

SOCIÉTÉ D'HABITATION DU QUÉBEC

HOUSING CONSTRUCTION IN NUNAVIK

GUIDE TO **GOOD PRATICES**



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Jacques-Parizeau Wing, 3rd floor
1054 Louis-Alexandre-Taschereau Street
Québec, Qc G1R 5E7
Tel: 1 800 463-4315 (toll-free throughout Quebec)
Fax: 418 643-4560
Email: infoshq@shq.gouv.qc.ca



(SHQ)



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Michel Allard,
Centre d'études nordiques (CEN)

Hélène Arsenault,
Société d'habitation du Québec (SHQ)

Marc Blouin,
architect

Mathias Brandl,
Société d'habitation du Québec (SHQ)

Watson Fournier,
Kativik Municipal Housing Bureau (KMHB)

Diane Frappier,
Ministère des Affaires municipales
et de l'Occupation du territoire (MAMOT)

Frédéric Gagné,
Kativik Regional Government (KRG)

Valérie Gratton,
Ministère des Affaires municipales
et de l'Occupation du territoire (MAMOT)

Jean-François Gravel,
Société d'habitation du Québec (SHQ)

Annie Grégoire,
Société d'habitation du Québec (SHQ)

Gilles Grondin,
LVM

Fatima-Zahra Karmouche,
Société d'habitation du Québec (SHQ)

Martin Lachapelle,
Quadrivium

Claude Lepage,
Société d'habitation du Québec (SHQ)

Emmanuel L'Hérault,
Centre d'études nordiques (CEN)

Katherine Mailloux,
Société d'habitation du Québec (SHQ)

Guy Robichaud,
Société d'habitation du Québec (SHQ)

Bertrand Roy,
Société d'habitation du Québec (SHQ)

Shun-Hui Yang,
Société Makivik

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GLOSSARY

ACTIVE LAYER:

Surface layer of the soil subject to the annual freeze-thaw cycle.

AGGRADATIONAL ICE:

Ice that forms at the base of the active layer as a direct result of permafrost aggradation.

CRYOFACIES:

Assembly of cryostructures, a permafrost composition and structure formed of sediments and ice.

CRYOSTRATIGRAPHY:

Vertical succession of a sequence of cryofacies.

CRYOSTRUCTURE:

Geometric patterns created by the three-dimensional assembly of ice in various forms (lenses and veins of various thicknesses, ice coating stones, ice in voids, etc.) and by sediments in the permafrost.

CRYOSUCTION:

Suction process that occurs in freezing or partially frozen fine-grained soil. Interstitial water migrates by capillary action to the freezing front, where it forms ice lenses.

CRYOTURBATION:

Disturbance of soil caused by the formation of ice and the freeze and thaw processes.

DEGREE-DAY:

Units used to calculate heat accumulated (above 0°C) or lost (below 0°C). For example, the cumulative degree-days above 0°C for a given time period is called the thawing index. This index is simply the sum of the daily average temperatures for all days on which the temperature is above 0°C. The sum of degree-days below 0°C for a given time period is called the freezing index.

FROST HEAVING:

Uplift movement of the ground surface caused by the formation of ice in the soil.

FROST-SUSCEPTIBLE SOIL:

Soil in which ice segregation (lenses) forms, causing frost heaving when low temperatures and water inflow are sufficient and persistent.

GELIFLUCTION:

Downslope movement of unfrozen material on a frozen substrate. For example, the active layer that thaws in summer flows downhill by gravity over the underlying permafrost. This is a fairly slow movement (a few centimetres a year) and ends up forming geomorphological features such as gelifluction lobes on slopes.

ICE WEDGE:

Massive ice body, usually in the shape of a wedge, with the narrow edge facing down. It results from water freezing in thermal contraction cracks. Repeated annual contraction, cracking and freezing of the infilled water gradually increase the width of the ice wedge.

INTERSTITIAL ICE:

Ice contained in the pores (voids) between soil particles.

INTERSTITIAL WATER:

Water found in the pores (voids) between soil particles (grains of silt or sand, stones, etc.).

N FACTOR:

Ratio of the soil surface freezing or thawing index to the air freezing or thawing index.

PERMAFROST:

Soil (or rock) that remains at a temperature below 0°C for a period of at least two consecutive years.

PERMAFROST TABLE:

The upper boundary of permafrost, typically ice-rich in frost susceptible fine-grained material.

RETICULATE ICE:

Horizontal and vertical ice veins that create a three-dimensional rectangular or square network.

SEGREGATION ICE:

Ice lenses formed by cryosuction.

STRUCTURED SOIL:

General term to designate any soil with an orderly, fairly symmetrical morphological surface pattern (e.g. ice wedge polygons, mudboils).

SYNGENETIC PERMAFROST:

Permafrost formed by the rise of the permafrost table as a result of the deposition of additional material on the ground surface and the subsequent equilibrium of the ground thermal regime. Syngenetic permafrost is common in deposits on slopes, alluvium deposited by rivers, eolian sand or accumulations of peat.

TALIK:

Unfrozen layer or part of the soil that occurs in a permafrost area because of a local anomaly in thermal, hydrological, hydrogeological or hydro-chemical conditions.

THERMISTOR CABLES:

Series of sensors (thermistors) inserted vertically into a borehole that measure the temperature at various depths. Thermistors are electric resistors that vary depending on temperature fluctuations and can be read manually with a voltmeter, or automatically using a datalogger.

THERMOKARST:

Process resulting in thawing of the permafrost and formation of an irregular topography (chaotic terrain) characterized by depressions due to loss of volume caused by melting ice. This thawing may be caused by climatic or anthropic factors.



INUKJUAK (PHOTOGRAPH : XAVIER DACHEZ)

BACKGROUND

Housing construction in Nunavik differs greatly from techniques in the rest of Quebec. The *Guide to Good Practices* was written to illustrate these differences and provide adapted performance criteria for architects, engineers, contractors, local administrators and anyone else involved in design and execution of this type of project. We encourage them to propose solutions that meet these criteria as fully as possible. Under no circumstances should the Guide act as an obstacle to development of innovations, but the suitability of innovations to the problems encountered in northern areas must be demonstrated (integration into the natural environment, enhanced energy efficiency, reduced costs, etc.).

The performance criteria set out here are not intended to replace the codes, standards and other applicable regulatory texts, but instead provide additional information. These basic regulations include the Building chapter of the Quebec Construction Code, although it has not been officially adopted by municipal authorities in Nunavik (those affected and with jurisdiction).

Over time, a certain number of products and methods that have worked well have been adopted by developers, designers and builders working in Nunavik. The Guide to Good Practices reviews the knowledge they have accumulated over the past 30 years building homes in Nunavik.

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NOTICE

This guide is the result of a process (currently being defined) for developing concepts and principles of sustainable development, applicable in the various phases of design, execution and operation of housing projects in Nunavik. This process specifically entails stages for review of the document's content using an adaptive evolutionary approach.

As it develops and future editions are published, it may address variations noted and observed with respect to the needs of occupants, imperatives of individual and community health, requirements dictated by environmental changes, financial constraints and other problems encountered. The Société d'habitation du Québec invites your comments and suggestions to help it revise and improve future editions of the guide to keep it current and relevant (see the Revision Proposal form).

INTRODUCTION

Growth is accelerating in the communities of Nunavik, as ever more developers and contractors enter the construction sector in the Far North. In addition, the Government of Quebec's plan to develop Northern Quebec's potential will draw more activities into this region.

However, the rules and regulations governing the northern construction industry are not always well known or followed. Lack of standardized written procedures has resulted in unnecessary conflicts between the communities, which seek compliance with municipal bylaws and construction rules, and developers or contractors, who feel they have not been clearly informed of the procedures they must follow and the permits they must obtain.

Furthermore, the housing stock in Kativik is overcrowded, with an estimated 30 percent of housing units having more occupants than the number of rooms, and a shortfall of about 1,000 units in 2015.

This guide was developed to:

- Create and institute a standardized procedure that applies to all construction projects in Nunavik;
- Facilitate the work of companies seeking to start construction projects in Nunavik;
- List all authorities that must be notified of projects to be built in their community;
- Promote compliance with rules and regulations (municipal bylaws, orders, occupancy permits for Class I lands, etc.);
- Improve knowledge of the specific of home construction in Nunavik.

Specifically, the Guide presents an overview of the procedures that must be followed for construction projects in Nunavik. In part, it explains the permits that must be obtained and the authority to which the application must be submitted. It specifies the design criteria that govern siting, exterior finish, architecture, foundations, building mechanics and, in a future edition, electrical systems, the environment and sustainable development.



1. LOCAL PROCEDURES AND AUTHORIZATIONS

1.1 GROUPS AND INDIVIDUALS INVOLVED

This guide is available to any organization or person planning to carry out or participate in a housing construction project in Nunavik, specifically:

- Northern villages;
- Landholding corporations;
- Housing project developers;
- Construction contractors;
- Design firms;
- Surveyors;
- Suppliers of construction products and materials;
- Any other person or organization involved in the construction of northern housing.

1.2 TYPES OF WORK

This guide provides information about the procedures, permits and performance criteria applicable to any housing construction project in Nunavik. This includes all types of housing, from single-family and semi-detached houses to multi-family buildings, whether new construction, additions or renovations.

For more information, contact municipal authorities (the northern village), the landholding corporation or Kativik Regional Government (KRG).

1.3 CONSTRUCTION PROJECTS

1.3.1 General organization

The construction season in Nunavik is shorter than in southern regions and this climate constraint is further complicated by lack of a highway connection to the rest of Quebec, which makes construction timelines dependent on shipping schedules for supply of materials and equipment. Due to high cost and limited space available for freight, aircraft are generally used only to bring in workers.

Shipping to communities in Nunavik is generally available from late June until October, depending on the ice pack. Calendars, rates and terms (reservation, packing, shipping of hazardous materials, etc.) can be viewed on the shipping companies' websites.

In winter, other constraints must be considered. The workday is shorter and granulates become virtually unusable. Moreover, removing material to construct granulate raft foundations is impractical because frozen soil is very difficult to excavate. In summer, when the surface soil thaws, it can be excavated and left for the heat to penetrate the substrate, before repeating the operation.

Contractors must ensure that construction sites and camps are kept clean and free of debris, and pose no risk of accident, over the full term of the construction project.

1.3.2 Administrative procedures

Procedures and the permits to be obtained differ slightly depending on the class of the land on which the project will be built (see sections 1.4, 1.6 and 1.7). The developer and contractor must obtain all necessary permits before work starts. The northern village and the landholding corporation in turn must ensure that permit requirements and conditions have been met.

Time must be allowed for issue of these permits. Developers should submit their applications as early as possible and allow at least 90 days before construction starts. Approval of major projects may take longer.

For construction camps, the northern village should be contacted (see Appendix I for contact information), because most villages have their own camps. Furthermore, equipment and materials may not be left in the community after construction is complete without first obtaining authorization from the municipal office and the landholding corporation (see Appendix I for contact information).

Landholding corporations may charge a fee for storing construction equipment in the community.

In communities where such bylaws are in force, northern villages may also charge fees if construction equipment or materials are left at the municipal dump, and penalties may be levied for failure to comply with certain municipal bylaws (governing materials sorting or the location where waste must be left in the dump, for example). Careful planning and organization of construction projects in Nunavik is important, because some logistical problems can cause serious delays.

The various procedures applicable to each land class in Nunavik are described below.

1.4 CLASS I LANDS

The land system under the James Bay and Northern Quebec Agreement (JBNQA) defines three land classes, ranked I, II and III. Class I lands are allocated to Aboriginal people for their exclusive use and are located in the usual locations where Aboriginal people live, as well as surrounding areas. On the following map, these are shown by the colours red (Crees), blue (Inuit) and purple (Naskapis):

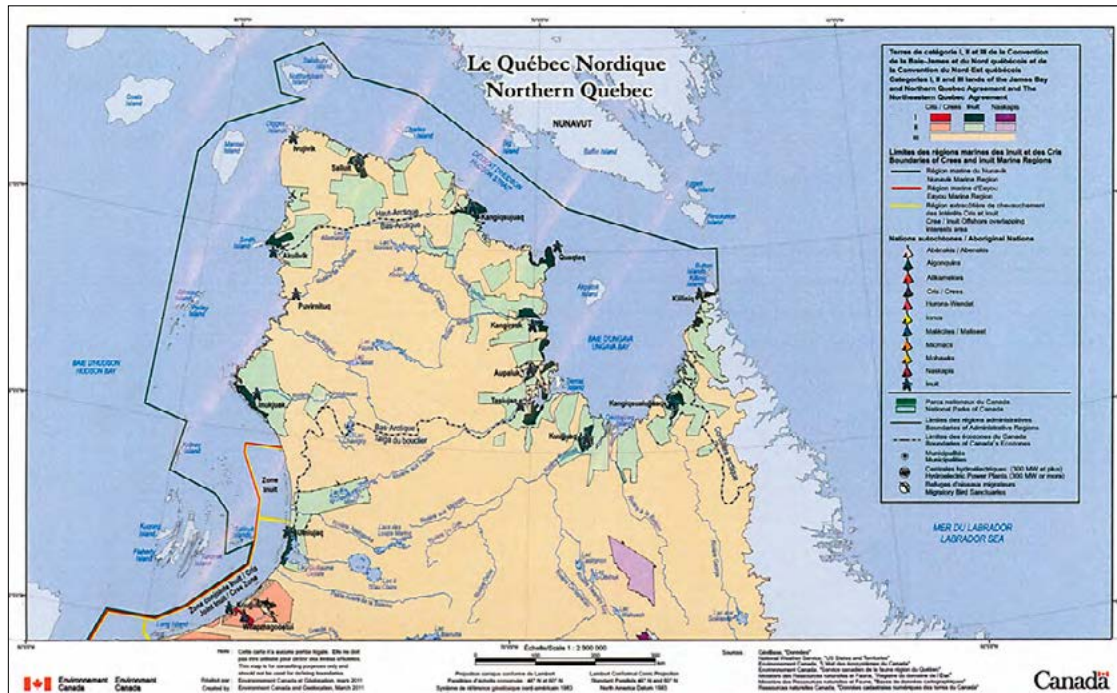


FIGURE 1.1: LAND CLASSES / SOURCE: ENVIRONNEMENT CANADA, <http://www.ceaa.gc.ca>

Construction projects within municipal boundaries or on Class I lands require formal permission for the project from the landholding corporation and the municipal council.

Here is the procedure.

First stage: Project proposal

The developer must submit an application to the northern village and the local landholding corporation at least 90 days before construction starts.

The following must be submitted: the permit application form filled out and signed, the non-refundable fees for the permit application and two copies of the site plan, location certificate, proposed building elevations and floor plans. The northern village also requires that an electronic copy of these documents be sent to the Kativik Regional Government landuse@krg.ca.

The form that must be submitted to the northern village can be obtained from the Kativik Regional Government development department at landuse@krg.ca, while that from the local landholding corporation is available on the Nunavik Landholding Corporations Association website at www.nlhca.strata360.com.

Second stage: Analysis of project proposal

The northern village and the landholding corporation review the project to ensure compliance with the municipality's master plan, zoning bylaws, any other applicable municipal bylaw and the community's general development objectives.

The landholding corporation authorizes occupancy of a plot of land. Developers should provide the northern village and the landholding corporation with thorough documentation during development of the project to avoid potential problems during the construction phase.

Third stage: Decision

The northern village and the landholding corporation send their written decision to the developer.

If the project is admissible, the northern village issues a development permit and the landholding corporation adopts a resolution confirming authorization to proceed with the project, by issuing a registration certificate to the developer. A land lease should then be drawn up between the developer and the landholding corporation. Note that the development permit must be issued and the resolution must be adopted before construction begins.

If the project is inadmissible, the developer must make the necessary changes or abandon it.

Fourth stage: Project approval

Once the project has been approved, the developer must notify the contractor selected for the project, to sign a memorandum of understanding with the landholding corporation on occupancy and use of the plot of land during the full term of the project, and to obtain a permit to operate a quarry, gravel pit, or both, for purposes of the project. Fees will be charged in both cases.

The contractor must then contact the northern village and the landholding corporation to make the necessary arrangements for the following aspects:

- Northern village: Discuss the municipal services that will be required during the project and the services the northern village can provide, such as human resources and heavy machinery rental, as well as the rental rates applicable.
- Landholding corporation: Sign a memorandum of understanding on occupancy and use of the plot of land throughout the project and obtain the rights to use natural construction materials (gravel and mineral materials). Some fees apply for occupancy and use of Class I lands; the rates vary depending on whether it is during construction season. Fees are also collected for extraction of natural materials. After signing the memorandum of understanding, the landholding corporation issues a termination of contract to the developer.

Fifth stage: Land surveyor

The land survey must be produced by a surveyor who is a member of the Ordre des arpenteurs-géomètres du Québec and must be submitted to and registered with the clerk of the Arpenteur général du Québec (GAGQ). Following this, GAGQ will send a copy of the document to the KRG land developer and to the appropriate landholding corporation. The permit holder has 12 months to submit a survey of the building and its siting on the lot to the landholding corporation, the northern village, the KRG land development department and the Minister of Energy and Natural Resources.

The surveyor retained for the project must ask the GAGQ for specific survey instructions, at least 30 days before performing the field work. For more information, additional instructions are provided in Appendix II of this Guide.

Appendix IV contains a table that reviews the permits required.

Additional requirements:

At all times during the term of the work, the developer must ensure that permits are visible from the street, and at the end of the contract, must ensure that the contractor removes from the area the supplies, items, equipment, materials, effects, etc. that were necessary to complete the project.

In some communities, the soil may be unstable and is not always suitable for construction. The developer is responsible for ensuring that all necessary soil studies have been performed. Université Laval's Centre d'études nordiques has produced maps of permafrost characteristics to guide development of the built environment in the 13 Nunavik communities in question. These maps are available in these communities and from the KRG.

Finally, some development projects may be subject to the "environmental and social impact assessment and review procedure" stipulated in chapter 23 of the JBNQA. It is recommended that developers check with the Makivik Corporation or the Kativik Environmental Quality Commission (KEQC) whether their project is subject to this process. The Commission is responsible for administering and monitoring the environmental and social impact assessment and review process in Nunavik. By way of information, Appendix III provides a description of projects that are automatically subject to this process and those that are exempt.

1.5 PUVIRNITUQ

For construction projects in the village of Puvirnituq, where there is no landholding corporation, the developer must contact the Direction générale du Nord-du-Québec for the necessary land lease permits. A development permit must be obtained from the northern village in question and a land lease must be signed with the Ministère de l'Énergie et des Ressources naturelles (MERN) and with the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC). The procedures for obtaining the development permit and specific survey instructions are the same as those described in section 1.4.

1.6 CLASS II LANDS

Class II lands located in Nunavik and falling under the JBNQA are provincial public lands subject to the legislation and regulations of Quebec governing lands involving exclusive hunting, fishing and trapping rights for the Inuit that do not grant them special occupancy rights.

- The landholding corporation, which must ensure that the project does not infringe on Inuit user rights
- KRG, which must issue a certificate of authorization confirming that the project complies with the master land development plan for the Kativik region or any bylaw or order adopted by the KRG council—developers must contact the KRG land developer
- MERN, to sign a land lease
- MDDELCC, to obtain a certificate of authorization for drinking water and sewage treatment as well as waste disposal
- GAGQ, to obtain specific survey instructions.

1.7 CLASS III LANDS

Finally, Class III lands are provincial public lands subject to the legislation and regulations of Quebec governing such lands, but on which Aboriginal people may continue their traditional activities year round, in addition to holding exclusive rights over certain animal species.

In Nunavik, Class III lands are all those not defined by the other classes.

The permits required for construction work on Class III lands are the same as those required for Class II lands (see section 1.6). However, formal authorization is not required from the landholding corporation.

1.8 NATURAL CONSTRUCTION MATERIALS

Most construction projects require gravel or other mineral materials. Before obtaining any mineral, a permit must be obtained from the authorities listed below and the applicable compensation must be paid.

1.9 EXTRACTION FROM CLASS I LANDS

Most communities already operate quarries or borrow pits. Some northern villages provide material extraction, crushing, cribbage and delivery services. The developer or contractor must contact the landholding corporation and municipal office for more information about the services available and rates charged. Under the JBNQA, landholding corporations may charge compensation fees for use and extraction of granulates. The landholding corporation is responsible for maintaining a register of all minerals extracted or removed from the quarry. This information may be forwarded to the northern village, which is responsible for transporting the material. This register must be signed jointly by the contractor, the northern village and the landholding corporation in question.

The developer or contractor may choose to extract minerals from a new site. Before extraction work starts, written authorization must be obtained from the following authorities:

- The northern village, which issues the permit confirming that the work does not violate any municipal bylaw
- The landholding corporation, which grants authorization to obtain and extract gravel or mineral materials
- The Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, which issues the certificate of authorization to operate a quarry or borrow pit

In all cases, the contractor must ensure that the site selected has been cleaned and graded at the end of the construction period.

1.10 EXTRACTION FROM CLASS II AND III LANDS

To extract natural materials from Class II and III lands, authorization must be obtained from the following authorities:

- The Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, for the certificate of authorization
- The Kativik Regional Government, for the certificate of authorization
- The Ministère de l'Énergie et des Ressources naturelles, for the mineral tenure and mine operating permit
- The clerk of the Arpenteur général du Québec, for specific survey instructions
- The Ministère de l'Énergie et des Ressources naturelles, to sign a land lease

The contact information for these authorities is provided in Appendix I.

1.11 OTHER CONSIDERATIONS

1.11.1 Electrical and telephone connections

When new construction must be connected to existing electrical and telephone systems, the developer or contractor must contact Hydro-Québec and Bell Canada to inform them of the exact location of the structure and the date on which the connection is required.

The applicant (developer or owner) may be required to pay costs if the structure is located beyond existing networks or in a location not appearing on the municipal master plan or zoning plan as an area for future development. In addition, if the building is erected at a distance that requires the installation of new posts specially intended for this building, the cost will be invoiced accordingly.

For the fees applicable or more information on a Hydro-Québec connection, visit:

<http://www.hydroquebec.com/affaires/moyen/raccordement.html>

For a new telephone line installation, contact Bell Canada's new installations department at 310-2355.

1.11.2 Equipment rental in communities

The equipment and heavy machinery needed for construction is increasingly available locally. In most instances, it can be rented from the administrators of northern villages, landholding corporations or private owners. Where this is not possible, transportation must be arranged by ship.

Renting equipment in the community where construction work will be performed is encouraged. Contact the northern village in question for information about the equipment available (description, manufacturer, model) as well as the hourly or weekly rental rate.

1.11.3 Archeological sites

Known archaeological sites are usually shown on regional and local land use plans. Protective measures must be taken during construction work to avoid destruction or damage to these sites.

If relics or artefacts are discovered during work on a project, work must be stopped immediately and the Ministère de la Culture et des Communications du Québec as well as the Avataq Cultural Institute must be contacted to ensure appropriate conservation measures are instituted before work resumes.

2. SITING AND LANDSCAPING

2.1 BUILDING SITING

When building a structure in Nunavik, choice of the site is important and must consider several factors.

Since there is no storm sewer system in the villages, drainage is by surface runoff or percolation. The site therefore must have good drainage and must be outside periodic flood zones. However, the natural grade must not slope too steeply, and fill and grading must be used as sparingly as possible. The site must also be far enough away from unstable soil such as river banks and the foot of cliffs, where landslides and avalanches are a concern. The lot must also be large enough to accommodate the building and provide the necessary space for service vehicle movements and parking of occupants' vehicles. Finally, the chosen site must not disrupt community habits and activities nor hem in another property.

Snow drifts may also block access to building entrances and exits, overload roofs, block windows and give unauthorized persons access to roofs. Buildings therefore must be constructed and oriented to effectively control the distribution and density of snow cover. This avoids drifting around the perimeter of buildings, obstruction of entrances and exits, soil warming and potential thawing of permafrost (see Chapter 3 – Architecture). There are fairly effective devices for reducing or eliminating drifting, using the wind to scour away the snow, but these should be used as a last resort because of their high cost.

To facilitate snow clearance from laneways, sidewalks and parking lots, sufficient space must be provided for depositing snow away from buildings. Choice of these spaces must factor in the possibility of these piles of snow in turn causing drifting.

Consideration must also be given to service vehicle (delivery of drinking water and heating oil, sewage removal, etc.) and personal vehicle (automobile, truck, snowmobile, ATV, etc.) access to buildings. Service vehicles must be able to approach close enough to the building or connection points to facilitate the operator's work and must be located away from public thoroughfares wherever possible.

Buildings should be raised above ground level to avoid heat transfer to the soil. This reduces snow accumulation under or near the building in winter (through the passage and acceleration of wind between the soil and the building floor) and protects the underlying soil from direct solar radiation that triggers summer thawing of permafrost.

Buildings must be oriented to capitalize fully on passive solar energy to minimize energy use and maximize natural sunlight. The principle is simple: solar energy enters rooms by radiation and is absorbed by walls, floors and furniture, then is released as heat. This principle is even more effective when materials and objects receiving sunlight have high thermal storage capacity.

2.2 USE OF URBAN INFRASTRUCTURE AND UTILITIES

Use of the existing road system should be optimized to avoid urban sprawl and promote appropriate density. This reduces the cost of infrastructure as well as sewage removal and drinking water and heating oil delivery services, which use tank trucks in Nunavik villages, except Kuujuarapik, which has municipal water and sewage systems.

Rear vision is often difficult in winter, so road design ideally should not require service vehicles to back up when making deliveries. Vehicle access lanes and parking areas used in the community, including those for fire trucks, must be designed to accommodate their turning radius.

2.3 LANDSCAPING

Exterior development should limit mineralized surfaces (asphalt and concrete) in favour of pale-coloured (or highly reflective) materials that absorb little solar energy, to avoid forming heat islands and transferring large amounts of heat to the soil, which could thaw the permafrost.

To limit the amount of mud and soil tracked into buildings by inhabitants in spring and fall, pedestrian walkways should be installed. Wood or stone edging should also be installed between earthworks, pedestrian walkways and parking lots that are resistant to heavy machinery used in snow clearance.

The location of access ramps and stairways leading to buildings should be optimized to facilitate snow clearance. These may be made of wood but steel or fibreglass slats are preferable as they are more durable. Steel components should be galvanized.

Wherever there are domestic service connections (delivery or drinking water or heating oil, removal of sewage, etc.), a stairway and a landing must be installed more than 1.5 metres above grade level. Ladders are not recommended due to the risk of injury and falls in winter.

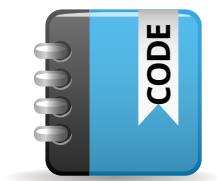
In Nunavik, snow and ice can melt suddenly. Care must be taken to ensure that meltwater runs far away from buildings and developed lands, to avoid flooding that might damage equipment, cause serious erosion and compromise the granular base's ability to support buildings.

Landscape planting should be encouraged. To extent the climate allows, well-designed plantings can play an important role in protecting soils from erosion caused by wind and runoff.

3. ARCHITECTURE

3.1 REGULATIONS AND RECOMMENDED APPLICATION

No construction regulations per se have been adopted by Nunavik authorities for design and construction of small residential buildings¹ and property developments. The Société d'habitation du Québec (SHQ) therefore recommends compliance with the regulatory provisions and techniques of the Régie du bâtiment du Québec (RBQ), mentioned below and designed to guarantee attainment of the minimum performance and quality levels it prescribes:



- Applicable **requirements** of the **Quebec Construction Code**², based on the most recent version legally in force in Quebec³
- Applicable **requirements** of the **Quebec Safety Code**, based on the most recent version legally in force in Quebec
- Applicable **requirements** of the Regulation respecting the professional qualifications of building contractors and owner-builders

The aforementioned regulatory texts also include all amendments published up to the deadline for acceptance of offers or bids. The transition periods stipulated in proposed regulations at the time of their adoption must also be taken into account. In the event of disagreement or contradiction in regulatory texts, the strictest requirements and criteria shall prevail.

In addition to the RBQ standards, there are other technical prescriptions under Quebec's jurisdiction that the SHQ deems relevant and recommends for all categories of residential construction in Quebec, such as the **technical requirements of the Novoclimat Program, "home" and "small multi-unit residential buildings" components**, published by Transition énergétique Québec (TEQ), as energy efficiency incentives (see Appendix V). Although compliance with the Novoclimat Program remains optional in Quebec, it is highly recommended, especially in northern areas with major energy efficiency stakes.

1. The Construction Code adopted by the Régie du bâtiment du Québec does, however, contain requirements that may apply to residential buildings, especially for plumbing, electricity, petroleum equipment and energy efficiency.

2. Use of the word "Code" in Part 3 below means the Quebec Construction Code.

3. The new section on energy efficiency (part 11) of the Building chapter of the Quebec Construction Code applies only to exclusively residential buildings (primary use: group C) with a built area of no more than 600 m² and a building height of no more than three storeys.

3.2 OPERATION AND MAINTENANCE – GENERAL

3.2.1 Mechanical and electrical equipment

Sufficient clearance and adequate access must be provided around and near mechanical and electrical devices and equipment for regular or sporadic inspection, adjustment, provisioning, maintenance, repair and replacement (see also section 4.1). Under no circumstances may this clearance be less than that required by Quebec regulations (see section 3.1) and stipulated in the manufacturer's recommendations. The design of work areas for maintenance personnel must also comply with the requirements of the Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST).

3.2.2 Finishing materials and products

The choice of materials and products, primarily those used for finish, should be based on their durability and ease of maintenance, repair or replacement.

The choice of materials and products should also be based on their availability, especially planned shipping dates, to avoid any additional costs and any work delays. Where delays are foreseeable, it is preferable to use substitute materials and products.

The choice of certified products is recommended. There must be assurance that the products and materials used meet the minimum quality standards set by recognized standardization bodies such as Underwriters' Laboratories of Canada (ULC) and the Canadian Standards Association (CSA).

Standardization of materials and products is also recommended. This means limiting the variety of materials used and the number of models of manufactured products for all projects or buildings, to reduce inventory of replacement materials and products. Ideally, materials and products of the same type should be sourced from a single manufacturer. This goal will be facilitated if consideration is given to materials already used in buildings in the same building stock. This approach should also promote a degree of esthetic uniformity in groups of buildings.

3.2.3 Inspection and maintenance planning

To optimize planning of inspection and maintenance operations for installed equipment, materials and products, a "building management manual" should always be provided by the contractor upon delivery, under a clause to this effect in the call for tenders documents.

This type of manual usually includes all useful information about components, such as the technical specifications of key materials, cleaning and maintenance instructions and frequencies, the list of spare parts and tools required, expiration or replacement dates, a description of applicable warranties, the full list of names, postal and email addresses, and telephone and fax numbers of suppliers and manufacturers. The manual also contains all methodology for checks, tests, settings and balancing of mechanical equipment, in electronic media, in a format accepted and approved by the owner's representative.

Under the same heading in call for tenders documents, training sessions for building maintenance personnel may be required.

