GEOTECHNICAL SITE INVESTIGATION GUIDELINES FOR BUILDING FOUNDATIONS IN PERMAFROST

Prepared for:

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SUMMARY

A geotechnical site investigation is the process of collecting information and evaluating the conditions of the site for the purpose of designing and constructing the foundation for a structure, such as a building, plant or bridge. A geotechnical site investigation in permafrost regions is more complex than in southern temperate climate regions because:

a) potential presence of ice within the soil or rock whose properties are temperature and salinity dependent;
b) climate change is warming the ground thereby decreasing the strength of the frozen ground and eventually thawing it and
c) the presence of saline soils in coastal areas.

Good planning for and management of a geotechnical site investigation is the key to obtaining sufficient and correct site information for designing a structure in a timely manner and with minimum cost for the effort needed.

The effort and detail of the geotechnical site investigation to obtain sufficient and correct site information to select and design a foundation for a building in permafrost is complex. It depends on:

a) design criteria of the proposed structure;
b) historic knowledge of general site conditions and building performance;
c) drilling equipment availability;
d) time of year the work needs to be done may determine the geotechnical site investigation method and finally;
e) the overall costs.

The collection of geotechnical data and the preparation of a report for a proposed structure should be considered in four phases:

1. Project definition prepared by the owner in conjunction with an architect, if selected. The project definition consists of architectural/engineering foundation criteria such as loading and settlement; on or above ground structure; service life of structure, and proposed design/construction schedule.

2. Preliminary site and project evaluation conducted by the geotechnical consultant selected for the geotechnical site investigation. It consists of preliminary site review of past geotechnical investigations of nearby sites and a selection of likely foundation design(s) based on published literature and the geotechnical consultant knowledge of the site. This preliminary evaluation and a consensus by the owner are used to develop the detail of the proposed geotechnical site investigation.

It will also determine if this phase would be done in one or two steps. In the case of small buildings located on good ground conditions, this phase could be done by means of an office evaluation to be followed by the geotechnical site investigation.

In the case of a major building and possible difficult permafrost, this phase could be done in two steps. It would include a preliminary site visit by a geotechnical engineer with permafrost experience to collect visible data and performance information of existing buildings in order to complete the office phase of the evaluation and discuss the findings with the owner and architect, if selected, to prepare the detailed site program.

3. Geotechnical site investigation (test holes and sampling) and laboratory testing for soils characteristics.

4. Geotechnical report preparation with recommended foundation system options.

The client may consider incorporating peer review in the overall process for projects that are large and/or located in difficult permafrost conditions. This should not be viewed as a confrontational exercise but as an additional resource to develop the best foundation design.

The scope of these guidelines is to plan a geotechnical site investigation in frozen soils, report the results from field exploration and laboratory testing in terms of internationally recognized classification systems, and provide foundation design and construction recommendations that address both the building requirements and climate change.

The planning and execution of geotechnical site investigation for buildings foundations in permafrost is summarized herein.

1. Building Design Concept Definition

The building development project authority, with the assistance of an architect/engineer building design consultant (if one has been selected), needs to outline the proposed building functional concept and its approximate structural requirements. The information that needs to be provided in a RFP and the execution of the geotechnical site investigations is:

Item	Criteria
General plan configuration and footprint of building, m^2	
Single or multi story	
Slab-on-ground, above ground, crawlspace/basement, etc	
Superstructure design and allowable settlement criteria	
Building service life, years	
Other	

2. Terms of Reference

The Geotechnical site investigation Report should contain the following major sections:

- Preliminary site characterization
- Actual field test holes, sampling and laboratory testing.
- Assessment of the information collected and presenting it in recognized formats; such as the ASTM Description and Classification Standards.
- Recommendation of one or more foundation systems that fulfill the project definitions.

These sections are described further as follows:

3. Preliminary Site Characterization (Description)

It is important that before a field investigation program is developed a preliminary site characterization based on published literature and clients and consultants information be prepared. The site characterization should include climate and ground temperature at commissioning of the building and at the end of its service life.

The extent and timing of the preliminary site characterization is a function of the size and settlement sensitivity of the building and the nature of the frozen ground. It can be an office (desk) study based on available information and may include a site visit. For larger and settlement sensitive buildings, it is suggested that a site visit be made during late summer when the ground thaw is at its greatest, when surface drainage and groundwater can be observed and test pits can be excavated at the proposed building site, and at potential construction borrow materials. Test pits during the deepest thaw depth, during August and September, allow a detailed examination of the first 3 m depth that may consist of a stratigraphy of fill, organic and disturbed soil layers respectively and the summer groundwater. This upper zone is frequently a critical zone in the design of the foundation, its excavation and grading plan.

4. Test Holes and Sampling

Equipment availability and the costs of mobilization of the drill equipment for advancing the test holes depends on road access. The four types of test hole advance equipment and their applications are given in the table below.

Equipment	Capability
Backhoe excavator	Test pits in thawed ground during summer
Air-track drill	Frozen ground and bedrock. Provides chips for soil description and water content measurement to assess likely thaw consolidation.
Augers mounted on truck or tracks	Remoulded ground. As above but better quality of samples.
Core drills with cooled drill fluid	Frozen cores. Best samples for visual classification and index and engineering testing.

The most frequently used equipment for test holes in the North are air-track (percussion) drills and augers for drilling and sampling. This equipment is sufficient for the design of most building foundations. For complex large structures it may be prudent to consider core drills that can retrieve frozen soil cores.

5. Test Hole Number and Depth

It is recommended that for small and intermediate buildings all the geotechnical information be collected in one geotechnical site investigation. This can readily be done with a diligent preliminary site characterization.

It is suggested that, depending on the size of the building and the results of the preliminary site characterization, 3 to 5 drill holes be advanced. Two to three of the test holes should be advanced to a depth of about 20 m for several reasons: a) provide information for deeper piles if this type of foundation is found desirable, b) be able to assess the thaw consolidation of the frozen ground below any piles, or other foundation type, should the permafrost thaw, and c) measure the existing frozen ground temperature that is typically constant all year round at a depth generally between 15 and 20 m.

For large structures and complex frozen ground conditions, it may be prudent to plan the geotechnical site investigation in two stages because:

a) first investigation would characterize the site to determine the best suited foundation type and make any adjustments to the building base and

b) second investigation would determine more precisely geotechnical permafrost engineering properties and concentrate the drill hole locations under the critical points of the building.

The advantage of a two stage approach is also beneficial because structural design or the location of the building may change due to the findings from the first investigation.

6. Ground Temperature Measurement

Ground temperature profile shall be measured in 15 to 20 m deep test holes by installing thermistor cables with individual thermistor sensors at progressively greater spacing with depth. Likely location of thermistors could be: 0.5, 1.5, 3.0, 5.0, 7.5, 10, 15 and 20 m depth below ground surface. Thermistor operation shall be checked before installation and then ground temperatures measured: immediately after installation, two days later, and at the completion of the investigation. It would be beneficial to arrange for subsequent thermistors readings to be made on at least a monthly basis for one year.

7. Test Hole Stratigraphic Description and Sampling

It is important that the progress of test holes advance be observed by a geotechnical technologist or engineer with permafrost experience to document soil stratigraphies, their changes, and the presence of ice inclusions.

Samples should be taken at 1.5 m depth intervals and sealed in plastic bags for transport to a laboratory for testing. Disturbed samples are derived from backhoe and air-track and auger drills. Drilling with coring capability will provide frozen cylindrical cores. In this case, cylindrical cores of representative frozen soil conditions shall be secured, wrapped in plastic and aluminum foil, and transported to the laboratory in a frozen state. In addition, representative broken/disturbed samples shall be collected to provide samples at 1.5 m depth intervals for laboratory testing.

8. Laboratory Testing

Laboratory tests to obtain index properties of the frozen ground will suffice in the majority of geotechnical site investigations. The index properties will be obtained by means of: water content, particle size distribution and liquid and plastic limit tests. The number of tests to be conducted should be as follows:

- Water content – on all samples.
- Particle size distribution – 3 to 5 tests from each major soil strata.
- Liquid & plastic limits – 3 to 5 tests from each major soil strata if soil is observed to have plasticity.

Laboratory testing for engineering properties may be required for large buildings on complex frozen ground stratigraphy. The types of engineering tests that may be conducted are thaw consolidation, and less likely, creep strength and thermal properties tests. These are not discussed further because of their infrequency of being conducted.

9. Soil Classifications

All frozen or unfrozen soil strata shall be classified according to ASTM classification systems. The soils should be described by the Soil Group Symbols established by means of laboratory test results.

10. Photographs

The site and the drill equipment in work progress shall be document by photographs. In addition, photographs shall be taken of representative disturbed samples and all frozen soil and rock cores.

11. Report

The report content should follow the report outline given in Section 6.0. The key issues that should be noted shall be:

a) Restate project definition;

b) Characterize the site so that surrounding conditions that may impact on the design and performance of the building foundation are understood and designed for;

c) State the present and the projected end of the building service life, climate and ground temperatures;

d) Classify the soil strata according to recognized ASTM Standards, based on quantitative laboratory results;

e) State the significance of the stratigraphy established by the test hole program, measured ground temperature and the impact of climate warming rate on the recommended building foundation design(s);

f) Identify foundation options appropriate for the proposed service life of the building; and

g) Provide guidance for the construction and construction scheduling of the foundation for the building.

12. Peer Review

The project management team may consider a peer review process by an independent senior geotechnical engineer with permafrost experience for the geotechnical site investigation program and the development of building foundations. The purpose should be to bring in additional technical resources to result in attaining the most suitable building foundation design.

It needs to be reiterated that design of building foundations in permafrost is complex, and it has become more complex by climate change that is warming and even thawing permafrost ground. Furthermore, there are limited case histories on the performance of building foundations under the present permafrost changes. Any additional technical resources for larger or complex projects would likely be beneficial.

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1.0 INTRODUCTION

1.1 General

A geotechnical site investigation is the process of collecting information and evaluating the conditions of the site for the purpose of designing and constructing the foundation for a structure, such as a building, plant or bridge. A geotechnical investigation in permafrost regions is more complex than in southern temperate climate regions because:

a) potential presence of ice within the soil or rock whose properties are temperature and salinity dependent;

b) climate change is warming the ground and thawing the permafrost; and

c) the presence of saline soils in coastal areas.

The following paragraph from Johnston 1981 is worthwhile repeating:

> *The importance of proper selection and investigation of sites and routes in permafrost areas cannot be overemphasized. Reconnaissance and detailed site and route studies must be made, and environmental considerations and the availability of construction materials must be taken into account. Increased costs of construction, operation and maintenance, as well as unsatisfactory performance of engineering structures, inevitably result when there is a lack of information on conditions and other terrain factors.*

In the time since the above observation was made, the impact of climate warming on the stability of permafrost has been identified and has to be addressed in a geotechnical site investigation report. Climate warming includes the ground temperature changes that may occur over the service life of the proposed structure, and foundation design has to be suitable for the final year of the structure.

