) explains the calculation methods of climate normals.

continuous permafrost, n. Ground where more than 90% of the surface is underlain by permafrost. French: pergélisol continu.

cryopeg, n. A layer of unfrozen ground that is perennially cryotic (forming part of the permafrost), in which freezing is prevented by freezing-point depression due to the dissolved-solids content of the pore water. (Reference: National Research Council of Canada, Glossary of permafrost and related ground-ice terms.) French: cryopeg.

cryostratigraphy, n. The study of frozen layers in the Earth’s crust that identifies frozen earth materials based on their cryostructure and cryotexture. French: cryostratigraphie.

cryostructure, n. The structural characteristics of frozen earth materials i.e. the amount, distribution, type and arrangement of ice within the frozen material. (Reference: National Research Council of Canada, Glossary of permafrost and related ground-ice terms, [adapted wording].) French: cryostructure.

cryotexture, n. The textural characteristics of frozen earth materials i.e. the grain and/or ice crystal size and shape as well as the nature of the contacts between frozen ground components. (Reference: National Research Council of Canada, Glossary of permafrost and related ground-ice terms, [adapted wording].) French: cryotexture.

degree-day, n. A measure of the departure of the mean temperature for a day from a given reference (or base) temperature. (Reference: National Research Council of Canada, Glossary of permafrost and related ground-ice terms.) French: degré-jour.
**depth of zero annual amplitude**, n. The depth in the ground at which there is practically no annual fluctuation in ground temperature. (Reference: National Research Council of Canada, *Glossary of permafrost and related ground-ice terms*, [adapted wording].) 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. A professional engineer responsible for the design and preparation and/or issuing of drawings or specifications for a construction project. {Reference: CAN/CSA-S500 [11], (adapted wording).} French: *conceptrice*.

**discontinuous permafrost**, n. Ground where some part of the surface, up to 90%, is underlain by permafrost. French: *pergélisol discontinu*.

**NOTE** — Depending on the scale, several subzones can be distinguished based on the percentage of the land surface underlain by permafrost (i.e. extensive discontinuous [percentage from 50% to 90%], sporadic discontinuous [percentage from 10% to less than 50%] and isolated patches [percentage of less than 10%]).

**disturbed sample**, n. A sample in which the structure of the soil has been changed such that the structural properties are not representative of in-situ conditions, and only properties of the soil particles (e.g., 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** — Building foundations are generally regrouped into two broad categories (shallow or deep) depending on where the loads are transferred in 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*.


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

**NOTE** — The MAAT is available from Environment Canada for specific locations.
mean annual ground temperature (abbrev.: MAGT), n. The mean annual temperature of the ground at a particular depth. (Reference: R.O. Van Everdingen, *Multi-language glossary of permafrost and related ground-ice terms* [70].) 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. The ratio of the surface freezing or thawing index to the air freezing or thawing index. French: *facteur n*.

permafrost, n. Ground (soil or bedrock and included ice and organic material) that remains at or below a temperature of 0°C for at least two consecutive years. (Reference: R.O. Van Everdingen, *Multi-language glossary of permafrost and related ground-ice terms* [70] (adapted wording).) French: *pergélisol*.

permafrost region, n. A region in which the temperature of some or all of the ground below the seasonally freezing and thawing layer remains continuously at or below 0°C for at least two consecutive years. (Reference: R.O. Van Everdingen, *Multi-language glossary of permafrost and related ground-ice terms* [70].) French: *région pergélisolée*.


talik, n. A layer or body of unfrozen ground in a permafrost zone. (Reference: National Research Council of Canada, *Glossary of permafrost and related ground-ice terms* [adapted wording].) French: *talik*.

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

thermosyphon, n. A two-phase passive refrigeration device charged with a working fluid that transfers heat from the ground to the air when appropriate temperature differentials prevail. (Reference: CAN/CSA-S500 [11].) French: *thermosiphon*.

undisturbed sample, n. A sample for which the conditions are close enough to the conditions of the soil in situ and for which the structural properties can be used to approximate the properties of the soil in situ. French: *échantillon non remanié*.
5 PLANNING OF A GEOTECHNICAL SITE INVESTIGATION

5.1 SCOPE

The scope and the limitations of the geotechnical site investigation shall be agreed upon by the geotechnical consultant and the client.

The scope of the geotechnical site investigation shall include provisions for collecting and analyzing the following information related to the building site that will be necessary for the design of the building foundations. The information shall include, as appropriate:

- surface conditions prevailing at the building site, including, but not limited to, the topography, vegetation cover, surficial geology, geomorphological landforms and surface water drainage;
- subsurface conditions, including, but not limited to, the stratigraphy, properties of the overburden and bedrock, active layer thickness and groundwater, presence and characteristics of ground ice, ground thermal regime, and availability of borrow materials;
- climate conditions including the seasonal and interannual climate conditions as well as the projected climate conditions over the service life of the building foundations;
- risks arising from the seismic hazard and the anticipated changes in the building site conditions over the service life of the building foundations.

The scope of the geotechnical site investigation shall also take into consideration the proposed concept of the new building or the description of the existing building for which the foundation rehabilitation plan is required. The information shall include, as appropriate:

- building description: location, size, configuration (number of storeys), above or on ground and a general site plan with the building outline;
- proposed function of the building and its operating conditions (heated or unheated, envelope heat loss assumptions, requirements for personnel and vehicle access, *National Building Code of Canada* from the National Research Council of Canada importance category, etc.);
- magnitude and type of loads, including dynamic loads;
- service life of the proposed building foundations, recognizing that the building components may be retrofitted several times on the original foundations;
- tolerance of building to deformation (total & differential);
• ancillary works (utilities) and structures;
• construction schedule limitations.

The scope and the limitation of the geotechnical site investigation shall be aligned with the client’s intended use of the geotechnical site investigation report.

The scope of the geotechnical site investigation shall comprise at minimum a preliminary site evaluation as specified in Chapter 7. The scope of the geotechnical site investigation may also include a site investigation as specified in Chapter 8 depending on the type and complexity of the building and the conditions prevailing at the building site.

5.2 DEVELOPMENT OF THE GEOTECHNICAL SITE INVESTIGATION PROGRAM

The geotechnical site investigation program shall be subject to the type and complexity of the building, knowledge of the local conditions, time of the year for conducting the investigation, and availability of sampling equipment. A flow chart of the steps to be undertaken (see Annex A) provides, for information purposes, additional guidance on the development of the geotechnical site investigation program.

The level of detail of the geotechnical site investigation and the establishment of foundation recommendations depend 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.

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. The measurement program shall define the parameters that shall be measured as well as the measurement period. It is recommended that consideration be given to integrate portions of the measurement program into a long-term performance-monitoring program for the building.

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 site is located. Geotechnical consultants and the subcontractors that they select for carrying out part of the work shall have the training, experience and expertise relevant to the subject matter and necessary to competently carry out the work in a permafrost environment.
6.2 QUALIFICATIONS OF THE SUBSURFACE INVESTIGATION CREW

The subsurface investigation crew shall use the proper equipment and have proper training, experience and expertise relevant to the subject matter and necessary to competently carry out subsurface investigations in a permafrost environment.

The subsurface investigation work shall be performed under the direction of the geotechnical consultant.

6.3 QUALIFICATIONS OF THE ORGANIZATIONS ENGAGED IN TESTING, ANALYSES, AND/OR INSPECTION

The organizations performing field testing and inspection of frozen and unfrozen soil and bedrock shall use the proper equipment, proper procedures, and staff with the training, experience and expertise that is required to competently carry out the field tests and inspections required by this standard. The field testing and inspection work shall be performed under the direction of the geotechnical consultant.

The organizations performing laboratory testing and analyses on frozen and unfrozen soil and bedrock shall use the proper equipment, proper procedures, and staff with the training, experience and expertise that is required to competently carry out the tests and analyses required by this standard. They shall be selected and supervised by the geotechnical consultant based on their capabilities and experience, as stated in their portfolios.

NOTE — The document ASTM D3740 [7] 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 assemble available information to characterize the geotechnical, hydrological and climate conditions at the building 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 as specified in Clause 7.2. It may include a building site visit as specified in Clause 7.3. It shall also include an assessment of the risk level of the project as specified in Clause 7.4 and a report of the findings as specified in Clause 7.5.