3.2.4 Materials and product replacement

Based on personal experience and prior maintenance and repair operations, the owner's representative, in cooperation with the maintenance crew leaders, should determine the materials and equipment that require supply of replacement products, so specific requirements can be included in call for tenders documents and the construction contract. The owner's representative will also have to determine where these products must be delivered and stored. Replacement materials normally should be related to the following components:

- Interior finish materials and products for floor coverings, walls, partitions and ceilings, including paint in each colour used

- Exterior wall and roof cladding materials and products, including paint in each colour used
- All common hardware parts deemed necessary for doors, windows and indoor furniture fittings
- All glazing units deemed necessary for doors and windows

Provision must be made for reasonable quantities of materials such as insulation.

3.3 VOLUMETRICS

3.3.1 Aerodynamics of volumetrics

In Nunavik, sturdy foundations combined with architecture and materials designed to provide strong wind resistance are essential for building sustainable housing, as extreme weather conditions often produce gusts exceeding 100 km/h.

When strong winds are present, buildings raised above grade (approximately 0.6 to 1.2 m) and low roof pitches or flat roofs provide aerodynamic qualities that let the wind pass freely under and over the house, thereby reducing pressure on the constructed volume and vibrations during storms.



FIGURE 3.1: HOUSE CLEARANCE ABOVE GRADE / SOURCE: SHQ

A raised building also reduces snow accumulation around constructed volumes, which helps maintain the permafrost.

Figures 3.2 and 3.3 show the flows and wind effects above and below a typical house built on adjustable jacks that lift it off the soil, and their aerodynamic effect on snow accumulation on the ground

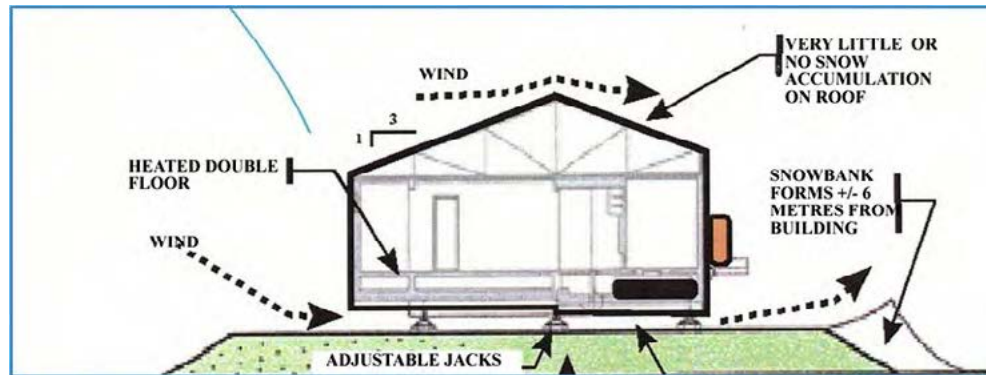


FIGURE 3.2: HOUSE AERODYNAMICS TO REDUCE SNOW ACCUMULATION
 SOURCE: TOPOCLIMAT ET MICROCLIMATS DE LA VALLÉE DE SALLUIT (NUNAVIK), THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES, UNIVERSITÉ LAVAL

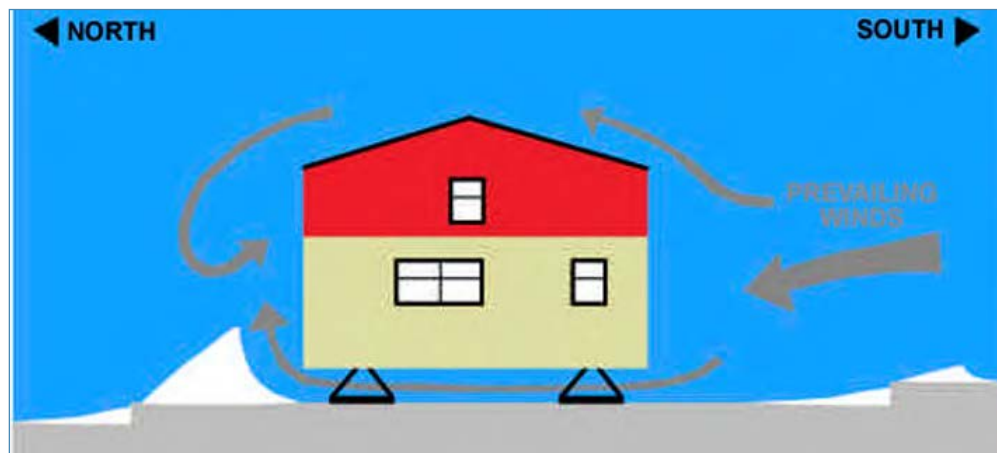


FIGURE 3.3: HOUSE AERODYNAMICS TO REDUCE SNOW ACCUMULATION
 SOURCE: CENTRE D'ÉTUDES NORDIQUES, UNIVERSITÉ LAVAL

3.3.2 Rationalization of volumetrics

To maximize energy savings during the cold season, building designers should reduce the ratio of perimeter exterior wall area to indoor floor area as much as possible to reduce the area of insulated walls and thus the amount of thermal loss. For this reason, a square is the best configuration. This rationalization of volumetrics also achieves savings in building construction costs (time and materials) and throughout the structure's life cycle.

3.4 BUILDING ENVELOPE

A building's envelope separates outdoor and indoor conditions for the comfort of occupants. The Building Code refers to this function as “separation of different environments.” The envelope design therefore must consider environmental parameters such as the site, orientation, climate and local geotechnical specifics.

The recommendations contained in this section strive for high-performance, sustainable design of the envelope in northern locations. They should also help clarify or complement the related requirements in the Building chapter of the Code, especially those in part 9, since these are designed for small-scale buildings. On this point, it should be noted that part 9 sets out very specific and relevant technical specifications to ensure that the building components covered in this chapter contribute to construction quality.

In the area of standards, also note that part 11 of the Building chapter of the Code covers energy efficiency of all new construction of three floors or less with total building area of no more than 600 m². These specifications apply to insulation and air and water seal of walls, roofs and floors, performance of doors and windows as well as indoor mechanical ventilation. Modelled on the Novoclimat Program of Transition énergétique Québec, these fairly recent requirements should achieve a 20 to 25 percent improvement in energy performance of new construction over the previous regulations, while maintaining and even improving occupant comfort.

Note that the following presentations include an instructional preamble for most of the concepts covered, to highlight the need for strict and reliable compliance with the installation of building envelopes in a northern climate.

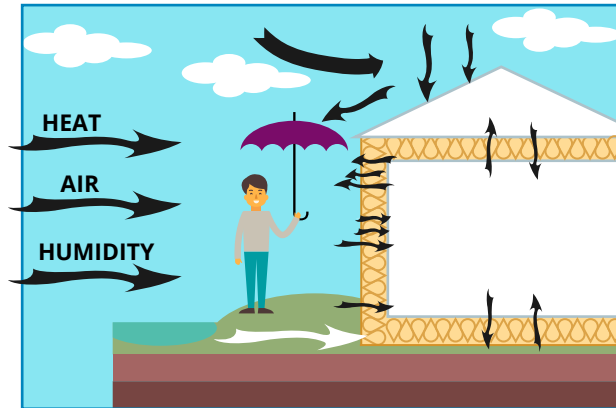


FIGURE 3.4: MOVEMENT OF HEAT, AIR AND HUMIDITY NEAR A BUILDING / SOURCE: SHQ

3.4.1 Envelope seal

Since a building's envelope must separate indoor and outdoor conditions, the seal must be as tight as possible. Uncontrolled movement of air, humidity or water through the envelope can have negative repercussions (see Appendix VI), so it is appropriate to address sealing solutions through three factors.

- airtightness
- water vapour seal
- precipitation seal

Note that in part 5 of the Building chapter of the Code, the specifications on “separation of different environments” cover the envelope seal in terms of these same three factors.

3.4.1.1 Airtightness

General

All architectural components that ensure overall building resistance to air infiltration and exfiltration are called the “air barrier system” or “airtightness system.” This is considered a system because it encloses all insulated planes of the envelope: insulated walls, floors and ceilings as well as the points where these planes intersect. The system may be formed of a single continuous material or various overlapping materials (see Figure 3.5).

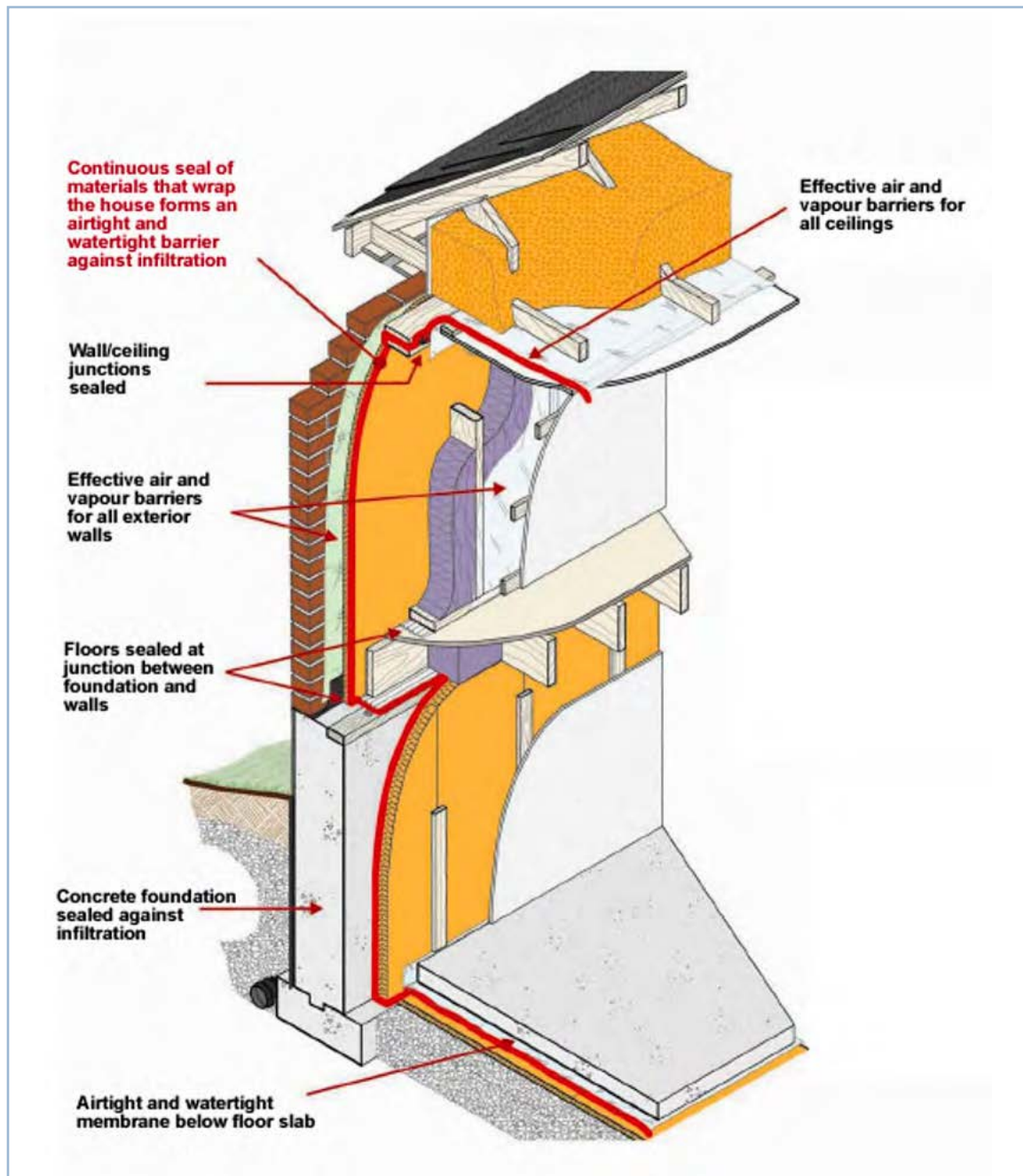


FIGURE 3.5: ILLUSTRATION OF AN AIR BARRIER SYSTEM BASED ON CONTINUITY (RED LINE) IN A STANDARD RESIDENTIAL BUILDING / SOURCE: MERN-NOVOCLIMAT

For the airtightness system to function effectively (see Appendix VII), good practices dictate that it possess at least the following properties.

- Continuity
- Structural strength
- Low air permeability
- High water vapour permeability
- Durability

Since air barrier quality is one of the keys to indoor comfort and energy savings in northern buildings, choice of a superior quality sealing system should be a priority. The air barrier system should consist of materials with above-average performance test values for common products in the market, rather than the minimum values dictated by the regulations.

It is difficult to predict the final airtightness of a specific construction assembly. Available data on the various systems used in construction are scarce and laboratory tests involve specialized facilities that are very expensive. For these reasons, an on-site infiltrometer test is highly recommended for all construction in Nunavik (see section 3.4.6).

General design

Two common design solutions are available for creating air barriers in northern applications.

- A so-called external membrane that combines the air barrier and rain screen functions is usually installed on the outside face of the insulation.
- A so-called “air barrier/vapour barrier” that combines these two functions must be placed on the inside face of the insulation.

Since uncompromised continuity is the essential quality of an air barrier system, the choice between these two systems will be specifically linked to obtaining the best possible continuity in system materials. For example, the air barrier in a ventilated attic must be formed by the vapour barrier sheet installed immediately behind the interior finish, since it is difficult to install a membrane on the cold side of flexible insulation in an attic obstructed with wood struts. In this specific case, the “air/vapour barrier” system must be chosen.

In the remainder of the air barrier system for the same building (in insulated walls, for example), it is quite feasible to switch to an “external” air barrier system, provided a sturdy, continuous connection is made between the wall and the attic.

To maintain total integrity of the building system, a sealed connection must be made between the wall air barrier and the foundation walls at the base of the building, or if the building is raised above grade, with the air barrier for the insulated floor.

Practical tips

Here is a series of practical tips about materials and design to install an effective, durable air barrier system in a northern building:

1. The air barrier membrane must be certified by the Canadian Construction Materials Centre (CCMC) not only in the “intermediate sheathing membrane” category but also the “air barrier” category, so it must have two certification numbers.
2. Regardless of the regulations, the “air permeability” value of the membrane used must be no more than 0.01 l/s/m² at 75 Pa.
3. Regardless of the regulations, the “water vapour permeability” value of the air barrier membrane must be at least 12 US perm if it is also used as an exterior rain screen.

4. The “water penetration resistance” value of the exterior membrane must be as high as possible to avoid water infiltration into the walls during construction. Under no circumstances should a membrane composed of microperforated polyethylene be used.
5. Selection of an exterior membrane should be based on its superior resistance to tearing and delamination, so as to maintain its integrity in frequently extreme conditions on construction sites.
6. To ensure the exterior membrane seal at rough openings for doors and windows, self-adhesive reinforcing membrane must be applied on all four edges of the opening and folded toward the interior and exterior of the wall in compliance with the CAN/CSA A440 standard on installation of doors and windows. Any extremity without an air barrier joining these openings must be sealed at the edge of the opening with a continuous double bead of compressed plastic sealant.
7. Airtightness of the exterior membrane where it meets architectural projections or electromechanical fixtures passing through the membrane must be ensured with plastic sealant for small wires and conduits, and with self-adhesive membrane for larger components.
8. Exterior membrane strips should always be sealed where they meet with the appropriate compatible tape, at a temperature of 50°C or more. Tape should only be applied in the same direction as furring for siding, by pressure and rubbing to optimize adhesion.
9. Mechanical securing—temporary or permanent—of exterior membranes that are not self-adhesive should be located beneath furring for siding or with screws through washers at least 25 mm in diameter. Use of a stapling hammer should be limited to nailing parallel to the furring for siding.
10. Exterior membranes should be backed by a rigid component such as sheathing or insulation panels to prevent potentially destructive vibrations in violent wind.
11. The new self-adhesive exterior membranes are an especially good choice because they require no mechanical anchors or backing panels for their protection and hermetically seal membranes between strips.
12. Exterior membranes composed of polyolefin fibres must not be left on the site, exposed to UV radiation longer than the time prescribed by the manufacturer, which is usually four months.
13. On walls of the exterior envelope, a single air barrier film should not be used as an “air barrier/vapour barrier” system because it does not provide the necessary structural resistance for lateral winds to which the wall envelope is exposed.
14. Choice of an air/vapour barrier system (installed on the interior face of the insulation) is acceptable provided the sheathing insulation protects it from any air convection that would cool it, otherwise damaging condensation points would form inside the system.
15. Any self-adhesive membrane used as a joining, reinforcing or transition material inside an air barrier system should be of the “winter” or “lt” (for low temperature) type, given the risks of low temperatures on the site during construction. These membranes should also be used only with a compatible primer applied to their substrate.

3.4.1.2 Water vapour seal

Figure 3.6 shows the interior face of a wall protected with a polyethylene sheet vapour barrier.

General

Remember that the purpose of a vapour barrier on an insulated wall is to minimize the migration and dispersal of water vapour from the indoor environment into the cold components of the building envelope, where this humidity would then condense and, over the long term, pose a risk of dampness and deterioration of materials. This risk of condensation is greater in a northern climate due to the very low outdoor temperatures to which buildings are subjected and their potentially higher level of humidity (especially in houses).

In addition to being required by good practices in the North American climate, water vapour protection is mandatory for all insulated wall, ceiling and floor surfaces under the Construction Code, which stipulates maximum water vapour permeability of 60 ng/Pa.s.m^2 (1.05 perm US) for the material used (see Appendix VIII).



FIGURE 3.6: WATER VAPOUR SYSTEM ON INTERIOR WALL FACE.
SOURCE : SHQ

General design

Interior water vapour barriers generally use plastic sheet (polyethylene 0.15 mm thick) or an aluminum film laminated to Kraft paper or a thin insulation batt. Products with an aluminum finish have double advantages: very low water vapour permeability and an additional insulating effect due to the ability of aluminum to reflect heat waves back to the building interior.

Alternatively, if composition of the envelope allows, the designer may opt for the solution of an air and vapour barrier integrated into a single membrane, described previously in section 3.4.1.1.

Installation of a vapour barrier is subject to requirements of continuity and durability identical to those detailed for the air barrier in section 3.4.1.1, one of their shared functions being to form an airtight barrier. When correctly designed, the vapour barrier should form a genuine protection “system” that covers insulated walls, floors and ceilings like a shell, with no breaks.

Obtaining acceptable continuity requires solid sealing of all junction points in the vapour barrier, including where it meets any interior structural (floor joists) or electromechanical (wires, piping, etc.) projections.

Unless it is designed as an air and vapour barrier system, the vapour barrier is installed on the interior face of the building frame. The Code prescribes that it “[...] shall be installed sufficiently close to the warm side of insulation to prevent condensation at design conditions.” This criterion allows some latitude in the exact placement in relation to the insulation: for example, it could be placed between insulated framing and rigid insulation placed on the interior face. A recognized rule is to place at least two thirds of the insulation value on the exterior (cold) side of the wall, with the vapour barrier to be placed within the interior third.

Practical tips

Following are a series of practical tips on materials and design for installing an effective, durable vapour barrier system in a northern building:

1. The vapour barrier membrane should greatly exceed the standard of 60 ng/Pa.s.m² for required minimum permeability and should be type I. Note that use of only an interior rigid foam insulation panel as vapour barrier will not attain the type I class, even with sealed joints.
2. Avoid perforating the vapour barrier by separating electrical boxes and wiring from the interior finish with 38 mm thick furring so electrical fittings are entirely on the surface of the vapour barrier membrane.
3. Mechanical fastening of sheet membrane should be limited to a few temporary securing points, since the membrane ultimately will be held in place by the interior finish system.
4. Continuity of the vapour barrier should be assured by a 100 mm overlap between adjacent strips of the membrane or junctions, and by application of a continuous sealant joint in the overlap formed.
5. Acoustic sealant in tubes is the preferred compound for sealing vapour barrier sheets due to its high adhesion properties and permanent flexibility.
6. Joints between two membranes should be taped over on the surface in addition to the sealant applied in the overlap.
7. The preferred tape for double joint sealing is the same as the exterior tape used for air barriers.
8. Ideally, acoustic sealant should be placed under each nail fastening wood furring.
9. When erecting the building framing, remember to incorporate strips of membrane in preparation for sealing all junction points in the insulated envelope where vapour barrier continuity is required (e.g. at the top of an interior bearing wall or where an interior partition meets an exterior wall or insulated ceiling).
10. When erecting the building framing, make provision to include membrane strips on insulated ceilings for future connection of the ceiling vapour barrier with the exterior wall air barrier, to ensure its continuity.
11. Where the vapour barrier meets rough openings for doors and windows, a continuous connection on all four sides with the air barrier membrane that usually surrounds the framing of these openings is recommended. The most effective method is to lap the air barrier over the indoor vapour barrier with adhesive between the two.
12. At rough openings for doors and windows, once the air and vapour barrier junction has been sealed, the vapour barrier system and the door or window frame must be securely sealed on all four sides.
13. Avoid stretching the membrane, especially at interior corners, to avoid tearing when carpentry components force it into the wall or ceiling framing.

3.4.1.3 Precipitation seal

General

Protection from rain and snow is one of the main methods of “separating different environments” (interior and exterior) as required by the Code. This is shown as the basic function of the building envelope, to prevent:

- infiltration of water or snow into interior spaces;
- premature deterioration of envelope components, by minimizing infiltration into its exterior components (see Appendix IX).

General wall design

Based on the two fundamental objectives indicated above, in section 9.27, Cladding, the Building chapter of the Code presents a series of highly complex, sometimes limiting specifications and design choices adapted to various climate or other conditions.

Residential buildings as well as those constructed in humid and cold areas are subject to specifications on wall resistance to precipitation. In this building category, the Code specifies the use of two types of protection for exterior cladding: an initial external protection, formed by the wall siding, and a second layer of protection, placed immediately behind the siding, consisting of a flashing assembly and drainage system containing one or more so-called “intermediate sheathing” materials (intermediate sheathing panel or intermediate sheathing membrane) designed to intercept and dissipate water or snow that manages to penetrate the first payer of protection.

In brief, we can conclude that the Code requirement applicable to residential buildings in Nunavik allows a choice between two wall types: the “hidden protection” or “rain screen” wall type (see Appendix X).

Beyond the Code, we find that the specific challenges of structures erected in a climate such as that in Nunavik involve their resistance to wind loads, which are violent and sustained, and drive rain, snow, hail, sand and even dust into the smallest gaps in exterior siding and roofing. For example, the general dirtiness of air barriers in buildings under renovation has been noted in this region, on which wood siding has been removed 25 years after installation, a sign that foul weather manages at some point to work its way through joints in the wall siding. This dirt on an air barrier diminishes its effectiveness for humidity.

Under such severe conditions of exposure, adequate sealing of the external wall envelope is especially important, even for ventilated walls of the “open rain screen” type. The importance of ensuring effective drainage and aeration of the cavity behind the sliding remains essential on these structures.

General roof design

In Nunavik, there are two architectural solutions in roof design for residential buildings.

1. A roof with a vented attic.
2. A vented sandwich roof with cathedral ceiling.

The option of a mechanically drained flat roof must be automatically ruled out. In most cases, the drain could not be connected to a sewer or storm drain system, as the water would freeze once it entered the open space under the house, and such systems are normally not present in northern communities.

While a pitched roof is preferable, the pitch must be fairly low, to reduce snow accumulation in winter, based on the aerodynamic principle that a flatter roof profile promotes natural shedding of snow. Wind strength and speed in Nunavik villages actually carry away the snow that falls on low-pitch roofs (see Figure 3.7). By contrast, snow and ice build-up on steep-pitch roofs pose a genuine hazard for people entering and leaving such houses.

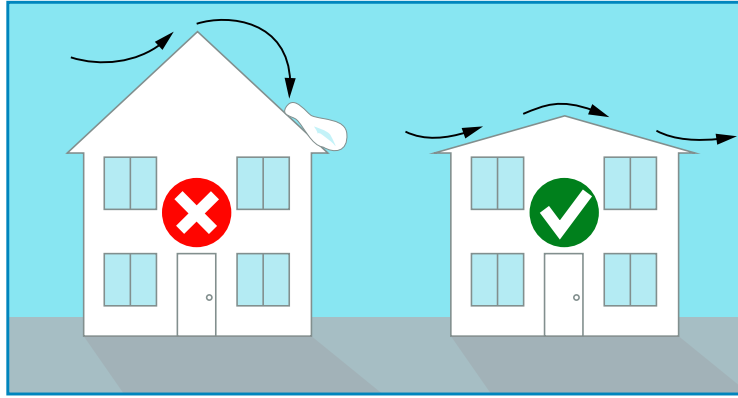


FIGURE 3.7: SNOW ACCUMULATION BASED ON ROOF PITCH
SOURCE: SHQ

Figure 3.7 shows the effect of wind on a steeply pitched roof where snow accumulates and on a gently pitched roof where it sweeps the snow away.

Between the two roof types mentioned earlier (ventilated attic or cathedral ceiling), the first is preferable in Nunavik based on two technical considerations, even though the second design may appear more architecturally interesting.

- An interior ceiling improves occupant comfort because there is less volume to heat in winter, which also saves energy.
- An accessible attic facilitates inspection of materials and maintenance, given that any open space under the roof is always subject to damage, often caused by condensation or water infiltration.

Regardless of which design is chosen, it is wise to remember that when storms rage in Nunavik, ventilated roofs are at risk of greater infiltration of light particles by the air currents to which attics are exposed. Two particular characteristics of northern regions combine here: wind strength and fine snow that, in certain weather conditions, takes the form of fog. Aeration of ventilated roofs must be designed to control these additional risks.

When roofs are exposed to rain, violent winds can sometimes drive the precipitation with incredible force and focused direction, forcing the designer to institute measures that increase roof strength and water-tightness. These measures include:

- Choosing cladding especially resistant to foul weather and the freeze-thaw cycle;
- Using extra-sturdy fasteners;
- Ensuring double water tightness.

Practical tips for walls and roofs

Following are a series of practical tips on materials and design to ensure that the exterior envelope of a northern building provides effective protection from precipitation.

1. Favour the “open type rain-screen” exterior wall design because it provides a barrier against very foul weather and the risk of water infiltration further into the wall envelope under the force of high winds.
2. It is wise to configure the ventilated cavity of “open type rain-screen” walls with the following design details.
 - Compartmentalize the cavity into sections no more than 6 m wide and one story high, closed at building corners, to balance pressure outside and beneath the siding.
 - Place siding furring vertically rather than horizontally to ensure drainage of water that might infiltrate behind the siding, and for siding requiring horizontal support, install a double row of cross-furring.
 - Install a filtering medium at the top and bottom of the cavity to block snow and dust particles.
 - Use an intermediate cladding membrane that complies with the CAN/CGSB-51.32 standard with a water penetration resistance of at least 200 cm based on AATCC (Association of Textile, Apparel & Materials Professionals) tests. This requirement to protect against water is generally easily met by the air barrier membrane required as part of the wall structure (see section 3.4.1.2).
 - Install a water cap board above door and window openings in compliance with the CAN/CSA A440 standard for fast drainage of water that may infiltrate behind the siding above these openings.
 - Install an exterior water table board at the bottom of door and window openings to carry runoff from water that may infiltrate behind the exterior siding.
3. Any roof covering should include a primary waterproofing system formed of a continuous bituminous membrane.
4. To ventilate voids under the roof, an extended access path must be provided between the void and the air intake, that includes a continuous filtering medium (or particle filter) at the entrance and exit of the ventilation circuit. The ventilated soffits used in southern latitudes are not recommended and preference should be given instead to the concept of a continuous horizontal air intake on the wall, integrated into the wall cladding 1.5 m or more below the level of the attic insulation (see Figure 3.8 below).

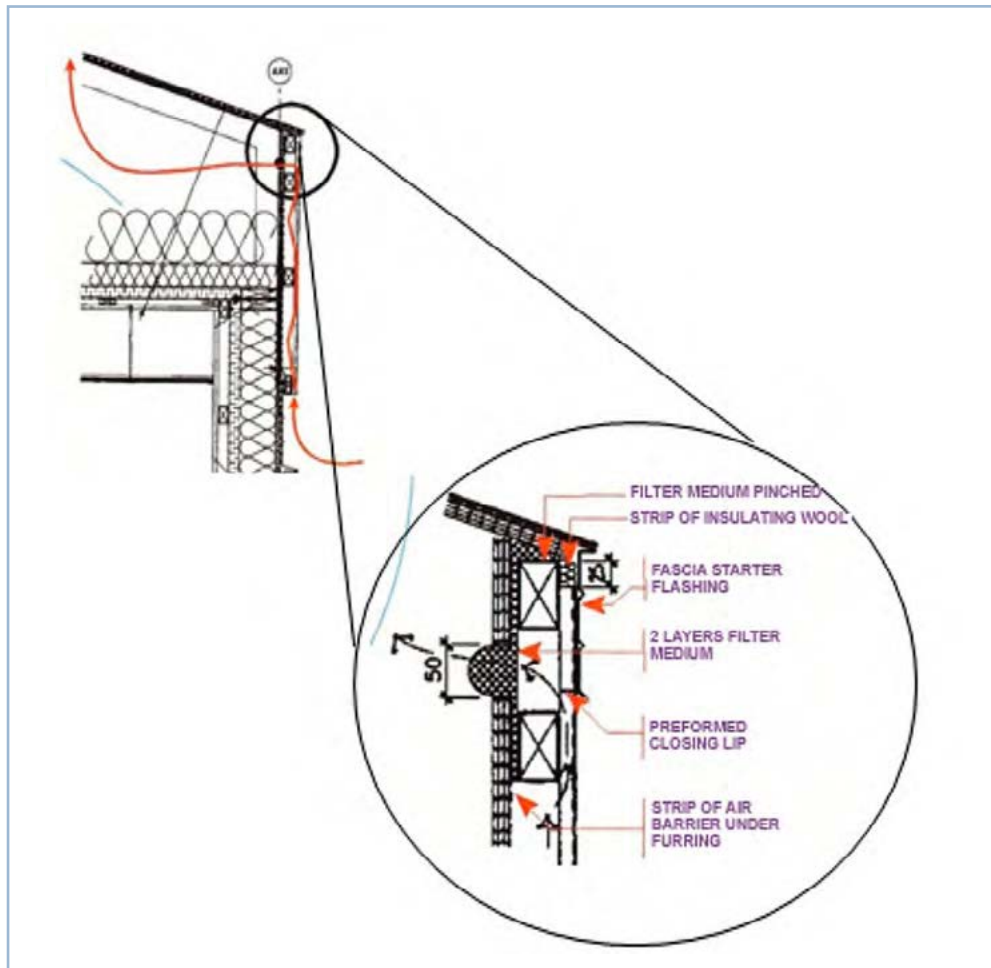


FIGURE 3.8: VENTING A VOID UNDER A ROOF / SOURCE: SHQ

Figure 3.8 shows how a void below a roof can be ventilated with additional protection against infiltration: air enters behind the exterior cladding where the upper section meets the lower section, and passes through a filtering medium before entering the attic.

3.4.2 Insulating the envelope

Insulation in the walls, raised floor or roof of buildings in a cold climate provides the envelope with thermal resistance and limits heat loss in winter. This is an overriding concern in building design in Nunavik, which has particularly cold, harsh winters.