The impact of climate warming on total service life of structures founded on permafrost has to be considered.

1.2 Scope

The design of a foundation system requires the collection and analysis of the following site related information:

- Physiography and geology plus topography & surface cover
- Climate
- Subsurface conditions
- Ground temperatures
- Hydrology and drainage
- Hydrogeology
- Construction materials

The effort and detail of the site study and the establishment of design recommendations varies depending on: the nature of the site, available historic information, the structure loads and settlement criteria of the proposed building.

The scope of this document (guidelines) is to provide a guide for:

a) planning
b) conducting a geotechnical site investigation
c) preparing a geotechnical site investigation report

Information in this document is grouped into four topics:

a) project planning and management
b) classification systems for soils and permafrost that should be used in a report
c) typical climate parameters and soil/permafrost index and engineering properties
d) geotechnical site investigation report content

To aid in the process of the geotechnical site investigation and preparation of a report, some common methods of soil investigation and sampling are noted, comments and typical values for relevant properties are provided, and classification systems to be used in a geotechnical site investigation report are summarized. The information which should be presented in a report is given and an outline of the geotechnical site investigation report suggested in Section 6.0, “Report Outline”.

1.3 Background

These guidelines are prepared to assist in planning, executing and reporting a geotechnical site investigation for building and infrastructure foundations located in permafrost. The appropriate detail of this process is determined by the magnitude and required performance of the proposed structure, site conditions, foundation type suitable for the structure, timing and costs.

This guideline is based on references given in the report and the writer’s field and design experience. Four main documents that guided the writer are:

- Permafrost, Engineering Design and Construction
  (G.H. Johnston 1981, out of print)
- Arctic and Subarctic Construction Foundations for Structures
  (U.S.A. Department of the Army and the Air Force, October 1983, out of print)
- Canadian Foundation Engineering Manual, 4th Edition
  (Canadian Geotechnical Society 2006)
- ASTM International Standards
  (Individual Standards)

The first two are excellent reference documents on permafrost, design and construction. However, they do not address climate warming that is now or will shortly be influencing the performance of structures in permafrost. Furthermore, these two documents are out of print. The Canadian Foundation Engineering Manual addresses geotechnical site investigations and design of foundations for sites with no permafrost, typically of southern Canada.

The ASTM International Standards provide a framework for describing the ice content in permafrost as observed during the field investigation and a formalized method of classifying the soils encountered. It is suggested the parties preparing and using the site information should obtain at least the first four ASTM Standards given in Section 8.0. Three of these Standards provide procedures prepared for unfrozen soils that are also applicable to frozen soils, and the fourth Standard provides a procedure for describing frozen soils. The remaining Standards given in Section 8 relate to test methods.

This document updates the information on geotechnical site investigation given in Johnston's textbook in regard to the present and future climate. It does not cover in as great detail the material given in that textbook that was prepared with the contribution of 31 experts.[1]

2.0 PLANNING

2.1 Geotechnical Site Investigation Program Overview

Good planning for and management of a geotechnical site investigation program is the key to obtain sufficient and correct site information for designing a building foundation in a timely manner and with minimum cost for the effort needed.

The effort and detail of the geotechnical site investigation program in permafrost is complex. It depends on:

a) design criteria of the proposed building;
b) historic knowledge of general site conditions and performance of existing buildings;
c) drilling equipment availability;
d) time of the year the work needs to be done that may determine the geotechnical site investigation method and costs.

[1] The reader is encouraged to obtain access to "Permafrost Engineering Design and Construction" through inter library load from Aurora College, University of Alberta, and similar technical reference collections, for a comprehensive review of engineering designs and construction in permafrost, before the advent of acknowledged climate warming.

The collection of geotechnical data and the preparation of a report for a proposed structure should be considered in four activities:

1. Project definition prepared by the owner in conjunction with an architect, if selected. The project definition consists of architectural/engineering foundation criteria such as: loading and settlement, on or above ground structure, service life of structure and proposed design/construction schedule.
2. Office study. Preliminary site assessment and selection of likely foundation design(s) based on published literature and knowledge of the geotechnical consultant of the site. This study may include a site visit by a geotechnical engineer with permafrost experience.
3. Geotechnical site investigation (test holes and sampling) and laboratory testing to establish soil characteristics.
4. Geotechnical report preparation.

An outline of a geotechnical site investigation program and the components that should be considered in its development are presented in Table 1. A geotechnical site investigation program consists of a combination of the components shown in the table and depends on the type of structure, knowledge of the local conditions, and availability of exploration equipment.

The effort and detail of the program vary between projects. A desk top study with a follow up site visit by a geotechnical engineer with some test pits during the summer may be sufficient for small structures that can tolerate some settlement and are located in an area with 'cold' permafrost. On the other hand, a multi-level large structure with low settlement tolerance may require rotary core drilling to obtain frozen cylinder soil samples for laboratory testing to determine engineering properties such as: thaw consolidation, creep, and thermal properties (thermal conductivity, heat capacity, and similar physical data.

Good planning and execution of a geotechnical site investigation program must consider four steps described in Section 2.2 that may involve the following major participants:

a) Building developer – who understands the purpose of the proposed building; will pay for the investigation, and construction, and will inherit the maintenance of the structure.
b) Architects & Engineers – who design the building and understand the tolerances of the structure. They also design the site contouring and utilities that may affect the foundation performance over time.

c) A Geotechnical Consultant – who will determine the site characteristics by field investigation and laboratory testing and who recommends one or more foundation types that will satisfy the requirements specified by the Architect and Engineer. The consultant should also address the construction constraints, identify an optimal construction schedule for the excavation, foundation installation and grading, and may provide construction overview/control.

d) Peer Review – on large or performance sensitive structures, the building developer may engage a geotechnical permafrost engineer expert to review and provide advice on the geotechnical program and recommendations.

Table 1. Geotechnical Site Investigation Program Components

Initial Structure Definition

1. Single or multi-story
2. Ground access requirements
3. Settlement sensitivity
4. Service life of building
5. Design & construction schedule

Preliminary Site Evaluation

1. Site characterization
2. Climate and ground temperature
3. Ground stratigraphy & permafrost regime
4. Local precedents & availability
of earth construction materials

Structure Class

A - Low sensitivity	B - Intermediate sensitivity	C - Deformation Sensitive
Small & one story Not highly sensitive to differential settlement	Large plan area Sensitive to differential settlement	Large area & multi-story buildings Sensitive to differential settlement
	Possible site investigation methods	
Test pit during summer Percussion drill (airtrack) Auger drill	Percussion drill Auger drill Rotary drill with frozen cores Diamond drill with frozen core	Rotary drill with frozen cores Diamond drill with frozen core Note: both with cooled fluid
	Frozen soils - sampling	
Disturbed samples	Disturbed chip & grab samples Possibly, undisturbed frozen core	Undisturbed frozen core for laboratory testing as given below
	Laboratory Testing	
Index properties	**Index Properties**	**As in A & B**
Water content, Gradation Atterberg limits Salinity Compaction tests	(as in A) Photographs of cores Lab in-situ density	As in A plus Thaw consolidation Frozen core creep strength
	Bedrock - sampling	
Rock chips	Rock chips & cores	Cores
	Measurements & tests	
None	Core recovery Rock Quality Determination (RQD)	Core recovery Rock Quality Determination (RQD)
	Ground Temperatures	
Thermistor cable(s) installation (short or long term monitoring)	Thermistor cable(s) installation (short or long term monitoring) consider data loggers	Thermistor cable(s) installation with data loggers (Monitor at least monthly for one year or longer)
	Potential other investigation methods	
Not needed	Seismic refraction Electromagnetic terrain conductivity Ground penetrating radar	As in B plus Pressuremeter Electrical resistivity

2.2 Planning Steps

2.2.1 Step 1 – Building Design Concept Definition

The first step in a geotechnical investigation is the concept design of the building by the client and architect/engineer. This information is required for setting the terms of reference for a geotechnical site investigation and enables the geotechnical consultant to understand specifics of the proposed structure. Information that should be addressed is:

- Building description; location, size, configuration (number or stories), above or on ground. And a general site plan with the building outline.
- Magnitude and type of loading
- Service life of proposed building
- Tolerance of building to settlement (total & differential).
- Ancillary works (utilities) and structures
- Schedule limitations

At this stage the building developer and architect/engineer should select a geotechnical consultant to carry out the geotechnical site investigation in two stages;

a) preliminary site evaluation

b) detailed geotechnical site investigation with test holes

The reason for conducting it in two stages is that the first stage may identify more clearly the key geotechnical condition and this in turn may lead to modifying or alternating the proposed foundation type. This could result in adjustment of the drilling and testing program and result in the development of a more effective geotechnical site investigation program.

2.2.2 Step 2 – Preliminary Site and Project Evaluation

The geotechnical consultants should gather available information in the client's domain, the consultant's office, published geological reports and maps to prepare a preliminary assessment of the site and suggest suitable foundation design options for the proposed structure. The amount of information available will vary with site.

The geotechnical consultant shall summarize and assess the following information:

- Surficial soil and bedrock
- Likely site stratigraphy and hydrology
- Climate, design air temperature and likely climate warming rate and mean annual ground temperature and annual thaw depth
- Surface hydrology and hydrogeology that may impact the building foundation
- Availability of granular construction material for foundation base and grading
- Potential foundation options and local precedents, if any

This information could be used to either evaluate the favoured foundation design, and if necessary, advise of alternative design options, or identify a likely foundation design. The results of this summary and discussion with the building developer and architect/engineer will lead to the acceptance of a detailed geotechnical site investigation program.

2.2.3 Step 3 – Geotechnical Site Investigation and Laboratory Testing

The actual geotechnical field investigation is the most critical and costly part of the work. Therefore, it should be based on information prepared in steps 1 and 2 and executed based on information provided in the next chapters. Discussion of this step will be given later in Chapter 4 after the components given in Table 1 are discussed, guidelines provided and typical values given, if applicable. The discussion of the site characterization and investigation are given in Chapter 3.

2.2.4 Step 4 – Analyses and Geotechnical Report Preparation

This step is discussed in Chapter 5.

3.0 GEOTECHNICAL SITE INVESTIGATION COMPONENTS

3.1 General

The following is a discussion of the significance of the geotechnical site investigation components and provides information, guidelines and typical values for these components.

3.2 Site Characterization

Site characterization provides an understanding of the formation of the underlying ground and its likely properties and homogeneity. This work should be done in the preliminary site evaluation (Step 2) since it will guide the development of the geotechnical field site investigation and assist in interpreting the results of the information obtained in the detailed investigation. The information that should be considered in site characterization is given below.

3.2.1 Geomorphology & Bedrock

Geomorphology indicates the process of how the site ground was formed and thereby also likely the type of material, its properties and homogeneity. It is recommended that published information, such as the Geological Survey of Canada reports and maps, air photos, Google Earth and a site visit be used to describe the site as fluvial, lacustrine, solifluction, marine deposits, till, esker, and other geological structures. The major deposition category groups represent unique type of soils and suggest the heterogeneity of the deposits.