NOTE — For low- and negligible-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 site. This might be the case for projects where direct related experience with the proposed type of building foundations and the conditions prevailing at the building site are available.
7.2  DESKTOP EVALUATION

7.2.1  General

The desktop evaluation shall comprise all the items listed in Clauses 7.2.2 to 7.2.13. It shall include and present existing information pertaining to the physical characteristics and properties of the ground surface and subsurface materials of the building site and nearby properties. It shall also summarize collected 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 building foundations. This work shall establish the need for, and guide the development of the specific requirements of the site investigation program (e.g. drilling, excavation of test pits, and/or geophysical investigation methods; specific laboratory tests and/or instrumentation; level of climate change analysis required; etc.) and assist in interpreting the results of the information obtained from the site investigation.

The desktop evaluation shall be appropriate for the type of building under consideration, including structural design elements such as crawl spaces or slabs on grade, number of storeys and potential foundation options.

NOTE — The building under consideration may be of any type, including large surface areas for light, flexible community housing buildings, heavier government buildings (including schools, health care centres, swimming pools, etc.), and very heavy industrial or municipal structures such as heated slab-on-grade garages, storage facilities, food stores, etc.

Resources and remote sensing technologies that may be used include, but are not limited to: satellite imagery, topographic plans, aerial photographs, LiDAR (Light Detection and Ranging) data, Interferometric Synthetic Aperture Radar (InSAR) data, digital elevation/terrain models, technical and scientific papers, existing surficial geology information, bedrock geology mapping, engineering reports, community development plans, information on the historic land use, spatial databases on ground temperatures, government climate data and models, and permafrost maps. Other information sources that are more indirect indicators of surface and subsurface conditions include: vegetation cover, climate data 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, active layer thickness, 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, the National Energy Board, 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 site for the proposed building project. It shall report climate data and trends for the area and the building site, and shall make a
preliminary assessment of how these conditions may impact the service life of the building foundations.

NOTES —

1 A variety of climate parameters can influence the thermal state of the underlying permafrost and modify its mechanical properties. ECCC and others sources including, but not limited to, provincial and territorial networks, road networks, and mine site data can be used to obtain climate and weather data for regions not covered sufficiently by ECCC climate data.

2 Data from nearby or representative meteorological stations may need to be interpreted if the building 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 thawing and freezing indices (ATI and AFI) — The air thawing index (ATI) and the air freezing index (AFI) 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 and buildings or topography, is a significant factor in permafrost foundation design. Snowdrifts around structures 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 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 — Evaluation of the building site microclimate shall include a general assessment of how local topography and nearby infrastructure may affect 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 building foundations. 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 building foundations under consideration, for the service life of those building foundations, as well as the effect these elements have on the ground thermal regime and permafrost conditions of the building 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 5 of the document CSA PLUS 4011 provides a discussion of global climate models (GCMs) and offers guidance for making screening-stage projections of climate change (Tables 5.2 and 5.3). Annex B provides additional information on climate change projections.

2 Some Canadian government data on climate change projections are available from the Canadian Centre for Climate Modelling and Analysis (CCCma) [15], and the Canadian Climate Data and Scenarios [16] website of ECCC.

7.2.3 Seismicity

The seismic hazard associated with the building site shall be determined in accordance with the National Building Code of Canada from the National Research Council of Canada.

7.2.4 Surficial geology and geomorphology

An analysis of the surficial geology and geomorphology of the building site area shall be performed.

As part of this work, the likely type of overburden, including the organic cover; its characteristics, including thaw sensitivity or frost susceptibility; homogeneity; origin; and previous disturbance, if any, shall be described. The types of bedrock, their origin, the probable expected 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 site, especially those related to ground ice such as, but not limited to, 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 National Research Council of Canada’s Glossary of Permafrost and Related Ground-Ice Terms.

Geomorphological processes that may adversely affect the building site and/or building foundations such as mass movement, retrogressive thaw slides, solifluction, erosion, and avalanches shall be identified.
### 7.2.5 Surface and groundwater hydrology

The surface water drainage and anticipated groundwater conditions at the building site shall be evaluated. The evaluation shall address any physical features at the building site that could adversely impact the building foundations 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 of creeks and nearby 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 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 building foundations, and the grading and drainage around the building.


### 7.2.6 Vegetation cover

In addition to exposure, the vegetation cover at the building site, including the type of shrubs, trees and low ground cover, and the thickness of the vegetative mat, including the thickness of organic soils and coverage percentage, shall be documented as well as historic forest fires.

**NOTES —**

1. Providing shade in summer and affecting the amount and pattern of snow distribution, vegetation has an important influence on permafrost distribution in the discontinuous permafrost zone and on ground temperatures and active layer thicknesses in the continuous permafrost zone.

2. Vegetation type is often representative of soil types, hydrology and the presence of permafrost, in particular in discontinuous permafrost zones.

3. Moss and peat at the ground surface, promoting latent heat absorption by evaporation and ground insulation, critically reduce heat transfer in the summer between the atmosphere and the ground, and strongly influence the thickness of the active layer and ground temperature.

4. At the southern fringe of the discontinuous permafrost zone, isolated patches of permafrost may be found in organic terrain.
7.2.7 Permafrost zone and local distribution

The permafrost zone in which the building site is located shall be determined by referring to the permafrost map of Canada (see the document Canada: Permafrost from Natural Resources Canada). 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 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 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 8.5.4.2), and projections of ground temperatures over the service life of the building foundations require statistical and/or numerical modelling (see Clause 8.5.4.2).

2 The use of an n-factor applied to the MAAT established as specified in Clause 7.2.2.2 may be used to obtain a preliminary estimate of the mean annual ground surface temperature, which can then be used to estimate the MAGT.

3 MAGT at a particular depth can be calculated using borehole temperature monitoring data available from national (i.e. Nordicana D [www.cen.ulaval.ca/nordicanad/en_index.aspx]) and international databases (i.e. Global Terrestrial Network for Permafrost [http://gtnpdatabase.org]).

7.2.8.2 Active layer thickness — The geotechnical consultant shall estimate the expected thickness of the active layer for the year the building is designed and over the service life of the building foundations. 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 active layer thickness, 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 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 Hivon and Sego (1993)[35].

7.2.9 Site-specific features

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

- the site elevation;
- the slope gradient and aspect of the ground surface at the building 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.
- the location of steep slopes;
- the location of snow stockpiles and details of snow management;
- the location and description of adjacent structures, including, but not limited to, buildings, parking lots, roads or utility infrastructure.

7.2.10 Building site access and logistics

If a site investigation is required as specified in Chapter 8, the associated logistics constraints, potential access challenges to the building 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, the ground subsurface and surface backfilling as well as the potential presence of contaminants at the building site shall be documented, if applicable.

The owner shall disclose any historic land use of the building site and provide any environmental site assessment reports.

Recreational use or use as a borrow pits shall also be identified, as well as fill areas such as previous granular pads or stockpiles.
7.2.12 Nearby structures

The geotechnical consultant shall perform an investigation of the foundation types of other buildings and structures in the vicinity of the building site, if available, and how they may relate to the proposed building foundations. The performance of the afore-mentioned foundations, and in particular, any foundation-related issues noted with any existing infrastructure shall be reported.

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 site shall be assessed as they may impact the type of foundations selected for the proposed building.

7.3 BUILDING SITE VISIT

When deemed appropriate by the geotechnical consultant, a building 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 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 complexity, sensitivity to climate change, tolerance of building 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 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 site visit may include interviews with local knowledge holders, the 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 site visit with the site investigation (see Chapter 8). Should it be the case, the timing of the combined building 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

As part of the preliminary site evaluation, the geotechnical consultant shall determine the risk level of the project. The risk level shall be established as specified in the “Stage One: Climate change screening” process presented in Chapter 7 of the document CSA PLUS 4011 using all the information compiled in the preliminary site evaluation. The risk levels are taken from Table 7.1 of the document CSA PLUS 4011:

- D: Negligible-risk project
- C: Low-risk project
- B: Moderate-risk project
- A: High-risk project.

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 REPORT OF THE PRELIMINARY SITE EVALUATION

The findings of the preliminary site evaluation shall be included in a report. This preliminary site evaluation report shall be presented in a way that enables the client to understand the conditions at the building 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:

- Option 1: The findings of the preliminary site evaluation are sufficient to proceed with the design of the foundations for the client’s building concept without a site investigation. The report shall be presented as specified in Chapter 9.

- 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 concept and a site investigation is required, as specified in Chapter 8.