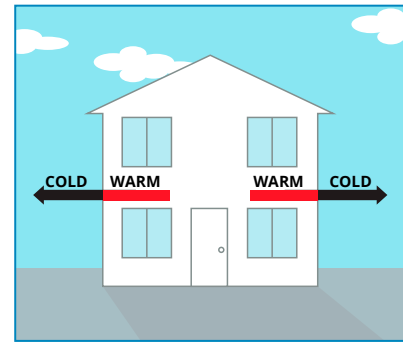
Many factors affect adequate insulation of building envelopes in northern regions, with the following goals.

- Ensure uniform indoor comfort for building occupants, regardless of the outdoor temperature, based on the principle that the better an exterior wall is insulated, the more uniform the interior comfort of the building. Conversely, insufficient insulation allows interior surfaces to cool due to excessive heat loss through thermal radiation, thereby making the building uncomfortable.
- Reduce energy consumption as heating oil is fairly expensive at this latitude.
- Extend the service life of building envelope components, given that insulation directly reduces the risks of condensation inside walls.
- Meet regulatory standards, which are quite strict in latitudes where heating degree days can reach 8,000 to 9,000, as in Nunavik (see Appendix XI).

Insulation specifications are found in two different sections of the Code's Building chapter: part 9.25, which applies generally, and part 11, which contains the mandatory minimum insulation requirements for new construction not exceeding three stories and with a floor area not exceeding 600 m².

Because it strives for high energy efficiency in all envelope components and contains a table of requirements specific to the coldest regions, where heating represents 6,000 degree days or more, part 11 of the Code's Building chapter constitutes a highly relevant reference for all residential buildings in Nunavik. The most useful requirements are the minimum insulation values in the form of thermal resistance coefficients expressed in RSI units for each building envelope component, as well as specifications on treatment of wood, steel or concrete thermal bridges (see Appendix XII).

To document the regulatory specifications on insulated walls, Table 3.1 reproduces Table 11.2.2.1 B of the Code's Building chapter with the minimum "total" thermal resistance values for primary exterior components of a building in Nunavik. "Total" resistance means that the insulating value is that required for the total composition of the wall, not that required strictly for the insulation, without allowing for thermal bridges created by framing.



SOURCE : SHQ

BUILDING COMPONENT	Total thermal resistance (TRSI)
Roof or ceiling separating a heated space from an unheated space or from the exterior air	9.00
Wall above grade except a foundation wall, separating a heated space from an unheated space or from the exterior air	5.11
Foundation wall separating a heated space from an unheated space, the exterior air or contiguous soil <i>NB: A foundation wall of which more than 50 percent of the surface is exposed to exterior air, as well as that part of a foundation wall framed in wood, must have a total thermal resistance equal to that required for an above-grade wall.</i>	2.99
Floor separating a heated space from an unheated space or exterior air	5.20

TABLE 3.1: TOTAL THERMAL RESISTANCE FOR BUILDINGS IN A LOCATION WHERE THE NUMBER OF DEGREE DAYS BELOW 18°C IS 6,000 OR MORE (TABLE 11.2.2.1-B FROM THE BUILDING CHAPTER OF THE QUEBEC CONSTRUCTION CODE)

On the regulatory provisions applicable to thermal bridges in walls, part 11 of the Code's Building chapter specifically stipulates that the insulation material must cover the building components that form a thermal bridge on the exterior or interior face or a combination of the two. Thus, wood or steel framing spaced less than 600 mm o.c., for example, must be covered by insulating material with a minimum thermal resistance of RSI 0.7 for wood and RSI 1.76 for steel. For thermal bridges in insulated floors, part 11 requires insulating covering with a minimum value of RSI 1.32.

It must be noted that to meet the regulatory requirement eliminating thermal bridges in wood frame construction, which includes the header and end joists, insulation is highly recommended on the exterior face of the framing for an effective solution. This design approach requires a break with current practice in Nunavik where, for a long time, thermal bridges were blocked on the interior side by adding insulating panels covering the walls and floor.

Adding insulation to the exterior of wall and floor framing under the specifications in part 11 of the Code's Building chapter on thermal bridges forces us to carefully consider the restrictions in other parts of the same chapter (section 9.25) on the placement of materials with low air and water vapour permeability within the building envelope. Popular rigid insulation panels such as extruded polystyrene have in fact been rated as vapour barriers: when placed on the warm side of insulated framing, this insulation will pose no risk of condensation, but if placed on the cold side, it must be thick enough for the dew point of the wall to be located within or on the cold side of the overlaid insulation panel. This highly important design aspect involves a calculation based on the table in the Code's Building chapter that specifically factors in the number of heating degree days in the region, which falls between 8,200 and 9,200 in Nunavik villages. Based on this table, in these villages, to place extruded polystyrene on the cold side, an insulation value of 50 to 55 percent of that for the insulation placed on the warm side must be provided.

The following three subsections propose certain measures applicable to floors, walls and roofs to ensure adequate insulation..

3.4.2.1 Floor insulation

In Nunavik, most buildings are raised above grade to prevent heat transfer to the underlying permafrost. The ground level floor therefore forms part of the building's exterior envelope. Insulating such a floor takes on special importance since 20 to 30 percent of heat loss in a northern climate is attributed to the raising of buildings.

In Table 11.2.2.1 A, the Code's Building chapter specifies a total thermal resistance of RSI 5.2 for an insulated floor raised above grade level. This requirement includes an insulating material of at least RSI 1.32 to block the thermal bridge formed by the framing. As stated earlier, the thermal bridge ideally should be broken on the exterior side of the framing so as to cover the header and end joists, the best solution for achieving continuity in wall-floor insulation (see Figure 3.9).

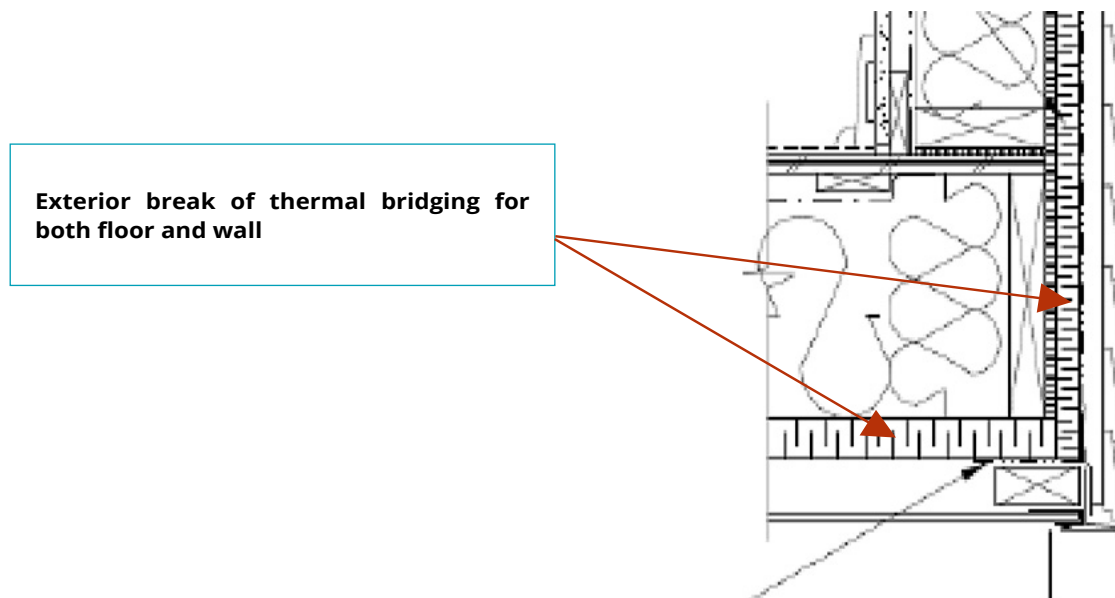


FIGURE 3.9: TYPICAL DETAIL OF WALL-FLOOR JUNCTION/ SOURCE: SHQ

Note that the exterior face of a floor raised above grade level rests at intervals on structural supports, usually steel beams, which also require minimum coverage with exterior insulation for a complete break of the thermal bridge.

A highly recommended construction concept for northern climates is a structural floor insulated to its full height, with a false floor above it, using the voids in the framing to run utility connections. This concept provides excellent continuity of insulation as well as an additional thermal break.

Use of structural framing consisting of wood I-beams or floor trusses rather than solid joists, insulated with blown glass wool, is also a wise choice because it further reduces thermal bridging in the floor.

In all cases, exterior insulation under the building must be protected by impact-resistant sheathing, since the open space between the ground and the floor rarely goes unused.

3.4.2.2 Wall insulation

Exterior wall insulation is dependent above all on the requirements of the Code's Building chapter, which specifies a total thermal resistance of RSI 5.11 for regions such as Nunavik, where heating represents 6,000 degree days or more.

This regulatory requirement includes installation of an insulating material as a thermal break for the wall framing consisting of studs, sills, plates and header and end joists that make up the exterior wall. Minimal resistance of the thermal break will vary from RSI 0.53 to RSI 1.76 depending on the type of framing (wood or steel) and the stud spacing. Under this heading, part 11 details the minimal RSI values for sheathing insulation as follows.

- a. requirement for wood framing
 - i. at least RSI 0.7 where wood framing is spaced less than 600 mm o.c.
 - ii. at least RSI 0.53 in other cases
- b. requirement for metal framing
 - iii. at least RSI 1.76 where framing is spaced less than 600 mm o.c.
 - iv. at least RSI 1.32 in other cases
- c. requirement for concrete construction
 - v. at least RSI 0.88 in all cases

Just as for wood floors, the thermal break should be located on the exterior side of wood framing so as to cover the header and end joists.

In this regard, since extruded polystyrene panels (blue or pink) are still widely used as exterior frame sheathing, it must be remembered that these constitute vapour barrier materials and that the Code governs their minimum thickness when installed on the cold side of framing. Thus, for a standard design wall with 2 x 6 insulated with 140 mm of RSI 3.34 glass wool (see Figure 3.10), calculation of the dew point under the Code will show that the insulating value of the polystyrene must be at least RSI 1.76, which means a panel at least 50 mm thick. We therefore can conclude that such a wall would produce a total insulation performance of RSI 5.91, which exceeds the required standard of RSI 5.11.

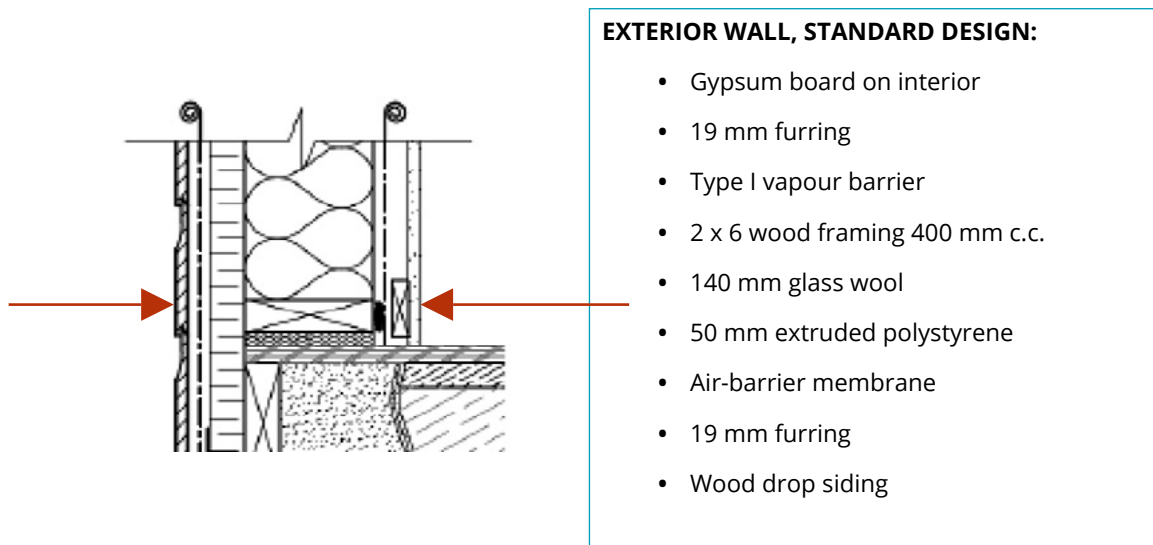


FIGURE 3.10: CROSS-SECTION OF STANDARD EXTERIOR WALL / SOURCE: SHQ

To create the thermal break required in part 11 of the Code's Building chapter on the exterior side, the solution to replace the vapour barrier insulation obviously is insulation that does not function as a vapour barrier, in this case, expanded polystyrene, a highly efficient material sold in high-density rigid panels with tongue-and-groove edges and with or without a laminated air barrier. Its insulating value is RSI 0.82 for a 25 mm thickness, which meets the Code's minimum requirement of RSI 0.7 for a thermal break on standard wood framing installed at 400 mm o.c.

Another solution in some Nunavik villages for obtaining a perfectly insulated wall envelope in northern areas is polyurethane foam sprayed in place for exterior coverage of framing. As an alternate solution instead of rigid exterior insulating panels, foam sprayed in place produces an effective air barrier containing no defects. Walls and floors insulated with this technique produce a building envelope of unmatched airtightness.

3.4.2.3 Roof insulation

Roof insulation value is dictated primarily by the requirements of the Code. As shown in Table 3.1, the required total thermal resistance for any "roof or ceiling separating a heated space from an unheated space or exterior air" is RSI 9.0 for regions where heating represents 6,000 degree days or more, as in Nunavik.

For a roof with a ventilated attic and a standard insulated ceiling finished with gypsum panels on furring, RSI 9.0 translates into a 460 mm depth of bulk mineral wool blown in between roof trusses, a substantial height.

Although the Code does not require a break in thermal bridges in insulated ceilings, the addition of insulating sheathing on the interior face of the roof trusses makes an attractive contribution to energy efficiency in a subarctic climate. As early as 1982, the SHQ introduced into its designs the installation of a 38 mm extruded polystyrene panel on the interior side of insulated ceilings. For a total performance of RSI 9.0 in the ceiling, this addition reduces the depth of bulk mineral wool blown into the attic to 385 mm.

The Code stipulates that the total thermal resistance of RSI 9.0 required for insulated ceilings below an attic may be reduced near the eaves where required by roof pitch and the necessary clearances for ventilation, provided, however, that the value is not less than that required for the wall. This solution must be combined with the installation of deflectors near the eaves to promote the free entry of airflows and ensure a minimum clearance of 25 mm below the roof decking (see Figure 3.11).

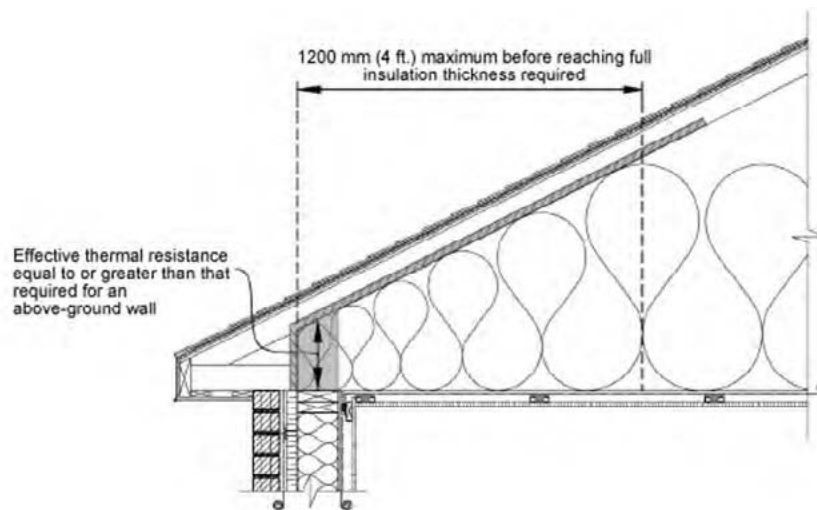


FIGURE 3.11: ROOF EDGE DETAIL / SOURCE: SHQ

A roof edge design with geometry that ensures full ceiling thermal resistance around the periphery, without reducing insulation depth, is the preferred solution. This design is found in the entire SHQ social housing stock allocated to the Inuit community (see Illustration 3.12).

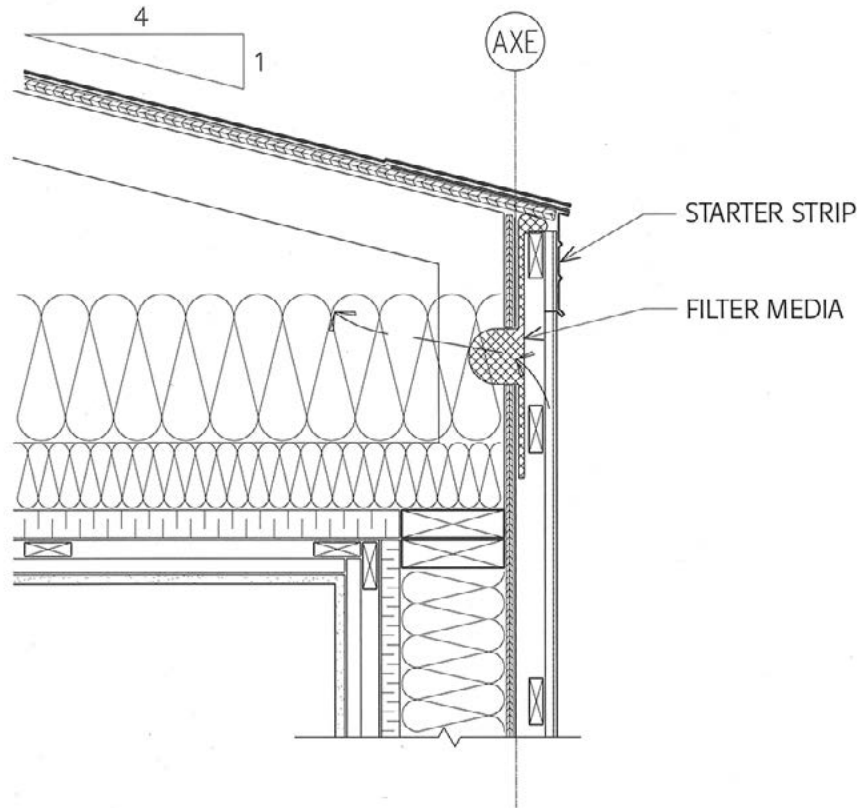


FIGURE 3.12: STANDARD DETAIL OF TYPICAL ROOF EDGE FOR LOW-COST HOUSING IN NUNAVIK / SOURCE: SHQ

The Code stipulates that there must be access to the insulated attic in each housing unit, in the form of an indoor access hatch at least 0.32 m² in area, one side of which must measure at least 545 mm. This hatch must be set in an insulated frame with double weather stripping and provide thermal resistance equal to that of the insulated ceiling. A design consisting of two superimposed hatches, such as those used by the SHQ in its major renovation projects, provides a more effective solution (see Figure 3.13).

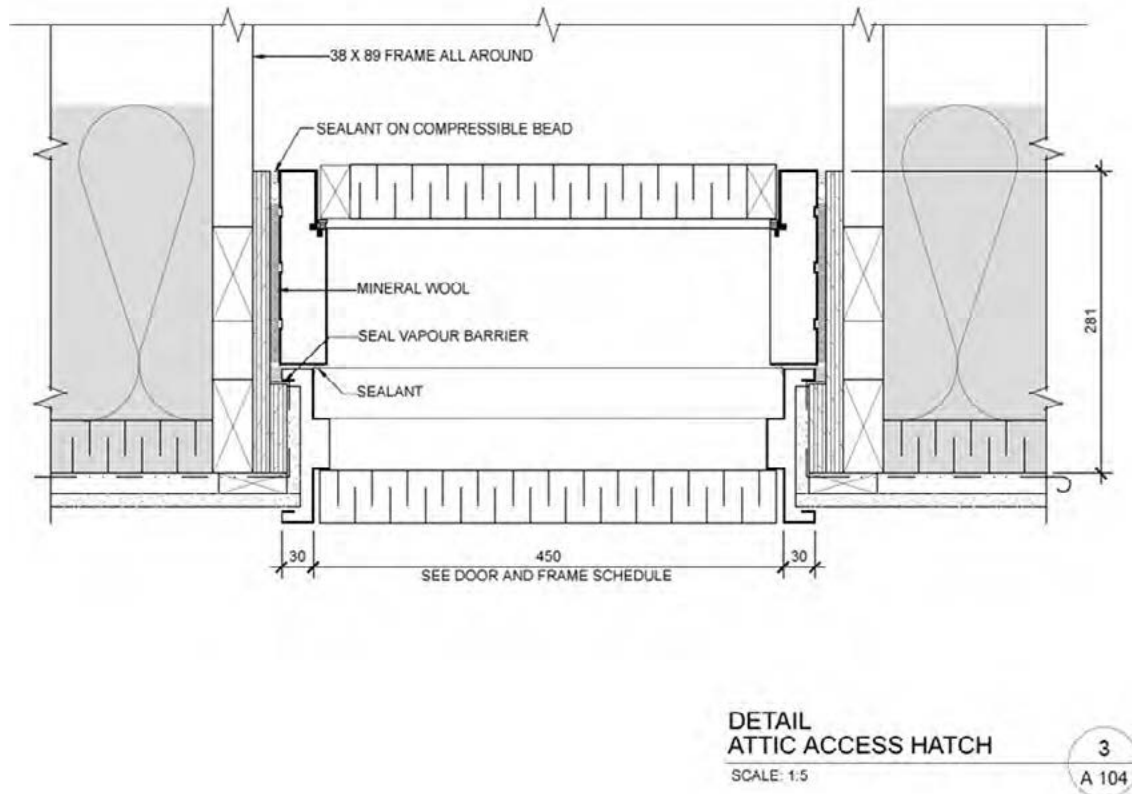


FIGURE 3.13: ATTIC ACCESS HATCH DETAIL
SOURCE: SHQ

No discussion on insulating voids under a roof is complete without addressing the quality of ventilation required for these spaces. Ventilation is required in all areas above ceiling insulation and is subject to strict standards set out in part 9.19 of the Code's Building chapter.

- The unobstructed area of all ventilation openings must be at least 1/300 the area of the insulated ceiling (1/150 if roof pitch is less than 1:6).
- At least 25 percent of the required flow must be located in the lower part of the void under the roof, with air intakes distributed to reach all parts of the insulation.
- At least 25 percent of the required flow must be located in the upper part. Note that the most efficient attic ventilation devices are the maximum type models, which must be located near the roof ridge. These ventilators must include a particle filtration medium as well as a drying pan at the base to capture condensation water.
- Ventilation must be distributed evenly between opposing sides of the building.

Insulated cathedral ceilings are subject to the same regulatory requirements as attics for insulation and ventilation. For optimal application, it is best to frame with roof trusses because their height can easily accommodate the necessary amount of mineral wool and still maintain the minimum required clearance of 63 mm between the top of the insulation and the underside of the roof deck.

3.4.3 Exterior cladding

As we have seen, building envelopes in Nunavik are exposed to extreme climatic conditions, so wall siding and cladding commonly used for residential construction in temperate climates is poorly adapted to this northern region, as their durability or performance is clearly inadequate.

3.4.3.1 Wall cladding

The architectural criteria for choosing exterior wall cladding in Nunavik have already been defined as follows.

- Proven resistance to impact in very cold weather
- Very low expansion coefficient
- Limited water absorption and good freeze-thaw resistance
- Resistance to abrasion by the “sandblasting” effect created by strong winds
- Modulation or installation promoting effective surface drainage
- Format that minimizes the number of surface joints
- Durable paint finish
- Ease of repair in the event of damage

The following cladding materials are deemed less suitable due to their disadvantages.

- Aluminum siding is extremely fragile to impacts and also subject to great thermal expansion and contraction during temperature changes.
- Vinyl clapboard expands and contracts during temperature changes and also becomes very brittle at low temperatures, and thus is subject to breakage from impacts.
- Wood composite drop siding (e.g. hardboard or “Masonite” panels) fades prematurely in Nunavik’s harsh climate and thus loses its water resistance.
- Prefinished engineered wood siding in boards or panels, where exposed, do not dry as effectively in northern climates, so damp engineered wood remains saturated with water, resulting in premature delamination at panel edges and board ends.
- Stucco is easily damaged and hard to repair.
- Reinforced fibrocement panels become brittle in cold weather.
- Reflective and pale-coloured cladding, especially on the southern face, reflects solar radiation, causing considerable build-up of energy (heat) in the soil around buildings, posing a risk of thawing and subsidence (see Figure 3.14).



FIGURE 3.14: EFFECT OF PALE-COLOURED REFLECTIVE SIDING ON PERMAFROST.
SOURCE: TOPOCLIMAT ET MICROCLIMATS DE LA VALLÉE DE SALLUIT (NUNAVIK), THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES, UNIVERSITÉ LAVAL

In conclusion, solid wood siding or prefinished ribbed sheet steel are the two preferred materials in a northern climate.

Solid wood siding

- Solid wood drop siding is a preferred type of siding because its profile greatly facilitates repairs of breakage.
- Horizontal application is preferable because it reduces the risk of water infiltration between boards. In addition, porous cladding such as wood dries faster when placed over vertical furring.
- Pine is recommended as this species is recognized as very stable. For resistance to rotting, pressure-treated pine must be used, a raw pine from Western Canada, such as Lodgepole pine used by the manufacturer Goodfellow.
- This siding must be painted to avoid a gloomy appearance when the siding is wet. A factory-applied prepainted finish provides excellent protection and a warranty for up to 15 years against fading.
- Factory-painted trim is also recommended because the paint is much more durable than that applied on site during construction.

Factory-enamelled sheet metal panel siding

- When sold with an industrial-quality prepainted finish, this siding provides unparalleled durability.
- However, this material should not be used on the lower walls of a building, where it would be exposed to impact. Even minor impacts can cause irreversible denting.

The design and installation of wall siding supports on a rain-screen type of wall (wood furring system) are subject to the following standards under the Code.

- Siding must be fastened not only to the rough sheathing panel but also to the wall framing.
- Minimum profile of 19 x 64 mm or 19 x 89 mm, depending on whether it is fastened at 400 or 600 mm o.c.
- Maximum spacing of 600 mm o.c.

Caulking: all joints and intersections on an exterior wall where water might infiltrate must be sealed with caulking compound. This includes butt joints with door and window openings as well as with any projection where it pierces the siding.

3.4.3.2 Roof cladding

In Nunavik, the extreme pressure exerted by wind on roofing dictates use of the sturdiest cladding, a watertight system with a continuous sealed elastomeric bituminous membrane or asphalt shingle roofing laid over a membrane.

For pitched roofs, asphalt shingles are the preferred economical solution. Given the wind strength, however, certain precautions must be taken.

1. A shingle roof should include an underlying self-adhesive protective membrane covering the entire roof surface. In cold weather, primer must be applied under the membrane before it is installed.
2. Shingles must consist of a non-organic fibreglass fabric, which is highly resistant to freeze-thaw cycles. A product with a 25 year warranty is the basic standard.
3. To provide adequate resistance to tear-off, each shingle must be secured on two edges with continuous sealant in addition to mechanical fastening with at least six roofing nails, two for each tab.

3.4.4 Exterior doors

Exterior doors of a building, the same as any other opening in the envelope, are considered a potential source of air leaks and heat loss. Because it opens, a door will never achieve the same thermal resistance as the wall in which it is installed. However, there are some solutions available to maximize the efficiency of doors subject to the climatic constraints of Nunavik.

Design

Exterior doors must be made of steel cladding insulated with a polyurethane core, in compliance with the CAN/CGSB-82.5-M88 standard (16-gauge galvanized steel with a minimum of RSI 1.3). If a glass light is integrated into the door, it must be of insulating glass and if its area exceeds 0.46 m², it must incorporate the following minimum characteristics: sealed double glass, inert gas between the panes (e.g.: argon or krypton), low-emission glass (low-E), separated with an insulating spacer. It is preferable to install an insulated steel door in a frame that provides a thermal break, such as a wood frame, with a double high-performance perimeter weather stripping system, one strip being compression-type as specified in the manufacturer's engineering. The opening then becomes an integrated door and frame system similar to that of a window. Steel frames, even when equipped with a thermal break, are not a wise choice in terms of insulation, given the climate conditions in Nunavik.

In a northern climate, an integrated door and frame system should form part of the architectural entrance concept to establish an airlock, thereby maximizing protection from the cold. An airlock effect can be achieved in two ways: double doors installed in a single frame (one opening out and the other to the inside), or creating a vestibule with an exterior door on one side and an interior door on the other. This second solution is the best, because it reduces the amount of cold air entering the house each time the door is opened. The vestibule does not necessarily have to be heated, but may serve as a "cold porch," a very common design in Nunavik.

Part 9.6 of the Code's Building chapter sets out the intrusion resistance requirements for residential entry doors that are appropriate and should be applied during installation. In addition, for doors that open out and thus are exposed to extreme winds, a firmly secured chain or other retaining device to prevent the likelihood of tear-off.

Energy efficiency standards

Part 11 of the Code's Building chapter, on energy efficiency, includes a subsection on thermal performance of windows, doors and skylights that specifies minimum manufacturing requirements in compliance with the CAN/CSA A-440 standard for windows (see section 3.4.5 below). Note, however, that these are inadequate in a harsh climate such as that in Nunavik.

It is important to note that house doors are among the products certified by the North American ENERGY STAR program, which serves as a very relevant reference for selecting doors in a harsh northern climate. In that program, ratings assigned to products must be selected based on the climate zone where they will be installed, with zone D being specific to subarctic conditions (see Appendix XIII).

3.4.5 Windows

The same as doors, windows are the weakest link in a building envelope. Their thermal resistance and resistance to air infiltration are key factors in energy savings and comfort for the buildings in which they are installed.

Energy efficiency standards

The standards for this aspect of windows are found in the Code's Building chapter specifying a short list of design requirements in Part 11 on energy efficiency.

- Windows and skylights as well as glass lights installed in doors must achieve minimum airtightness of A2 under section 10.2 of the CAN/CSA A-440 standard for windows.
- The total area of rough openings in building components for windows, doors, skylights and other similar components must not exceed 30 percent of the above-ground wall area.
- The thermal characteristics of windows, doors and skylights must be determined in compliance with the CAN/CSA A440.2 standard on energy performance of window systems, as well as the user's guide, CSA A440.2-09 standard on energy performance of window systems, and must meet the values shown in Table 3.2.

Table 3.2 specifies the maximum U values and minimum EER values based on two geographic areas in Quebec: those requiring heating of fewer or more than 6,200 degree days.

BUILDING COMPONENT	Building located in municipality with no more than 6,200 degree days under 18°C	Building located in municipality with more than 6,200 degree days below 18°C
Maximum total thermal transmission coefficient (U) for doors without lights	0.9	0.8
Maximum total thermal transmission coefficient (U) / Minimum energy efficiency ratio (EER) of windows and doors with lights	2.0 / 21 or 1.8 / 13	2.0 / 25 or 1.6 / 17
Maximum total thermal transmission coefficient (U) for skylights	2.85	2.7

TABLE 3.2: MAXIMUM OVERALL HEAT TRANSFER COEFFICIENT (U) AND MINIMUM ENERGY EFFICIENCY RATIO (EER) FOR WINDOWS, DOORS AND SKYLIGHTS (TABLE 11.2.2. 4 TAKEN FROM THE QUEBEC CONSTRUCTION CODE)

The Code requirements are less than those of the North American ENERGY STAR program that provides certification for windows based on a division of the province into four climate zones, of which zone D fully reflects conditions in Nunavik (see Appendix XIII). The key ENERGY STAR requirement for windows certified by the program is the maximum U factor value of 1.2 (overall heat transfer coefficient). To achieve this value, however, does not require sealed triple-pane glass, a very high-performance component that is thick, heavy and expensive.