The characterization should include the identification of the bedrock types at the immediate site and vicinity, the thickness of soil overburden and presence of rock outcrops in the vicinity. This information is useful for deciding if the structure could be founded on bedrock and identifies granular material that could be obtained from quarries if sand and gravel deposits are scarce or not available.

3.2.2 Terrain

Terrain is the description of the surface features of the immediate site. This may include the slope and orientation of the ground surface, vegetation such as: trees, shrubs, moss and similar plant cover, surface drainage description that includes the presence or proximity of creeks and ponds and rock outcrops. Availability of a topographic map of the site and site photographs is greatly helpful.

The terrain description should include the description of existing and adjacent structures and if the site was previously occupied by a structure(s) that was removed and the ground subsurface and surface backfilled/modified.

3.2.3 Surface Drainage and Groundwater

Surface drainage is present only during the warm part of the year during snow thaw and when it rains. In permafrost the groundwater is normally restricted to the near surface annual thaw zone (active layer) that is normally 1 to 3 m deep in soils. Surface water and groundwater may cause construction problems: erode final grading around the building, flood basements and cause ice lensing and frost heave during the fall freeze up. Therefore, it is necessary to identify these in the investigation so that these features can be considered in the selection and design of the foundation and the grading and drainage around the building.

3.2.4 Seismicity

The majority of the Northwest Territories is in a low seismic risk zone (NRC Atlas) and therefore seismicity has little impact on the design of structures. Seismicity may be of concern in the western region of Northwest Territories that lies in or adjacent to the Rocky Mountains. Comment on seismicity for the particular site in question is prudent in a geotechnical report.

3.2.5 Construction Materials

Type and availability of granular construction material is important in the design of the foundation and site grading and minimizing their cost. Construction materials may be required for concrete, pipe or liner bedding, granular pads, road base and surface course. Even silty or clayey till has its use in applications such as: subgrade for roads and foundations and groundwater control.

The geotechnical consultant should identify sources of the granular and other construction materials, estimate their quantities and establish their properties. Granular construction sources that should be identified are:

a) Granular that may be of greatest demand may have limited availability

b) rock quarries whose blasted rock requires crushing and screening to produce excellent structural granular fill

c) native soils that may be used as general fill or subgrade topped with high quality granular

Native soil may be obtained directly from foundation excavation if the building has a basement or crawl space.

3.2.6 Transportation and Site Access

Access to the site impacts greatly the costs of bringing in construction equipment and materials and the scheduling of construction. The access to sites in the North varies greatly from being remote where access has to be built to having an all season road that connects the site to a large southern community. Other access means may be by ice road, marine transport during the short summer shipping season and by aircraft.

3.3 Climate

3.3.1 Air Temperature

Air temperature is the main factor that determines the presence and future changes of permafrost and it has been observed that the ground temperatures are warmer than the air temperatures in northern Canada. Air temperature is the main factor that determines the presence and future changes of permafrost. An approximate relation between mean annual air temperature (MAAT) and mean annual ground temperature (MAGT) shows the MAGT to be about 4.5°C warmer than the MAAT (Smith & Burgess 2000).

This means that air temperature records can be used to obtain a preliminary estimate of the ground temperature at sites where no ground temperature measurements are available for the design year.

However, the MAAT changes from year to year and has been increasing during the last 200 years. This means that the design MAAT for a new project has to be derived from a linear trend of MAAT records from the nearest meteorological station(s) that has 30 or more years of records.

The development of the MAAT linear trend analysis is illustrated in **Figure 1** using data from Inuvik, NT.

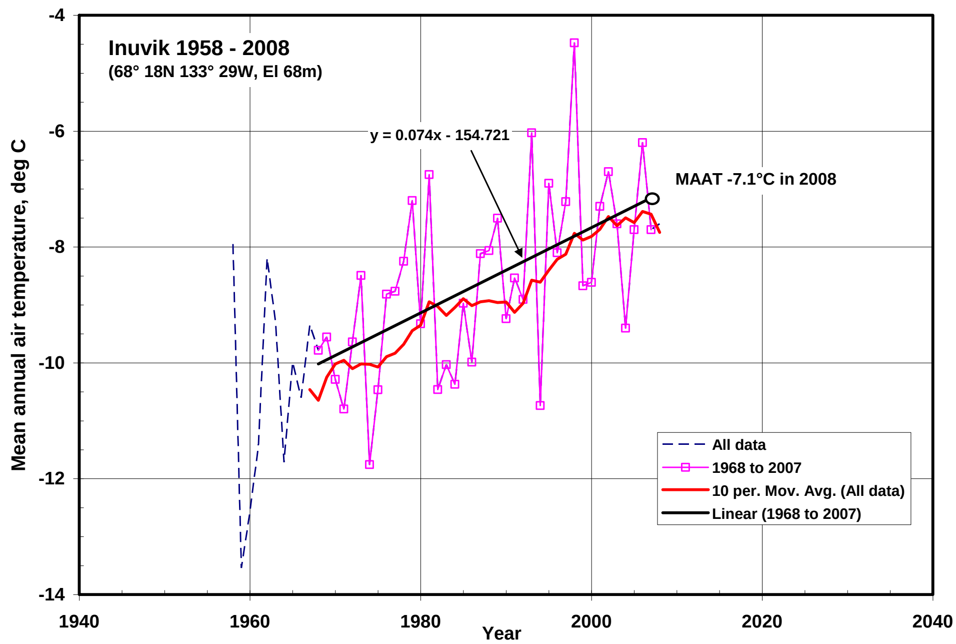


Figure 1 Mean Annual Air Temperatures and Air Temperature Design Values
Inuvik, NT (Data from EC climate office)

The data in **Figure 1** illustrate:

- MAAT air temperatures fluctuate greatly from year to year,
- A linear trend analysis shows a warming rate of 0.74°C per decade (based on 40 year span).
- The linear trend suggests a design MAAT for 2008 to be -7.1°C. It is noted that recent years have recorded a low MAAT of -10.7°C in 1994 and a high MAAT of -4.5°C in 1998.

Historic air temperature data from meteorological stations can be obtained from Environment Canada advanced weather search at:

http://climate.weatheroffice.ec.gc.ca/advanceSearch/searchHistoricData_e.html.

3.3.2 Climate Warming

It is essential that the foundation for the proposed building be designed for the service life of the building. This means that the design of the foundation in permafrost has to consider the ground temperature parameters at the end of the service life of the building that could be about 50 years in the future. Since the ground temperatures will be warming at a similar rate as the air temperatures, the air climate warming rate can be used to estimate the ground temperature at the end of the service life of the structure.

A climate warming rate to be used for the estimation of future air temperatures, and therefore ground temperatures, is still under discussion and will likely continue for some time. A recent report issued by National Resources Canada (2007) suggested that the median climate warming for the western area of the North is about +6.0°C with a high of +12.5°C. from years 1961-1990 to a period 2070-2099; this translate to a climate warming rate of 5.5°C/100 years for a median estimate and 11.4°C/100 for a high estimate.

It is suggested that until newer information becomes available, a warming rate of 0.8°C per decade can be assumed and be used to estimate the likely ground temperature at the end of the service life of a new building. This is also supported by the linear trend line for Inuvik (Figure 1) that shows a warming rate of 0.74°C per decade.

3.3.3 Freezing Index

It is necessary to estimate the freezing index (FI) at the start of the service life of the proposed building for the design of a thermosyphon foundation if it is considered for the proposed building. The freezing index is the cumulative number of *degree-days* below 0°C for a given period. It has been decreasing over the years due to climate warming similar to the mean annual air temperature. This decrease is illustrated with data from Inuvik, NT in Figure 2. This decrease has to be taken into account in the design of thermosyphon foundations that have to perform to the end of the service life of the building that could be 30 to 50 years.

One method to estimate the FI at the end of the service life of the building is to extend the linear trend line of freezing index to the service end year of the building. For example, the FI at Inuvik would change from 3,890 C degree-days in 2010 to 3,030 C degree-days in 2050 over a 40 year period.

Figure 2 shows that the freezing index at Inuvik has been decreasing at about 215°C days per decade.

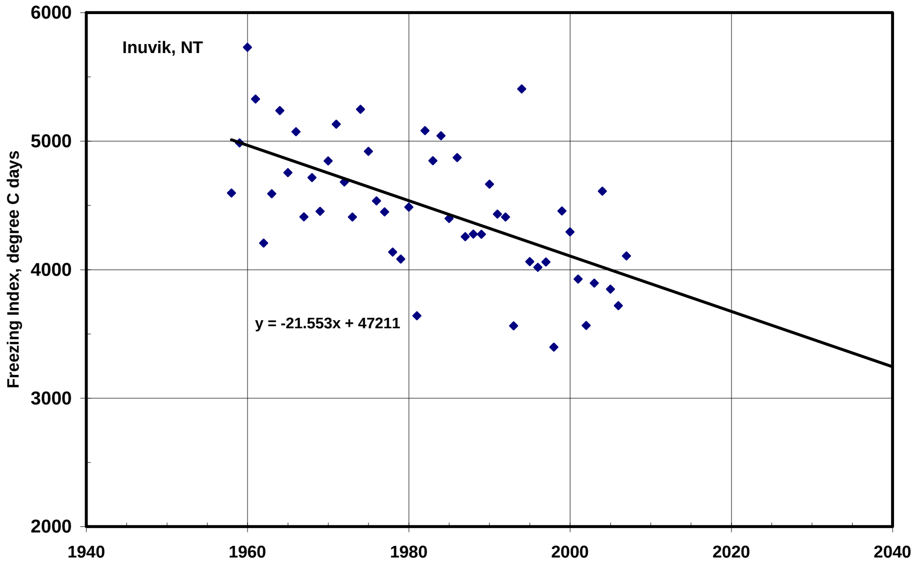


Figure 2 Freezing Index Changes at Inuvik since 1958, NT (Based on EC data)

Example air temperature design data for an assumed building with service life of 40 years completed in Inuvik, NT, in 2008 is given in Table 2.

Table 2 Air and Ground Temperature Data for Inuvik, NT

Parameter	Value in 2008	Value in 2048
MAAT, degrees C	-7.1	-3.1
Standard Deviation, °C	0.8	0.8
Estimated MAGT, C	-2.6	+1.4
Anticipated warming rate per decade, Centigrade Degree (°C)		
Median	0.8	
Maximum	1.0	
Freezing Index, degree C days	3930	3060

3.3.4 Precipitation and Surface Drainage

Precipitation in the permafrost region is relatively low, being generally less than 300 mm per year, and is practically equally distributed between snow and rain. Its impact on building foundation design is the need to control the snow melt water during spring runoff and rainfall runoff during the summer. The geotechnical report should provide the mean annual rainfall and total precipitation for grading guidance. It should be noted that the meteorologists anticipate that precipitation may increase by 15 to 30% in the North (NRC 2007).