- Option 3: The findings of the preliminary site evaluation are sufficient to recommend alternative building foundations and determine whether a site investigation is required, as specified in Chapter 8.

- Option 4: The findings of the preliminary site evaluation are sufficient to recommend that the current building site is not suitable for the client’s building concept. The report shall include the justifications as specified in Clause 9.13.1.
8 SITE INVESTIGATION

8.1 SITE INVESTIGATION PROGRAM

When a site investigation is required, the site investigation program shall be agreed upon between the geotechnical consultant and the client. It may include some or all of the 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 building site.

The timing of the site investigation 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 site investigation program shall define the number of test pits and boreholes required and their location and depth; the field sampling method, equipment and soil/bedrock sampler to be used; the inspections and tests that shall be performed to establish the soil and bedrock properties; and, if applicable, the remote sensing technologies and the geophysical investigation methods to be used to support the excavation of test pits or the drilling operations.

NOTES —

1 The selection of the appropriate method and equipment depends to a large extent on the experience and judgment of the geotechnical consultant and the results of the preliminary assessment of:
   • the sensitivity of the building site to climate change;
   • the associated risks to the building foundations over their service life.

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 ASSESSMENT OF ENVIRONMENTAL CONDITIONS

8.2.1 Climate change projections

Depending on the risk level of the project, a more detailed assessment of the climate conditions may be required. The results of the tests on the properties of the soils carried out as specified in 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 (projects ranked as A or B as specified in Clause 7.4), 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.

These projected climate conditions should be determined by following the guidelines presented in Annex B. Climate expertise should be used to generate updated regional climate change projections relevant over the service life of the building foundations.
The assessed climate factors shall consist of, at minimum, the mean monthly air temperature and precipitation, the AFI, and the ATI from the year the building is designed to the end of the service life of the building foundations. The geotechnical consultant shall document how they were established.

Mean monthly rainfall and total precipitation shall be considered for surface water management. Air temperature and snow depth shall be considered to assess their effect 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 building foundations 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 Clause 9.12.1. This shall include a description of the methods used and the results obtained.


8.4 GEOPHYSICAL SURVEY METHODS

If used, the results of geophysical surveys shall be recorded in the geotechnical site investigation report as specified in 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

As indicated in Clause 8.2.1, the results of the tests on the properties of the soils may influence the need to carry out further assessment of the impacts of climate change. They may also influence the need for some specific analyses specified in Chapter 8.
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 site should be at least one for every 200 m$^2$ of the building footprint area with a minimum of three boreholes per building site. Additional boreholes shall be drilled if subsurface conditions are highly heterogeneous or particularly complex. Borehole locations shall be chosen based on observed surface features, topography or other specific requirements.

Exploration at the building site shall extend to a depth of 10 m or to a depth at least equal to the minimum width of the building foundations 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 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.


All core and other samples shall be logged as specified in 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* published by the Canadian Geotechnical Society. 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 may be provided based on Murton and French (1994) [54] or Linell and Kaplar (1966) [45].

2 The document ASTM D4083 is based on the document *Guide to the field description of permafrost for engineering purposes* [17], [15].

3 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%).

8.5.4 Ground thermal regime

8.5.4.1 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 active layer thickness.

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 have 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.

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. The graphs shall show:

a) the temperature variation throughout the measurement period;

b) the minimum temperature throughout the measurement period;

c) the maximum temperature throughout the measurement period.

If merited, due to the complexity of the project, a temperature trumpet curve (see Annex E) should be generated from the ground temperature data. When required (e.g. in discontinuous permafrost zones), the base of the permafrost should be determined from the ground temperature curve either through direct reading from the curve, or through inference from extrapolation.

8.5.4.2 Mean annual ground temperature (MAGT) — The ground temperature measurements recorded as specified in Clause 8.5.4.1 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 Clause 8.5.4.1, the MAGT shall be determined at the maximum depth of the borehole.

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 building foundations shall be estimated taking into consideration the climate change projections determined as specified in Clause 8.2.1. The geotechnical consultant shall document how it was established.
8.5.4.3 Thickness of the active layer — The geotechnical consultant shall estimate the thickness of the active layer 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 8.5.4.1. 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 site shall be recorded.

NOTE — Measurements made from late summer to early fall, depending on the location, will determine the thickness of the active layer 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 m² are possible.

2 The post-construction active layer thickness 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 will increase the active layer thickness.

The projected thickness of the active layer over the service life of the building foundations shall be estimated taking into consideration the climate change projections determined as specified in Clause 8.2.1. The geotechnical consultant shall document how it was established.

8.5.5 Index properties of the soils

8.5.5.1 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 Clauses 8.5.5.2 to 8.5.5.8.

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.

8.5.5.2 Water content — Water (moisture) content of the soils shall be determined as specified in the document CAN/BNQ 2501-170, ISO 17892-1 or ASTM D2216.

8.5.5.3 Particle size — Particle size of the soils shall be determined as specified in the document ASTM D6913.
8.5.5.4 Liquid and plastic limits — Liquid and plastic limits of the soils shall be determined as specified in the document CAN/BNQ 2501-090, CAN/BNQ 2501-092 or ASTM D4318.

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

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

8.5.5.7 Density — Density shall be measured in a laboratory as specified in the document ISO 17892-2 or ASTM D7263. Alternatively, density may be measured in-situ as specified in the document CAN/BNQ 2501-052 [1], CAN/BNQ 2501-054 [2], CAN/BNQ 2501-058 [3], CAN/BNQ 2501-060 [4] or ASTM D1556/D1556M [6].

8.5.5.8 Other index properties — The maximum dry density and optimum water content of soils to be used in earthwork shall be established by carrying out a compaction test. The compaction test shall be carried out as specified in the document CAN/BNQ 2501-250 or ASTM D698. Alternatively, the compaction test may be carried out as specified in the document CAN/BNQ 2501-255 [5] or ASTM D7382 [10].

NOTE — The standard effort test of the document ASTM D698 was historically referred to as the *Standard Proctor Test*.

8.5.6 Properties of frozen soils

8.5.6.1 General — The site investigation program shall specify which properties of frozen soils shall be measured or determined as part of the geotechnical site investigation. The site investigation program shall also specify if the properties of frozen soils shall be determined from laboratory or field testing, or if the engineering design parameters shall be derived, based on a risk-informed decision, from correlations published in the literature and the index properties established as specified in Clause 8.5.5.

If the properties of frozen soils are to be measured by laboratory or field testing, this shall be carried out as specified in Clauses 8.5.6.2 to 8.5.6.8 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 while they are shipped 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.
8.5.6.2 Bulk density — Bulk density shall be measured in a laboratory as specified in the document ISO 17892-2 or ASTM D7263.

8.5.6.3 Thaw weakening susceptibility — Thaw weakening susceptibility shall be determined as specified in the document ASTM D5918 if thaw weakening is considered critical for the building by the geotechnical consultant. A minimum of three frozen core samples shall be taken and tested to establish the thaw weakening susceptibility.

8.5.6.4 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 building foundations are considered susceptible to thaw by the geotechnical consultant.

   NOTE — Estimates of thaw strain can be made by using correlations developed by Hanna et al. (1983) [33]. Morgenstern and Nixon (1971) [52] and Morgenstern and Smith (1973) [53] provide further information on thaw consolidation.

8.5.6.5 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 — Patterson and Smith (1981) [57], Smith and Tice (1988) [64], Tice, Anderson and Banin (1976) [69], and Watanabe and Wake (2009) [78] provide useful information on the measurement of unfrozen water content.

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

8.5.6.7 Strength properties — The strength properties of permafrost frozen soils shall be determined as specified in the geotechnical consultant’s recommendations.

   NOTE — Properties are strain rate and temperature dependent.

8.5.6.8 Adfreeze strength — The adfreeze strength properties of permafrost frozen soils shall be determined as specified in the geotechnical consultant’s recommendations.

   NOTE — The adfreeze strength used for the design of building foundations may be calculated as illustrated in Weaver and Morgenstern (1981) [79] or Ladanyi and Thériault (1990) [44].

For final design, subsurface temperature distributions shall be obtained as specified in Clause 8.5.4.1 and the adfreeze strengths calculated along the ground profile as a function of temperature. For preliminary design, the average permafrost temperature may be used to estimate the average adfreeze bond.
8.5.7    Thermal properties

8.5.7.1    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
Clauses 8.5.7.2 to 8.5.7.4.