Quebec's Novoclimat energy efficiency program, which covers residential window performance, refers to the ENERGY STAR program. Novoclimat also provides a highly relevant diagram in the appendix illustrating the energy efficiency issues related to windows in a cold climate (see Figure 3.15) and explaining the benefits of a design based on the following technical characteristics.

- Frame manufactured to the CAN/CSA A440 standard for windows
- Low-E coating integrated into the sealed glass unit
- Insulating divider around the perimeter of the two panes in the sealed glass unit
- Argon gas between the two panes in the sealed glass unit

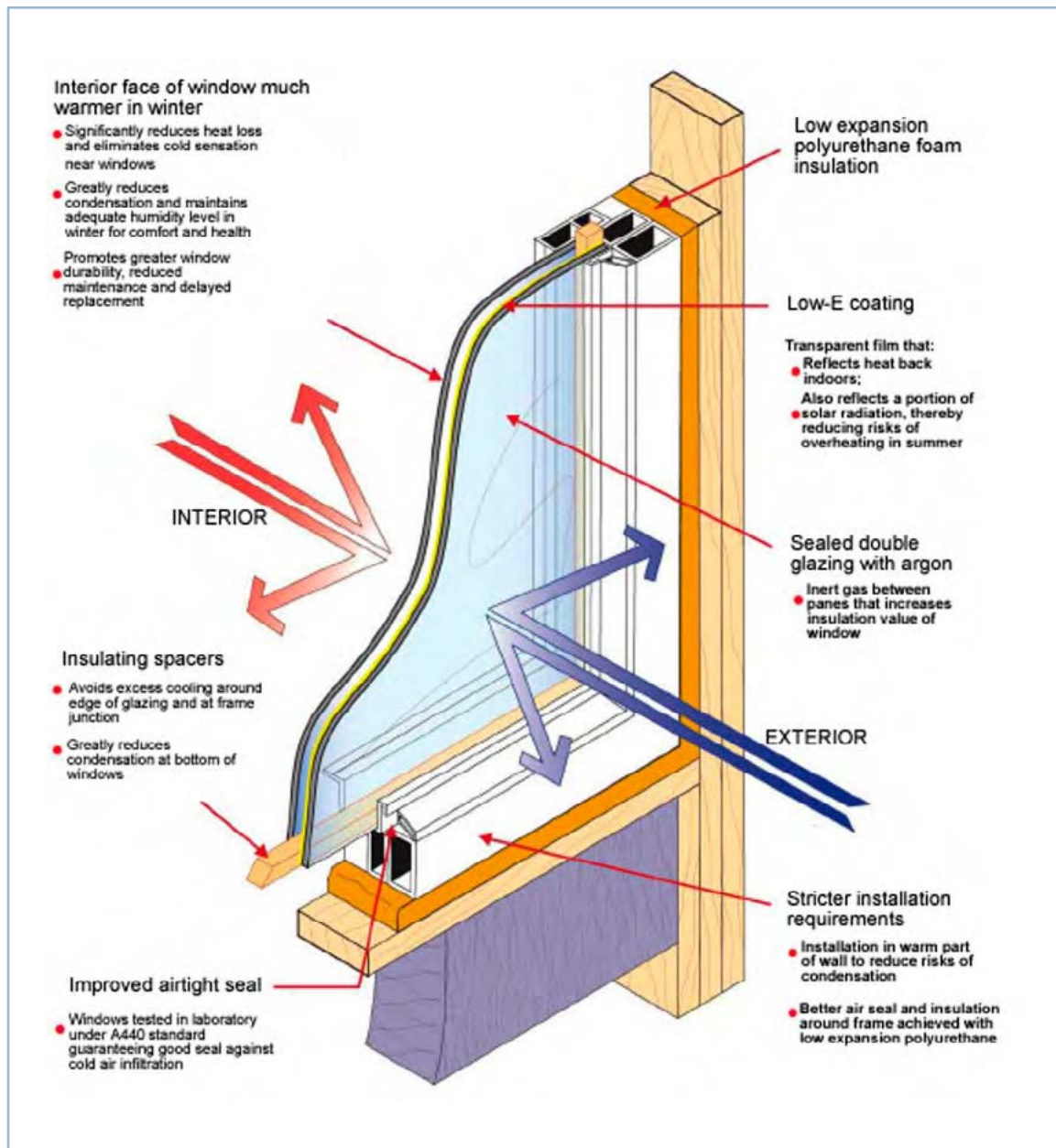


FIGURE 3.15: ILLUSTRATION SHOWING THE COMPONENTS OF A WINDOW WITH SUPERIOR CHARACTERISTICS (THOSE OF THE NOVO-CLIMAT PROGRAM) / SOURCE: MERN-NOVOCLIMAT

Regulations

In addition to the energy efficiency requirements in Part 11, the Code's Building chapter stipulates other specifications in Part 9.7 on various design aspects that must be considered when selecting windows for residential construction.

Safety and protection: Bedroom windows must allow emergency egress with a minimum clear opening of 380 mm within a minimum clear area of 0.35 m². In addition, a window with a sill less than 900 mm from the floor must be equipped with a device to limit its opening to 100 mm and thus prevent falls by a young child. Finally, intrusion prevention requirements are included in the A-440 requirements for windows with a sill less than 2 m above the adjacent grade level. Under certain conditions, a guard rail may be required outside a window in areas common to several housing units.

Manufacture: All windows must be designed to comply with the CAN/CSA A-440-00 standard, which establishes performance classes for buildings based on their height and geographic location. All window products therefore must comply with this standard in a given class in laboratory tests.

Glass calculation: Window glass must be calculated in compliance with the CAN/CGSB-12.20-m standard, which specifies minimum thickness based on glass type, area and the wind pressure to which it is exposed.

Design aspects

Aside from the energy performance and regulatory aspects, window choice for residential construction is dependent on certain other design criteria appropriate for Nunavik, primarily involving material, opening method and strength.

Material: Windows may be of fibreglass, wood, aluminum, polyvinyl chloride (PVC) or composite materials.

- Aluminum is a preferred material in Nunavik due to its resistance to impact and its high strength. When used with a PVC thermal break, its insulating properties are positive, even in an extreme climate. However, its cost is high. For reasons of ease of sealing, if aluminum is chosen, a closed tubular profile is preferable to an open profile.
- PVC is a product well adapted to Nunavik's climate because the fact it is extruded and hollow gives it attractive insulating properties. Also, because the colour is incorporated into the product material, it requires no maintenance. The welded corner assemblies provide a good seal and the cost is very affordable for such a sturdy product. The material chosen must be at least 1 mm thick, however, as the thinner, less expensive versions do not provide the same performance.
- Fibreglass used in the manufacture of windows is the material that provides the highest quality, but is also the most expensive. There is a hybrid window, however, composed of PVC-fibreglass, in which the PVC is jointly extruded on the inside of the profiles as reinforcement.
- Because it requires high maintenance when used for windows, raw wood is not recommended for Nunavik, despite its excellent insulating properties. Its use a composite product with an exterior PVC or aluminum coating is also questionable given the thinness of these finishes, which provide little impact resistance.

Opening method: the various models of series windows available in the residential market are distinguished primarily by their opening method, which generally can be categorized as follows: casement (hinged on the side, opening out), awning (hinged on the top, opening out), hopper (hinged at the bottom, opening in), single or double hung (vertical sliding), hopper-casement (opening in both modes) and horizontal slider. Each model has benefits and drawbacks, which can be summarized as follows.

Casement and awning mode: these two opening methods are the only ones with an outward pivoting component and an insect screen on the inside, and they are equipped with a crank mechanism to control the infinitely variable degree of opening, which has great advantages. However, the hardware for these models is considered fragile and vulnerable to malfunction, generally resulting in high maintenance costs. Moreover, windows that open out are at risk of jamming in Nunavik under certain weather conditions, due to accumulation of hardened snow or ice.

- **Hopper mode:** the main disadvantage of this model is that it opens in and thus obstructs interior space. There are adjustable brake opening limiters to control the opening, however. The benefits are largely in the ease of operation and the very effective airtightness of the sashes, due to multipoint hardware that ensures even pressure on all four sides of the sash. This hardware is also considered extremely sturdy.
- **Hopper-casement mode:** this model has one sash that opens in, either in casement or hopper mode, thus constituting a sophisticated variant of the latter. The major drawback for use in Nunavik is the casement mode opening in, which exposes the sash to “banging in the wind,” since no opening retaining device is available in casement mode.
- **Single or double hung and sliding mode:** sliding windows lack compression weather stripping on sash edges, using a friction fuzzy pile strip that limits their airtightness in strong winds. For this reason, they are poorly adapted to climate conditions in Nunavik. Double hung windows, however, with inner and outer sashes, provide the undeniable benefit of indirect and secure ventilation through alternate opening of the inner and outer sashes.

Sturdiness: the sturdiness provided by a window is measured by combining its resistance to wear of the hardware and weather stripping, deformation, impacts and air and water infiltration. There is one window superior to all others for Nunavik’s climate: the PVC-fibreglass window with hopper opening. This model is also among the few that, with high efficiency glazing, can obtain the Passivhaus certification for construction materials.

Installation aspects

The presence of windows in a building envelope represents a potential breach of air and water tightness if not installed in compliance with a specific protocol that is specified in the CAN/CSA A440 standard, the main recommendations of which are listed below.

1. Centre the frame in the middle of the wall insulation or slightly to the interior, but not to the exterior.
2. Install the frame plumb, square and level, with shims at the bottom and on the sides.
3. Install the window in a rough wall opening that has previously been sealed with the air and vapour barriers folded into the opening and the joints sealed, to create an underlying membrane.
4. Apply a sturdy, continuous air/vapour barrier sealant all around the edge of the window. This sealant joins the frame to the underlying membrane with a highly adhesive and durable concealed product, such as a bead of tube sealant on a bead of foam, or a self-adhesive elastomeric membrane, or extra thick tape sold specifically for this purpose. It is preferable to make this seal on the interior side of the insulated wall to avoid trapping water if the window fails.
5. Apply insulating caulking in the open space around the frame, using injected foam or insulating wool.
6. Insert a metal sill under the air membrane at the top of the opening to drain away any water infiltration at this location, and seal it fully to the air barrier.

3.4.6 Infiltration tests

The air seal test, also called the infiltration test, is an excellent tool to ensure effective airtightness of a building envelope. This test measures air infiltration or the amount of air entering a building and locates air leaks.

This test can be performed on new or existing buildings. In a new building, it is highly recommended to conduct the test once all air seal components have been installed, before the interior finish is applied, so changes can be made before closing in the walls. However, the exterior wall insulation, vapour barrier, interior partitions, ceilings, electrical outlets and switches must all have been installed.

For new construction in Nunavik, it is highly recommended to schedule at least one infiltration session on the site to check the reliability of assemblies.

Once construction has been completed. Airtightness can easily be measured by a second infiltration test, using the CAN/CSGB standard process. This can be combined with a thermographic analysis if the specific location of anomalies must be determined (see Appendix XIV).

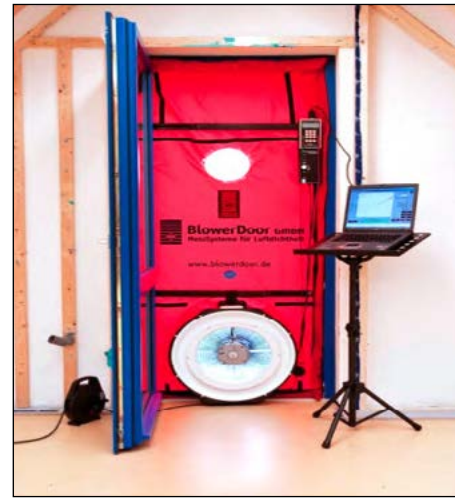


FIGURE 3.16: EQUIPMENT USED TO CONDUCT AN INFILTRATION TEST
SOURCE: GOOGLE IMAGES

3.5 INTERIOR FINISH

In Nunavik, due to the environment and active lifestyle of the local population, the use of resistant, low-maintenance interior finishes is indispensable for durable construction. The long-term availability of products used must also form part of the selection criteria with a view to future repairs.

3.5.1 Floors

Floor covering must be adapted to both Nunavik's climate and the use of the room in which it is installed. In a utility room, for example, painted plywood is deemed quite adequate.

Common residential floor coverings are reviewed below, with their respective benefits and drawbacks. The type of construction used should influence the choice of floor finish, since a raised building resting on a raft foundation cannot accommodate a rigid floor finish such as ceramic tile or solid hardwood due to the excessive risk of deformation; only flexible floor covering is appropriate.

3.5.1.1 Resilient flooring

Resilient flooring, also known as flexible floor covering, generally includes materials such as vinyl, vinyl composite, rubber and linoleum, sold in tiles or sheets. Tiles are easier to repair, but are subject to joint contamination if the floor covering is not meticulously maintained. For the same reasons, resilient sheet flooring must always favour a product that uses welded joints.

Following is an assessment of the main resilient floor coverings recommended.

- Linoleum: this totally natural product is not considered the most flexible of flexible finishes but is appropriate for all living and rest areas, with a minimum thickness of 2.5 mm. It should be avoided in high traffic areas of a building.
- Sheet vinyl: this product has properties very similar to linoleum but slightly more resistant.
- Sheet rubber: this flooring combines antiskid characteristics with the properties of vinyl. It should be chosen for high-traffic areas and entrance vestibules, in thicknesses of 1.8 or 2.5 mm. This is the only finish recommended for unheated spaces such as cold porches, where it acts as a waterproof membrane if applied in a single sheet and sealed around the edges.
- Vinyl tiles: this highly resistant non-porous material requires little maintenance but is not suited to unheated spaces.

3.5.1.2 Wood

Hardwood floors are not recommended in Nunavik, due to the cold, dry climate and the danger of water damage to joints between the individual boards.

3.5.1.3 Ceramic

Ceramic tile is durable and resistant, but its use must be limited to buildings with foundations resting on rock.

3.5.1.4 Carpet

Canada Mortgage and Housing Corporation recommends avoiding carpet in houses because it accumulates dust that is partly responsible for poor indoor air quality. Also, few Nunavik residents own a vacuum cleaner.

3.5.2 Partitions

Interior partitions must be strong enough to provide superior resistance to impact, as do reinforced gypsum panels. This is a recommended finish for all building partitions in Nunavik.

Non-bearing walls can be wood or steel framed.

Common walls between two units must have effective soundproofing and ideally should be double framed with studs extending below the floor.

If habitable rooms are adjacent to utility rooms, it is important to ensure that:

- Partitions have effective thermal and acoustic insulation;
- Continuous acoustic insulation extends down below the floor to limit transmission through the structure.

3.5.3 Interior doors

Interior doors are subject to wide variations in air humidity between winter and summer, and due to often intense indoor activities linked to the large number of residents in housing units. Use of solid wood core interior doors is highly recommended under these conditions for greater durability. Interior door frames may be of wood or heavy-gauge metal.

3.5.4 Ceilings

Gypsum panel is recommended as the finish material for ceilings due to its fire resistance and ease of repair.

Textured ceiling finishes are not recommended because dust and smoke soil and stain them.

3.6 OUTFITTING CONSIDERATIONS

3.6.1 Built-in furniture and equipment

Built-in furniture (lavatory cabinets, kitchen counters and cabinets, sinks and fixtures, vestibule and laundry shelves, etc.) as well as fixed equipment and devices (shower enclosures and fixtures, built-in medicine cabinets and mirrors, toilet paper holder, etc.) included in construction must be sturdy and resistant to damage, and where necessary, must be adapted to traditional Inuit activities (e.g. counter-tops of material that can withstand butchering of game and cleaning of fish). Post formed kitchen and bathroom counters must be avoided as they are often easily damaged, especially at the nosing and edges. All built-in furniture components should be prefabricated to accelerate and simplify installation on site.

For safety and maintenance reasons, glass and glazing should be avoided. If this type of material is absolutely necessary, choose resistant materials such as tempered glass.

3.6.2 Vestibules

Each single-family or semi-detached home should have an unheated entry vestibule known as a cold porch. This space should be large enough for occupants to safely store heavy equipment (boots, coats, fishing and hunting gear, etc.), ideally in a closet with shelves.

Ensure that the size and spacing of hooks for parkas and coats are adequate for the winter clothing used by the Inuit (recommended: 25 mm diameter with rounded ends and mechanical fastenings).

3.6.3 Kitchens

Here are a few recommendations for design of kitchens, based on Inuit culture.

- Adjust the room size to the number of occupants in the housing unit.
- Provide a central kitchen counter wide enough for butchering game.
- Install large stainless steel sinks so occupants can prepare large amounts of food.
- Adapt the ergonomics of work areas to Inuit customs.
- Provide extensive storage space.
- Install windows that open easily in the kitchen.
- Place the sink under the window to maximize contact with the outdoors when working in the kitchen.
- Preferably, install reduced-flow faucets in the kitchen (flow of 8.3 l/min or less at 413 kPa pressure).

3.6.4 Bathrooms

Bathrooms can easily cause problems if not correctly ventilated and with high humidity, so a good ventilation system must be installed as well as highly resistant accessories and finishes. Overcrowding in Nunavik homes means the single bathroom is very heavily used.

Simple, durable products must be selected in the design phase. For example, fibreglass shower stalls and bathtub profiles in fibreglass, polyethylene, reinforced acrylic or preformed PVC are highly recommended, as ceramic tile is unreliable due to constant shifting of buildings that are normally raised above grade level. Preformed finishes are also especially durable and easy to clean.

For plumbing, all bathrooms should be equipped with water-saving fixtures, such as toilets that use 4.8 litres or less per flush, a reduced-flow faucet of 8.3 l/min or less at a pressure of 413 kPa, and a water-saver shower head using 9.8 l/min or less at 551 kPa pressure.

Since the bathroom is used by a large number of occupants, the laundry should be located outside the bathroom, but could be placed in an adjacent area. For energy savings, it is also recommended that all plumbing be located in the same area of the home to shorten plumbing runs.

3.6.5 Utility rooms

Each single-family house must have a utility room for the central heating equipment, water heater, drinking water tank and pump system, as well as access to the holding tank. Semi-detached houses and multiple-unit residential buildings generally have only a single utility room. Utility rooms must be insulated and preferably accessible only from outdoors. Facilities must be maintained by qualified staff and occupants should not have free access.

3.6.6 Storage

Many large storage areas of various shapes must be provided in Inuit housing. Inclusion of the following specialized storage space is required: clothes closet in each bedroom; linen closet near the bathroom; pantry in the kitchen; general purpose storage near the entry door (of at least 3 m²).

4. MECHANICAL

4.1 MAINTENANCE DESIGN AND FUNCTION

The design of mechanical systems must allow for maintenance, verifications and test that must be performed after delivery of the building. Maintenance of facilities and equipment must be minimal and simple.

All ventilation ducts and other concealed mechanical equipment above ceilings or under floors must be accessible to facilitate maintenance.

Utility rooms and sanitary voids must be large enough for qualified staff to maintain and replace the equipment.

4.2 PLUMBING

4.2.1 Drinking water

Drinking water is delivered by truck to all buildings (except in Kuujjuarapik, where there is a water supply system).

4.2.1.1 Water supply system

Except in Kuujjuarapik, buildings have tanks and supply systems for drinking water. All plumbing fittings must be located inside the building's thermal envelope.

Water supply piping must be sloped to a low point, and a valve must be installed at each low point for drainage.

All plumbing equipment must be equipped with an easily accessible shutoff valve for maintenance.

4.2.1.2 Tank

The drinking water system must be located in a room where the temperature can be maintained between 5°C and 15°C to reduce the risk of bacteria growth in the tank.

The building structure must be designed to bear the weight of the water held in the tank.

Since there usually is no water delivery on weekends, water tank capacity must ensure independence for at least three days.

All water tanks must be built with non-corrosive material, equipped with a UV stabilizer and comply with a recognized standard for drinking water storage.

All tanks must have a drain that can empty the tank completely by gravity. There must be a cleaning and maintenance opening at least 500 mm in diameter with a safe, watertight cover. At least 1200 mm clearance must be provided above the access to the tank to facilitate maintenance.

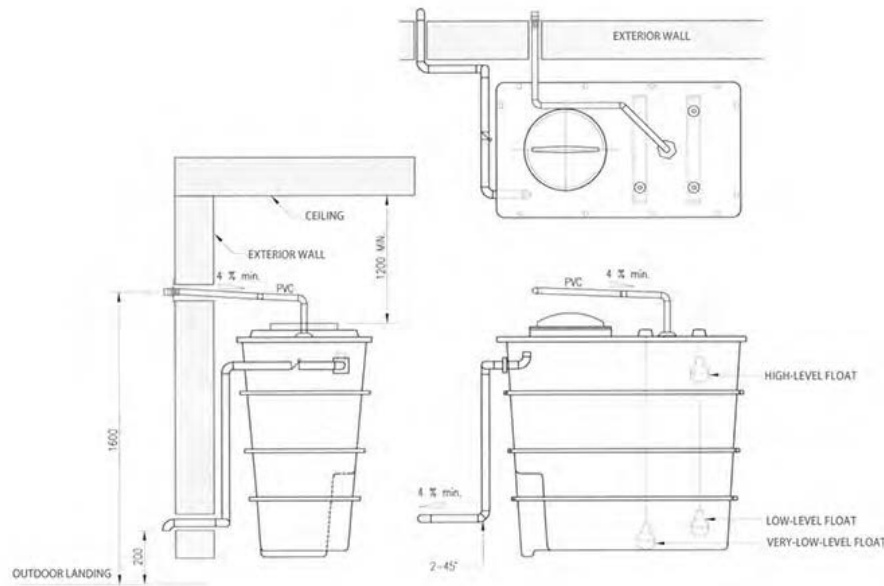


FIGURE 4.1: DRINKING WATER TANK / SOURCE: SHQ

A 75 mm diameter overflow pipe must be provided that drains to the outdoors, to avoid spills within the utility room. A check valve must be placed in the upper part of the overflow pipe to prevent cold air from entering the tank. The drinking water tank must have a PVC fill pipe inside the building and copper or brass pipe in the segment that extends through the exterior wall. This pipe must have a minimum slope of 4 percent toward the tank to avoid spilling outside. The exterior fill pipe connection must be compatible with the 38 mm rapid connection adapter on the delivery hose used in the village.

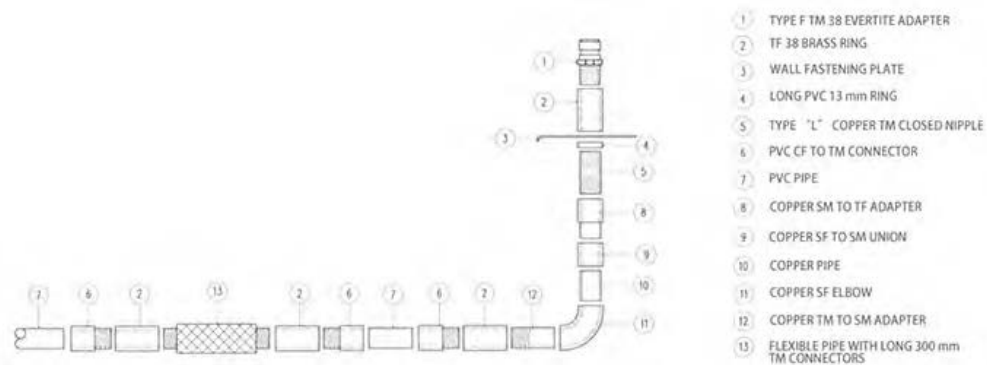


FIGURE 4.2: DRINKING WATER TANK FILL PIPE / SOURCE: SHQ

To prevent drinking water delivery equipment from resting on soil in a location where contaminants such as sewage might be present, the exterior drinking water filling connection must be located at least 1500 mm horizontally and at least 1000 mm vertically from the sewage pump-out connection (see Figure 4.3).

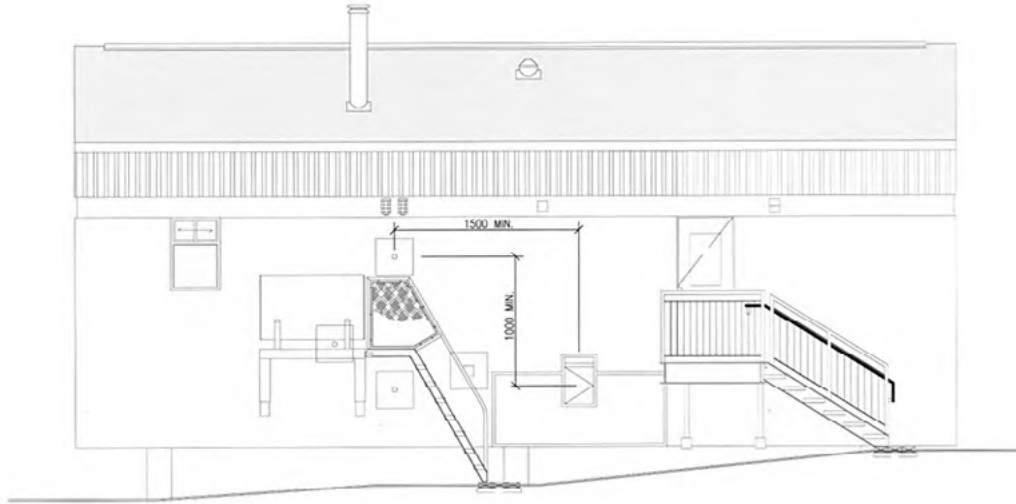


FIGURE 4.3: DRINKING WATER FILL PIPE CONNECTION / SOURCE: SHQ

The tank must be equipped with a system of level indicator floats and an electromechanical control system with the following components.

- A high-level indicator float that activates a blue lamp outside when the water level reaches 25 mm below the tank overflow, to notify the delivery technician that the tank is full
- A low-level indicator float that activates an amber lamp inside the house when the water level drops to 150 mm above the bottom of the tank
- A very-low-level indicator float that stops the pressure pump supplying the system and activates a red lamp inside the house when the water level drops to 25 mm above the bottom of the tank

4.2.1.3 Pressure pump

The use of stainless steel jet pumps is recommended for shallow tanks. Each pump must be installed with two shutoff valves for maintenance or replacement of the pump without having to empty the tank. A pressure gauge should be installed at the pump output.

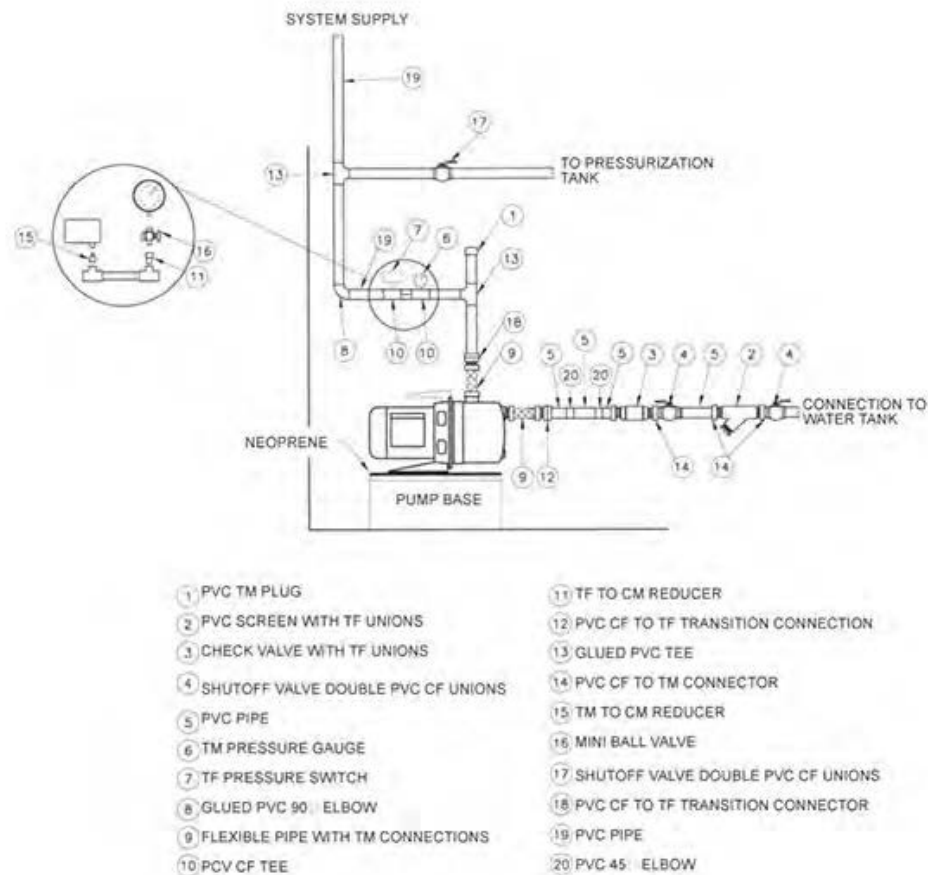


FIGURE 4.4: PRESSURE PUMP / SOURCE: SHQ

The system must be equipped with a pressurization tank downstream from the pressure pump.

4.2.2 Domestic hot water

Domestic hot water can be supplied by a direct or indirect water heater. The energy source used is heating oil, since electrical rates are very high when a home is electrically heated. Electric water heaters therefore are not a recommended solution in Nunavik. A floor drain must also be installed near water heaters.

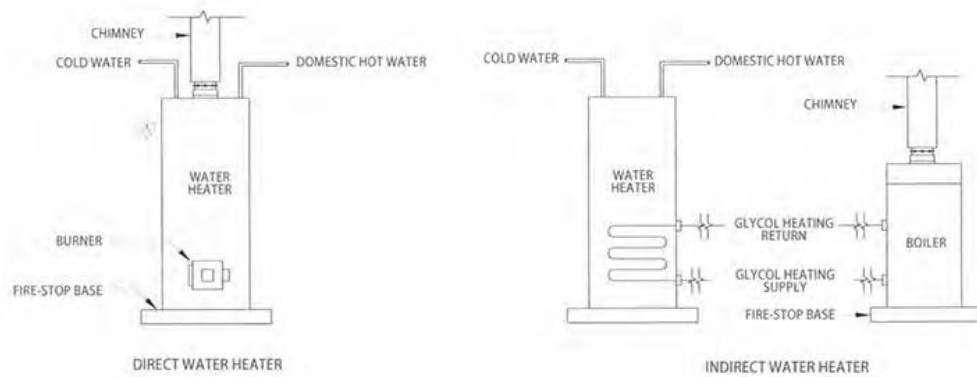


FIGURE 4.5: WATER HEATER / SOURCE: SHQ

4.2.3 Sewage system and holding tank

All housing units are equipped with a waste water holding tank, which must be located inside the building's thermal envelope in a location where waste water can drain by gravity. This tank may be installed in the lower part of the building and must be easily accessible for inspection and repair. Tanks buried in the ground are not recommended, for several reasons.