The report should also address any physical features of the site that could adversely impact the foundation due to ground and surface water movement during the summer and the grading requirements to control this water flow. Items that should be commented on are: slope and vegetation cover of the site, presence of creeks and nearby ponds; likelihood of a high groundwater table in the active layer during the summer, and any other features noted.

3.4 Ground Temperature and Permafrost

3.4.1 Ground Temperature

The knowledge of the ground temperature (soil and rock) at the time of construction and its estimated value at the end of the service life of a structure is required for the design of foundations at sites with frozen soils with ice content.

The definition of permafrost is a ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years (Everdingen 1998, revised 2002). It is important to note that there are no concerns with founding buildings on rock or coarse sands and gravels with little ice. The design challenges develop in frozen fine grained soils, such as fine sands, silt, clay and a mixture of these soils with ice.

It has to be noted that ice in fine grained soils may start to thaw around -0.5°C, and design criteria for adfreeze piles may require a maximum ground temperature of -2°C. Furthermore, saline soils have a much lower freezing/thawing temperature than 0ºC.

Mean annual ground temperature (MAGT) is used in the design of building foundations. It is not a constant. It varies greatly over the year in the near surface depth, less than 10 m, and increases with depth as given by a gradient illustrated in Figure 3. The thermal gradient was noted to be about 1°C per 54 m depth (Johnston 1981).

The zero ground temperature amplitude observed at a depth of about 15 m suggests that the MAGT can be estimated from a one time ground temperature measurement in a drill hole 15 to 20 m deep drilled any time of the year.

The depth of the annual thaw, active freeze-thaw zone, can be obtained by either measuring the ground temperatures profile on a regular basis over the year or by test pits or holes conducted in mid August when a maximum thaw is normally observed. It has to be noted that the depth of the freeze-thaw zone is very dependent on the vegetation, thickness of organic layer and groundwater during the thaw. Changes to these during site preparation and grading of the site will likely change the depth of the annual thaw. The freeze thaw zone would be deeper if the vegetation and organic layer are removed.

It has to be realized that the MAGT is not constant but has been increasing over the years and will continue to do so due to recent climate warming. The recent changes of the ground temperature can be illustrated from the observations at Inuvik, NT. MAGT in 1961 as reported in Smith & Burgess (2000) was -4.6°C. Ground temperature measurement in 2008 (AMEC 2008) gave a ground temperature of -2.2°C at 20 m that would be representative of the MAGT. However, for a structure to be constructed at the present time, it is necessary to consider the likely ground temperature increase over the service life of the building and the implication on building foundation performance.

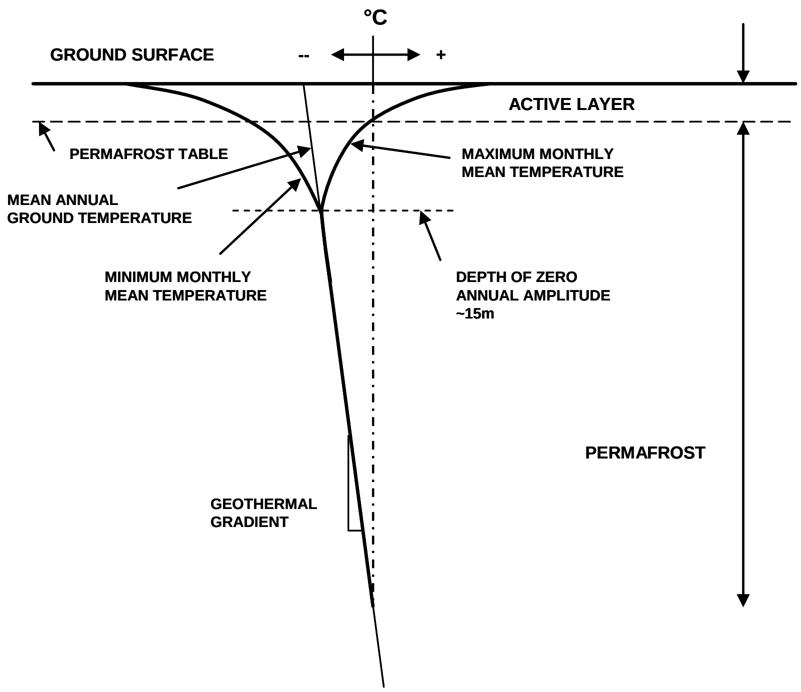


Figure 3 Typical Ground Temperature Regime in Permafrost.

It needs to be noted that as permafrost warms due to climate warming, the ground temperature at about 15 m may temporarily remain constant around -0.3°C to -0.5°C for some 10 years or so because of the latent heat of fusion; especially in ice rich soils.

It is suggested that the design MAGT be estimated as follows:

1) By monitoring the ground temperatures with thermistor cable that is equipped with 7 or more thermistor sensors at increasing spacing with depth to 15 to 20 m. It is suggested that ground temperatures be measured on at least a monthly basis for a year.
2) As above, but reading only for a month, or until the thermal condition recovers from the drilling that will establish the MAGT at about the depth with zero temperature fluctuation.

3) In known cold permafrost, such as locations in western Arctic Islands, the MAGT could be derived from historic measurements and correlation to the MAAT.

The geotechnical site investigation report should provide:

- MAGT for the structure design year and how it was established.
- Likely and high climate warming rates.
- Estimated MAGT value(s) at the end of the service life of the new structure.
- Estimate depth of the active layer for the completed ground beneath and around the structure.

The post-construction active layer depth may differ from the existing undisturbed condition. Shallow active layer depth is observed in areas with thick organic materials underlain by fine grained soils with large water contents. Removal of the organic layer and likely introducing groundwater control during the construction of a building will increase the active layer depth.

3.5 Permafrost

Permafrost is an encompassing term that indicates only that the ground, including soil and rock, is at or below zero degrees Celsius for more than two consecutive years. Therefore, permafrost could be bedrock or low ice content coarse sand and gravel or a frozen fine grained soil, such as a silt or clay with large volume of ice. It would be safe to locate a building on the first two as long as there is no significant ice lensing within these strata. On the other hand, the fine grained soils or mixture of soils with ice require different design approaches to result in competent foundations for the service life of a building.

The main aim of a geotechnical site investigation is to determine the underlying rock/soil stratigraphy and to either establish degree of rock fracturing and ice lensing within the fractures or establish the frozen soil stratigraphy (including ice description), index and engineering properties of the soil and the ground temperatures. The following sections deal with soil permafrost.

For design of building foundations on frozen soil permafrost it is necessary to describe them by a combination of:

a) visual observation of the ice matrix of the frozen soils

b) index properties of the soil in the unfrozen state

c) finally estimate/measure the index parameters of the frozen mass

These are discussed in the following sections:

3.5.1 Frozen Soil Description

Description and classification of frozen soils was developed by the U.S. Army Cold Regions Research & Engineering Laboratory (CRREL) as an extension of the Unified Soil Classification of unfrozen soils (Linell and Kaplar 1966). In these guidelines the frozen soil classification is given first because of the importance of ice within the mineral soil matrix. This frozen soil description/classification was refined with time and finally published as an ASTM International Standard (Designation D 4083 – 89; reapproved in 2007). The classification was developed so that the frozen soils are described in a uniform and concise manner.

In the visual description the frozen soil observations are first grouped into three types, namely:

a) N – frozen soils in which segregated ice is not visible.
b) V – frozen soil in which ice is visible, and
c) Ice
    - The N type of frozen soils in which segregated ice is not visible; it is further described as friable (Nf) and well bonded (Nbn) frozen soils.
    - The V type of soils are subdivided based on the type and volume of visible ice.

Photos in **Figure 4** illustrate a) frozen soil with no visible ice (Nf) and b) frozen soils with distinct ice lenses (Vs). Photos in c) and d) illustrate that even if the frozen soil has no visible ice, it may still have considerable ice volume as is illustrate on the collapse of the frozen soil structure when thawed.

Schematic illustrations of the frozen soil structure for deriving the frozen soil classification are shown in **Figure A1** and the classification is given in **Table A1** in the Appendix.

3.6 Unfrozen Soil Classification and Properties

3.6.1 General

Frozen soils derive their engineering properties from a combination of the soil matrix, bonding of ice, the properties of excess ice once the soil voids are filled, and the ground temperatures since the creep of ice is temperature dependent. Frozen soils with no excess ice behave as unfrozen soils under long-term conditions. However, as the amount of excess ice increases, the ice starts to increase its impact on the creep strength of frozen soils and also increases thaw consolidation upon a thaw of the frozen soil.

The basis of determining the frozen soil properties are the unfrozen soil composition and properties. These are determined by the soil composition as given by the Unified Soil Classification System (ASTM D 2487-06) and index properties of the unfrozen soil.

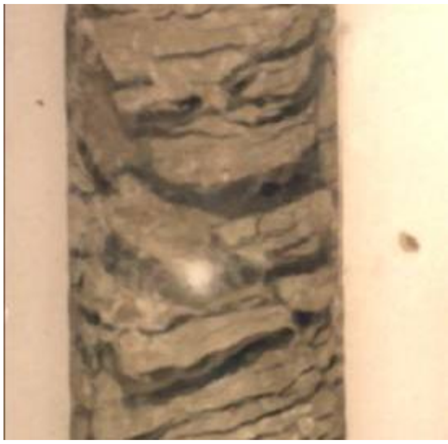
3.6.2 Soil Description and Classification

A soil can be either made up of only one sized particles (uniform gradation) or normally composed of a range of particle sizes that may be classified either as well graded soil consisting of a wide range of particle sizes that progressively fill the voids produced by the larger particles or poorly graded soils that have some sizes missing. The definitions of the major soil components are given in Table 3.

Table 3 Definition of Soil Components and Fractions

Material	Sieve size	
Boulders	Plus 300 mm	Plus 12 in.
Cobbles	75 – 300 mm	3 – 12 in.
Gravel	4.76 – 75 mm	No.4 Sieve – 3 in.
Sand	0.074– 4.76 mm	No. 200 – No. 4 Sieves
Fines (Silts & clays)	Passing 0.0074 mm	Passing No. 200 Sieve

a) Ice poor frozen till core (Nf)



b) Ice rich frozen silt core (Vs)

c) Lump of frozen gravelly silty sand till

d) Gravelly silty sand till when thawed illustrating high water content

Figure 4 Photos Illustrating Visual Ice Content in cores and physical changes of a frozen gravelly silty sand till upon thawing (Photos from Holubec files)

Soils consisting of a range of particle sizes can be assigned into groups that exhibit similar engineering properties. These groups are presented in the Unified Soil Classification System (USCS) that evolved from an Airfield Classification System developed by A. Casagrande in the early 1940's. A modified version has evolved and adopted by the ASTM under Designation D 2487-06.

The USCS provides a prescribed method of grouping soils which exhibit similar behaviour. This system is based on laboratory determination of particle-size characteristics and liquid and plastic index of representative soil samples. A simplified USCS table is given in **Table A1** in the Appendix.