NOTE — Thermal properties of selected materials can be estimated based on typical values available
from literature {e.g., Kersten (1949) [40]; de Vries (1966) [28]; Alter (1969) [18]; Johnston (1981) [39];
Lunardini (1981) [46]; and Farouki (1981) [31]}. 

8.5.7.2    Thermal conductivity — Thermal conductivity of permafrost soils in their frozen or
unfrozen conditions should be measured as specified in the document ASTM D5334 [8]. 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 Harlan and Nixon
(1978) [34].

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 by Farouki (1981) [31] and Johansen 1975 [38]. 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%.

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

8.5.7.4    Latent heat of fusion — The latent heat of freezing or thawing soils shall be
calculated based on available literature.

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 Clause 8.6.2 and the properties of the bedrock shall be
examined as specified in Clauses 8.6.3 to 8.6.7.

8.6.2    Core sampling

Sampling of bedrock shall be performed by coring the bedrock and securing intact samples. This
should be done with drilling equipment equipped with double- or triple-tube core barrels using
1.5-m-long core runs. If thermally undisturbed samples are required, the drilling operation shall be
accomplished 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 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:

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

8.6.4 Rock quality designation (RQD)

Rock quality designation (RQD) shall be established as specified in the document ISO 14689-1 or ASTM D6032.

8.6.5 Bedrock temperature

The temperature of the bedrock shall be measured in situ as specified in Clause 8.5.4.1.

8.6.6 Depth to bedrock

The depth to bedrock shall be measured and recorded by the geotechnical consultant. Where bedrock is encountered, boreholes shall be advanced deep enough to prove its existence, determine the thickness of the weathered or fractured zone, and assess its competency in both a frozen and thawed condition.

8.6.7 Compressive strength

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

NOTE — When extensive testing or prompt information is required for reconnaissance activities, alternative tests performed as specified in the document ASTM D5731 [9] 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.
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 site conditions.

9.2 SCOPE

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 proposed conceptual design of the building that is under consideration or the description of the building 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, etc.) shall also be documented.

9.3 CLIMATE CONDITIONS

The geotechnical site investigation report shall include a description of the climate conditions influencing the building 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 building foundations. This information shall address the requirements specified in 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 building foundations.

NOTE — Particular emphasis is needed regarding temperature but perhaps even more significantly the impact of changes in precipitation patterns, 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 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 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 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 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 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 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 site. This part of the report shall address the items specified in Clause 7.2.11.

9.11 NEARBY INFRASTRUCTURE

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

9.12 SUBSURFACE CONDITIONS

9.12.1 Summary of the site investigation program

The geotechnical site investigation report shall include a summary of the site investigation program that was executed to characterize the subsurface conditions prevailing at the building site. The summary of the site investigation program shall specify all the methods that were used to assess the subsurface conditions. These methods can include the desktop evaluation (see Clause 7.2), the use of remote sensing technologies (see Clause 8.3), and the use of 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 site and their variability. The report shall specify if the properties were measured by field or laboratory tests, or how the properties were estimated. The level of accuracy and precision of the measurements should 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 building foundations.

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

- the stratigraphy and cryostratigraphy of the soils and bedrock (see Clauses 8.5.3 and 8.6.3);
- the ground thermal regime (see Clauses 7.2.8 and 8.5.4);
- the index properties of the soils (see Clause 8.5.5);
- the properties of the frozen soils (see Clause 8.5.6);
- 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 Clause 8.5.7 shall be included.

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.

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

- 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;
- detailed soil/bedrock stratigraphy determined from recovered samples, visual logging, drilling difficulties/behaviour and drillers’ comments where appropriate;
- sample location and sampling technique including degree of disturbance as well as the field or laboratory tests carried out on each sample;
• drilling methods;
• cryostratigraphy including volumetric ice content;
• instrumentation installed in the borehole, if any;
• groundwater conditions, including characteristics and extent of cryopegs, if present, and the presence of any water inflow including details from where the water is originating or where it was encountered;
• any notes pertaining to instability of the borehole/test pit.

If instruments were installed, the measurements from these instruments shall be included in the report. In particular, ground temperature profiles showing seasonal variation shall be provided, if available. Comments shall be included in the report regarding the stability of the instrument readings. Details on instruments installed, including, but not limited to, sensor manufacturer, calibration, data logger setup, performance, maintenance requirements, and download frequency, shall be included in the report.

9.13 RECOMMENDATIONS

9.13.1 Suitability of the building site

The geotechnical site investigation report shall provide recommendations on the suitability of the building site. If the recommendations are such that the current building site is not suitable for the client’s building concept, the justifications shall be included in the report.

9.13.2 Foundation recommendations and alternatives

The geotechnical site investigation report shall provide recommendations on the type of foundations suitable for the permafrost conditions identified and for the structure criteria of the building. The recommendations for the foundations shall consider the impact of projected climate conditions on the ability of the foundations to support the building throughout the service life of the building foundations. Current status and possible changes in snow drifting/scouring (see Clause 7.2.2.4) shall also be taken into consideration when drawing up recommendations as this can have a significant impact on the thermal behaviour of the supporting foundation soils/bedrock.

The recommendations for the building foundations shall be based on the assessment, characterization, and communication of uncertainty related to the projected ground conditions, which are linked to the uncertainties in the projected climate conditions.

The report may suggest other viable types of building foundations and address the pros and cons of the recommended foundations and foundation alternatives.

In the case of a geotechnical site investigation performed to support the design of a rehabilitation plan for existing building foundations, the report shall provide recommendations to moderate the effect of permafrost degradation on the building foundations.
If the proposed design requires the installation of instruments to monitor the performance of the building foundations over time, it shall be documented in the geotechnical site investigation report. Similarly other monitoring requirements shall be stated (e.g. thermosyphon operation checks, settlement surveys, visual inspections, etc.).

### 9.13.3 Site preparation

When included in the scope, the geotechnical site investigation report shall summarize the required site preparation to construct the building foundations as well as the optimal site preparation schedule considering potential limitation 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 included in the scope, the geotechnical site investigation 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 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 schedules

When included in the scope, the geotechnical site investigation report shall provide comments and guidance on onsite issues that may impact the selection and design of the building foundations, such as: excavation of peat and surface 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 included in the scope, the geotechnical site investigation 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 that the geotechnical site investigation was carried out as well as the impact of the timing on the near surface characteristics observed (e.g. active layer thickness, ground temperatures, water flow in the active layer, surface water flow, and snow cover).
9.15 LIMITATIONS OF THE 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>
<thead>
<tr>
<th>Seasonal Timing</th>
<th>Pros</th>
<th>Cons</th>
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| Spring — early summer | - Frozen ground permits easier drill rig access and better cores in the active layer.  
- Air temperatures are higher, requiring fewer cold temperature interventions.  
- Surface water sources may be available for use during drilling.  
- Evidence of snowdrifts or snowbanks may still be present.  
- Evidence of some periglacial features occurring in winter such as frost blisters or icing are discernible.  
- Surface drainage conditions may be most discernible in spring or early summer.  
- Daylight hours are longer.  
- A building site visit in spring or early summer may provide sufficient time for site investigation later in summer/fall. | - Active layer is not fully thawed to maximum depth.  
- Summer groundwater conditions are not fully developed.  
- Test pits are limited to depth of frost in active layer.  
- Lingering snow cover may conceal topography, vegetation, or other important surface features.  
- Freeshet may impact the site investigation. |
| Mid-summer — autumn  | - Active layer is at or near maximum depth and best suited for test pits and measurement.  
- Surface water and groundwater conditions are most developed.  
- Surface features are easily discernible. | - Softer ground may complicate rig access and is more sensitive to disturbance.  
- Caving or sloughing of the active layer soils may complicate drilling methods.  
- A building site visit in late summer or autumn may not provide sufficient time to develop and execute a site investigation during the same summer. |
| Winter               | - If they are not hidden by snow, periglacial features occurring in winter such as frost blisters or icing are discernible.  
- Snowdrifts are discernible.  
- There is potential of less disturbance to the natural ground surface.  
- Access to drill sites is often easier over snow than across rough tundra.  
- Recovery of frozen undisturbed samples is easier if drilling is proposed.  
- A building site visit in winter can facilitate site investigation in spring and possibly same-year summer construction. | - Limited daylight hours and frigid temperatures reduce efficiency and are hard on equipment.  
- Snow cover conceals micro-topography, vegetation and other surface features.  
- Active layer depth cannot be determined.  
- Surface drainage and groundwater conditions cannot be observed.  
- Finding a source of water for drilling may be more difficult.  
- Delays to work and travel due to weather may greatly increase costs. |

NOTES —
1 The time of year selected for conducting a site investigation may impact on sampling methods and cost.
2 In the western Arctic, access by road in winter or barge in summer may factor into the timing of a site investigation.
3 In the eastern Arctic, the annual sea lift schedule does not allow to mobilize 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.
ANNEX A
(informative)
[non-mandatory]

GEOTECHNICAL SITE INVESTIGATION PROGRAM

Figure A.1 provides some guidelines on the development of the geotechnical site investigation program based on the project risk level (see Clause 7.4). The risk level determines the level of climate change analysis and associated geotechnical investigative measures that are required to adequately characterize the building site.