- They are difficult, if not impossible, to inspect for water tightness of their exterior walls.
- They may contaminate the soil if a leak is not detected.
- They may cause heating of the permafrost due to release of the heat contained in waste water.
- Exterior piping connecting the building's drainage system to the outdoor tank must be heated.
- Exterior piping may crack or break due to freeze-thaw cycles and the associated movement of soils.

Exterior access must be provided for easy removal of the tank from the building.

The tank must be made of polyethylene, fibreglass or PVC to prevent corrosion, and must have been designed and manufactured to CSA standards. Concrete or steel tanks are not recommended due to the risk of cracking and corrosion.

Holding tanks must ensure at least three days' independence. For this reason, a volume of one and a half times the capacity of the drinking water tank is usually sufficient.

All tanks must have access at least 450 mm in diameter and a safe, watertight cover for inspection and repair. It is important to ensure that all connections and openings are air and water tight to avoid emission of foul odours.

The sewage pump-out connection must be far away from doors and windows. The connection must be compatible with the community's service equipment. A 75 mm fast connection adaptor should be compatible with the pump-out services, but it is preferable to check with the municipality. The pump-out pipe must be insulated in the exterior portion and for the first two metres on the interior.

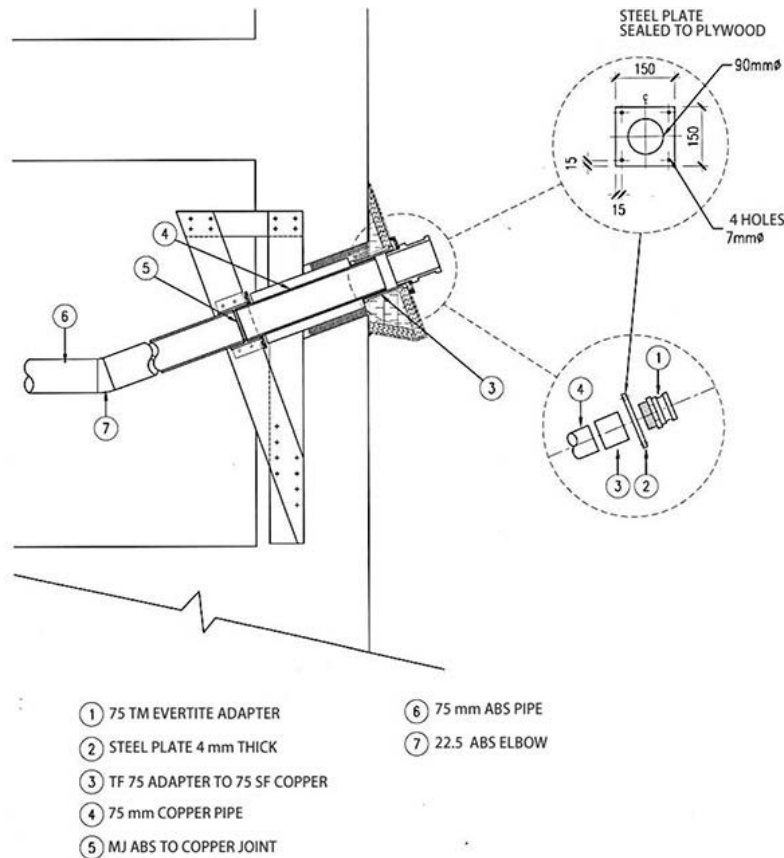


FIGURE 4.6: SEWAGE PUMP-OUT CONNECTION / SOURCE: SHQ

To ensure airtightness of the holding tank, an air pressure test must be performed.

1. The air test must be performed by closing all openings in the tank and filling it with air at a pressure of at least 35 kPa.
2. The test is deemed satisfactory when the pressure remains stable for 15 minutes without adding more air.
3. The pressure gauge must be graduated from 0 to 70 kPa.

After installation of all sanitary equipment and before commissioning any portion of the sewage or ventilation systems, a water pressure test is required.

1. Water must rise to a level at least three metres above all parts of the section being tested.
2. The water test must be conducted by closing all openings in the drainage system and the section to be tested, except the upper end where the water is fed in, until the system has been completely filled.
3. The test is deemed satisfactory if the water level remains stable for 15 minutes.

When the water level in the holding tank rises to 50 mm below the maximum level, a level indicator float must send an electrical signal to the electromechanical control system which must then activate a lamp inside the house to alert occupants to request sewer pump-out service.

When water level in the holding tank rises to 25 mm below the maximum level, a level indicator float must send an electrical signal to the electromechanical control system which will cut off electrical power to the building's drinking water pressure pump. At the same time, an exterior red indicator lamp must activate to indicate that the holding tank must be pumped out.

4.2.4 Exterior ventilation outlets

The sewage system stack vent on the roof must be insulated over its entire length when it is located outside the building's thermal envelope. The vent terminal on the roof must also be heated to avoid the formation of ice dams.



FIGURE 4.7: ICE FORMATION AT THE VENT STACK OUTLET
SOURCE: SHQ

Formation of an ice dam at the vent outlet can cause serious problems when the cleanout truck pumps out the holding tank. The truck's pump is actually powerful enough to empty all traps in the building's plumbing system, thereby allowing toxic gas contained in the holding tank to escape freely into the interior of the housing unit.

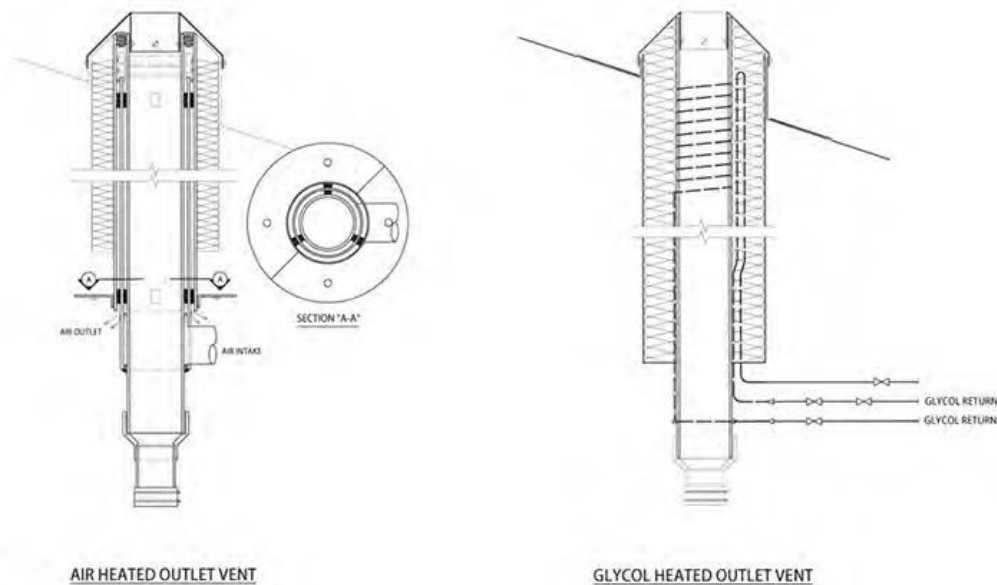


FIGURE 4.8: VENT STACK OUTLET HEATING SYSTEM / SOURCE: SHQ

4.3 HEATING

Light heating oil is the primary energy source for producing heat (space heating and domestic hot water) in Nunavik. The annual number of heating degree days⁴ below 18°C can reach about 9,000 in Salluit, compared with 4,500 in Montreal.

4.3.1 Heating oil storage tank

Each residential building must be equipped with a heating oil tank located outdoors and above the ground. The installation of oil tanks, piping and accessories must comply with the requirements of the Petroleum Equipment Installation chapter of the Quebec Construction Code.

Since that chapter's requirements applicable to this type of installation essentially involve the manufacturing standards for tanks and piping used for housing in Nunavik, we recommend referring to the latest version of the CSA-B139 standard, Installation Code for Oil-burning Equipment, for the other installation aspects.

Oil tank capacity must be calculated from the volume needed to operate the heating system at maximum capacity for at least two weeks.

Tanks must be located as far as possible from entrances to the building. The tank supporting structure must be made of non-combustible material and a safe ladder or staircase must be provided so the delivery technician can reach the fill pipe on the top of the tank. Necessary platforms, hand rails or guard rails must be provided to ensure the safety of the delivery technician. Ladders with one or two rungs may be used, but taller ladders must be avoided to facilitate the delivery technician's task of climbing up to the fill connection with the delivery hose. All metal works must be of hot-dipped galvanized steel.

4. The number of heating degree days is obtained by adding all daily variances in a year between the daily average temperature and 18°C, when this average is less than 18°C.

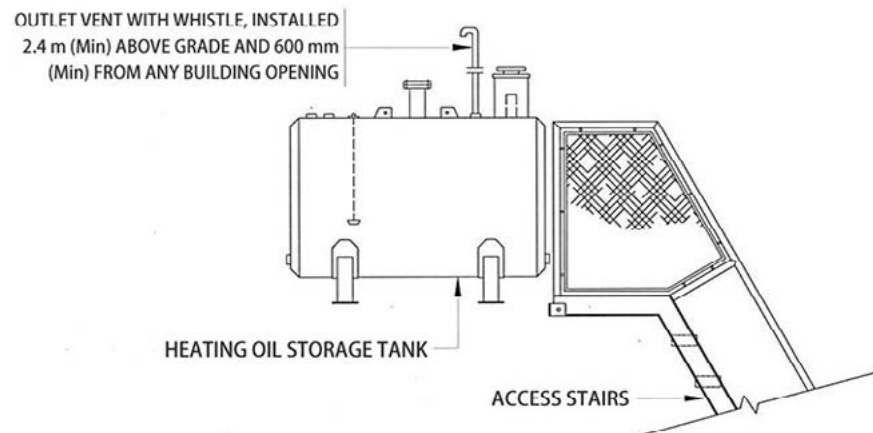


FIGURE 4.9: HEATING OIL TANK / SOURCE: SHQ

4.3.2 Heating oil supply

Tanks must be installed above grade outside buildings, at a height sufficient to supply the burner or burners by gravity without need of a pump.

All equipment (piping, joints, valves, etc.) and all materials used for the heating oil must be compatible with petroleum products.

A small leak-proof steel drip pan must be solidly secured to the floor beneath each piping joint (burner, filter, etc.) inside the building to contain any minor leaks.

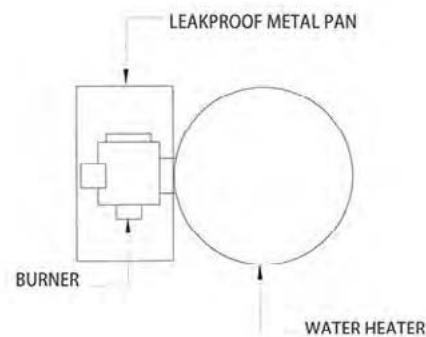


FIGURE 4.10: LEAKPROOF METAL DRIP PAN / SOURCE: SHQ

4.3.2.1 Heating oil temperature

Cold heating oil does not burn well. Before it reaches the burner, it must be preheated in a small auxiliary tank with a preheating oil pipe or serpentine supply tube inside the utility room near the burner.

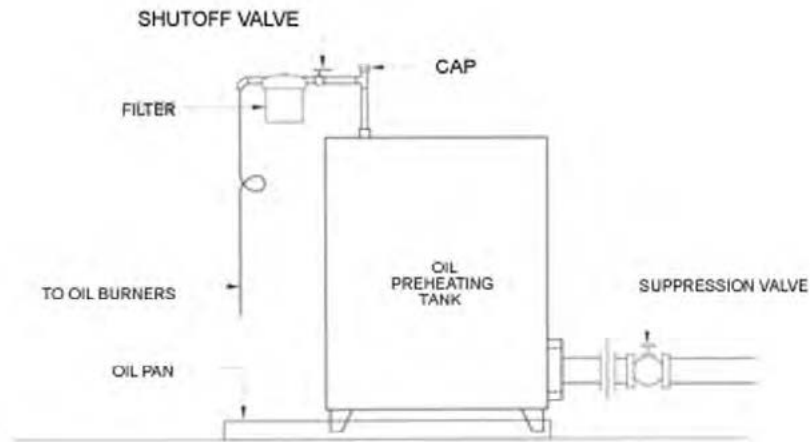


FIGURE 4.11: LEAKPROOF METAL DRIP PAN / SOURCE: SHQ

4.3.2.2 Piping

All exterior piping must be of hot dipped galvanized steel with series 40 threaded joints and a minimum diameter of 50 mm.

Supply piping must be equipped with a cleanout drain near the tank to trap water and sediment for removal. There must be a valve at tank outlet followed by a T with a branch at least 150 mm long running down and capped at the end. In Figure 4.12, this service connection is shown very close to the tank, outside the building. However, it could also be installed indoors to facilitate servicing, but the interior piping configuration does not always allow a 150 mm-long downward connection at its lowest point.

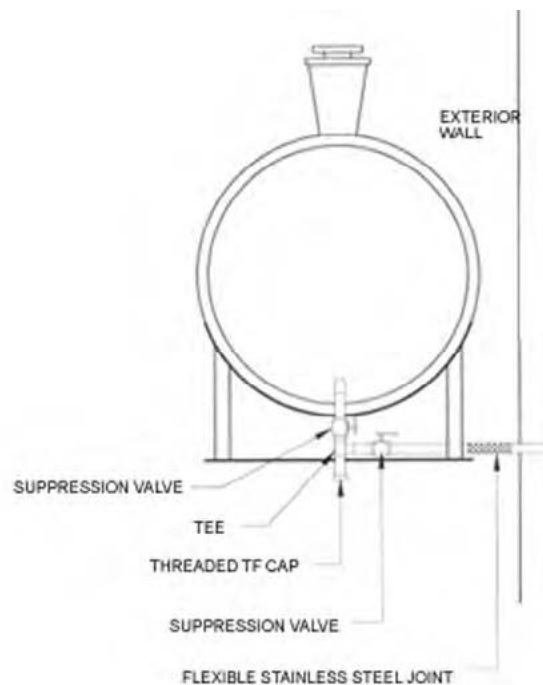


FIGURE 4.12: EXTERIOR PIPING FOR HEATING OIL SUPPLY LINE / SOURCE: SHQ

Piping connecting the tank outside the building must be equipped with a flexible joint in stainless steel mesh at least 600 mm long or a swivel joint⁵ near the exterior wall of the building. A flexible joint is preferable, especially where the tank and building are not resting on the same foundation.

The vent outlet must be equipped with a whistle and must be located at least 2.4 m above grade and 600 mm away from any opening in the building (see CSA-B139 standard for more details).

The burner must be connected with flexible pipe to facilitate maintenance and must be equipped with a leak-proof metal tray to capture any oil dripping off the bottom of the connections. Type K copper pipe or a flexible joint in stainless steel mesh may be used, the latter being preferable for maintenance.

4.3.2.3 Valves

A shutoff valve must be installed as close to the tank as possible (this valve may be similar to that used to purge the drip outlet) and another must be installed immediately next to where it enters the building. All equipment installed on the feed pipe that requires maintenance must be equipped with a valve at the entrance and exit (see Figure 4.12).

The feed pipe for each device must be equipped with a fuse valve installed at least one metre away from the burner, which shuts off in the event of fire.

4.3.3 Combustion and ventilation air

The air needed for oil-burning devices must enter freely through a special duct installed for this purpose. The combustion air intake duct should enter through the floor of the utility room so as to draw air from beneath the building. The combustion and ventilation air section of the CSA-B139 standard, Installation Code for Oil-burning Devices, provides more details.

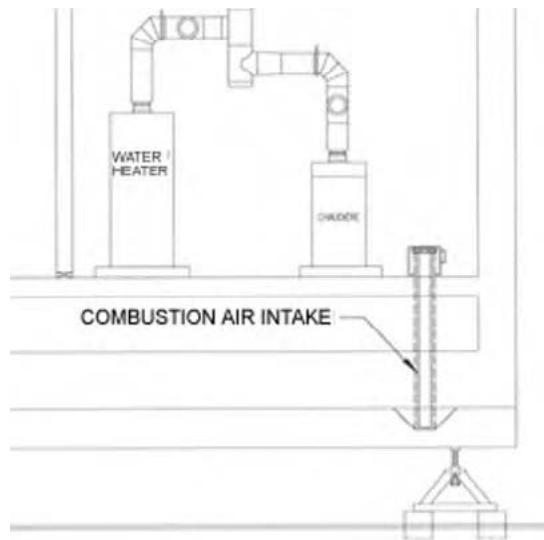


FIGURE 4.13 : ADMISSION D'AIR DE COMBUSTION / SOURCE : SHQ

Tightly sealed motorized dampers must be installed in combustion and ventilation air ducts.

The motorized damper in the combustion air duct must be synchronized with the combustion equipment so that it starts only when the damper is fully opened.

5. A swivel joint consists of two 90° elbows separated by a length of pipe.

The ventilation opening in the utility room must be placed close to the ceiling. The size of air intakes and exhausts must be calculated based on section 4 of the CSA-B139 standard, Combustion Gas Exhaust and Air Supply.

Air intakes and outlets must be very carefully positioned to avoid freezing equipment in the utility room (water pipes and pumps, heating oil supply lines, etc.).

Air temperature in the utility room must be regulated by a thermostat. An electromechanical control system must allow simultaneous opening of the motorized damper in the combustion air intake and the motorized damper in the room ventilation system.

The utility room ventilator must be interlocked with the combustion air intake damper so that it operates only when the motorized dampers are fully open. This should be an exhaust ventilator to let air enter naturally through the combustion air intake.

4.3.4 Combustion gas exhaust

Installation must comply with section 4 of the latest version of the CSA-B139 standard, Combustion Gas Exhaust and Air Supply.

It is preferable to install a single chimney for all combustion equipment (domestic water heater, furnace, etc.).

The chimney must be securely anchored to the building structure (roof flange and brace, anchor plate, etc.).

All fire safety clearances must be observed. Where a chimney passes through a floor and ceiling, radiant fire breaks must be installed.

Where horizontal exhaust ducts are necessary, these must be securely fastened to the building structure using a trapeze support and threaded rod.

An insulated T must be installed at the base of the chimney for cleaning out solid particles resulting from chimney sweeping.

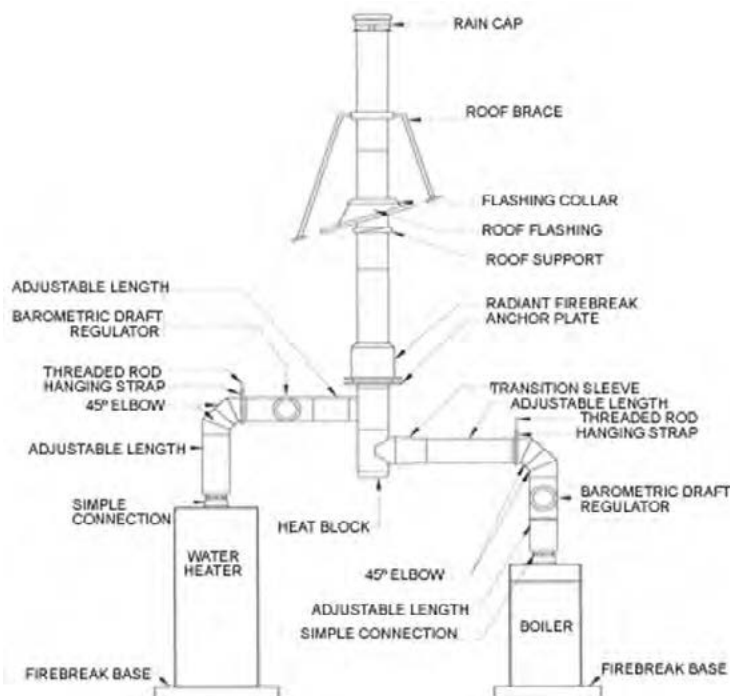


FIGURE 4.14: EXHAUST DUCTS AND CHIMNEY FOR COMBUSTION GAS / SOURCE: SHQ

4.3.5 Heating capacity

The heating system should be designed to produce no more than 100 percent of the maximum demand calculated from the applicable design parameters.

Heating systems perform best when running continuously. Oversized systems result in cycling (frequent stops and starts), which accelerates equipment wear and increases fuel consumption.

4.3.6 Heat-generating devices

The annual fuel usage efficiency (AFUE) of the heat-generating device determines which products perform best.

The higher the AFUE rating, the more efficient the device.

Some devices are rated at 85 percent or more. The energy performance rating must be certified by a recognized organization such as CSA International.

Even if not required by the manufacturer, a firebreak base of non-combustible materials must be installed below devices sitting on a combustible floor

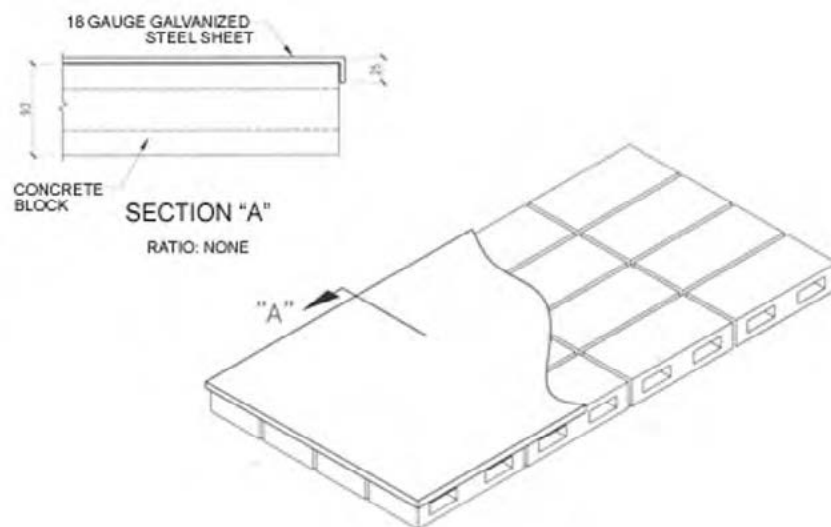


FIGURE 4.15: FIREBREAK BASE / SOURCE: SHQ

4.4 VENTILATION

4.4.1 General

Ventilation of residential buildings refers mainly to air exchange between indoor and outdoor, air distribution between rooms or air circulation within a given room (Institut national de santé publique du Québec [INSPQ], 2006). The introduction of fresh air indoors specifically helps dilute contaminants (White, 2003).

4.4.2 Natural ventilation

Natural ventilation primarily involves air movements resulting from opening doors and windows, all the small cracks and openings in the building envelope as well as the poorly sealed perimeter of doors and windows (INSPQ, 2006).

Natural ventilation occurs either through infiltration (passage of air from outdoors to indoors) or exfiltration (passage of air from indoors to outdoors). In a home, the movement of air (infiltration and exfiltration) is generated by a pressure differential between the interior and exterior. This pressure differential may be caused by a temperature difference (chimney effect) or wind action.

A house is deemed airtight when it has very little infiltration and exfiltration.

Natural ventilation is highly random and hard to control since it is affected by various factors such as airtightness of the envelope, temperature difference between outdoors and indoors, wind speed, etc. (Canada Mortgage and Housing Corporation [CMHC], 2004). Houses with a very high natural infiltration rate are also subject to large energy expenses (Efficiency and Renewable Energy Clearinghouse [EEREC], 2002).

4.4.3 Mechanical ventilation

Increased airtightness and insulation of houses have contributed to the development of mechanical ventilation (Environmental Protection Agency [EPA], South Dakota), which is an effective way to control air exchanges and thereby improve air quality and comfort inside buildings without sacrificing the benefits of a more airtight envelope (Reardon et al., 1990).

Mechanical ventilation refers to any motorized device that exhausts and takes in air to facilitate the aeration of rooms by exhausting stale air and replacing it with fresh air from outdoors (INSPQ, 2006). Mechanical ventilation systems are divided into three main categories.

- **Simple exhaust systems:** One or more ventilators expel air, while replacement air enters by infiltrations.
- **Simple air intake systems:** One or more ventilators draw outdoor air into the building while existing indoor air is expelled through openings in the envelope.
- **Balanced systems:** One or more ventilators expel stale air and draw in fresh air.

4.4.3.1 Primary ventilation system

Installation must comply with section 9.32, Ventilation, and part 11, Energy Efficiency, of Chapter 1, Building, Quebec Construction Code, current edition.

The primary ventilation system must:

- Have an extraction capacity consistent with the following table:

NUMBER OF BEDROOMS IN THE HOUSING UNIT	PRIMARY VENTILATOR'S EXTRACTION CAPACITY IN NORMAL OPERATION, L/S	
	MINIMUM	MAXIMUM
1	16	24
2	18	28
3	22	32
4	26	38
5	30	45
More than 5	Installation must comply with the CAN/CSA F326-M91 standard.	

TABLE 4.1: EXTRACTION CAPACITY

b. Include a heat recovery ventilator (HRV) for which:

- Heat recovery efficiency (HRE) is certified by the Home Ventilating Institute (HVI) under the CAN/CSA C439 standard, Standard laboratory methods of testing for rating the performance of heat/energy- recovery ventilators;
- Heat recovery efficiency (HRE) is at least 60 percent and determined at a dry thermometer temperature of -25°C;

Each dwelling unit therefore must be equipped with its own heat recovery ventilator (HRV). The HRV should be located in the utility room, to mitigate noise and facilitate maintenance by qualified staff.

c. Ensure minimum fresh air flow equal to the total needs of each room as in the following table:

USE OF ROOM	MINIMUM FLOW (L/S)
Master bedroom	10
Single bedroom	5
Living room	5
Dining room	5
Family room	5
Kitchen	5
Bathroom	5
Laundry room	5

TABLE 4.2: REQUIRED FRESH AIR FLOW

NOTE: ROOMS USED ONLY AS AN ENTRANCE, EXIT OR STORAGE AREA, SUCH AS VESTIBULES, HALLS, LANDINGS, SERVICE CLOSETS AND HEATING AREAS DO NOT REQUIRE INTAKE OF FRESH AIR.

d. Replace air in the dwelling unit at a renewal rate of 0.3 air volume per hour (CMHC – technical series 08-100);

e. Include a defrost cycle through air recirculation to avoid depressurization of the dwelling unit.

The HRV control device should be easy to use and located in the living room. The control device should include the following functions.

- Turn off the HRV.
- Operate the HRV continuously in outdoor exchange mode.
- Operate the HRV in exchange in scheduled mode (e.g. 20 minutes in exchange mode and 40 minutes in recirculation mode).
- Operate the HRV in exchange mode when relative humidity exceeds the set point.

During the heating season, relative humidity inside a housing unit should not exceed 50 percent. In periods of extreme cold, relative humidity should be close to 30 percent to prevent condensation on windows (CMHC, Moisture and Air – A Guide for Understanding and Fixing Interior Moisture Problems in Housing, 2012).

4.4.3.2 HRV fresh air intake

The fresh air intake must be designed and installed to avoid obstruction by aspirated snow, through the use of a downward opening duct. The intake opening must be at least 600 mm above grade and the section must be large enough to attain an air intake speed of less than 1.5 m/s.

The fresh air intake must be placed where it cannot be blocked by accumulated snow, and on the opposite side of the building from potential sources of contamination such as sewage pump-out connections, heating oil fill pipes, etc. The placement of fresh air intakes must also consider factors such as prevailing winds, parking areas for automobiles, all-terrain vehicles, snowmobiles, etc. If not located on the opposite side from sources of contamination, fresh intakes must be at least two metres away from these points.

Fresh air intakes should be located underneath the building. If snow does accumulate in the air intake duct, the water from melting snow and ice can drain directly to the outdoors by gravity with no risk of serious damage to the thermal envelope due to infiltration.

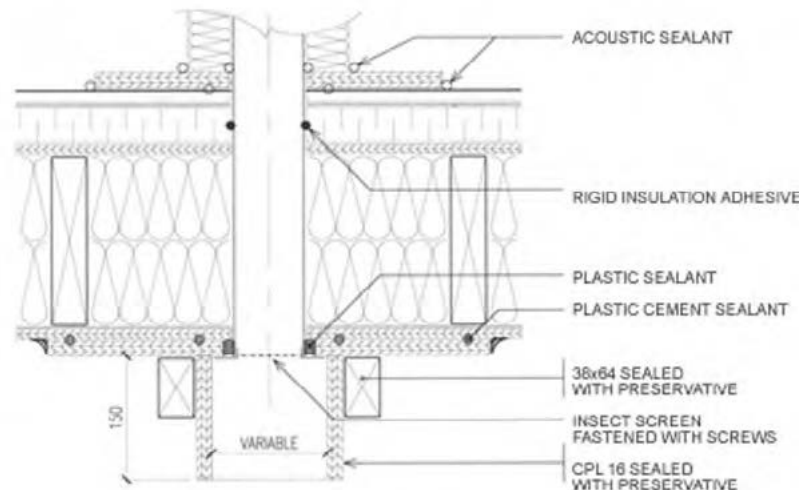


FIGURE 4.16: FRESH AIR INTAKE / SOURCE: SHQ

A removable insect screen should prevent the intake of insects in summer and can be removed in winter if air intake might be blocked by snow.

When the building's central ventilation system is not operating or is in recirculation mode, a tightly sealed device must prevent fresh air from infiltrating into the building.

4.4.3.3 HRV stale air exhaust

The heat recovery ventilator (HRV) stale air exhaust must not be located where snow might accumulate and where it would be exposed to prevailing winds.

Snow accumulation can prevent the system from effectively exhausting stale air from the building.

4.4.3.4 Kitchen range hood

The range hood must exhaust stale air directly out of the building. The extraction ventilator must have a nominal capacity of at least 50 l/s.

The range exhaust outlet should be located beneath the building so that water generated by condensation can drain directly outdoors.

A gravity check valve should be installed at the end of a horizontal duct upstream from the vertical segment that passes through the thermal envelope.

Installing the check valve in the heated portion of the building avoids problems associated with ice blocking the valve. When it does become blocked, the range cannot effectively exhaust the excess humidity generated by cooking food.

4.4.3.5 Bathroom

The primary ventilation exhaust intake should be located in the bathroom. The HRV thus can recover a significant portion of the energy contained in the air while also supplying replacement air in the dwelling unit. A manual control in the bathroom should place the HRV in exchange mode for a limited time (e.g. 20 minutes), after which the HRV will resume normal operating mode. Nominal exhaust capacity must be **at least 25 l/s**.

If the exhaust air intake is not located in the bathroom or toilet room, an additional exhaust device must be installed. This device must be controlled by a wall switch and have a nominal capacity of **at least 25 l/s**.

4.5 HYDRONIC HEATING SYSTEM

4.5.1 General

Hydronic heating systems use a heat transfer fluid to carry heat to the various rooms in the house.

4.5.2 Operation

A boiler equipped with an oil burner heats the water-glycol (heat transfer) mix and a pump circulates this mix through a closed loop of radiators in the rooms of the house before it returns to the boiler. Each radiator (or group of radiators) can be controlled by a valve and a thermostat to maintain the desired temperature in a specific zone.

In other words, each heating zone can be controlled by a thermostat that activates the valves near the radiators to heat this zone.

The thermostats in a zone open or close the valves for the zones they control to start or stop circulation of the hot water-glycol mix in the radiators.

The burner is activated by a control that maintains the temperature of the water-glycol mix in the boiler within the selected set points. This boiler can also heat domestic hot water. A separate hot water loop connects to the water heater tank and is controlled by the thermostat on that tank.