The following illustrates the meaning of the USCS symbols:

- GW – Identifies a well graded gravel (more than 50% particles retained on No.4 sieve) that has less than 5% fines. It represents a good 'structural' material for gravel pads & road sub-base.
- SM – Silty sand with more than 12% fines. This would still be base material for foundations but not as good GW or GP. This material would have low permeability and be frost susceptible.
- ML – Silt, with less than 50% of coarse grained soils. A silt and clay (CL) are distinguished by their plasticity given by liquid and plastic limits measured in the laboratory.

This shows that a group of two symbols identifies the major particle size component, well or poorly graded and the type and percentage of the fines. These parameters determine greatly the engineering properties of the unfrozen soils.

Finally, it has to be stated that the properties/criteria that determine the Group Symbol are determined by two laboratory tests, namely, D 6913 (Test Methods for Particle-Size Distribution and D 4318 (Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils).

3.6.3 Index Properties

Design of foundations or solving geotechnical problems begin with the determination of the soil properties and these can be divided into index and engineering properties. Index properties provide a means to assign the soils into groups with known behaviour and thereby estimate the required design parameters. The simplest and most valuable index properties are: water content, particle size distribution (gradation), liquid and plastic limits if it is judged that the fines exhibit some plasticity. Secondary index properties may be: density, specific gravity and maximum dry density, determined by the Standard Proctor Test and relative dry density values.

Water (Ice) Content

Water content is an indicative and useful property that can be determined economically. In fully saturated soils the water fills all the voids and by its weight, indicated by water content, indicates its likely soil type. Typical water contents for major soil groups are illustrated in **Table 4**.

Typical soil groups	Water Content, range %		Estimate water content
	Minimum	Maximum	for low ice content, %
Well graded gravel, sand & fines	5	25	<11
Silty sand & gravel	5	32	<14
Silty Sand	11	34	<18
Silt	15	37	<22
Sandy or silty clay	9	65	<28
Clay	18	80	<35

Table 4 Water Content Ranges for typical soil groups and limit of water when excess ice may be likely

Note: The above values are typical values to provide guidance in assessing excessive ice in frozen soils from water content determinations. The ranges were obtained from Hough 1957.

For a given soil that is saturated (below the water table), water content value is a good indicator of the soil's likely density and can be used to estimate some engineering properties from published correlations. Finally, water content may also act as an indicator of excess ice by comparing it to published minimum and maximum water content for typical groups of soils as was done in **Table 4**.

Knowledge of excess ice, as given by water content, in frozen soils is important because it greatly influences the engineering properties; such as, thaw consolidation (settlement), creep strength, and thermal properties.

It is recommended that measuring water content from samples should be a dominant part of a geotechnical site investigation, both in unfrozen and frozen soil regions. (ASTM D2216).

Particle Size

Particle size and the distribution of particle size determine many of the engineering properties and also many of the properties of frozen soils. The four variables that influence the behaviour of unfrozen and frozen soils are:

- Coarse or fine grained soils.
- Volume of fines within soil matrix.
- Distribution of the particle sizes; e.g. poorly or well graded, and
- Plasticity of fines.

It is important that particle size analysis tests be conducted on selected samples for the purpose of correctly classifying the soil of major soil zones at a site. (See Section 3.6.2). Furthermore, various measurements from the particle size analyses provide means to estimate engineering properties of the soil. Several particle size distribution test procedures are given by ASTM. The test to be used depends on the type of soil encountered.

Liquid and Plastic Limits

Strength and deformation behaviours of frozen and unfrozen fine grained soils are influenced by their mineralogy. They are grouped into silt and clay soils by their characteristics that are governed by the mineralogy. Liquid and plastic limits tests determine the plasticity of fines particles and thereby allow them to be defined as either silts or clays soils.

It has to be emphasized that a fine grained soil can only be classified correctly as a silt or clay in the Unified Soil Classification System by determining the liquid or plastic limits if the fine grained soils exhibit some plasticity.

Salinity

Saline deposits are common near the Arctic Ocean and have been observed as far as 175 km south of the Beaufort Sea (Hivon & Sego 1991). Saline soils are due to continental and marine deposits affected by sea level changes and sea water saturation (2004).

Soviet investigators (Johnston 1981) define salt content of a frozen soil (salinity) as the ratio of the weight of salts in the soils to the dry weight of the soil (including the salt) expressed as a percentage. They consider a frozen soil to be salty by criteria given in **Table 5**.

Table 5 Saline Soil Criteria (U.S.S.R. 1973)

Soil	Percent of salt
Silty sands	0.05
Fine to coarse and gravelly sands	0.10
Sandy loam	0.15
Clay	0.25

The impact of salinity on the frozen strength of soils is illustrated by **Figure 5**.

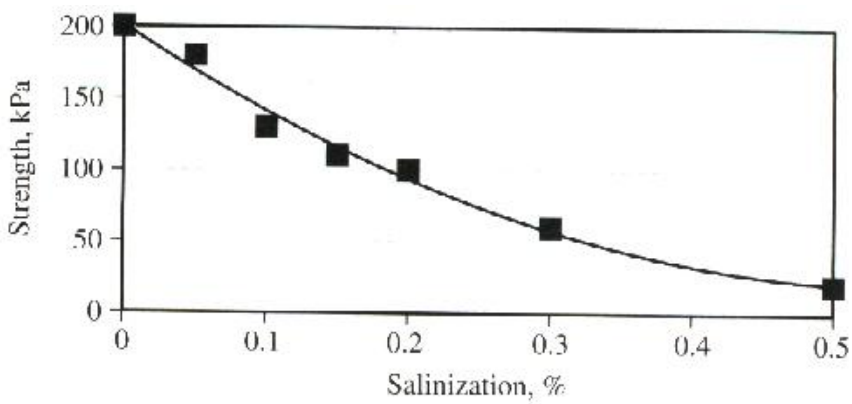


Figure 5 Long-term Strength for Concrete and Marine Sand at -3°C
(Brouchkov 2004)

Other Index Parameters

Other common index parameters that may be determined in the laboratory or estimated are: specific gravity, dry unit weight and maximum dry density.

3.6.4 Engineering Properties and Parameters

Measuring engineering properties by laboratory and/or field testing is complex and costly because of variability of ice lensing aside of changes of soil strata and these properties are dependent on temperature. Since, during the time of laboratory testing, the final long-term ground temperature has not been established, it is normal to conduct the laboratory testing at two temperatures that represent the likely range. Because of the complexity and cost of measuring the engineering properties in the laboratory or in the field, it is common to derive the engineering design parameters from published field and laboratory data using index properties established during the field and laboratory testing.

Some engineering properties and parameters that are used in design or evaluation of foundations and earth structures on permafrost are:

- Thaw consolidation (settlement).
- Creep Strength at design ground temperature and creep rate.
- Adfreeze creep strength at design ground temperatures and creep rate.
- Thermal properties for thermal analyses.

The following are brief descriptions of the these properties and the method of testing.

Thaw Consolidation

Time dependent compression resulting from thawing of frozen ground and subsequent draining of excess water. Thaw consolidation has caused major settlement of early structures built with heated ground floors on soils with excess ice. But, on the long-term, thaw may also be produced due to climate warming. Thaw consolidation is determined in the laboratory by allowing frozen soils cylinders (cores) to thaw. Because ice lensing in frozen soils is heterogeneous, a large number of frozen core samples have to be taken and tested.

Creep Strength of Frozen Soil

Instantaneous strength of frozen ice rich soils is high, but in cases of large loading, (such as end bearing of piles or piers, or large embankments) may result in creep of the ground that may lead to excessive deformation or failure. Creep strength is defined as the failure strength of a frozen soil at a given strain or a given period of time under a constant load. The creep strength is dependent on: soil type, excess ice, temperature and time. The determination of creep strength requires testing of a number of frozen samples subjected to a given load at a given temperature over a long period; in terms of weeks.

Adfreeze (creep) Strength

Adfreeze strength is commonly used in the design of piles for buildings in permafrost. It is defined as the shear strength which has to be overcome to separate two objects that are bonded together by ice (Everdingen 1998). Adfreeze strength is dependent on the ice content of soil, the roughness of the object (pile) it adheres to, and temperature.

Adfreeze strength is only a fraction of the creep strength and depends on the ‘roughness’ of the perimeter surface of the pile. It increases progressively if the roughness of piles is increased by: sand blasting of a steel pile, cutting of openings in pile, welding on protrusions. Determination of adfreeze strength is complex and normally is determined in pile field load tests. In design of pile foundations adfreeze strength is normally estimated from published results of laboratory and field tests.

Thermal Properties of Frozen Ground

The properties of the ground governing the flow of heat through it, and its freezing and thawing conditions (Everdingen 1998). The basic thermal properties of frozen ground are *thermal conductivity*, *heat capacity and latent heat of fusion.*

4.0 DRILLING, SAMPLING AND LABORATORY TESTING

4.1 Drilling Method

Many Northern sites have limited availability of drill equipment and therefore transporting suitable equipment to obtain the ideal samples and field information must be carefully considered in obtaining value for expenditure. It is important to select a geotechnical site investigation that will secure the necessary subsurface information and minimize the need of requiring a follow-up investigation. The selection of the appropriate method and equipment depends to a large extent on the experience and judgment of the geotechnical engineer and the design requirements of the proposed building.

Planning of a geotechnical site investigation at remote sites is a balance between obtaining complete site information and the cost of the drill methods for obtaining it.

Typical geotechnical site investigation methods/equipment and their capabilities/uses are summarized in: **Table 6**.

Some observations on the information given in **Table 6** are:

a) Test pits. Test pits provide the most economical means of obtaining subsurface information. However, they are limited to near surface ground that thaws during the summer; the greatest thaw depth occurring in August/September. They are most frequently used to obtain samples of granular construction material.

   Test pits conducted with excavators may reach depths of 6 m if the permafrost consists of organics, frozen clay and some silts at ground temperature >-2C. Shallow test pits may be sufficient for the structure founded above ground or on thermosyphons foundation.

b) Auger drills. They are very common in temperature climate regions and are used in permafrost areas near larger centers and at sites with road access. Transport by air normally requires Hercules sized aircraft.

   Auger drills with solid stem augers are frequently used in the North to obtain remolded (disturbed) samples from the auger flight. Cylindrical, slightly disturbed samples may be obtained in fine grained soils with ground temperatures at or above -5°C using the split spoon sampler.

Hollow stem auger drills allow sampling or coring of the undisturbed frozen ground through the center of the auger. They are infrequently used in permafrost because coring requires a fluid and coring in permafrost results in great wear of the auger stems.

c) Vibratory (sonic) drill. It’s use is normally limited to unfrozen fine grained soils.

d) Percussion (air-track) drill. This is the most widely used drill in small northern communities with no road access. This drill pneumatically drives a heavy drill bit into the rock/frozen ground and blows cuttings to the surface by compressed air introduced by the hollow steel rods to which the bit is attached.

e) Becker Hammer Drill is a double wall reverse circulation drill with down hole hammer that allows sampling and coring at the base of the casing. It is efficient in coarse gravel, rockfill and permafrost. However, it is a large truck mounted drill that is available only in a few large cities. It is costly to mobilize and therefore it is rarely used in permafrost regions.

f) Core drill. This is a widely available drill in the North because it is used in mineral exploration. It is very suitable for taking undisturbed cores of frozen soil. Normally the coring is done with a double tube N size barrel that produces 54 mm cores. For best results a salt cooled or refrigerated fluid is used to preserve the frozen samples.