Continued on next page
FIGURE A.1 — GEOTECHNICAL SITE INVESTIGATION PROGRAM COMPONENTS
ANNEX B
(informative)
[non-mandatory]

CLIMATE CHANGE

B.1 PREAMBLE

Climate change is modifying the ground thermal regime thereby changing the properties of the permafrost. Since this standard covers geotechnical site investigations for building foundations in permafrost zones, it is of the upmost importance that geotechnical consultants have an understanding of climate change and, if required, consult with a climate change expert.

This annex was included in this standard to provide background information regarding the requirements on climate change projections, which are specified in Clauses 7.2.2.6 and 8.2.1.

B.2 INTRODUCTION

Over the past decades, from 1961-2010, the North warmed more than any other region in Canada and more than most regions on Earth. Recent studies show that much of the warming and other changes to climate have occurred since the 1970s, with the most recent climate change models projecting ongoing or accelerating climate changes into the future [23], [19], [50], [56]. The mean annual temperature in the circumpolar Arctic is now more than 1.5°C higher than the 1971-2000 average, and more than double the warming recorded at lower latitudes for the same period [65], [66]. This rapid warming of Arctic regions at more than twice the rate of the global and lower latitude averages highlights an atmosphere-ocean-land feedback process known as Arctic amplification. The Arctic amplification is expected to increase in coming decades, likely bringing changes in atmospheric circulation, vegetation and the carbon cycle that will have substantial impacts both within and well beyond the Arctic [62].

The impacts of climate changes in the Arctic are already resulting in permafrost thawing in some regions, along with decreasing sea ice and changing landscapes. Many studies project that extensive permafrost warming and thawing is likely to occur by the end of this century, with warmer, thinner or disappearing permafrost in the southern discontinuous permafrost zones and a thickening of the active layer and decrease in permafrost thickness in colder permafrost regions [23], [19], [65], [66]. Approximately half of Canada’s permafrost regions are currently underlain by permafrost warmer than -2°C, which will likely disappear under projected climate warming rates [66].

NOTE — For further discussion on the various climate factors of importance to permafrost warming and thawing, see the document CSA PLUS 4011.
B.3 CLIMATE CHANGE TRENDS — AIR TEMPERATURE

Evidence from long-term climate data, together with evidence from near-surface permafrost temperature measurements, melting glaciers, decreasing sea ice and changing landscapes, all show warming in Canada’s North that is unprecedented (at least for the last 400 years) [19]. The Arctic amplification process is now recognized as a characteristic feature of the Earth’s climate system, and has a suite of causes or atmospheric feedback processes operating on different temporal and spatial scales [56], [62]. For example, changes in snow cover and sea ice feedbacks are considered to be fast amplification feedbacks while changes in vegetation and permafrost feedbacks operate more slowly, on timescales of decades to centuries. The slowest amplification feedbacks operate on even longer timescales and are related to changes such as the growth and decay of continental ice sheets. Put together, the magnitude of the Arctic amplification may depend on the extent to which these slow vs. fast feedbacks engage, and whether they are hemispherically uniform or not [62]. Figure B.1 below illustrates some of the feedback and amplification processes while Figure B.2 compares trends in mean annual land temperatures for Arctic circumpolar regions with lower latitude averages.

Since the amplification feedbacks lead to considerable year-to-year and multi-decadal variability, any analyses of northern climate trends or variability will be highly sensitive to the choice of the sub-period chosen. It is critical that climate expertise be consulted whenever extrapolating, detecting and interpreting any climate trends for the Arctic [22].

**FIGURE B.1 — ARCTIC ICE AND LANDSCAPE FEEDBACKS AND THEIR IMPACTS ON SHORT- AND LONG-TERM TEMPERATURE WARMING TRENDS**
B.4 HISTORICAL TRENDS OF MEAN ANNUAL TEMPERATURE

The *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) [37] notes that average annual surface temperatures over the circumpolar Arctic increased by about 1°C during the previous three decades, which is double the global rate [37], [36]. Analyses of the Canadian Arctic indicate average annual surface temperature increases of more than 2°C in many regions since the 1950s, as shown in Figure B.3 [82], [73], [74]. These climate-warming trends have varied seasonally, with greater winter than summer warming. Figure B.4 indicates winter warming rates in many regions of about 4°C. The warming in the western and central Arctic regions since 1950, especially in the fall season, has contributed to statistically significant increases in thaw season duration of 1.2 days/decade [22].

In Canada’s North, the limited number of climate stations with long-term data records makes it difficult to estimate local and regional trends in temperatures, particularly for extremes. Analyses of climate trends are normally based on specialized or homogenized temperature datasets and require professional interpretation of trends, variability and statistical significance.
Key: Grid squares with trends statistically significant at the 5% level are marked with a dot.
The units are degrees Celsius per 65 years.

FIGURE B.3 — TRENDS IN MEAN ANNUAL TEMPERATURE FOR 1948-2012 [74]

Key: Grid squares with trends statistically significant at the 5% level are marked with a dot.
The units are degrees Celsius per 65 years.

FIGURE B.4 — TRENDS IN MEAN TEMPERATURE FOR 1948-2012 FOR WINTER AND SUMMER [74]
B.5 HISTORICAL TRENDS OF EXTREME TEMPERATURE

Similar to mean annual temperature trends, warming of near extreme temperatures (i.e. 1-in-20-year return period levels) over the period from 1961-2010 was more intense and more extensive for winter low temperatures than for summer high temperatures. The mean rate of warming for the 1-in-20-year return period extremes of maximum and minimum temperatures over the 1961-2010 period is estimated to be as high as 6.8°C of warming/century or about 0.7°C/decade for the winter low temperatures and 6.2°C/century for winter high temperature warming [77]. The 1-in-20-year return period summer extremes are also warming but at slower rates, with historical climate datasets indicating warming of 1.7°C/century for summer minimums and maximums [77].

B.6 HISTORICAL TRENDS OF PRECIPITATION

Precipitation trends are more difficult to detect and interpret than temperature trends. The climate-observing network in Canada has changed considerably since the 1990s and will continue to change, with station closures and relocations as ongoing issues [48]. Nonetheless, based on available specialized or adjusted daily precipitation data, trends in mean annual total precipitation over land areas of the Arctic have shown regional increases during the last several decades, as shown in Figure B.5 [48], [59]. The greatest increases are shown for the high Arctic regions, although average annual precipitation amounts are relatively low at these latitudes. Except for the southeastern parts of Yukon, Figure B.6 indicates that the greatest increases in precipitation are in winter, with high Arctic regions showing increases of > 50% since 1950 [74].

Overall, the average period of snow cover has decreased in many Arctic regions due, in part, to higher temperatures. Analysis of in-situ daily snow depth observations shows that the period of snow cover in the North has decreased an average of about 15 days since 1950 with most of the decrease coming from earlier snowmelt [22]. Satellite data also confirm this is part of a pan-Arctic trend towards earlier snowmelt.

There is evidence of increased total winter snowfall across many regions of the Arctic except for southeastern Yukon, as seen in Figures B.6 and B.7, and in the snow-water equivalent, during some winters [48], [74]. One study [22] noted an increase in snowpack weight and snow-water equivalent of about 10 mm/decade as seen in snow survey data north of Yellowknife and around Inuvik. Increasing trends in snowfall amounts and snowfall to rainfall ratio trends north of 55°N are mainly due to increasing precipitation, winter season warming and/or increasing storm frequency.
Key  Grid squares with trends statistically significant at the 5% level are marked with a dot.
The units are % change per 65 years.