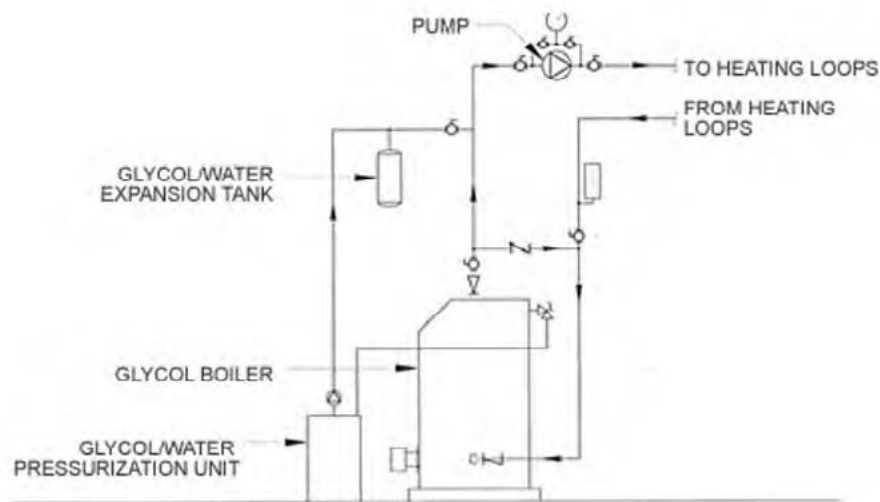


FIGURE 4.17: HYDRONIC HEATING LOOP FLOW DIAGRAM / SOURCE: SHQ

4.5.3 Components

Hydronic heating in Nunavik uses a heat transfer fluid composed of equal parts water and propylene glycol (by volume). The glycol prevents freezing and damage caused by ruptured pipes in the event of an extended outage.

The expansion tank absorbs dilation of the heat transfer fluid volume and must be large enough to handle the expansion coefficient of the mix.

The boiler's safety release valve must be connected to the pressure unit tank to the water-glycol mix can be recovered if the valve is opened.

A pump circulates the water-glycol mix through the piping loop to move the heat to the radiators. This loop must be equipped with drainage valves at the low points and air purgers at the high points in the loop.

4.6 FIRE SAFETY

4.6.1 Smoke detector

One of the most important principles of fire safety is speed of fire detection. Smoke detectors must be installed in the following locations in all dwelling units.

- On each floor
- In the hall close to bedrooms
- In each bedroom where someone sleeps with the door closed
- Close to stairways

The goal is to ensure that occupants can hear the alarm regardless of what they are doing.

Installation of smoke alarms is discouraged, however, in certain locations close to doors into the kitchen or bathroom, ventilation duct outlets, curtains, peaks of vaulted ceilings, wall corners, etc.

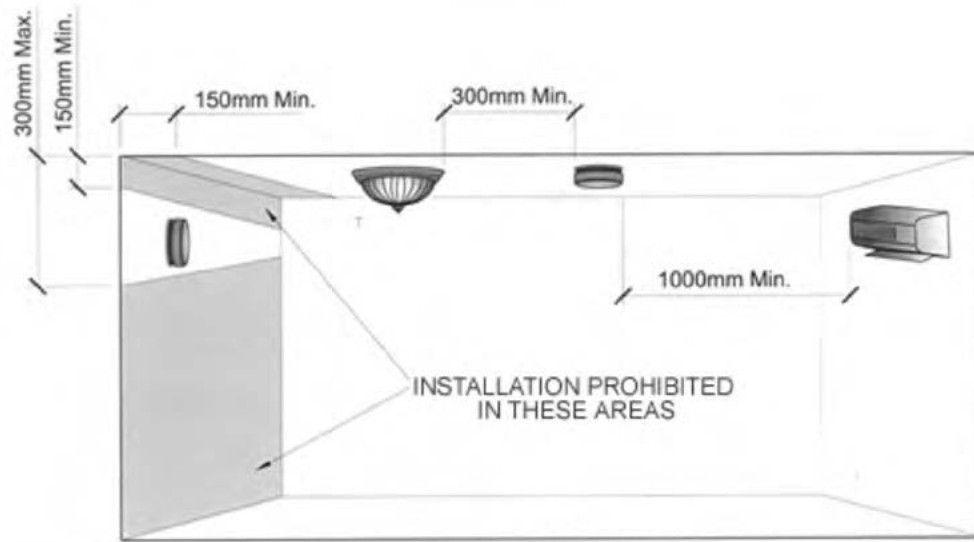


FIGURE 4.18: SMOKE DETECTOR PLACEMENT/ SOURCE: SHQ

4.6.2 Portable extinguishers

Portable extinguishers may be used by occupants when their safety is not compromised and the fire is small, to avoid serious consequences.

Class A, B and C extinguishers approved by Underwriters Laboratories Canada (ULC) are recommended. Extinguishers must be designed for the conditions in which they will be stored, especially where the temperature is below freezing.

4.6.3 Fire stops

Air within a building must not be able to move from one dwelling unit to another through ventilation ducts, heating ducts or a joint utility room.

In the event of fire, smoke generated in one dwelling unit must not spread to other units.

Fire stop registers must be installed in ventilation ducts where smoke might spread from one unit to another.

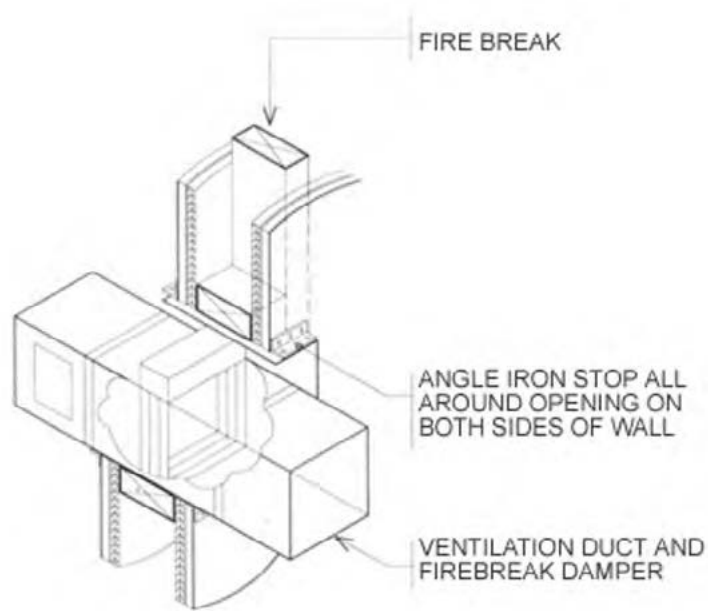


FIGURE 4.19: FIRE STOP REGISTER / SOURCE: SHQ

Fire stop registers must be accessible, through a hatch or other type of opening, for maintenance, inspection and resetting.

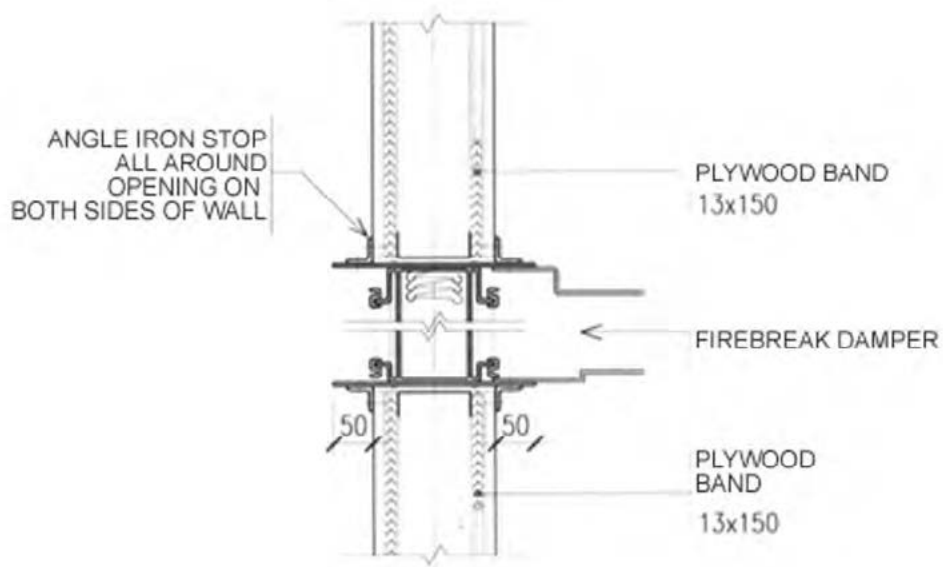


FIGURE 4.20: FIRE STOP REGISTER / SOURCE: SHQ

4.7 COMMISSIONING AND MAINTENANCE (PLUMBING – HEATING – VENTILATION)

4.7.1 Replacement parts and equipment

Maintaining an inventory of replacement parts and equipment is recommended for the most important components (drinking water pressure pumps, heating water circulation pumps, burners, burner sprinklers, fuses, etc.) to ensure the safety of occupants despite delivery delays, which can be very long.

4.7.2 Testing and maintenance

Operational and commissioning testing for heating and plumbing systems must be conducted to ensure their proper operation.

Before delivery of the building, the contractor must ensure that:

- Ventilation ducts and filters have been cleaned and fire stop registers have been tested;
- The sewage removal and ventilation system has been tested for airtightness and water tightness;
- The sewage holding tank has been tested outdoors before being installed in the building, and a water tightness test has been conducted once all plumbing has been installed;
- The drinking water tank and supply system have been cleaned and disinfected with a chlorine solution, which must then be disposed of; the tank and system must then be rinsed with drinking water and all screens must be cleaned;
- All indicator lamps (interior and exterior) must be tested.

Air pressure test

1. The air pressure test must be performed by closing all openings in a system or any part of a system to be tested, and filling it with air at a pressure of at least 35 kPa.
2. The test is deemed satisfactory if the pressure remains stable for 15 minutes, without having to add more air.
3. The pressure gauge must be graduated from 0 to 70 kPa.

Water pressure test

1. Water must be raised to a level at least three metres above all parts of the section tested.
2. The water test must be conducted by closing all openings in the drainage system and the section to be tested, except the top end where water is introduced until the system has been completely filled.
3. The test is deemed satisfactory if the water level remains stable for 15 minutes.

4.7.3 Access

Adequately sized access points must be provided for maintenance, replacement or operation of dampers (intake, return and exhaust), fire stop registers, filter, heat exchangers, etc. Heat exchangers, for example, must be able to be cleaned on each side to remain efficient.

5. FOUNDATIONS ON PERMAFROST

5.1 BASIC CONCEPTS OF PERMAFROST

5.1.1 Introduction

The presence of permafrost is a characteristic of cold regions. Before even considering erecting any building or infrastructure, it is important to clearly understand what permafrost is. First, it is a thermal phenomenon. Its ability to support infrastructure and foundations depends on keeping it below the freezing point. Second, it is crucial to understand that permafrost contains ice, often in very large quantities. The mix of frozen soil and ice constitutes a very solid substratum. Once it thaws, however, permafrost often liquefies and loses all consistency as well as its ability to support buildings and infrastructure. In this natural environment, thawing of permafrost can trigger compaction of the land surface, destabilize slopes, affect soil drainage and the hydrographic system, cause the formation of small lakes and drain others. The ecosystem is altered by deterioration of the permafrost, also called thermokarst⁶.

This section defines what permafrost is. It explains the geographic distribution of the phenomenon in northern Québec, as well as the key components of the permafrost thermal regime, which is intimately linked to climate. Special attention is paid to measurement and thermal monitoring, as well as ways to represent these. The main forms in which ice occurs in permafrost are described and explained, and then linked to the surface deposits most common in northern Québec. The landforms specific to permafrost are named, described and briefly explained.

5.1.2 Definitions

Permafrost is defined as: “Ground (soil or rock) that remains at or below 0°C for at least two years” (Associate Committee on Geotechnical Research, National Research Council Canada, 1988).

This definition is based solely on the thermal criterion, regardless of lithology, granulometry, and water and ice content. A rocky substrate, for example, or unconsolidated deposit with a temperature below zero is considered permafrost even if it contains no ice in its pores or structure.

Although the official definition refers to a period of at least two years below the freezing point, permafrost is a phenomenon that actually lasts for centuries. In Nunavik, permafrost has been present under the tundra since the last deglaciation, which ended 7,000 to 8,000 years ago.

South of the tree line, in the forested tundra, permafrost is more recent and in large part has existed since the cold period known as the “Little Ice Age,” which extended from 1300 to 1900 AD.

Paleoclimatic reconstructions actually indicate that permafrost has been present in Québec for centuries or millennia (Allard and Séguin, 1987a; Chouinard *et al.*, 2007).

6. NB: The term *thermokarst* refers to both the permafrost deterioration process and the resulting disturbed land relief.

5.1.3 Permafrost depth

Permafrost depth varies by location. It may extend down only a few metres at the southern edge of its range, but often exceeds several hundred metres in the continuous zone. At the Raglan mine in Nunavik, for example, the permafrost is 630 metres thick. As a rule, the colder the climate, the deeper the permafrost. But in a region with the same temperature, it is often much thicker in rock than in unconsolidated deposits, because the thermal conductivity of rock (its ability to transfer and lose heat in a cold climate) is much greater than that of unconsolidated soils, which contain more water and have components (e.g. stones, grains of sand, microscopic grains of silt and clay) are not as densely compacted. Permafrost depth is measured between its table and base. The permafrost table is located at the base of the active layer, the maximum depth of the surface layer of the earth that thaws in summer. At the permafrost table, the average annual temperature is fairly close to the air temperature (with some differences, explained below). As depth increases, the temperature rises gradually. The permafrost base is located at the depth where the temperature again rises above 0°C (Figure 5.1).

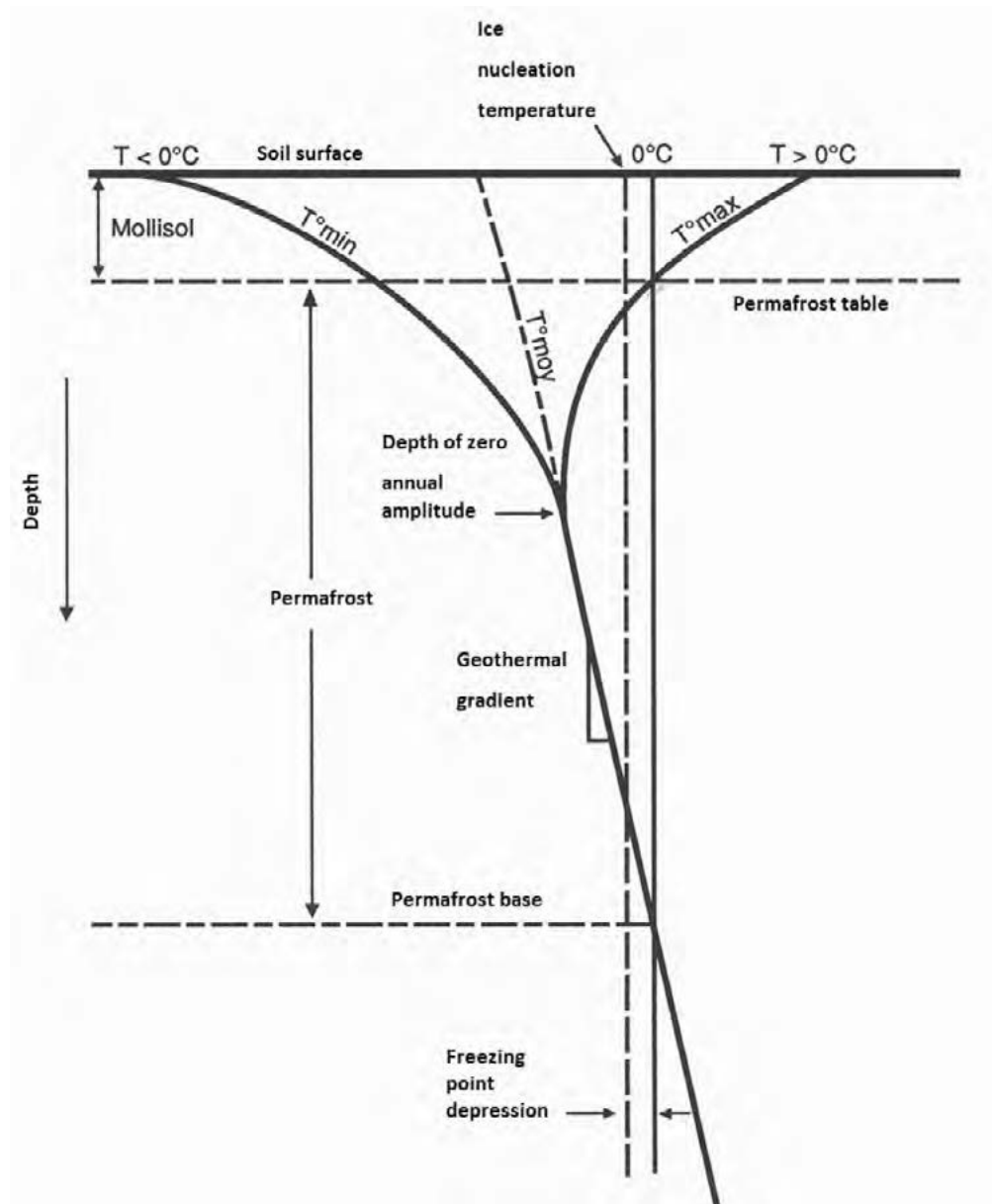


FIGURE 5.1: GENERAL THERMAL PROFILE IN PERMAFROST AND DEFINITIONS.

5.1.3.1 The active layer

The top layer of earth that thaws in summer and freezes again in winter is known as the active layer. The surface soil is frozen in winter but quickly begins to thaw when summer starts. Over the days and weeks, the thawed layer extends downward from the surface. The thawing front is said to move down through the soil, and generally matches the 0°C isotherm (line of equal temperature) in the soil. The maximum depth reached by the thawing front at the end of summer defines the thickness of the active layer. In years with warmer summers, the active layer extends deeper or is thicker, and the reverse holds true in cooler summers. In fact, the depth of the active layer varies from year to year (by a few centimetres or decimetres depending on the type of soil and the amplitude of climate variations). Once atmospheric temperatures drop below 0°C at the end of summer, the soil starts to freeze again. Freezing temperatures (0°C isotherm) move downward from the surface; this is the advance of the freezing front. In regions where the permafrost is colder, however (for example, a few degrees below 0°C), a second freezing front moves up from the base of the active layer. This is two-sided freezing (Figure 5.2).

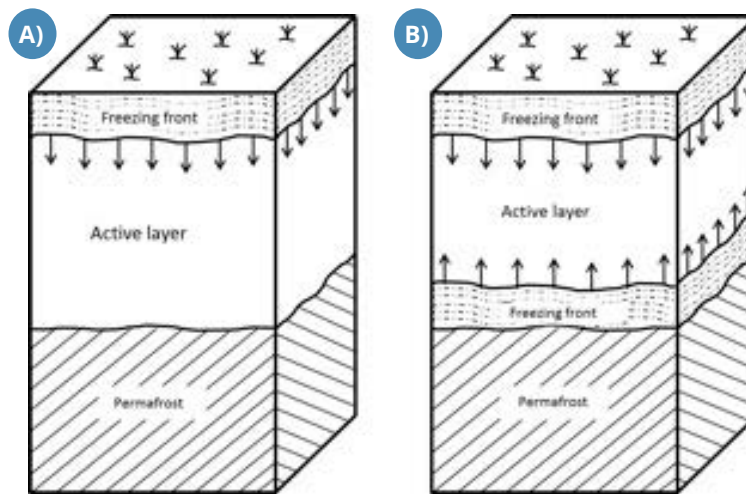


FIGURE 5.2: ILLUSTRATION OF FREEZING AND THAWING OF THE ACTIVE LAYER
A) REFREEZING FROM ABOVE, B) REFREEZING FROM ABOVE AND BELOW.

5.1.3.2 The permafrost thermal regime

Throughout the land, the sum total of heat exchanges determines the temperature in permafrost, as well as the thickness and variations of the active layer.

The essential condition for the existence or maintenance of permafrost is an average annual temperature on the soil surface at or below 0°C. In construction, the goal is to maintain the permafrost under the building or infrastructure to ensure it is supported. The foundation design therefore must meet this inescapable condition that the temperature of the natural ground under the building must never rise above 0°C. However, there is no need to keep the ground under a structure below 0°C when building on solid rock or a deep surface deposit that we are absolutely certain contains no excess ice (see below).

In the natural environment, several factors determine surface soil temperature. Some of these are purely climatic: air temperature, wind speed, solar radiation and precipitation. However, air temperature is by no means the climate component that contributes the most to the thermal regime of permafrost. Since the climate behaves similarly over vast areas, it is what governs regional conditions of the permafrost thermal regime. Local factors, however, govern heat exchanges between the atmosphere and the land surface. The most important ones are: snow cover on the ground, height and density of plant cover, presence of moisture on the ground surface and, finally, the nature of the surface, which may be mineral or composed of an organic horizon. These factors are interdependent; for example, dense shrub vegetation secures windblown snow in winter, while its dark shades absorb more solar radiation in summer (low albedo). Thus, shrubs and snow cover act together to mitigate the influence of air temperature on soil and warm its surface.

Land conditions, primarily snow on the ground and vegetation, can mean that in the same climate, the soil surface temperature varies across the landscape within a given region. Sufficiently deep snow cover can result in a positive average annual temperature (i.e. $> 0^{\circ}\text{C}$) on the soil surface and the absence of permafrost. For example, Figure 5.3 shows two charts illustrating the relationship between snow depth at the end of winter (March-April) and average annual temperature of the soil surface, one at Salluit, the other at Tasiujaq. We see that permafrost is not viable in Tasiujaq at snow depths exceeding about 80 cm; in Salluit, this critical depth approaches one metre. However, the latter also varies due to snow density, which is linked to its compaction by wind or human activity (e.g. banks or mounds linked to snow-clearing operations).

Due to snow, vegetation, surface humidity and soil type, soil temperature may not be below zero in all places where air temperatures are milder but still below freezing. The variable distribution of these factors over the land is the primary reason for the existence of the discontinuous permafrost zone

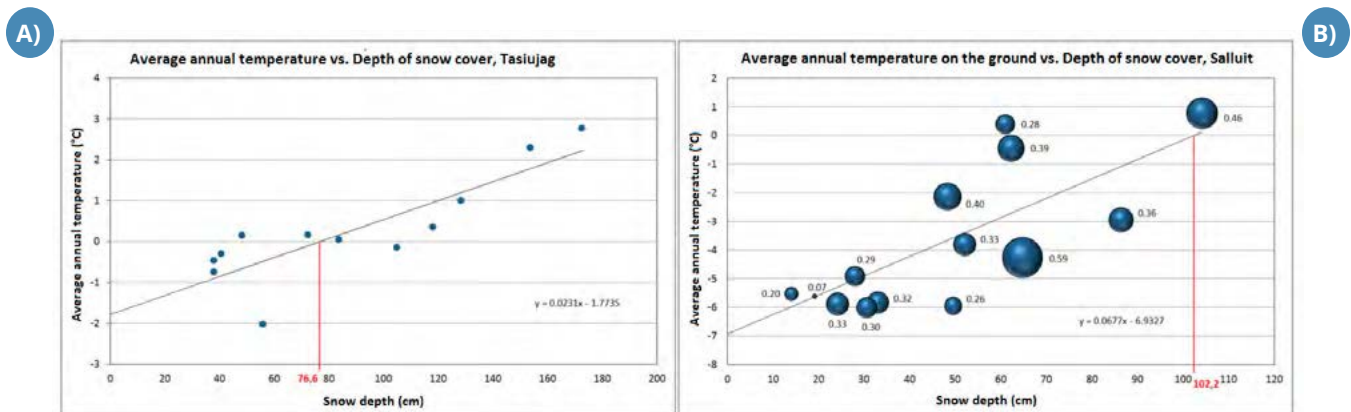


FIGURE 5.3: RELATIONSHIP BETWEEN SNOW DEPTH ON THE GROUND AT THE END OF WINTER AND AVERAGE ANNUAL TEMPERATURE AT THE SURFACE OF THE GROUND. A) TASIUJAQ, B) SALLUIT. CIRCLE SIZE IS PROPORTIONAL TO OVERALL DENSITY OF SNOW COVER.

Permafrost zones are defined by the continuity of permafrost distribution over the land (Figure 5.4). In northern Québec, the so-called *continuous permafrost* zone extends roughly above the 58th parallel north and on the high plateaus east of the George River. In the continuous zone, permafrost is believed to extend under all types of rocks and terrain. It is absent, however, beneath lakes and rivers, which occupy vast expanses of this region; the bottom of all bodies of water at a depth greater than winter ice thickness cannot reach freezing temperature, so there can be no permafrost below them.

For large enough lakes, this unfrozen zone, called *talik*, extends vertically down between all bordering permafrost areas.

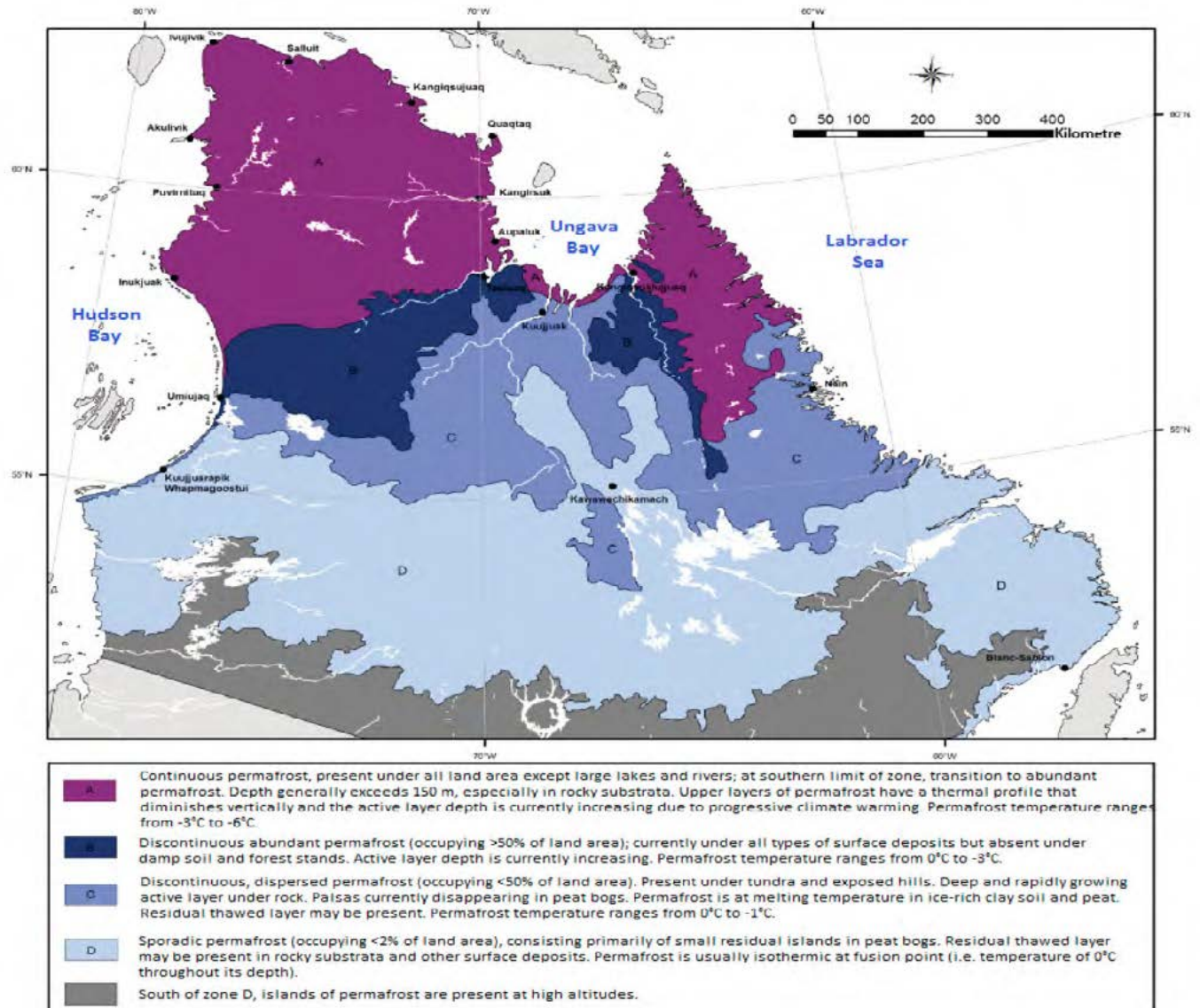


FIGURE 5.4: DISTRIBUTION OF PERMAFROST IN NORTHERN QUÉBEC.

Average air temperatures in the continuous permafrost zone are roughly below -3°C . The permafrost is very thick; for example, it reaches 630 metres in a borehole at the Raglan mine. The discontinuous permafrost zone extends on both sides of the tree line, generally across the isotherm for an average annual air temperature of 0°C .

In very approximate terms, the discontinuous permafrost zone is divided into two sub-zones: the abundant discontinuous permafrost zone, where more than half the land area is occupied by permafrost, and the dispersed discontinuous permafrost zone, where permafrost occupies less than half the land area. The tree line coincides almost exactly with the boundary between these two sub-zones. The many forest islands in the forested tundra are snow covered and generally damp, without permafrost, while the barren summits covered with tundra are windswept in winter, so have little snow cover and thus are favourable to the persistence of permafrost.

The southern sector of northern Québec is the sporadic permafrost zone. Permafrost there is thin, very rare and often short lived (a few years). It is found in small plates in peat bogs and on the summits of high hills where the climate is colder.

The Inuit communities of Kangiqsualujjuaq, Kuujuaq and Umiujaq are located in the discontinuous permafrost zone. The remaining communities—Inukjuak, Puvirnituq, Akulivik, Ivujivik, Salluit, Kangiqsujuaq, Quaqtaq, Kangirsuk, Aupaluk and Tasiujaq—are in the continuous permafrost zone. Note that Tasiujaq is located just a few kilometres north of the “discontinuous-continuous” boundary. There is no permafrost in Kuujuarapik and Whapmagoostui.

5.1.3.3 Measuring temperature in permafrost

Although there are various techniques for measuring soil temperature (e.g. thermometers, thermocouples), thermistors are by far the most commonly used instrument. This consists of an electrical resistor roughly the size of a match head connected to two small wires; when electrical current is applied, the resistance value varies as a function of the ambient temperature. This resistance is easily measured with a multimeter. The electrical resistance, converted into temperature, can be measured and recorded by a datalogger (see diagram in Figure 5.5). A correctly calibrated thermistor can be accurate to 0.01°C. Thermistors are usually installed along multistrand cables and distributed vertically at various depths in a borehole to measure the vertical temperature profile.