Table 6. Typical Equipment and Their Capabilities/uses for foundation geotechnical site investigation in permafrost

Method	Approx Max'm Depth m	Material			Sample Condition				Tests			
		Fine Grained	Coarse Grained	Rock	Thawed	Frozen	Disturbed	Undisturbed	Water Content	Gradation & Plasticity	Engineering Type	Ground Temperature
Test Pits												
Hand excavation	2	X	X	-	X	-	X	-	X	X	-	-
Heavy equipment												
Dozer	4	X	X	-	X	-	X	-	X	X	-	-
Backhoe/excavator	6	X	X		X	X	X	?	X	X	-	-
Drilling												
Auger												
Solid stem	15+	X	X	-	X	X	X	-	X	X	-	X
Hollow stem[B]	15+	X	X	?	X	X	X	X	X	X	?	X
Vibratory[C]	20	X	-	-	X	X	X	?	X	X	?	X
Percussion (air-track)	30+	X	X	X	X	X	X	-	X	X	-	X
Hammer (Becker)	30+	X	X	X	X	X	X	X	X	X	X	X
Core drill – warm fluid	30+	X	X	X	X	X	X	?	X	X	?	X
Core drill – Cool fluid	30+	X	X	X	X	X	X	X	X	X	X	X

From Johnston 1981(Table 5.8, p 204)

4.2 Sampling

Geotechnical site investigation by means of test pits and drilling secures information on the soil and rock stratigraphy by observation of the test pit and drill hole advance and collecting samples for laboratory testing. Visual observation of the progress of the backhoe bucket or the drill rod advance and the disturbed material that comes to the surface allows visual classification of the permafrost strata and sampling location. In uniform strata samples are normally taken at about 1.5 m intervals. However, the location and frequency may be modified when strata changes are observed when engineering sensitive permafrost conditions are encountered; such as high ice concentration, unfrozen zone and similar changes of strata.

The type of samples that may be obtained by the various drill methods are given in **Table 7**. This can be summarized as follows:

Test pits	Disturbed or block samples.
Augers	Disturbed from auger flight or driven penetration samples from base of hole.
Vibratory	Cylindrical samples that may have little disturbance.
Percussion	Continuous frozen soil and ice chips.
Hammer Drill	Continuous frozen soil and ice chip with the ability to obtain driven penetration samples at base of drill rod or core samples.
Core Drill	Continuous soil/rock wash material and the ability to obtain driven penetration samples at base of drill rod or core samples.

Disturbed samples need to be sealed in plastic bags or jars to preserve the water content after the samples thaw. Frozen soil cores have to be preserved in frozen condition.

4.3 Laboratory Testing and Properties

Laboratory testing entails the establishment of index and engineering properties as discussed in Section 3.4. Laboratory testing purpose is to quantify the index properties of the soil and frozen soil encountered and thereby allowing the soils to be classified according to defined rules. Soils named according to standard classification system have the same meaning to engineering and construction professionals and can be used to estimate engineering properties for the design of the foundation.

The design parameters can be obtained either by employing the index properties and published correlations of these to engineering properties in journals and textbooks or by measuring the engineering properties directly. However, even if the engineering properties are measured directly, it is necessary to compare these to the published engineering properties. To do this latter, it is necessary to relate the measured and published information by the measured index properties.

4.4 Bedrock

Establishing bedrock for foundation selection or design in permafrost is done for the purpose of confirming that bedrock surface, and not a large boulder was encountered, designing of the depth of penetration of a grouted pile in bedrock, or basing the pile design for end bearing. Normal practice in the investigation of bedrock is to core the bedrock and secure intact core samples. This is done with 1.5 m long single or double tube barrels; double tube core barrels are the preferred barrels (they minimize the disturbance of fractured bedrock cores).

The cores are described by rock types, fracture frequency, orientation and inclusions. The quality of the intact rock is given by *recovery ratio* defined as the percentage of the length of the core recovered and the length of the core drilled on a given run and the *Rock Quality Designation* (RQD) which is expressed in percentage as total length of intact rock pieces of core length greater than 100 mm divided by the total length of drill run. Breakages caused by drilling are ignored.

Rock quality description based on RQD is given in Table R8.

Table 7 Relation of RQD and *In-Situ* Rock Quality (Peck et al 1974)

RQD, %	Rock Quality
90 – 100	Excellent
75 – 90	Good
50 – 75	Fair
25 – 50	Poor
0 – 25	Very Poor

However, it has to be noted that foundation geotechnical site investigation for small structures often use air-track drills that do not allow coring of rock. In this case, it is possible to deduce major soil and rock strata and presence of ice lenses from observations of the drill rod advance during drilling, and collecting soil particles and rock chips for further analyses. Water content and particle size analysis laboratory tests permit some estimate of the possible excess ice and soil classification of the unfrozen soil particles.

5.0 FIELD & LABORATORY PROGRAM

5.1 General

Field investigation programs for building foundation design in permafrost obviously depend on a large number of variables including: size and complexity of structure, physiography of the site and existing site information, present and anticipated ground temperatures at the end of the service life of the structure, availability of test/drill equipment and project schedule.

A good and efficient program depends greatly on the work done in project definition and preliminary site and building project evaluation discussed in Chapter 2, and the experience of the geotechnical consultant. The following provides some guidelines for the field and laboratory work.

5.2 Test Pits and Drilling

The selection of the field program should be based first on the design requirement of the proposed structure, the degree of knowledge of the physiographic conditions, and the availability of drill equipment. The range of field exploration programs includes:

- Test Pits – Most frequently used to sample borrow sources but could also be considered for small buildings to be supported on foundations that will maintain frozen ground and where good information is available on the local ground, and foundation performance for similar buildings.
- Air-track – Most common drill equipment in northern remote areas. It provides frozen ground and rock chips for the field geotechnical engineer or technologist to estimate the likely ground stratigraphy. Visual classification is approximate and only major strata changes, such as, organics, ice and bedrock distinctly identified. Water content from thawed samples provides a good indication of soil type and ice content.
- Auger Drill – Auger drill provides continuous remolded material on the auger wall and allows drive samples at the bottom of the hole if the soil is fine grained and the ground temperature is above -5°C. Grab samples from the auger spiral allow improved visual classification of the soil and more representative grab samples for laboratory testing; as compared to air-track samples.
- Rotary and Diamond Drills – Provide the best quality of undisturbed frozen samples that allow visual observation of ice presence and distribution that can be used to conduct laboratory testing to establish engineering properties; such as: thaw settlement, frozen soil creep strength, adfreeze creep strength and thermal properties.

5.3 Test Hole Depth and Frequency

5.3.1 Test Pits

Test pits are normally conducted in thawed material within the active zone whose maximum depth occurs during August and September. Maximum thaw depth varies with the presence of organic cover and water content of the ground. This depth may vary from 1 to 6 m, with likely depth between 1.5 m to 3 m in alluvial and till deposits, and 2 m to 4 m in granular beach, kame and esker deposits.

It is suggested that a minimum of 2 to 3 test pits and representative samples should be taken at potential granular borrow areas, and 3 to 5 test pits to establish near surface conditions for small buildings to be supported on permanently frozen foundation.

The purpose of the test pits is to identify poor ground within near surface (2 to 4 m depth), such as, organic zone and/or poor quality fill, and very loose ground at the base of the active layer of a high groundwater within a highly permeable thawed gravel zone. Good ground conditions indicate these do not exist, or if they are present, the geotechnical engineer will propose a plan of how to deal with these.

5.3.2 Number and Depth of Drill Holes

The number of holes and depths should be planned so that the entire subsurface zone that may be affected by the load and thermal changes of structure is determined, and alternative foundation designs could be considered. For a single structure, a minimum of 3 drill holes should be considered. The depth of drill holes may vary and depend on the number of drill holes planned, likely subsurface conditions and size of the building/foundations.

In fine grained frozen soils that may have ice lenses, which are potentially ice rich and may be in a saline environment, drill holes to depths of 15 m to 20 m should be considered, unless ice-free bedrock is present, and proven, at a shallower depth.

In coarse ground with expected low ice content, 10 to 15 m deep drill holes may be considered. It is suggested that at least one 15 m deep hole should be drilled for determining the likely mean annual ground temperature that is represented by the zero ground temperature fluctuation at about this depth.

5.4 Ground Temperature

Knowledge of the mean annual ground temperature as given at the depth of zero ground temperature fluctuation, and the estimated likely climate warming rate, is important to ensure that the designed foundation will function at the end of the service life of the building. It is recommended that one or two thermistor (temperature sensors) cables be installed to a depth of 15 to 20 m in the drill holes. The thermistor cables shall have 7 to 8 sensors spaced at increasing distances from the ground surface downward. The thermistor cable shall be placed within a 25 mm PVC, or other plastic pipe, that is capped at the bottom and sealed at the surface opening. The pipe does not need to be filled.

Thermistor readings shall be taken after installation and two weeks later to eliminate the effect of thermal disturbance produced by the drilling. The second set of readings should represent the in-situ conditions. It is recommended that arrangement be made for the thermistors to be read on a monthly basis thereafter and the results be processed by the geotechnical engineer at suitable intervals for one year to obtain the annual ground temperature fluctuation.

5.5 Classification, Sampling and Laboratory Testing

Important steps in foundation investigations are accurate descriptions and classifications of the ground, rock and ice content. These are based on a combination of visual observations during the field drilling and laboratory testing of representative soil samples collected during the soil investigation to determine the index properties of the unfrozen soil matrix. The laboratory established index properties allow an accurate soil classification of the soils.

Visual classification of disturbed and undisturbed samples should be made according to recognized procedures as summarized in this document and given in detail in ASTM Standards D40083-89(2007) and D2488-06. Photographs of selected representative disturbed and undisturbed samples should be taken and provided in the report.

Disturbed and undisturbed samples shall be taken to determine the index and engineering properties by laboratory testing. Purpose of samples, type and number are given below:

Index Properties

Water Content (Water Content method ASTM D 2216)

Indicates the likely ice content, type of soil, and uniformity of the frozen soil zone. Samples shall be taken in drill holes at about 1.5 m, or smaller intervals near the surface, that could be important for the excavation plan and design of the foundation, and placed in sealed plastic bags for laboratory water content determination. At least two samples shall be taken from each test pit; preferably from mid depth and bottom of the test pit.

Particle Size Analysis and Liquid and Plastic Limit Tests

These tests are important to classify the encountered thawed soils by recognized criteria as given in ASTM D2487 and D4318 respectively. It is suggested that at least 3 to 5 representative samples be secured of major ground strata for particle size analysis and liquid and plastic limit tests.