FIGURE B.5 —  TRENDS IN ANNUAL TOTAL PRECIPITATION FOR 1948-2012 [74]

Key  Grid squares with trends statistically significant at the 5% level are marked with a dot.
The units are % change per 65 years.

FIGURE B.6 —  TRENDS IN TOTAL PRECIPITATION FOR 1948-2012 FOR WINTER AND SUMMER [74]
Key
Upward and downward pointing triangles indicate positive and negative trends, respectively.
Filled triangles correspond to trends significant at the 5% level.
The size of the triangle is proportional to the magnitude of the trend.

FIGURE B.7 — TRENDS IN WINTER SNOWFALL FOR 1950-2009 [48]

The incidence of freezing precipitation has increased recently across Arctic regions [32], [76], [60]. One study indicated that freezing rain and ice pellets occurred, on average, 3-9 times, and as many as 29 times per year at selected airport locations in Nunavut [60].

B.7 HISTORICAL TRENDS OF STORMS

Some scientific assessments indicate that the Arctic may have become stormier over the past 50 years [36], [49]. For example, Vavrus (2013) [71] found that Arctic winters had been characterized by an increase in the frequency and intensity of cyclones crossing northern waters from Alaska to Iceland, often accompanied by hurricane-like winds. These cyclones are characterized by strong regional drops in sea level pressure.

Wang et al. (2006) [76] also found that winter storm systems or cyclones in the lower Canadian Arctic had become significantly more frequent, longer lasting, and stronger over the last 50 years (1953-2002), but less frequent and weaker in some regions of southern Canada. These findings are consistent with studies indicating that storms from mid-latitudes moved further north in the period from 1950 to 2006 [63], [76], [83], [81]. The regionally increased storm activity has likely also increased temperature fluctuations and incidence of high impact wind events in many regions. Some studies have highlighted increasing wind speeds in Alaska, in the central and eastern Canadian Arctic, and Yukon [47], [75]. Unfortunately, wind station records in the Canadian North are limited in quantity, coverage and quality of data.
A study [71] reported that extreme cyclones in the North may have increased by as many as two to three storms per decade, starting around the 1850s through to 2005, and been accompanied by a simultaneous and significant drop in atmospheric pressure. The changes were noted to be greatest near the Aleutian Islands and Iceland. Figure B.8 highlights the increases in storm frequency and intensity during the cold season for the entire Northern Hemisphere from 60°N-90°N [49].

Key

- The bar for each decade represents the difference from the long-term average.
- Storm frequency and intensity have increased in high latitudes.

**FIGURE B.8 — VARIATION OF WINTER STORM FREQUENCY AND INTENSITY DURING THE COLD SEASON (NOVEMBER-MARCH) FOR HIGH LATITUDES (60°N-90°N) OVER THE PERIOD 1949-2010** [49]

Additional details on documented climate change trends and future temperature and precipitation projections and their uncertainties can be found in Chapter 5 of the document CSA PLUS 4011.

**B.8 CLIMATE CHANGE PROJECTIONS AND THEIR UNCERTAINTIES**

**B.8.1 THE CHANGING CLIMATE AND PERSPECTIVES FOR ENGINEERS**

Recognizing that the climate is changing and will continue to change and impact infrastructure long into the future, the World Federation of Engineering Organizations (WFEO) has unanimously approved the *Model Code of Practice: Principles of Climate Change Adaptation for Engineers* [80]. This Model Code was derived primarily from a guideline prepared by Engineers Canada entitled *Principles of Climate Change Adaptation for Engineers* [30]. Both of these documents inform, provide guidance, and encourage engineers and consulting engineering firms that provide infrastructure planning, design and construction services to be proactive in the management of the...
impacts of a changing climate on engineered systems such as civil infrastructure and buildings. Both documents recognize that historical climate data are becoming less representative of the future climate, and that future climate risks may be significantly underestimated. They highlight that historical climate trends cannot be simply extrapolated into the future as a basis for engineering planning, design, operations, and maintenance of infrastructure.

Given that most engineers will not be experts in climate change, the WFEO Model Code of Practice and the Engineers Canada guideline advocate that they are expected to be aware of the limitations of their professional scope, and access other qualified professionals concerning issues where they may not be fully qualified. Both documents also recognize that access to appropriate information on weather, climate and climate change can be technically demanding and may contain considerable uncertainties. As a result, both documents advocate that engineers and climate and weather specialists should work together to develop the types of climate design data needed to address the engineer’s technical requirements, and that weather and climate specialists are best able to convey a full understanding of the strengths or uncertainties and limitations of the information.

The WFEO Model Code of Practice and the Engineers Canada guideline indicate that the key to understanding future climate conditions is a fundamental knowledge of historical and current climate conditions or baseline climate conditions, which can be augmented with climate change considerations in order to project the risks of future climate change. Engineers can then apply risk management principles and practices to plan and implement adaptation options in order to manage risks and opportunities associated with the current and future climate.

**B.8.2 THE CHANGING CLIMATE AND PROFESSIONAL CLIMATE GUIDANCE**

Much like the changing climate, scientific information and knowledge on climate change is ever changing. Climate change adaptation decisions should be based on the best available information at the time of reporting, which often implies the use of recent climate change assessments, projections and guidance. The *Guidebook on Climate Scenarios: Using Climate Information to Guide Adaptation Research and Decisions* [24] published by Ouranos is a document that can be consulted to help in this regard.

For Arctic regions, it is not recommended that climate trends be extrapolated into the future for periods longer than 10-15 years due to the considerable variability of climate signals, Arctic amplification, and difficulties in selecting appropriate sub-periods for historical trends. Subsequently, for community infrastructure projects with planned service lifespans of building foundations longer than 15 years, climate change projections should be used to help assess future permafrost stability. These climate change projections are mostly derived from global or regional climate models, which give a general tendency and range of expected future changes, but lack the ability to include local details without incurring considerable uncertainties. The climate change projections are based on physical models of the coupled atmosphere-ice-ocean-land system run on supercomputers and predict a range of greenhouse gas (GHG) emissions.

Different climate change models typically provide different climate change projections for a region. The outputs differ among models, even when given similar initial or baseline conditions, model physics and assumptions about future GHG emissions. These differences among models (uncertainties) stem from the natural variability inherent in the climate system, the limitations in the climate community’s ability to model a very complex climate and ocean system, and the many
unknowns about global changes in GHGs and other emissions. These uncertainties do not imply “not knowing”, but refer instead to statistical confidence in the projections of climate conditions. For transparency and scientific reasons, climate scientists tend to highlight their levels of uncertainty to convey how well a projection or climate phenomenon is known (or unknown). Although scientists have gained significant insight into how the climate system functions, they still do not have 100% confidence in their climate change projections — and they never will. Instead, climate change science accounts for the uncertainties in its projections through use of multiple climate change models, which are referred to as a range of plausible projections of climate conditions dependent on future GHG emission assumptions, among other influences.

B.8.3 CLIMATE CHANGE PROJECTIONS

B.8.3.1 Air Temperature

The rate and extent of future climate warming and change are strongly dependent on ongoing and future GHG emission rates. For example, given limited efforts to reduce GHG emissions globally or business-as-usual assumptions (RCP8.5), and using the most recent set of climate model projections, an ensemble of multi-model projections shows an Arctic end-of-century mean annual temperature increase of up to 10°C. The greatest warming is projected for the winter months, with warming up to 16°C by 2100 while summers on average will warm by 6°C. With more aggressive reduction of global GHG emissions (RCP4.5), less warming is projected with a mean annual temperature increase of up to 5°C in the north by the end of this century. Again, the greatest warming is projected to occur in the winter months, with increases of as much as 7°C over land by 2100 in this lower emission scenario. These significant ranges in projected temperature increases demonstrate the heightened sensitivity of the Arctic to GHG emissions [56].

It is possible that the most recent climate change models used by the IPCC in developing climate change projections may be too conservative or slow in their projections for the North. However, there is robust evidence that the downward trend in Arctic summer sea ice extent since 1979 is now reproduced by more of the recent models than with the previous set of climate models (AR4) [36]. About one quarter of the climate models released in 2013 show a trend in sea ice reduction that is as strong as, or stronger than, the trend during the satellite-observations era 1979-2012.