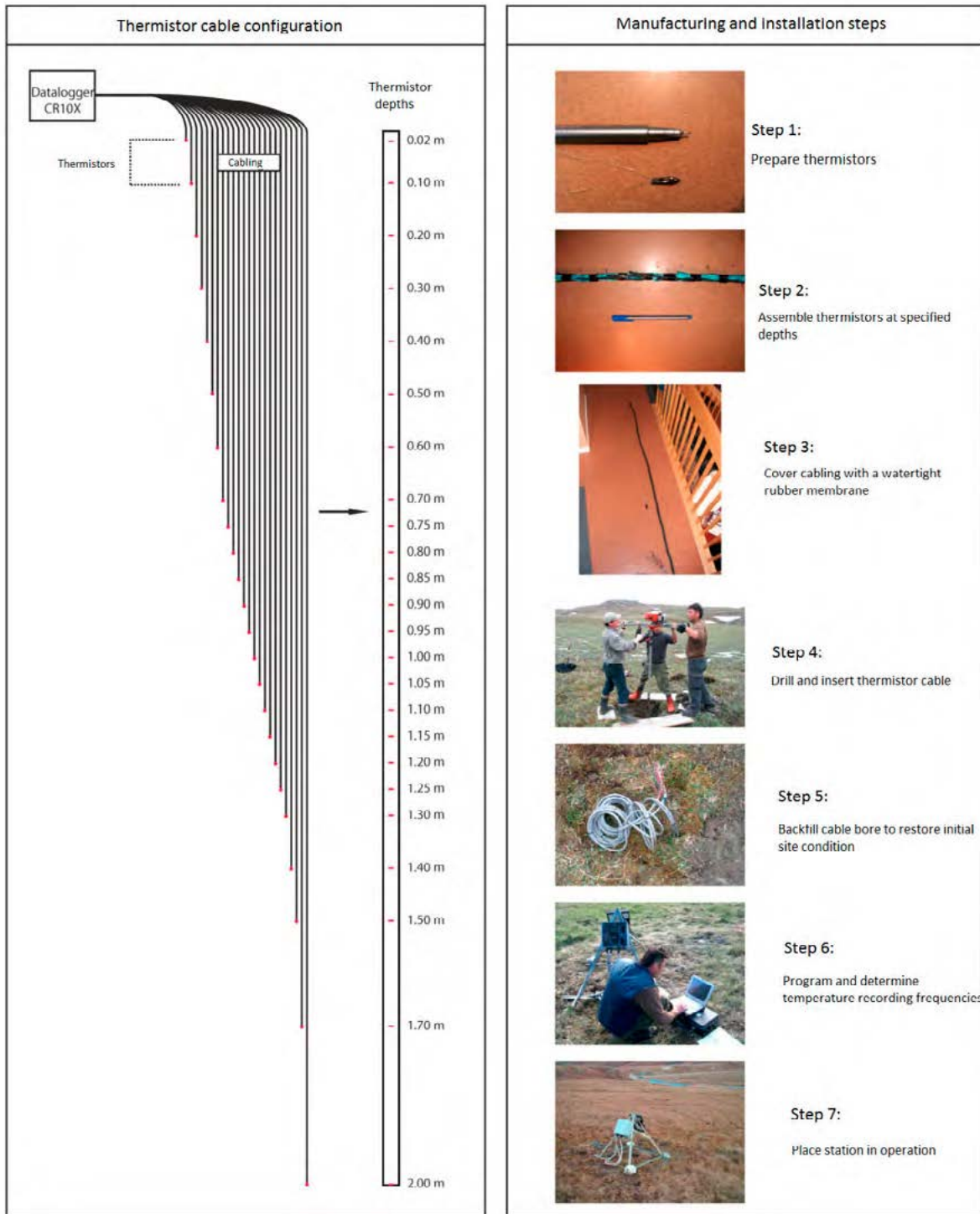


FIGURE 5.5: ALTHOUGH THERE ARE VARIOUS TECHNIQUES FOR MEASURING SOIL TEMPERATURE (E.G. THERMOMETERS, THERMOCOUPLES), THERMISTORS ARE BY FAR THE MOST COMMONLY USED INSTRUMENT. THIS CONSISTS OF AN ELECTRICAL RESISTOR ROUGHLY THE SIZE OF A MATCH HEAD CONNECTED TO TWO SMALL WIRES; WHEN ELECTRICAL CURRENT IS APPLIED, THE RESISTANCE VALUE VARIES AS A FUNCTION OF THE AMBIENT TEMPERATURE. THIS RESISTANCE IS EASILY MEASURED WITH A MULTIMETER. THE ELECTRICAL RESISTANCE, CONVERTED INTO TEMPERATURE, CAN BE MEASURED AND RECORDED BY A DATALOGGER (SEE DIAGRAM IN FIGURE 5.5). A CORRECTLY CALIBRATED THERMISTOR CAN BE ACCURATE TO 0.01°C. THERMISTORS ARE USUALLY INSTALLED ALONG MULTISTRAND CABLES AND DISTRIBUTED VERTICALLY AT VARIOUS DEPTHS IN A BOREHOLE TO MEASURE THE VERTICAL TEMPERATURE PROFILE.

5.1.3.4 Methods for representing the permafrost thermal regime

There are two main methods for graphic representation of thermal data measured with thermistor cables: 1- representation with a series of vertical profiles, sometimes called a “trumpet diagram”; 2- representation by temperature curves moving over time, at various depths.

5.1.3.5 Vertical temperature profiles

Each profile traced on a trumpet diagram represents the measurement of the thermal profile at a particular time, for example, on a given day. It can also show average monthly or seasonal temperature profiles or maximum and minimum temperatures measured at various depths. When it shows maximum and minimum temperature profiles, a trumpet diagram illustrates the amplitude of temperature variations at various depths over the course of a year. A profile of maximum temperatures or at summer's end (e.g. mid September) can determine the depth of the active layer to the point where the profile crosses the 0°C line (Figure 5.6).

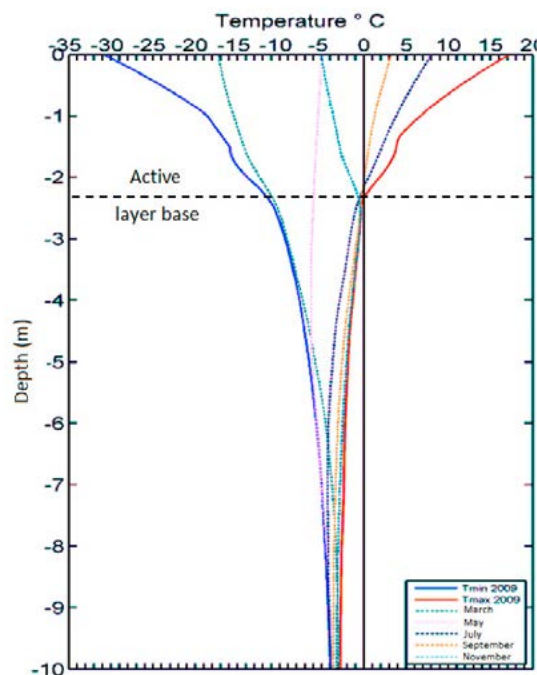


FIGURE 5.6: TRUMPET DIAGRAM WITH TEMPERATURE PROFILES ON VARIOUS DATES IN A YEAR AND MINIMUM AND MAXIMUM TEMPERATURES ENVELOPE. THE MAXIMUM TEMPERATURES PROFILE CROSSES 0°C AT THE BASE OF THE ACTIVE LAYER. EXAMPLE FROM PERMAFROST IN SAND AT QUAQTAQ.

Profiles measured in sufficiently deep bores will reach a level where the annual fluctuation (amplitude) is minimal (less than 0.1°C). The greater the depth, the more gradually the temperature tends to rise. The slope of the profile (in metres per degree) is the geothermal gradient (Figure 5.1).

In the case of sufficiently long climate change, the minimal variations that occur deep in the earth over time will change the slope of the thermal gradient. Similarly, beneath infrastructure or a building that would warm the surface of the soil, the deep temperature profile will change. Adequate instrumentation, such as thermistor cables, can monitor the impact of thermal change on the surface due to climate change or infrastructure.

5.1.3.6 Temperature curves over time

This method of graphic representation highlights the temperature changes that occur at various measurement depths over the seasons. Air temperature variations are often added to this chart to analyse how the soil reacts to the climate (Figure 5.7). This method can also detect the impact of specific factors on the thermal regime, such as snow cover or a sudden infiltration of water into the soil. In freeze or thaw situations, in fall and spring, it can also detect the presence of water in the soil through the effect of the zero curtain, a period during which temperature remains stationary during the time needed to convert water into ice in the soil or, conversely, during a thaw, the time for ice in the soil to melt. This phenomenon is caused by one of the fundamental properties of water: latent heat of fusion.

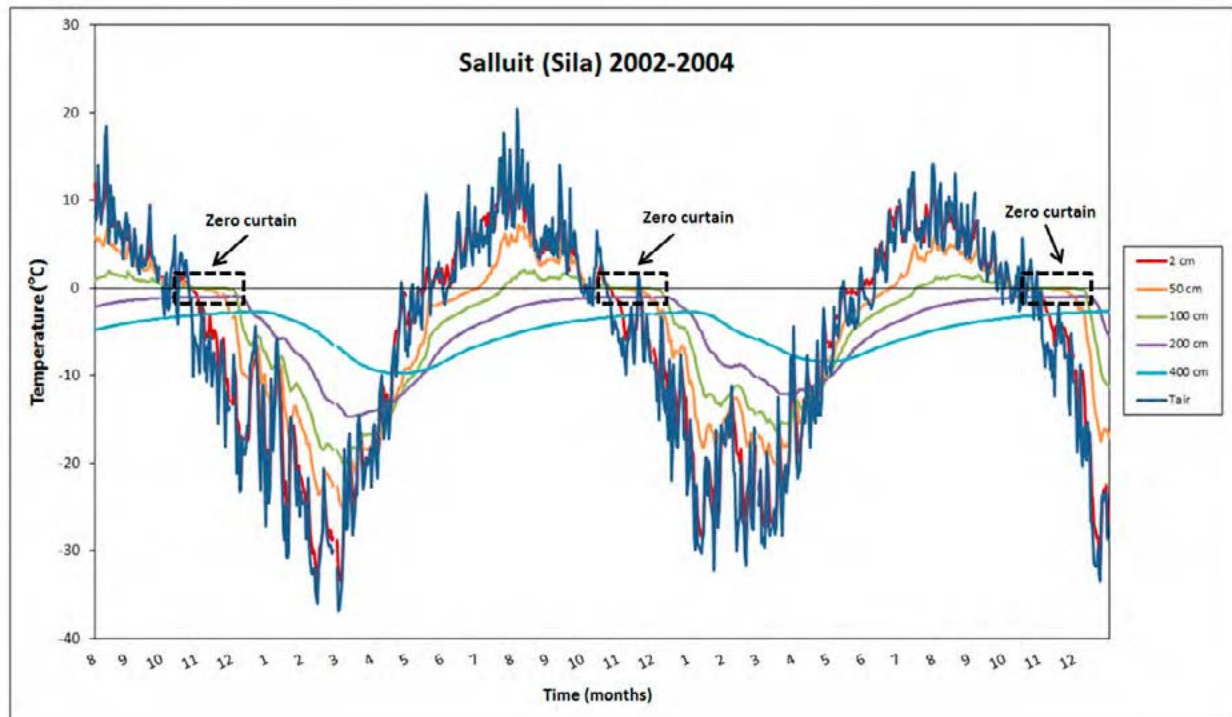


FIGURE 5.7: DIAGRAM OF TEMPERATURES OVER TIME. THE DECLINE IN AMPLITUDE OF TEMPERATURE VARIATIONS FROM THE SURFACE DOWN IS VISIBLE, AS WELL AS THE DEPHASING OVER TIME. AT 100 CM, DURING REFREEZE, TEMPERATURE REMAINS STATIONARY AT THE ZERO PERIOD FOR SEVERAL DAYS, THE TIME REQUIRED TO FREEZE THE WATER IN THE ACTIVE LAYER. THIS IS THE “ZERO CURTAIN.” THE SOIL AT THIS SITE IS TILL.

This type of diagram also shows that temperature variations recorded at the surface, especially seasonal temperatures, spread in the soil but decline as depth increases (declining amplitude) and the time lag (dephasing) increases. This method of graphic representation readily shows that the winter “cold wave,” fairly mitigated at the surface, spreads through the soil with mitigation and dephasing. The same applies to the summer “heat wave” (Figure 5.7). This phenomenon is linked to another fundamental property of permafrost: thermal diffusivity.

5.1.4 Thermal properties of soil

Temperature change rates in soil, thermal amplitudes, and depths reached by variations from the surface are all components of the thermal regime dependent on four basic properties: thermal conductivity, heat capacity (or specific heat), thermal diffusivity and latent heat of fusion. The scientific definitions appear in Table 5.1.

THERMAL PROPERTY	SYMBOL	DESCRIPTION
Thermal conductivity	k or λ	Quantity of heat that will transit a unit of area in a unit of time in a unit of thermal gradient (W/m.K).
Heat capacity (~specific heat)	C	Quantity of heat required to raise the temperature of a unit of mass (kJ/kg.K) or volume (kJ/m ³ .K) by one degree.
Thermal diffusivity	α	Index representing the relative ease with which a material can change temperature (mm ² /s); $\alpha = k/C$.
Latent heat of fusion	L	Quantity of heat required to melt (or freeze) water in a volume of soil. This quantity of heat accumulates or is lost with no change of temperature (normally at 0°C) ($L = 334 \times 10^3 \text{ Sn kJ/m}^3$) where S is saturation of the soil and n is porosity.

TABLE 5.1: THERMAL PROPERTIES OF BASE PERMAFROST.

5.1.5 Parameters commonly used to characterize the local climate regime and its influence on permafrost

In simplified manner, the permafrost thermal regime in a given location can be explained through a few basic parameters linked to climate and land surface factors. These parameters are average annual air temperature, that for permafrost, the freeze index, the thaw index as well as the n -factors for freezing and thawing.

All regions where average annual air temperature is at or below 0°C are likely to contain permafrost. Its presence, however, depends on local factors that affect heat transfer between the atmosphere and the soil, in this instance, lack or a critical depth of snow cover, tundra surface vegetation or trees and shrubs, organic or fine-textured soils, or a combination of these factors.

Organic and fine-textured soils (silt and clay) have low thermal conductivity in thawed state, so the summer thaw progresses slowly in them, but have high conductivity in frozen state. They therefore lose more heat to the atmosphere in winter than they gain in summer, resulting in a negative balance.

Average annual temperature at the soil surface is not the same as that of the air; in fact, it is almost always warmer. The factors that make the soil surface often warmer than the atmosphere are primarily snow cover, which insulates part (or all, depending on depth and density) of the soil in winter, and plant cover in summer, which has a fairly low albedo (portion of solar energy reflected). To this can be added other factors such as thickness of the organic surface horizons (insulating and promoting a lower average temperature), the presence of pools of water (which capture solar heat and transfer it to the soil below) and surface colour (e.g. dark asphalt surfaces).

The annual freezing index (Fi) in a cold season is the sum of degree-days below 0°C. To calculate this, we add the daily average temperatures for the cold season. The thawing index (Ti) is calculated in the same way with summer days when the average is above 0°C. Table 5.2 shows the freezing and thawing index values measured in various Nunavik communities.

COMMUNITY	PERIOD	AAT (°C)	FI (GEL)	TI (THAW)
Akulivik	2007-2011	-5.71	3044	1013
Aupaluk	2007-2011	-5.19	2794	947
Inukjuak	2009-2012	-4.6	2738	1194
Kangirsuk	2007-2011	-5.87	2992	903
Kuujuaq	2008-2012	-3.34	2625	1433
Kuujuarapik	2008-2012	-1.9	2159	1523
Puvirnituq	2007-2011	-5.73	3189	1154
Salluit	2007-2011	-5.89	2866	902
Quaqtaq	2007-2011	-5.28	2581	704
Tasiujaq	2007-2011	-4.54	2824	1150

TABLE 5.2: AVERAGE ANNUAL AIR TEMPERATURES (AAT), FREEZING INDEXES (FI) AND THAWING INDEXES (TI) IN SELECTED NUNAVIK COMMUNITIES (AVERAGES FOR THE PERIOD FROM 2007 TO 2012) (SOURCE: ENVIRONMENT CANADA AND SILA NETWORK)..

The freezing and thawing n-factors are multipliers applied to atmospheric indexes to obtain an approximation of these same indexes, but on the soil surface. A few typical n-factors for various surface types without snow cover are presented in Table 5.3.

SURFACE TYPE	N-FACTOR (N_F)	N-FACTOR (N_T)
Spruce, shrubs, moss on peaty soil	0.29 (under snow)	0.37
Moss on peaty soil without trees or shrubs	0.25 (under snow)	0.73
Peat	0.5	1.0
Snow	1.0	—
Paving (asphalt) without snow or ice	0.9	—
Sand and gravel	0.9	2.0
Mineral soil surface	0.33	1.22
Asphalt paving (probable values in northern conditions)	0.29 - 1.0 or more (0.9 - 0.95)	1.4 - 2.3
Concrete paving (probable values in northern conditions)	0.25 - 0.95 (0.7 - 0.9)	1.3 - 2.1

TABLE 5.3: N-FACTORS SPECIFIC TO VARIOUS SURFACE TYPES: N_F FREEZING N-FACTORS, N_T THAWING N-FACTORS (FROM JOHNSTON, 1981, AND ANDERSLAND AND LADANYI, 2004).

Small, fairly inexpensive dataloggers can measure soil surface temperature continuously, for example, under a snow drift, road surface or building, or in nature. The freezing and thawing indexes can then be calculated through the ratio between average annual temperature at the soil surface and average annual air temperature, measured with these small, simple thermal measurement systems.

When air and surface temperatures as well as those at various depths are plotted on a chart by month of the year, the areas between the temperature curve and 0°C provide the freezing and thawing indexes. A weather station and thermistor cable connected to a datalogger can measure variations in freezing and thawing indexes as well as corresponding soil temperatures over the years. Caution! To be consistent, monitoring must be based on “climatological years,” not calendar years, i.e. conducted over 12-month periods that include complete freezing and thawing seasons (for example, from early June to late May or from early October to late September) (Figure 5.8).

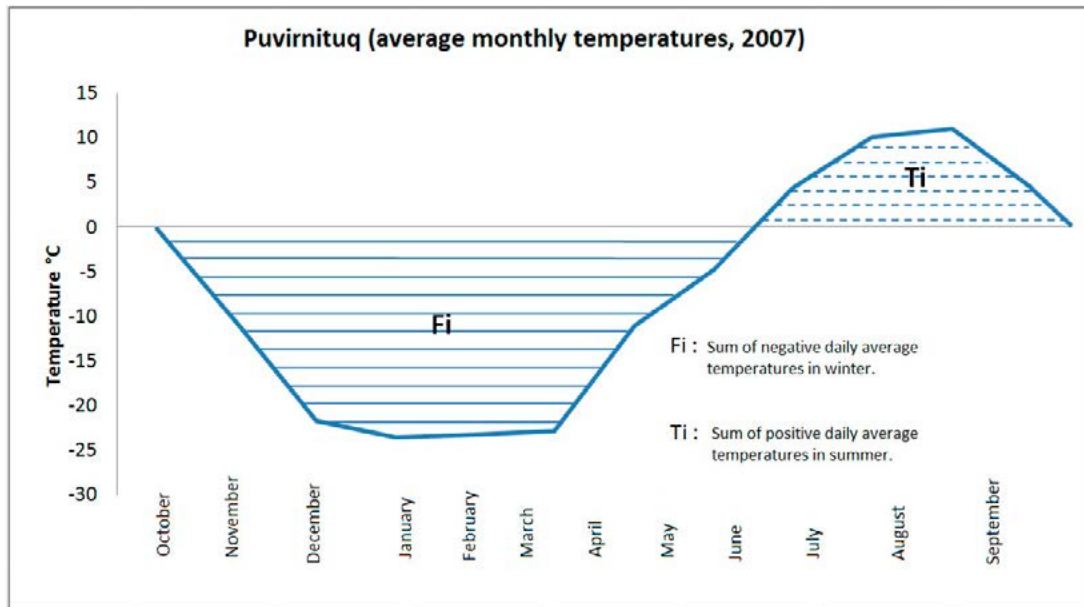


FIGURE 5.8: CHART OF FREEZING AND THAWING INDEXES.

5.1.6 Types of ice in permafrost

The appearance of permafrost, its hardness (mechanical resistance) and the type of ice it contains are dependent on a series of factors, primarily: the granulometric composition of unconsolidated deposit, the original sediment structures of unconsolidated deposits, the thermal regime when the ice was formed, and the presence of peat at the surface or in the soil stratigraphic sequence. In Nunavik, permafrost contains several types of ice, the main ones being ice wedges, segregation ice in lenses and reticulate ice, interstitial ice, and intrusive ice. Under certain conditions, massive ice may also be found.

5.1.6.1 Ice wedges

When the active layer is frozen in winter and soil temperatures are already very cold (below approximately -12°C, usually -18°C), soil may crack due to thermal contraction during cold spells (e.g. when temperature drops to -30°C or more). A pattern of cracks then opens to depths between seven and eight metres in the permafrost. In spring, meltwater from snow quickly infiltrates into open cracks and freezes in the permafrost. In summer, the vein of ice in the active layer melts, but that in the permafrost remains. Over the years, the soil periodically cracks in the same place and the accumulation of successive ice veins forms an ice wedge (Figure 5.9). On the ground surface, ice wedges form series of tundra polygons (Section 5.1.9.2).



FIGURE 5.9: ICE WEDGE AT SALLUIT (IN TILL).

5.1.6.2 Segregation ice

This type of ice, very abundant in fine-textured soils (silt, clay, fine and very fine sand), appears as lenses ranging in thickness from less than 1 mm to several centimetres (Figure 5.10 A). These lenses or layers are formed when the water contained in sediments is aspirated toward a stationary freezing front, at least for a time, at a specific level. This process is called cryosuction. Lenses are also usually parallel to this freezing front. Quite often, however, ice also appears in oblique or vertical veins following migration of water from the soil into cracks during freezing.

The network of horizontal lenses, oblique veins, vertical veins and fractures that affect them (microfaults) constitutes what is called reticulate ice (Figure 5.10 B).



FIGURE 5.10: DIFFERENT TYPES OF SEGREGATION ICE: A) LENSES, B) RETICULATE ICE, C) AGGRADATIONAL ICE.

When the active layer is thawed and contains water, part of this may be aspirated into the partially thawed permafrost below, along the temperature gradient. This creates a slight inflow of water by suction, which leads to a gradual thickening of existing lenses near the permafrost table. The result over time is that the upper layers of permafrost, in the first decimetres under the base of the active layer, are often enriched with ice in which soil aggregates appear suspended, with volumetric content that may exceed 80 percent. This segregated ice at the active layer/permafrost interface is also called aggradational ice (Figure 5.10 C).

Due to its formation process, which produces a supplemental inflow of water and the growth of ice lenses and veins, the segregation ice content in permafrost quite often exceeds the natural porosity or pore volume (or saturation) of the same soil when not frozen. In weighted terms, content can reach 300 and 400 percent. The fraction beyond the saturation value (usually in the 30-percent range) is called excess ice.

The formation of segregation ice in the soil causes an increase in volume that causes uplift of the land surface, called frost heaving. Seasonal formation of ice lenses in the active layer during refreezing triggers this phenomenon, which can lift and deform transportation infrastructure and buildings (because it is uneven over space). Conversely, melting of ice lenses results in surface compaction each summer.

Over the long term (a few years), the melting of segregation ice that occurs with thawing of permafrost leads to major compaction and reduces the soil's bearing capacity, often to the point that buildings and infrastructure become unusable.

5.1.6.3 Interstitial ice

Interstitial ice can be defined as ice contained in the pores of sediments and rocks. This ice is not found in excess in the soil, because the volume of ice is less than or equal to soil pore volume (Figure 5.11). Unlike segregation ice and intrusive ice, it does not cause frost heaving or serious soil compaction during thaws. This type of ice acts as cement and greatly increases the cohesion of unconsolidated deposits. It is found primarily in gravel and sand deposits.



FIGURE 5.11: INTERSTITIAL ICE IN SOIL COMPOSED OF SAND AND GRAVEL. NOTE THE ICE-FILLED CAVITIES LEFT BY THE STONES THAT HAVE FALLEN OUT OF THE WALL.

5.1.6.4 Intrusive ice

This is ice formed by freezing of water injected under pressure into permafrost or the active layer in winter. The water usually comes from sources that, when sealed in by freezing of the soil surface, become trapped aquifers in which strong pressure builds up, that heaves the underlying soil.

Pockets of this type of water are the origin of cores of intrusive ice found in the centre of pingos in the Mackenzie delta. These forms do not exist in Québec. However, hummocks with a core of intrusive ice are sometimes found, most of which melt in summer, although some occasionally survive more than one summer in colder-than-average years. Intrusive ice forms crystalline beds with a vertical columnar structure (Figure 5.12).



FIGURE 5.12: MASS OF INTRUSIVE ICE IN AN ORGANIC DEPOSIT ON SAND AT KANGIQSUALUJJUAQ. NOTE THE COLUMNAR ICE STRUCTURE. SEASONAL ICE-CORE HUMMOCK.

5.1.6.5 Massive ice

Large masses of fairly pure ice in permafrost may have various origins. For example, these may be layers of ice formed by incoming water contacting a clay bed stratified over a sand bed. While the freezing front remains stationary at the interface, the constant feed of water contained in the sand promotes the formation of a very thick layer of ice. This growth method, thermodynamically possible in theory, has not often been verified in nature, but constitutes the theory of massive segregation.

Another origin for massive ice, which has been proven, is the persistence in quaternary deposits of glacier ice that never melted. In 2010, beds of massive ice were found in a fluvio-glacial deposit near the Raglan mine (Figure 5.13).

One hypothesis, not yet scientifically validated, holds that these are ice fragments from the Wisconsin glacial that receded some 7,000 years ago, buried in an esker by the fluvio-glacial sedimentation; this old ice allegedly never melted in the cold climate that has continued since deglaciation. This type of ice therefore might be found in the continuous permafrost zone in Québec.



FIGURE 5.13: LAYER OF MASSIVE ICE IN A FLUVIO-GLACIAL DEPOSIT ON THE KATINNIK PLATEAU. THIS IS PROBABLY ICE FROM THE LAST GLACIATION, BURIED BETWEEN LAYERS OF GRAVEL IN AN ESKER.

5.1.7 Factors that control ice formation in permafrost

A few factors specific to the materials that make up the soil affect ice formation in permafrost when this occurs. These factors are the granulometry, sedimentary structures of unconsolidated deposits, especially stratifications, and the presence of layers rich in organic matter, such as peat. Another factor is the thermal regime prevailing during formation of the permafrost.

5.1.7.1 Granulometry

Coarse sand and gravel are microporous and have little cohesion; however, freezing of interstitial water solidly cements the grains and stones together. In this type of material, unless retained by an impermeable layer, water from the soil is expelled ahead of the freezing front when permafrost forms.

This phenomenon is caused by an increase in volume of about 9 percent that occurs when the water changes into ice. This 9 percent additional water is “pushed” or expelled ahead of the freezing front invading the soil. There generally is no excess ice or frost heaving because the final volume of ice contained in the permafrost does not exceed the volume of the pores. By contrast, fine sand, loam and clay are microporous; when the freezing front advances into these soils, water is drawn in by capillary suction. This creates ice lenses that expand and heave the layer of soil affected by the freezing (Figure 5.14) (Williams and Smith, 1989; Williams, 1986).

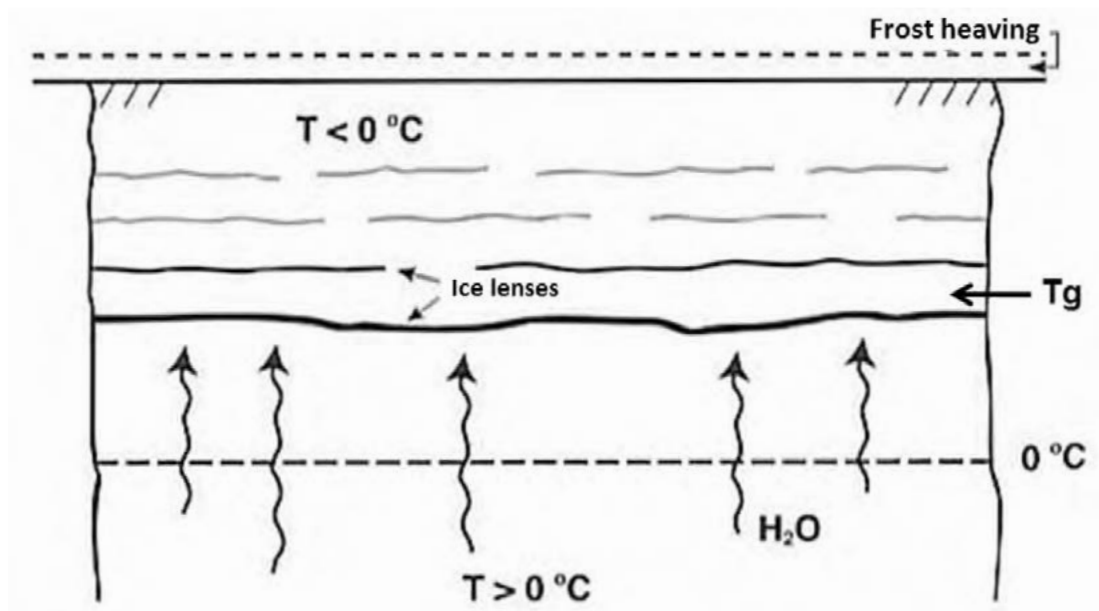


FIGURE 5.14: PRINCIPLE OF CRYOSUCTION IN FINE SEDIMENTS THAT FORMS LENSES OF SEGREGATION ICE. PRESSURE IN THE “FROZEN FRINGE” BETWEEN THE 0°C ISOTHERM AND THE ICE FORMATION TEMPERATURE SLIGHTLY BELOW 0°C (TG) CAUSES THE WATER THAT FORMS THE ICE LENSES TO MIGRATE.

5.1.7.2 Sedimentary structures

Stratifications with alternating layers of sand and clay loam create granulometric discontinuities along which segregation of ice lenses is likely to occur. This accentuates the formation of lenses in marine loam and other fine stratified deposits (Figure 5.15).



FIGURE 5.15: THICK ICE LENSES FORMED AT STRATIGRAPHIC CONTACTS BETWEEN LAYERS OF SAND AND LAYERS OF CLAY, AT UMIUJAQ.

5.1.7.3 Peat and organic horizons

Peat and thick organic horizons have a considerable effect on the land thermal regime. Saturated with water and frozen, they have high thermal conductivity that allows heat to escape into the cold atmosphere in winter (“penetration” of cold into the soil). In summer, however, the dried peat surface changes into a very good insulator that protects the subsoil from thawing, by limiting heat penetration. The permafrosted mineral soils below the peat therefore remain colder and the seasonal thermal gradients near the surface are sharper. These environments, suited to the development of permafrost, can allow the formation of many layers of segregation ice several metres down, as in palsas (see section 5.1.9.1).

5.1.7.4 Thermal regime

As Figures 5.1 and 5.6 show, the temperature gradient in the soil only reverses direction with the seasons above the zero annual thermal amplitude depth. In winter, the top of the profile is colder than the bottom, while the reverse occurs in summer. In the frozen soil, a certain proportion of water (microscopic film coating the grains of soil) remains liquid, often even down to temperatures below -2°C (Farouki, 1981). This water tends to migrate along the thermal gradient from the warmer zones to the colder zones (Williams, 1967). This results in downward migration in summer, from the active layer toward the top layers of the permafrost, while part of this water tends to rise back up toward the permafrost table in winter. The net long-term result is greater ice content in the first metres of permafrost, just below the active layer (see section 5.1.6.2, aggradational ice).