Salinity

Salinity tests need to be performed on samples obtained from marine or near marine areas, and inland in areas that were likely inundated by sea water during or after the ice age. It is suggested that 5 to 8 samples be identified from 2 to 3 drill holes for salinity testing. Salinity shall be expressed as the ratio (in percent) of the weight of salts in the soils to the dry weight of the soil (including the salt).

Unit Weights

It is recommended that sufficiently large samples be collected from the air-track cuttings or auger grab samples to conduct at least one compaction test to establish the maximum dry density and optimum water content of major and foundation significant soil zones. Relating water contents from the drill holes to maximum density provide a means to judge excess water or ice content of the foundation material. Test methods ASTM D698 and D7382 would be suitable for this.

5.5.1 Engineering Properties

The determination of engineering properties by laboratory testing requires frozen core samples. Great care needs to be exercised to select appropriate sections of the frozen core and in preserving the frozen state while the core samples are shipped to the laboratory.

There are only a few projects that proceed to determine the engineering properties by means of laboratory testing because of the effort required to obtain the representative samples, the number of tests required to cover the likely ranges ice content and temperature conditions, and complexity and costs of the tests. These tests would likely only be conducted for large buildings founded on piles within ice rich soil.

The selection of engineering properties for most foundation designs are based on published information using the index properties of the soils by laboratory tests. The one exception could be thaw consolidation. This test is relatively simple and can be done at a reasonable cost. But representative frozen cores are required.

6.0 REPORT OUTLINE

The content of a geotechnical site investigation report depends on the requested terms of the investigation, the magnitude and complexity of the structure, and the site condition. Therefore, contents and detail of the reports may vary. The following outline provides a general table of contents based on literature and the writer's experience. It is suggested the report should be based on:

- Structure information/requirements and building engineering design provided by the architect/design engineer.
- Stratigraphy and properties obtained from investigation and laboratory testing appropriate to the structure requirements and site complexity.
- Testing and classification of the soils be based on internationally recognized standards.
- Engineering properties and foundation design requirements to take into consideration the service life of the proposed structure and the potential impact of climate warming.

6.1 Introduction

It is suggested that the report be prepared to provide information to the owner, architect/design engineer and the contractor. As such, the introduction should make adequate reference to:

- The requested terms of reference of the investigation, and
- Scope (program) of work provided in fulfilling the requested terms of reference.

The procedure of the geotechnical site investigation could be left for the appendix.

6.2 Background

This chapter provides the physical setting of the project and should include:

Proposed Structure

Detail of the structure guides the extent and detail of investigation. Therefore, it is necessary that the architect/engineer provide information as given below.

- Technical detail of the proposed structure, e.g., single or multi-story, plan area, above ground, slab-on grade, or with basement.
- Service life of the proposed structure; e.g., 30, 50 years or more.

The information could be given in table format as illustrated below:

Table R1 Proposed Structure Information

Item	Criteria
Size in plan, m^2 and general plan configuration	
Single or multi story	
Slab-on-ground, above ground, crawlspace/basement, etc	
Superstructure design and allowable settlement criteria	
Building service life, years	
Other	

Geological Setting

Overview of the site as provided by geomorphology and bedrock geology obtained from published information and prior research.

Terrain

Description of surface features of the immediate site that should include: topography, vegetation and nearby structures.

Hydrology and Immediate Surface Drainage

Water presence and surface flow may influence the design of surface grading and impact the ground temperatures.

Climate

Present and future climate is an important consideration in the design of foundations in permafrost. The projected climate warming rate (likely and high) and selected value, needs to be estimated. This could be given in table(s) as illustrated below.

Table R2 Climate Information

Parameter	Project Design Year (Year)	At End of Building Service Life (Year)
Mean Annual Air Temperature, °C		
Standard Deviation, °C		
Freezing Index, C degree days		
Thawing Index, C degree days		
Precipitation, mm		
Snow (equivalent water), mm		
Rain, mm		

Freezing Index (approximate) – calculated from the mean monthly air temperatures for a specific station without making corrections for positive degree days (T>0ºC) in spring and fall (Boyd, 1973).

Thawing Index (approximate) calculated from the mean monthly air temperatures for a specific station without making corrections for negative degree days (T<0ºC) in spring and fall (Boyd, 1973).

Note: Four types of indices have been used; including design indices that are based on the coldest winter or warmest summers respectively over the last 30 years, if available (Everdingen 1998).

Table R3 Mean Monthly Air Temperature and Precipitation

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air. °C												
Snow, mm												
Rain, mm												

6.3 Subsurface Conditions

6.3.1 Investigation Program Summary

Includes a description of the method(s) used to assess the ground conditions, equipment used, number of test holes, dates executed, and laboratory tests conducted. Detailed description of these should be presented in the Appendix, preceding the field logs and laboratory testing.

6.3.2 Subsurface Conditions

Description of the major soil and rock formations observed and identification of localized anomalies observed that could affect the building foundation should be provided. The description should be based on both visual observations and laboratory tests, and based on standard soil and permafrost classifications. Each formation should be described under its own heading and the description should include the mean and range of index properties, such as water content, major soil fractions (especially fines content), and salinity.

The subsurface conditions should be summarized in a table as illustrated below for an easy overview.

Table R4 Illustrative Soil Strata Summary

Strata Soil Group	Depth in meters	Classification Symbols		Water Content, %	Salinity, %
		Soil	Permafrost		
Fill – Crushed minus 20 mm	0 – 0.5	GP		8	NA
Peat, fibrous	0.5 – 1.5	Pt	Vr	250	NA
Sand (Poorly graded sand with silt)	1.5 – 6.0	SP-SM	Vx/Vs	25	25
Silty Sand (Silty sand with gravel)	6.0 – 15.0	SM	Vx	13	20

Note: Classification symbols should be based on ASTM D2487 and D4083 that assign the symbols by prescribed percentage ranges of soil groups and plasticity, when applicable.

6.3.3 Ground Thermal Regime (Ground Temperature)

The ground thermal regime should be represented by the actual ground temperature measured in the field, and estimation of the likely ground temperatures at end of construction and the end of the service life of the building. The depth of the annual thaw (active layer) has to consider any changes to the vegetation ground cover, removal and replacement of existing peat layer or other organic zones, and shading and heating effects created by the structure. The mean annual ground temperature should be reported at 15 m depth, normally the depth at which little or no ground temperature fluctuation occurs. Ground temperature profiles should be presented in the Appendix.

Ground temperatures at the time of investigation, and the likely range of values at the end of the structure service life, should be provided in a table as illustrated for Inuvik in **Table R3.**

Table R5 Typical Ground Temperature Information

Parameter	Study Year 2008	Likely range at end of structure design life (2060)
Mean annual ground temperature at 15m depth, °C	-2.4	-0.3 to +1
Mean annual thaw depth, with existing peat, m	1.5	Annual frost
Mean annual thaw depth, peat removed /m	2.5	Annual frost

The above example displays a suggested range of ground information based on a mean annual air temperature warming rate of 6 to 10 degrees per 100 years. The mean annual thaw depth is difficult to predict because it greatly depends on the latent heat of fusion of the frozen zone. Depth and type of organic zone and amount of ice content within the soil have a great bearing on the thaw depth for a given summer air temperature profile.

6.3.4 Construction Materials

The report should identify all possible earth construction materials that include,

a) granular form esker, kames and beaches;

b) bedrock for quarries, and

c) native soil.

The report should provide index properties of these materials and likely quantities available.

6.3.5 Design Properties and Criteria

The geotechnical engineer may consider summarizing the most relevant site conditions and design criteria on one, or at most, two sheets. The summary sheet(s) would provide an easy overview of the important building design criteria, climate and ground information, geotechnical and thermal properties and engineering design properties.

6.4 Design Recommendations

6.4.1 Foundation Design and Alternatives

The report should recommend the optimal foundation design suitable for the established frozen ground conditions and the structure criteria. It should comment on:

- Recommended foundation design (granular pad with air space, piles or thermosyphons).
- Pile adfreeze strength including design ground temperature.
- Likely uniform and differential settlement over the service life of the structure.

The report should suggest any other viable foundation design(s) and address the positives and negatives of the recommended and the alternative foundation designs.

6.4.2 Site and Construction Material Preparation

The report should summarize the required site preparation to construct the foundation. This may include: surface water control, organic layer removal, work pad etc. Furthermore, the near surface ground conditions change through the summer months when most site work is done, and therefore an optimal site preparation schedule should be given.

6.4.3 Grading

Foundations that depend on frozen ground may be impacted by surface and ground water flows and ponded water during the summer. The report should provide guidance for grading around the structure and the management of seasonal surface and ground water.

6.4.4 Construction Aspects and Schedules

The report should provide comments and guidance on the above. Detailed material specifications will be prepared in a foundation design report.

The site investigation report should comment on site issues that may impact on the selection and design of the foundations, such as: excavation of peat and surface ice rich soils, dewatering of the excavation, re-use of the excavated inorganic thawed ground for backfill, and/or other issues. It should also provide months for greatest thaw depth for ease of excavation, and month by which the earthwork should be completed by.

6.5 Conclusions

Highlight of the key findings and recommendations.

6.6 Limitations of the Investigation

The geotechnical consultant may state the practical and legal limitation of the geotechnical site investigation and the derived information. This typically contains a limitation in use and reliance to the organization for which the report was prepared (client).

6.7 APPENDICES

6.7.1 TEXT

A - Classification Tables, Figures & Charts

B - Geotechnical Site Investigation Procedure

6.7.2 GRAPHICS & DATA

C - Site Location Map

Detailed Plan with contours, existing structures & water bodies

D - Photographs (Site, exploration equipment & typical materials from samples)

E - Stratigraphic and Geotechnical Profiles (if applicable)

F - Boring Logs with all necessary pertinent information on soil, rock and groundwater

G - Ground Temperature Profiles

H - Laboratory Data & Graphs

7.0 Selected ASTM International Standards

ASTM Standards are developed and maintained by ASTM Internationals that evolved from the American Society for Testing Materials. The standards are produced by committees of experts and provide a guide in the classification and testing of materials. The standards are identified by designation and their titles.

The first four standards listed below provide the base of much of these guidelines. They provide the following:

ASTM D 420 - Standard Guide to Site Characterization for Engineering Design and Construction Purpose

This standard was developed for the guidance of geotechnical site investigation in non-permafrost areas. While it does not address permafrost and its characteristics, it provides a great amount of information that is applicable also to permafrost. The guide does not include foundation design in permafrost nor the most recent impact of climate warming on permafrost, and therefore, how this should be taken into consideration in the design of building foundations in permafrost.

ASTM D 4083 - Description of Frozen Soils (Visual-Manual Procedure)

This standard provides guidelines on the description of frozen soils (permafrost).

ASTM D 2487 - Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

The Unified Soil Classification System provides rules for categorizing unfrozen soils into groups with common characteristics and show similar behaviour. The classification is based on the results on laboratory test results and therefore on defined criteria. While the classification is for unfrozen soil, the properties and characteristics of an unfrozen zone influence the engineering properties of frozen soils.