The document CSA PLUS 4011 provides gridded and mapped projections of air temperatures derived from an ensemble of previous generation global climate models (GCMs) that were evaluated and validated for Canada’s North. In particular, Tables 5.2 and 5.3 in the document CSA PLUS 4011 provide a useful starting point for desktop evaluations as required by Clause 7.2.2.6 and may be sufficient for shorter planned infrastructure lifespans (e.g. of up to 15 years) and for projects with low or negligible risk (projects ranked as C or D as specified in Clause 7.4). For high- and moderate-risk projects (projects ranked as A or B as specified in Clause 7.4), more complete details in the projections are needed; the geotechnical consultant should consult with a climate specialist conversant with projections from recent climate change models.
B.8.3.2 Precipitation

There is a growing consensus among scientists that decreasing Arctic sea ice will likely increase Arctic precipitation regionally. Several studies [21], [26], [43], [36] have projected precipitation increases of as much as 50% for Arctic regions by the end of this century for the higher GHG emission assumptions, linked to both warming and sea ice decline. These marked precipitation increases, peaking in late autumn and winter, are among the highest projected globally. Studies have shown that, as sea ice declines, more moisture evaporates from Arctic waters and contributes more heavily to regional precipitation. The increase of Arctic mean precipitation per degree of temperature warming is 4.5%, versus the much smaller global value of 1.6% to 1.9% per degree [21]. The climate research community has not reached a conclusion on whether the increased precipitation would fall as snow or rain. Several studies [41], [27], [67] have indicated that the precipitation increases may create a climate feedback process that is comparable in response to a doubling of global GHGs, adding significant additional uncertainty to climate change models and projections. If the additional precipitation falls as rain, Arctic snow could melt earlier and increase the warming effects of increasing GHGs, but if more falls as snow, an increased albedo in the Arctic would reflect more radiation and slow warming trends. Current trends have shown increases in snowfall accumulations in parts of Canada’s North, but a significantly shorter snow season.
ANNEX C
(informative)
(non-mandatory)

DRILLING AND SAMPLING

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, subsurface investigations using common excavators in cold permafrost ($\leq -2^\circ$C) are ordinarily prohibitively slow unless ground temperatures are just slightly below $0^\circ$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 are 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.
Some of the types of drill rigs that have been used on Arctic and sub-Arctic geotechnical investigations in the past include:

- hand-held drilling equipment
- air-track percussion hammer drill rigs
- auger drill rigs — solid- and hollow-stem drilling
- sonic drill rigs — high frequency vibratory drilling
- 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 [72]. 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. However, 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.

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 rig is shown in Photo C.2.
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 areas 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.
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.
Another small ATV-transportable auger drill rig is shown in Photo C.4.

![Photo C.4 — ATV-TRANSPORTABLE SMALL AUGER DRILL RIG](image1)

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 being considered.

![Photo C.5 — RAT-HOLE AUGER DRILL RIG](image2)
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.

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 sample of frozen fine-grained soil.

PHOTO C.7 — CRREL CORE BARREL AND RECOVERED SAMPLE OF FINE-GRAINED FROZEN 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.
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.
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.

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.3 BOREHOLE DRILLING METHODS FOR SOILS

Table C.1 outlines typical drilling and sampling techniques that can be considered 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:

- the specific objectives of the investigation (stage of design, depth of investigation, and sample requirements);
- the site location and access;
- the expected subsurface conditions;
- 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.
Continued on next page
### TABLE C.1

**COMPARISON OF VARIOUS DRILL RIGS AND METHODS**

<table>
<thead>
<tr>
<th>Drill rig</th>
<th>Application</th>
<th>Drilling Method</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| Rotary drill rigs       | To procure all types of soil and bedrock samples                              | Drill bit on end of power-driven rotating drill rod to which pressure is applied hydraulically | Drilling is relatively rapid  
Most types of materials can be penetrated  
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 core barrel  
Boulders and cobbles can be delineated based on “operator’s feel of drill bit progress” or refusal of drill | These drills are difficult to use in swampy or on rugged terrain  
Truck-mounted drills require trail or road and require a level platform for drilling  
Cuttings are very disturbed and can be difficult to log  
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 the drill bit  
Drill bit wear can be prohibitively expensive  
Drill refusal is possible in competent bedrock  
These drills are generally not suitable for sampling cold, well-bonded frozen soils |
| Continuous-flight auger drill rigs | To drill small to moderate-sized holes for continuous but disturbed samples  
Normally used in cohesive soils with adequate strength to prevent open borehole collapse | Rotating continuous flights of helical augers  
Removal of all flights allows for examination of all soil cuttings | 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  
Some are, or can be reconfigured to be helitransportable | Sampling methods are limited  
Hole collapses when auger is withdrawn from weakly bonded (warm frozen) cohesive or cohesionless granular soils  
Auger samples are disturbed  
Auger advance is slow in well-bonded frozen soils  
Auger refusal is possible in cobbles, boulders, bedrock and dense, well-bonded frozen soils |
### TABLE C.1
(continued)

**COMPARISON OF VARIOUS DRILL RIGS AND METHODS**

<table>
<thead>
<tr>
<th>Drill rig</th>
<th>Application</th>
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<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow-stem auger drill rigs</td>
<td>To drill small to moderate-sized holes for soil sampling</td>
<td>Similar to continuous-flight auger except auger is advanced into ground to act as casing</td>
<td>Method is rapid in weak to moderately strong soils SPT and undisturbed sampling are possible in poorly bonded (warm) frozen soils</td>
<td>Method affords slow progress in most frozen soils 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</td>
</tr>
<tr>
<td>Large-diameter auger drill rigs (bucket, disk, helical, or caisson drill rigs)</td>
<td>To drill large-diameter holes for disturbed samples and soil strata examination in cohesive soils where hole remains open</td>
<td>Rotating large-diameter auger cuts soil to form hole</td>
<td>Method is rapid Close examination of subsurface soil conditions is possible by observing auger cuttings May be possible to adapt to use a CRREL barrel (without using a drilling fluid) or take Shelby tube samples</td>
<td>Depth is limited by groundwater and bedrock conditions Large machine requires easy access to site Method is not suitable in cohesionless soils, soft clays, or organic soils Samples from flights are disturbed Collecting frozen soil samples is difficult Drill refusal is possible in boulders and bedrock</td>
</tr>
<tr>
<td>Hammer drill rigs (including Becker Hammer Drill Rig)</td>
<td>To drill water wells To drill exploratory holes through cobbles and boulders</td>
<td>Diesel pile-driving-type hammer used to drive double-wall casing while circulating air through annulus to blow cuttings from inner barrel</td>
<td>Penetration is relatively rapid through cobbles and boulders Method is well suited to exploratory holes in non-plastic frozen tills Obtaining a relative measure of resistance is possible by recording hammer blows per unit length of penetration</td>
<td>Limitations are similar to those of percussion drills, except progress is much more rapid Progress is very slow in plastic soils Adapting to CRREL barrel is not possible SPT and undisturbed samples are only feasible in warm, fine-grained permafrost</td>
</tr>
</tbody>
</table>
### TABLE C.1  
(continued)

**COMPARISON OF VARIOUS DRILL RIGS AND METHODS**

<table>
<thead>
<tr>
<th>Drill rig</th>
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<th>Drilling Method</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| Pneumatic percussion drill rigs  
(including seismic drill rigs and air-track drill rigs) | To drill holes for bedrock anchors or blasting | Percussion bedrock bit chips and crushes rock with hammer blows as bit rotates; chips removed by air pressure | 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 | Samples are small chips and therefore not ordinarily used for sampling  
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 |
| Diamond drill rigs  
To carry out continuous coring of rock and frozen overburden for geotechnical site investigations | Continuous coring is accomplished by setting one or more casings and advancing 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 | 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 heliportable  
Preservation of ground ice in frozen core is effective  
SPT testing can be conducted | 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 |
### TABLE C.1
(continued)

**COMPARISON OF VARIOUS DRILL RIGS AND METHODS**

<table>
<thead>
<tr>
<th>Drill rig</th>
<th>Application</th>
<th>Drilling Method</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonic drill rigs</td>
<td>To advance cased 150-mm-diameter to 300-mm-diameter holes to depths as great as 150 m using a fast and versatile system</td>
<td>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</td>
<td>Method provides fast drill penetration through all overburden soil types including cobbles and boulders Undisturbed or disturbed but stratigraphically intact continuous core samples are provided Some drill 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 Sonic drills can be used successfully in permafrost regions Some drill rigs are helitransportable</td>
<td>Drill system produces substantial heat if soil and bedrock are encountered; therefore continuous core samples are often thermally disturbed Although capable of penetrating boulders and bedrock, this method is slow and very expensive 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</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Truck- or Track-Mounted Drilling Equipment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonic drill</td>
<td>Sample disturbance may be significant; drilling is slow</td>
</tr>
<tr>
<td>Becker drill</td>
<td>Not suitable for sampling</td>
</tr>
<tr>
<td>Rotary drill</td>
<td>Assessment is by feel of drill reported by driller; most rotary drills are converted to diamond drilling</td>
</tr>
<tr>
<td>Diamond drill</td>
<td>Used commonly for high-quality bedrock samples</td>
</tr>
<tr>
<td>Solid-stem</td>
<td>Not adequate for sampling; may probe some weathered rocks</td>
</tr>
<tr>
<td>Hollow-stem</td>
<td>Not adequate for sampling; may probe some weathered rocks</td>
</tr>
<tr>
<td>Excavator with hammer</td>
<td>Feasible although not used commonly for this purpose</td>
</tr>
<tr>
<td>Large auger (Texoma)</td>
<td>Not adequate for sampling; may probe some weathered rocks</td>
</tr>
<tr>
<td>Percussion hammer (seismic or air-track)</td>
<td>Not adequate for coring; may delineate weathered vs. competent bedrock</td>
</tr>
</tbody>
</table>
ANNEX D  
(informative)  
[non-mandatory]

GROUND-BASED GEOPHYSICAL SURVEY METHODS

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 Kneisel et al. (2008) [42]. Scott, Sellmann and Hunter (1990) [61] is another reference that can be consulted for further information.

Photos of typical resistivity and Ground Penetrating Radar (GPR) survey equipment in use in an Arctic location are shown in Photos D.1 and D.2, respectively.
PHOTO D.1 — RESISTIVITY SURVEY EQUIPMENT

PHOTO D.2 — GROUND PENETRATING RADAR (GPR) SURVEY EQUIPMENT
<table>
<thead>
<tr>
<th>Geophysical Survey Method</th>
<th>Penetration Depth</th>
<th>Data Processing</th>
<th>Applications</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistivity tomography (ERT)</td>
<td>0.15-0.2 times current electrode spacing (Wenner array)</td>
<td>Software packages available (e.g. RES2DINV)</td>
<td>• Detecting massive ice, e.g. in rock glaciers, ice-rich frozen till, moraines and other periglacial phenomena&lt;br&gt;• Mapping isolated ice occurrences&lt;br&gt;• Monitoring change of permafrost properties over time, and evolution of the active layer&lt;br&gt;• Mapping frozen ground distribution&lt;br&gt;• Analysing the ice origin in rock glaciers&lt;br&gt;• Quantifying/comparing ice contents</td>
<td>• 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)&lt;br&gt;• Experience in data inversion is needed for data processing&lt;br&gt;• Differentiation between ice, air and specific rock types can sometimes be difficult&lt;br&gt;• ERT is insensitive to manmade electromagnetic noise</td>
</tr>
</tbody>
</table>

**Table D.1**

**CHARACTERISTICS OF GEOPHYSICAL SURVEY METHODS**
### TABLE D.1
CHARACTERISTICS OF GEOPHYSICAL SURVEY METHODS

<table>
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<tr>
<th>Geophysical Survey Method</th>
<th>Penetration Depth</th>
<th>Data Processing</th>
<th>Applications</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 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: $SD = 500 \frac{\rho}{\sqrt{f}}$ where $SD$: skin depth, in metres $\rho$: resistivity, in ohms $f$: frequency, in hertz. | Software packages available (e.g. RES2DINV) | - Detecting permafrost bodies and taliks in the discontinuous permafrost zone  
- Monitoring change of permafrost properties over time, and evolution of the active layer  
- Mapping frozen ground distribution  
- Quantifying/comparing ice contents | - There is no need for galvanic contact  
- Method offers rapid deployment and fast data acquisition  
- Method is suitable for electrical resistivity surveys on roads  
- Surveys over a terrain characterized by a rugged topography or a dense vegetation may be challenging  
- Method is best for highly resistive areas  
- Experience in data inversion is needed for data processing |
| 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 | - Mapping isolated ground ice occurrences  
- Mapping the boundaries of ice-rich zones and other periglacial phenomena  
- Mapping horizontal differences in the active layer thickness  
- Determining the degree of heterogeneity to assess the representativeness of single point measurements | - Equipment is lightweight  
- Different surface conditions may greatly influence the survey results  
- Instrument drift may lead to erroneous results due to small measurement values  
- Data processing is simple  
- Results can be frequency dependent  
- Equipment is sensitive to manmade electromagnetic noise (power lines, etc.) |
### TABLE D.1  
(continued)

**CHARACTERISTICS OF GEOPHYSICAL SURVEY METHODS**

<table>
<thead>
<tr>
<th>Geophysical Survey Method</th>
<th>Penetration Depth</th>
<th>Data Processing</th>
<th>Applications</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 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 | • Detecting massive ice in ice-rich till, rock glaciers, moraines and other periglacial phenomena  
• Mapping isolated ice occurrences  
• Differentiating between ice, air and specific rock types, each exhibiting anomalously high resistivity values  
• Mapping the active layer thickness | • Number of receivers should be at least twelve, with shots between every receiver or every second receiver location  
• A sledgehammer can be used as a source for most applications  
• Geophones are sensitive to weather (wind and rain) and construction activities (drilling and trucking), leading to noisy data sets  
• Experience in data inversion is needed for data processing |
**TABLE D.1**

**CHARACTERISTICS OF GEOPHYSICAL SURVEY METHODS**

<table>
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<tr>
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<th>Penetration Depth</th>
<th>Data Processing</th>
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<th>Comments</th>
</tr>
</thead>
</table>
| Ground penetrating radar (GPR) | Difficult to predict — depends on attenuation and frequency | Software packages available (e.g. REFLEXW, EKKO_Project) — experience needed | • Carrying out stratigraphic investigations  
  • Delineating the boundaries of massive ice in ice-rich till, rock glaciers and other periglacial phenomena (e.g. ice wedges)  
  • Mapping active layer thickness  
  • Mapping subglacial topography  
  • Monitoring seasonal hydrothermal changes in glaciers  
  • Mapping ice and snow thickness | • Penetration depth is small in the case of conductive near-surface layers (e.g. fine-grained material, poorly drained terrain, water bodies, etc.)  
  • Application is difficult in very heterogeneous media  
  • Survey speeds are fast for ice, snow, and linear infrastructures (e.g. roads and runways)  
  • Choice of suitable antenna frequency is important as it will influence the resolution and depth of the survey  
  • The depth scale of the radargram (velocity-depth conversion) is difficult to determine  
  • Experience in data processing is needed  
  • Equipment is sensitive to manmade electromagnetic noise (power lines, etc.) and reflectors above ground (rock wall, cables, etc.) |
ANNEX E
(informative)
[non-mandatory]

TEMPERATURE TRUMPET CURVE

FIGURE E.1 — EXAMPLE OF A TEMPERATURE TRUMPET CURVE
ANNEX F
(informative)
[non-mandatory]

INFORMATIVE REFERENCES

The references below are cited in this document, but are of a non-mandatory nature.

F.1 DOCUMENTS FROM STANDARDS BODIES

BNQ (Bureau de normalisation du Québec) [www.bnq.qc.ca]

(Sols — Détermination de la masse volumique du sol en place à l’aide d’une membrane élastique — Appareil de type Washington).

[2] 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).

[Sols — Détermination de la masse volumique du sol en place à l’aide d’une membrane flexible (volume d’eau).]

(Sols — Détermination de la masse volumique du sol en place selon la méthode du cône de sable.)

[Sols — Détermination de la relation teneur en eau-masse volumique sèche — Essai avec énergie de compactage modifiée (2700 kN•m/m³).]

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CSA Group [www.csagroup.org]


F.2 GOVERNMENT DOCUMENT


F.3 OTHER DOCUMENTS


[40] KERSTEN, M. S. “Thermal properties of soils”, *Bulletin* 28, Minneapolis (Minnesota), Engineering Experiment Station, University of Minnesota, 1949.


ANNEX G
(informative)
[non-mandatory]

BIBLIOGRAPHY

The references below are helpful in the understanding and application of this document, but are not cited and are of a non-mandatory nature.


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