ASTM D 2488 - Practice for Description and Identification of Soils (Visual-Manual Procedure)

This is a companion standard to ASTM 2487. It provides a guideline to describe the soil based on visual observations. It extends the ASTM 2487 in that it describes for instance the angularity of gravels etc. Again it was developed for unfrozen soils but it is also useful for frozen soils.

The remaining Standards provide guidelines for conducting laboratory tests and method for classifying and testing peat. These tests are given for reference reasons.

Standard ASTM Designation	Title

Guidelines

D420 – 98 (2003)	Standard Guide to Site Characterization for Engineering Design and Construction Purpose
D4083 – 89(2007)	Description of Frozen Soils (Visual-Manual Procedure)
D2487 – 06	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
D2488 – 06	Practice for Description and Identification of Soils (Visual-Manual Procedure)

Reference Documents

(Employed by geotechnical engineers but not included in this document. They are applicable to laboratory testing of unfrozen soils).

C117	Test Method for Materials Finer than 75-μm (No.200) Sieve in Mineral Aggregates by Washing
C136	Test Method for Sieve Analysis of Fine and Coarse Aggregates
C702	Practice for Reducing Samples of Aggregate to Testing Size
D422	Test Method for Particle-Size Analysis of Soils
D1140	Test Methods for Amount of Material in Soils Finer than No. 200 (75-μm) Sieve
D2216	Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D2217	Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants
D2607	Classification of Peats, Mosses, Humus and Related Products
D4318	Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils
D4427	Classification of Peat Samples by Laboratory Testing
D6913	Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis
D698 – 00	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)
D7382 – 07	Standard Test Methods for Determination of Maximum Dry Unit Weight and Water Content for Effective Compaction of Granular Soils Using Vibratory Hammer.

8.0 REFERENCES

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9.0 APPENDIX

Tables and a figure providing guidance for describing and classifying frozen ground and unfrozen soils. Based on ASTM International Standards.

Table A1 Ground Ice Symbols and Description

Based on Linnel and Kaplar (1966) and ASTM D 4083)

Category	Group Symbol	Subgroup Symbol	Description
Non-visible	N	Nf	Poorly bonded or friable frozen soil.
		Nbn	Well bonded frozen soil with no excess ice
		Nbe	Well bonded frozen soil with excess ice. Free water present when sample thawed.
Visible Ice Less than one inch thick	V	Vx	Individual ice crystals or inclusions.
		Vc	Ice coatings on particles.
		Vr	Random or irregularly oriented ice formations
		Vs	Stratified or distinctly oriented ice formations.
Visible Ice Greater than One inch thick	ICE	ICE & Soil type)	Ice greater than one inch thick with soil inclusions.
		ICE	Ice greater than inch thick without soil inclusions.

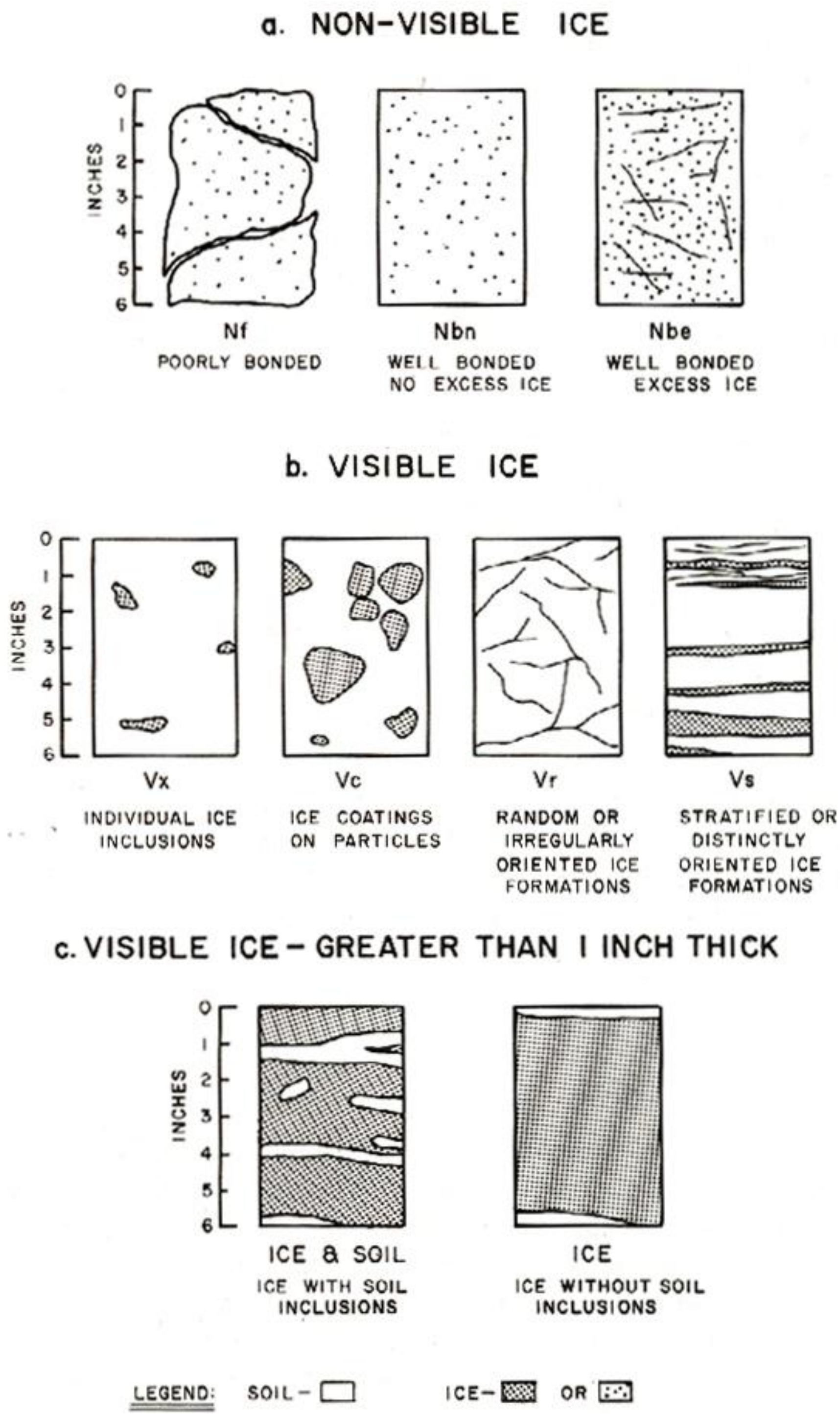


Figure A1 Schematic Description of Ice Inclusions (See subsection 3.5.1)
Based on Linnel and Kaplar (1966) and ASTM D 4083)

Table A2 Unfrozen Soil Classification

Visual Identification of Soils; Definitions of Soil Components and Fractions

1. Particle Sizes

Material	*Fraction*	*Sieve Size*	
Boulders		Plus 300 mm	Plus 12 in.
Cobbles		75 – 300 mm	3 – 12 in.
Gravel	Coarse	19 – 75 mm	¾ – 3 in.
	Fine	4.76 – 19 mm	No. 4 to ¾ in.
Sand	Coarse	2.0 – 4.76 mm	No. 10 – No. 4
	Medium	0.42 – 2.00 mm	No. 40 to No. 10
	Fine	0.074 – 0.42 mm	No. 200 – No. 40
Fines (Silts & clays)		Passing 0.0074 mm	Passing No. 200

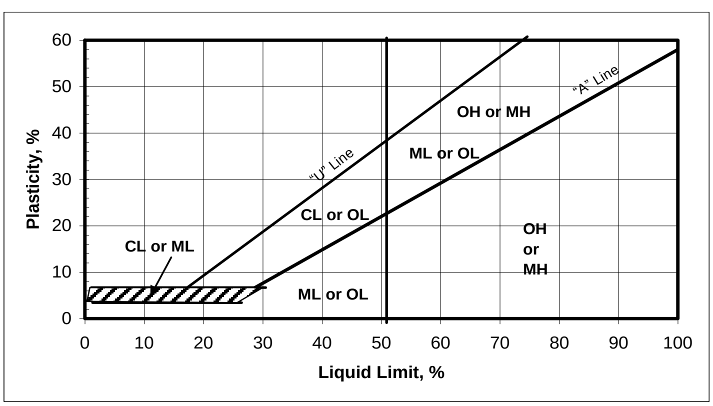
2. Coarse- and Fine Sized Soils (After Department of the Navy 1983)

Description	*Percentage Requirements*
trace	1 – 10
little	10 – 20
some	20 – 35
and	35 – 50

Table A3 Unified Soil Classification System

(Based on ASTM Designation D 2487 – 06

GROUP NAME Criteria for assigning Group Names and Group Symbols			Soil Classification Group Symbol with Generalized Group Description	
COARSE-GRAINED more than 50% retained on No. 200 sieve	GRAVELS 50% or more of coarse fraction retained on No. 4 sieve	Clean GRAVELS Less than 5% fines	GW	Well-graded Gravels
			GP	Poorly-graded Gravels
		GRAVELS with fines More than 12% fines	GM	Gravel & Silt Mixtures
			GC	Gravel & Clay Mixtures
	SANDS More than 50% of coarse fraction passes No.4 sieve	Clean SANDS Less than 5% fines	SW	Well-graded Sands
			SP	Poorly-graded Sands
		SANDS with fines More than 12% fines	SM	Sand & Silt Mixtures
			SC	Sand & Clay Mixtures
FINE GRAINED SOILS 50% or more passes the No. 200 sieve	SILTS AND CLAYS Liquid limit 50% or less	INORGANIC	ML	Non-plastic & Low-plasticity Silts
			CL	Low-plasticity Clays
		ORGANIC	OL	Non-plastic & Low-plasticity organic Clays Non-plastic & Low-plasticity organic Silts
	SILTS AND CLAYS Liquid limit greater than 50%	INORGANIC	CH	High-plasticity Clays
			MH	High-plasticity Silts
		ORGANIC	OH	High-plasticity organic Clays High-plasticity organic Silts
HIGHLY ORGANICE SOILS	Primarily organic matter, dark in color, and organic odour		PT	Peat



Plasticity Chart

Explanations:

First and/or second letters

Letter	Definition
G	gravel
S	sand
M	silt
C	clay
O	organic
Pt	peat

Second letter

Letter	Definition
W	Well graded (diversified particles sizes)
P	Poorly graded (uniform particle sizes)
L	Low plasticity
H	High plasticity

Notes: Gravels and sands may be described by two sets of symbols if they contain between 5 to 12% of fines (clay or silt). Also a low plasticity clay may be described by a combined symbol of CL-ML. See ASTM D 2487-06 for detail.

Well and poorly graded soils are based on coefficients of curvature (Cc) and the uniformity that coefficient (Cu) are determined from ratios of particle sizes corresponding to the cumulative particle-size distribution curve. See ASTM D 2487-06 for detail.

Silt and clay are identified by liquid and plastic limits of the fines and plotted on a plasticity chart. See ASTM D 2487-06 for detail.