The finer the soil granulometry, the greater the amount of water absorbed around the grains; this water retained by very high surface tension only bonds with the ice in the pores at very low temperatures (Burt and Williams, 1976; Anderson and Morgenstern, 1973; Nersesova and Tsytoich, 1963). This means that a fine soil, such as marine clay silt or clay matrix till at a temperature between 0 and -2°C can contain a large fraction of unfrozen water, ranging from 10 to 30 percent. The proportion can be even greater if mineral salts are dissolved in the water from the soil and lower the freezing point of this environment. This proportion of unfrozen water gives the permafrost a certain plasticity that can pose problems of bearing capacity and creep under loads bearing on the soil surface, especially at the base of pilings under load. This liquid water content in the permafrost varies over the year, based on temperature fluctuations.

5.1.8 Permafrost and geological surface formations

Three of the factors mentioned in the previous section are very closely linked to the composition and structure of the rocks and unconsolidated deposits. The granulometry and structure (strata, cracks, etc.) are inherited from the geological history which therefore is indirectly responsible for the properties of the permafrost. The organic covers are added to the soil surface after deglaciation or emergence of the land. Various properties of permafrost therefore can be linked with the types of surface formations. Each type of permafrosted surface formation has different mechanical, geocryological and thermal properties; each is likely to pose distinct geotechnical and environmental problems.

5.1.8.1 Rock

With the exception of certain Precambrian sediments from the Labrador and Ungava troughs, the rocks of northern Québec are generally massive. The ice in the rock permafrost is found primarily in the structural elements, that is, the stratification planes, joints and fractures. The result is virtually no water circulation. Very fractured or friable sectors sometimes have a high ice content. As seen on northern airport construction sites, permafrost found in the rock poses virtually no drilling or dynamiting problem. However, drill rods must not be left inactive for too long and bores must be filled with explosives before water filters in and freezes. Where the structural layout allows, blocks defined by cracks are lifted to the land surface following the development of strong hydraulic and cryogenic pressure in the active layer during the winter refreeze (Michaud and Dyke, 1990; Michaud and Dionne, 1987; Dyke, 1984).

The basalts in the Hudson shore cuestas are especially sensitive to this phenomenon, which also occurs more sporadically elsewhere in Nunavik (Figure 5.16), especially in the metasediments in the Kangirsuk region.

In addition, heaving of rocky quarters can damage structures. On sites with friable rock and frost heaving of rock, core boring to a depth of about 10 metres should detect the presence of ice layers likely to affect overlaying construction by expanding or melting.



FIGURE 5.16: ROCK EJECTION FORMS.

5.1.8.2 Tills

These glacial deposits are very widespread in Québec. They form moraines of varying depth that conceal the rock shield. When cemented by ice, they form a hard, consolidated conglomerate. Tills contain both interstitial ice, when sandy, and segregation ice, when their matrix consists of fine sand, silt and clay. Undulating ice lenses are then found between the blocks and stones contained in the deposit.

The best observations of permafrost in till have been made at Salluit in winter, when dynamiting permafrost to excavate a settling pond (Figure 5.17). Moraines of frozen till have also been sampled at the Salluit, Akulivik, Quaqtaq and Kangirsuk airports. At all these sites, the volumetric ice content fluctuated from 10 to 70 percent depending on the spatial variations of the deposit's granulometry. Thawing of the till, observed under roads and airport runways, resulted in extensive compaction. Permafrosted till therefore is a material to be considered with precaution on development sites.



FIGURE 5.17: ICE-RICH TILL AT SALLUIT.

Tills pose many drilling problems because of the countless stones they contain. The thermal disturbance caused by the friction of the diamond or carbide bits pulls stones out of the wall and jams the equipment. To drill in this sediment, it is usually necessary to install tubing (caisson) and use drills equipped with a coolant system.

Even with the support of a bulldozer or mechanical shovel, excavating permafrosted till is problematic because the solid components are cemented together with ice. At Kangiqsualujjuaq, for example, digging a trench in till at -1°C in the late 1980s posed costly problems: it was hard to dig with a mechanical shovel, the till absorbed the shock waves from dynamiting and would not fragment. The contractor had to improvise a method that consisted of installing a percussion hammer on the shovel (Figure 5.18).

In undrained excavations, by contrast, the sand and loam matrix changes into slurry when it thaws and sloped ground becomes very unstable. To avoid the problem of liquefying till in a large excavation, one approach is to excavate with dynamite in winter the same as in a rock quarry.



FIGURE 5.18: PERCUSSION HAMMER EXCAVATING PERMAFROST IN TILL AT KANGIQSUALUJJUAQ.

Cuts are not recommended in permafrosted till because banks of this material become unstable when the permafrost is exposed (Figure 5.19). Upon thawing, even with fairly gentle slopes, tills undergo a phenomenon of solifluction due to their high ice content and low permeability. When they cannot be avoided, cuts require structures, such as creation of a drainage mat of dynamited rock, to prevent instability caused by thawing of the permafrost.



FIGURE 5.19: DESTABILIZED CUT IN TILL AT PUVIRNITUQ.

5.1.8.3 Fluvioglacial deposits

Consisting of sand and gravel, sometimes stones and pebbles in fairly thick strata, these deposits are found in the form of outwash plains, perched deltas and eskers. Generally cemented by freezing (interstitial ice), they pose the same boring and drilling problems as tills because of the many stones they contain. However, they are not highly subject to creep or compaction, since no natural or artificial segregation of fines occurs in the material. Interstitial ice usually just binds the stones and sand to each other without exceeding the natural porosity (Figure 5.11). However, massive ice layers have been observed in a fluvioglacial deposit near the Raglan mine (Figure 5.13) and in a gravel pit at Iqaluit, under comparable climatic conditions. It therefore may be worthwhile drilling with recovery or cores when planning to erect a building on such deposits, to gauge the risk. In general, when these deposits are used as borrow pits, this type of ice mass may be discovered by chance and make the material difficult to excavate, while complicating meltwater drainage in the gravel pit.

5.1.8.4 Marine deposits

Marine deposits were laid down during postglacial marine transgressions (Tyrrell Sea in the Hudson Sea basin; Iberville Sea along Hudson Strait and Ungava Bay). They emerged following the isostatic uplift. These deposits, on which most of the coastal villages are built, display highly variable facies and can pose multiple problems for overlaid construction, especially if the nature of these soils is not clearly identified and considered in the foundation study.

Clay silt and fine sand are the deposits best suited to development of segregation ice lenses. In permafrost, their ice content is often very high, up to 80 percent of total volume in some samples. When thawed, their geotechnical properties are comparable to those of marine clay in the St. Lawrence Valley. These soils are hard to drain, as they compact and liquefy upon thawing. In addition, heavy machinery moving over clay terrain sinks into the active layer mud, seriously damaging the natural environment (Figure 5.20). As much as possible, it is best to avoid construction work on these soils. These fine deposits, laid down in seabeds or calm sea arms, are usually several metres thick.



FIGURE 5.20: RUTTING IN ACTIVE LAYER CLAY MARINE SEDIMENTS CAUSED BY MACHINERY AND AFFECTED BY THERMAL EROSION.

When it has fine granulometry, well sorted, sometimes stratified marine sand contains segregation ice. Massive fine sand in turn is cemented by interstitial ice and forms an almost liquid mud upon thawing. In this type of deposit, ice content varies greatly depending on the geomorphological and stratigraphic context. For example, sand may contain a great deal of ice when it overlays clay, as the latter's impermeability effectively increases the quantity of water in the granular materials.

Around the edges of the postglacial Iberville Sea (Figure 5.22), tides were very high, as they continue to be today. They brought in floating ice that deposited many blocks and mounds of sand and gravel on the mudflats. This mix of mud, sand and stones of various sizes forms a glacial-marine diamict. In the former bays now uplifted, these silt diamict layers often lie just below the soil surface over vast expanses. They are frequently found covered by a fairly thick layer of sand or organic matter. The very widespread diamicts contain excess ice, but these deposits may also be covered by more recent sediments. Thus, a layer of intertidal diamict covered with fluvial sand extends under the Tasiujaq airport runway at a depth ranging from 0.3 to 1.5 m (Figure 5.21). In this case, boring and excavation are necessary to detect this type of deposit.



FIGURE 5.21: SEGREGATION ICE IN A HOLOCENE INTERTIDAL DIAMICT AT TASIUJAQ (UNDER THE AIRPORT RUNWAY).

Thick, well drained beach sand and gravel behaves in the same way as fluvioglacial deposits. In a preliminary study of coastal regions, the marine limit (maximum altitude reached by postglacial seas) marks the highest level at which marine sediments may be found. Large masses of clay silt generally are found in valley bottoms, well below this altitude, but may still be located up to this altitude.

Figure 5.22 shows the extent and altitude of the marine limit in permafrost regions of Québec.

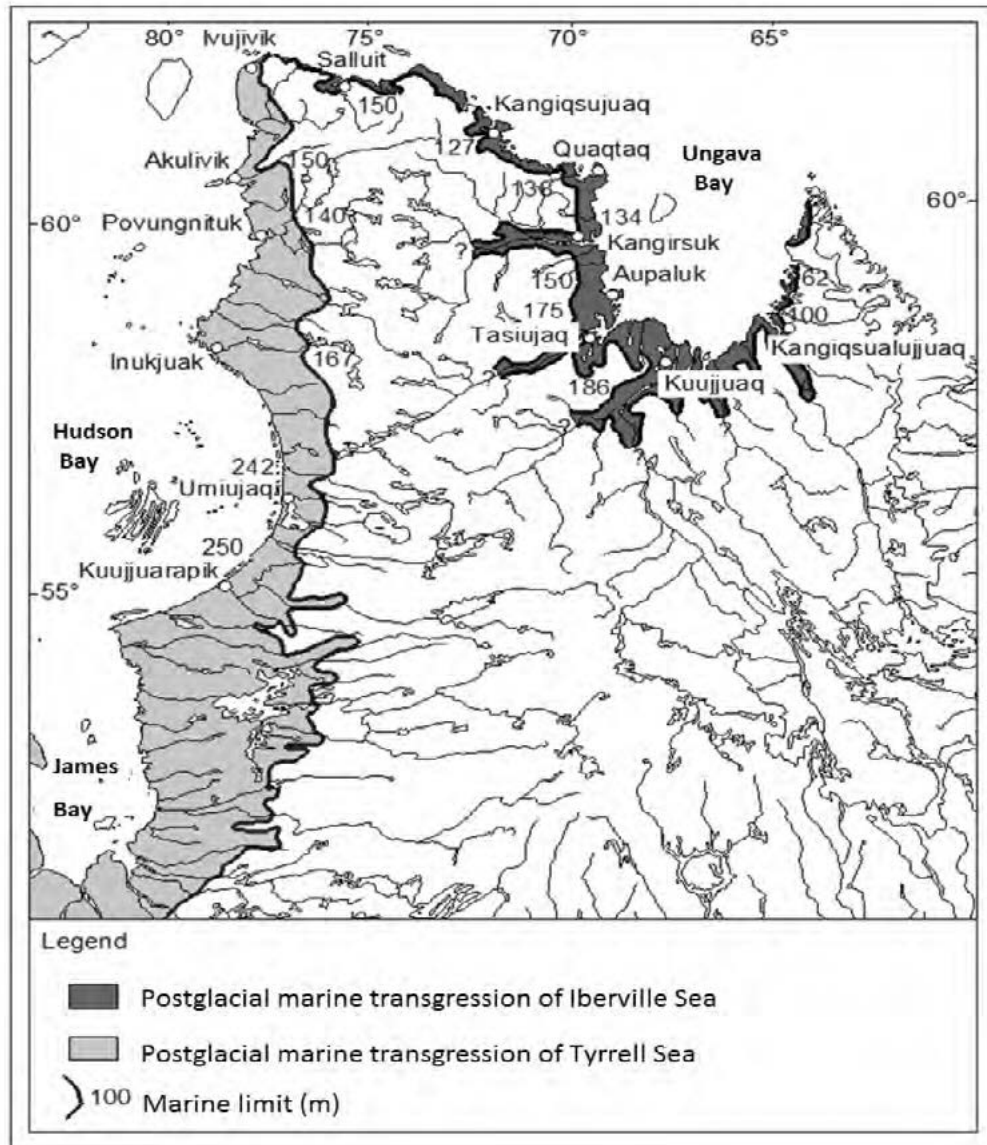


FIGURE 5.22: NORTHERN QUÉBEC LAND AREA COVERED BY POSTGLACIAL SEAS WHERE ICE-RICH MARINE SEDIMENTS ARE FOUND.

5.1.8.5 Eolian sand

This coarse, very highly sorted sand appears in the form of dunes and deflation hollows, mainly on marine terraces along the Hudson Bay coast (Filion, 1983; Filion and Morisset, 1983). It is not very abundant and mostly forms a thin veneer of limited area, associated with fluvioglacial deposits. Although no permafrost has been observed in this sand, given its porosity, we can deduce that it is almost never over-saturated with ice and cemented very little by freezing.

Often barren or with only very scattered vegetation, eolian sand is quickly penetrated by summer thawing, leading to the formation of a thick active layer (>3 m). Wind erosion and sand movement are significant factors to consider in engineering work. It is vital to keep the natural surface intact to avoid deflation and movement of sand on windy days.

5.1.8.6 Organic deposits

Peat has accumulated in northern Québec over the past five or six millennia on flat, poorly drained land. Organic cover 30 to 40 cm thick is very abundant in the tundra. In turn, peat bogs are generally about a metre thick, although some may reach two metres.

When saturated with water, in the fall and early winter, peat takes a few weeks longer to freeze because of the latent heat associated with its high water content. Once frozen, however, its thermal conductivity increases considerably and approaches that of ice; the cold can then quickly extend down, especially when snow cover is thin or absent. Once summer arrives, the heat and long hours of sunlight, combined with wind, restore peat's insulating properties by drying its surface. Progression of the thawing front is then delayed and the overlying soil stays colder than outside the peat area. It follows that the active layer is thinner in this type of material, about 40 to 60 cm, than in gravel and sandy sediments.

In the discontinuous permafrost zone, especially on palsas, permafrosted peat appears relatively ice-poor (Figure 5.23). By contrast, in the continuous permafrost zone at Salluit, very high ice content is visible (Figure 5.24). This difference may be linked to the way permafrost forms in organic deposits. On palsas in the discontinuous zone, peat bogs actually form before permafrost appears: they therefore freeze with their original saturation, generally in minerotrophic peat (epigenetic permafrost).

In the continuous permafrost zone, moss and sphagnum (ombotrophic peat) gorged with water over impermeable permafrost have accumulated over time and promote the growth of permafrost (syngenetic permafrost). In this zone as well, frozen peat bogs are often interspersed with series of tundra polygons underlaid with ice wedges that ultimately occupy a large expanse of land. Frozen peat is generally very hard to excavate, as its behaviour and resistance are similar to those of ice. Ice degradation when permafrost thaws makes the terrain impassible. All this explains why, to the extent possible, construction projects should avoid frozen peat bogs.



FIGURE 5.23: FROZEN MINEROTROPHIC PEAT (COMPOSED PRIMARILY OF SEDGE RESIDUE), CORE FROM A PALSA BORE NEAR UMIUJAQ. EPI-GENETIC PERMAFROST, FORMED AFTER THE PEAT WAS DEPOSITED. FINE LENSES OF SEGREGATION ICE WERE ABLE TO FORM IN THIS HIGHLY DECOMPOSED AND PARTLY MINERALIZED PEAT.



FIGURE 5.24: OMBOTROPHIC PEAT (COMPOSED OF MOSS AND SPHAGNUM) VERY RICH IN ICE. SYNGENETIC PERMAFROST, FORMED DURING PEAT ACCUMULATION.

5.1.9 Primary forms of relief and structured soils associated with permafrost conditions

Several types of periglacial forms and various structured soil types associated with the presence of permafrost are found in Nunavik. These phenomena, characteristic of the land surface, can serve as indicators or symptomatic elements of textural soil composition, and of the type and quantity of ice contained in the underlying permafrost. These forms can be observed in the field and on aerial photographs and high-resolution satellite images.

5.1.9.1 Palsas, palsa plateaus, lithalsas and permafrost plateaus

These forms are found only in the discontinuous zone, where they often constitute islands of permafrost (Figures 5.25 to 5.28). These are hummocks and small plateaus a few dozen or a few hundred square metres in area that reach average heights of two to three metres and, sometimes, maximum heights of six to seven metres. These relief forms developed due to the growth of many thick ice lenses during permafrost aggradation in clay soils in Holocene cold periods.

This aggradation of segregation ice in the soil caused uplifting of the ground surface. There is no permafrost under the thickets of shrubs and under the topographical depressions between the hummocks and plateaus.



FIGURE 5.25: PALSA, UMIUJAQ REGION.



FIGURE 5.26: LITHALSAS AND THERMOKARST LAKES EAST OF HUDSON BAY.



FIGURE 5.27: PALSA PLATEAUS IN THE BONIFACE RIVER REGION.



FIGURE 5.28: PERMAFROST PLATEAUS AND THERMOKARST LAKES NEAR THE NASTAPOKA RIVER. NOTE THE MANY MUDBOILS ON THE SURFACE OF THE PLATEAUS.

Palsas are hummocks of various shapes, often almost circular or elliptical, while palsa plateaus are larger and have a fairly flat summit. These two types of landform are characterized by peat covering their summit, in which the active layer is confined and very thin in this insulating material (about 60 cm). Peat thickness on the palsas and palsa plateaus averages 1.1 m, but may be less where the peat has been eroded by wind and rain.

Lithalsas are hummocks comparable in size to palsas. Like the latter, they are uplifted by aggradation of segregation ice in silt and clay sediments. Unlike palsas, however, they have no peat cover. The same is true of permafrost plateaus, with forms comparable to but larger than lithalsas. The surface of lithalsas and permafrost plateaus is usually punctuated by multiple mudboils, circular or oval veneers of earth scattered in fields (see section 5.1.9.3).

Several geophysical (electrical resistance) surveys and a few bores in palsas, lithalsas, palsa plateaus and permafrost plateaus have shown that the height of the hummock or plateau is usually a quarter or a third of the total permafrost thickness, normally between 10 and 20 m. In Québec, the age, geographic distribution and internal structure of these forms of segregation ice have been extensively documented (Allard *et al.*, 1987; Dever *et al.*, 1984; Dionne, 1984 and 1978; Lagarec, 1980; Séguin and Crépault, 1979; Payette *et al.*, 1976; Hamelin and Cailleux, 1969, as well as others, more recently). Many cores have demonstrated the high segregation ice content of these hummocks. Some layers contain up to 80 percent ice; although once spread over the entire hummock, the ice averages about 30 percent of total volume (Leroueil *et al.*, 1990; Séguin and Frydecki, 1990). Since these hummocks are located in the discontinuous permafrost zone, their internal temperature, slightly below the freezing point (between 0°C and -2°C), makes this type of permafrost susceptible to slow creep.

East of Hudson Bay, between Umiujaq and Inukjuak, lies one of the greatest concentrations of palsas and lithalsas in the world, in clay sediments deposited in the postglacial Tyrrell Sea. There are also many palsas and lithalsas in the Kuujuaq and Kangiqsualujuaq regions south of Ungava Bay (Allard and Séguin, 1987b; Séguin and Allard, 1984b; Lagarec, 1980; Payette and Séguin, 1979).

Several recent studies of aerial photographs dating back to the 1950s with satellite images and field observations show that these forms are now rapidly disintegrating, perhaps due to climate warming. Their fusion usually results in their replacement by many small lakes known as thermokarst lakes (Figure 5.26).

The permafrost in palsas, lithalsas and related forms is very rich in ice and extremely sensitive to disturbance. It is preferable to avoid any construction on these landforms. In Québec, there is still no known case of human disturbances of such hummocks, because so few are located in built-up areas, but it is highly likely that serious disturbance caused by heavy machinery, for example, would trigger a process of irreversible degradation.

5.1.9.2 Tundra polygons

Easily visible in aerial photos, tundra polygons are geometric figures with four to seven sides and an average diameter between 8-10 and 20-25 m. The land may appear fairly flat and traversed by furrows that contain cracks (Figures 5.29 and 5.30). The furrows are laid out in fairly closed or organized polygonal patterns. The polygons may have a concave centre (low-centre polygons), in which the sides of the polygon next to the furrows are higher than the depressed and often damp centre. In some cases, where ice wedges under the furrows have melted, these subside and fill up with water; the centre of the polygons is then higher than the edges; these polygons have a convex centre (high-centre polygons).



FIGURE 5.29: TUNDRA POLYGONS ON PEAT SOIL AT SALLUIT.



FIGURE 5.30: POLYGON FURROWS IN SANDY SOIL AT AKULIVIK, NEXT TO THE AIRPORT RUNWAY.

The furrows are a few decimetres deep (Figure 5.30); an ice wedge has formed below them over the years. Polygons with ice wedges are very widespread in far northern Québec. Great numbers are found in the territory of the communities of Akulivik, Salluit, Kangiqsujuaq, Quaqaq and Aupaluk.

They form in uplifted coastal sand and gravel as well as in sandy fluvial terraces or in till. For example, polygons are found atop many drumlins in tundra zones. Polygon fields often appear in peat deposits covering other unconsolidated deposits. Although ice wedges are concentrated in the continuous permafrost zone, they do occur elsewhere, occasionally in palsa plateaus or palsas (Lévesque, 1986; Payette et al., 1986; Couillard and Payette, 1985; Dionne, 1983b) in the discontinuous permafrost zone. These ice wedges, however, may be vestiges of a climatic period colder than the present day.

At Salluit, some corners measure up to two metres in width on the permafrost table and reach depths of four metres. At Akulivik and Aupaluk, ice wedges 30 cm wide have been measured in uplifted coastal sand and gravel located around airport runways.

There are two main types of ice wedges. Syngenetic corners form simultaneously with the accumulation of the sediments they traverse, while epigenetic corners form subsequent to the deposit (Mackay, 1990). Some corners, inherited from a colder climate, no longer crack under the current climate conditions; they are simply preserved in the permafrost. Generally, a very simple way to determine whether they are active is to check for an open crack in the furrows.

In winter, this crack is sometimes seen in fresh or icy snow deposited in the furrow; in summer, a thin crack can often be seen in the moss or lichen; the crack may not be visible on the surface but its presence can be determined by parting the vegetation with one's hands.

From a geotechnical perspective, a pattern of ice wedges represents a large quantity of ice spread out in the soil in a structured pattern. A disturbance that would cause this ice to melt is likely to create a chaotic relief and many differential compactions. Thermal erosion of ice wedges is especially likely along excavations and trenches that, once dug, collect the surface runoff, which travels through the system of furrows in the polygon field.

5.1.9.3 Mudboils

Under the cryosol classification developed by Washburn (1979), mudboils or frostboils (Shilts, 1978) belong to unclassified circles. They look like fairly circular patches of mud with no plant cover. Their diameter varies but is usually between 0.5 and 2 m. Although it is not uncommon to find isolated mudboils, they are usually grouped in fairly dense fields. In particular, they are scattered across marine clay surfaces affected by permafrost and are very common on lithalsas and permafrost plateaus (Figure 5.31).



FIGURE 5.31: RAISED-CENTRE MUDBOILS ON MARINE CLAY AT SALLUIT.

The most likely hypothesis is that they are formed by the presence of fine supersaturated sediments in water and the freeze-thaw cycles that trigger the development of cells in which convection movements are generated. The length of a complete cycle (rise and fall of sediments in the cell) apparently extends over many years (a few decades). The top layer of soil therefore is constantly transformed during the thaw period. Mudboil activity, however, is not permanent. When vegetation invades the surface of an mudboil, this indicates a slowing or stoppage of the convection movements.

Given that mudboils form in soils with a high proportion of fine sediments, they are found only in certain categories of unconsolidated deposits (fine-matrix glacial deposits, marine deposits, etc.). The places suitable to their formation are normally exposed to the wind, devoid of trees and shrubs, and have thin snow cover. Although mudboils are quite widespread in the permafrost zone, this is not the only place they are found. They are also observed in sites with intense seasonal freezing and where the depth of unconsolidated deposits over rock is less than the depth of the annual thaw.

In northern Québec, mudboils are very abundant and have many morphological varieties. Raised-centre mudboils and low-centre mudboils, however, are the most common (Jetchick, 1988; Zoltai and Tarnocai, 1981). Raised-centre mudboils are dominant on marine clay; their presence allows us to estimate the distribution of land very rich in segregation ice.

Low-centre mudboils (Figure 5.32) are observed primarily in diamict soils such as tills: here again, these are characteristic forms useful for mapping this type of unconsolidated deposit. Mudboils are often scattered within polygons over tills (Jetchick and Allard, 1990).



FIGURE 5.32: LOW-CENTRE MUDBOILS ON TILL AT AKULIVIK.

Fine sediments gorged with water and on low slopes, combined with annual thaws, are sufficient to result in gelifluction of surface materials. Mudboils therefore migrate slowly down a slope and become deformed. They often develop in terraces parallel to elevation curves (Figure 5.33). On very gentle slopes, they extend down the slope, sometimes for several dozen metres, and resemble spills or striated soil.



FIGURE 5.33: MUDBOILS EXTENDING DOWN A SLOPE.

From the presence of mudboils, one can deduce the presence of a significant fine fraction in the soil, a water table positioned at the base of the active layer in summer and large volumes of ice in the permafrost. Fine-textured mudboils are sometimes found “piercing” the surface of a coarser deposit (e.g. through a sandy surface deposit); the reason in this case is that the overlying coarse deposit is thin and thawing of the active layer penetrates a layer of fine sediments stratified below, promoting the rise of fine particles to the surface by convection. The fine soil below is what must be considered when designing construction foundations.

5.1.9.4 Coulees and gelifluction lobes

Gelifluction consists of runoff or creep of the thawed layer saturated with water on the surface of the terrain over the frozen substrate. The damp soil must have a certain plasticity, resulting from the presence of a proportion of fines in the granulometric composition. Thus, in Nunavik, gelifluction is most often observed on moraine slopes and slopes covered with till, because these deposits generally contain a significant portion of silt and clay. Organic matter also provides fine particles (colloids) that, when mixed with mineral soil, increase its plasticity.

Over time, creep leads to a certain segregation of fine particles which become more abundant in the frontal part of the coulee. When digging, it is not uncommon to find that gelifluction lobes contain old soil buried by the overlap of coulees and tables.

Gelifluction is a major factor in movements, even weak movements, on slopes. The presence of a permanently frozen layer (virtually impermeable) confines the infiltration of rainwater and meltwater (soil snow and ice) in the active layer. During the summer thaw, supersaturated sediments lose their cohesiveness and the material begins to creep. Fine-matrix soils (silt and clay) on a slope between 5° and 20° are more susceptible, although appreciable movement has also been observed on much gentler slopes ($\approx 1^\circ$).

On aerial photographs and in the field, forms specific to gelifluction are easily distinguished. In general, a stretching and alignment of sediments or low plant structures is noticed parallel to the slope. The most common forms are gelifluction tables or lobes (Figures 5.34 to 5.36). These feature a fairly uniform surface of varying inclination and an abrupt front usually 50 to 150 cm high.



FIGURE 5.34: STRIATED SOIL ON A SLOPE.



FIGURE 5.35: GELIFLUCTION LOBES (OR TONGUES) IN TILL ON VALLEY SLOPES AT SALLUIT.



FIGURE 5.36: ORGANIC BURIED SOIL HORIZONS IN A GELIFLUCTION LOBE.

In Nunavik, by all appearances, many of these forms parallel to the slope originate from the deformation of polygons or mudboils that stretch out due to runoff on a slope. The transition from one type of form to another can in fact be seen in the field. Striated soils, elongated mudboils, terracing, lobes and coulees are all visible (Figures 5.33 to 5.36).

The dimensions vary, with each strip of elongated soil measuring up to about a metre wide and extending several dozen or even hundreds of metres in length. The speed of movement down the slope is not uniform, but depends on the granulometry of the material and the angle of the slope. Fine sediments appear to migrate faster than coarse sediments. Creep speed is a function of the specific conditions at each site: a few centimetres a year and rarely exceeding 15 cm a year.

The presence of gelifluction forms reveals soil potentially rich in subsurface ice. Since these forms appear on slopes, there has been little or no construction on these slopes to date. This could change, however, with the development of new sectors and road construction. Gelifluction can be expected to place pressure on obstacles such as embankments and retaining walls. There is also reason to believe it can be stopped by triggering deeper thawing of the active layer or raising the permafrost table in an overlaid embankment.

5.1.9.5 Turf hummocks and thufur

Turf hummocks or thufur, from the Icelandic, are small mounds (0.2 to 0.5 m high and 0.5 to 1 m in diameter) consisting of fine sediments covered with a layer of peat and living plants (Figure 5.37). This type of hummock is very common in Arctic, subarctic and Alpine regions (Scotter and Zoltai, 1982). These forms are usually found on flat or gently sloped (1 to 10°) damp terrain. They are usually formed by freeze-thaw cycles and differential accumulation of plant cover. In northern Québec, they are quite common on poorly drained till deposits with a low slope and on other diamict soils such as former foreshore flats raised by isostatic uplift. Turf hummocks and thufur therefore are indicators of the presence of a perched watertable in the active layer in summer.



FIGURE 5.37: CUT IN A THUFA AT KANGIQSUALUJJUAQ.

5.1.10 Summary and conclusion on basic concepts

The forms and cryosols linked to permafrost are presented in Table 5.4, where they are associated with the types of unconsolidated deposits with which they are most often found and, by association, with the probable abundance of ice in the permafrost under the surface.

The characterization study of permafrost for a construction project should, in principle, start with recognition of the periglacial forms and cryosols leading to mapping of the surface formations associated with ice content. At the very least, soils with excess ice should be surveyed on a preliminary basis for subsequent drilling to increase the accuracy of the characterization. Simple excavation in the active layer, without taking samples from the underlying permafrost, is insufficient in most cases to determine the amount and type of ice contained in the permafrost.

Determining the thermal regime requires measurements and datalogging with thermistors to calculate averages and indexes, and ensure monitoring over time. However, local data are now available from the network of weather stations and thermistor cables recently installed by the Ministère des Transports, de la Mobilité durable and de l'Électrification des transports (MTMDDET), the Ministère des Affaires municipales and de l'Occupation du territoire (MAMOT), and the Centre d'études nordiques.

FORM AND CRYOSOL	NATURE OF GEOLOGICAL SURFACE FORMATIONS	TEXTURE	PERMAFROST REGION	TYPE OF SOIL ICE	PROBABLE PRESENCE OF EXCESS ICE
Cryogenic hummocks	Marine silt and clay Sand (lower hummocks)	Clay silt Fine and medium sand	Discontinuous and widespread Discontinuous and dispersed	Segregation	Yes
Palsas	Peat Peat/silt and clay Peat/sand or till (rare)	Fibrous or humic peat on generally fine soil	Discontinuous and widespread Discontinuous and dispersed	Segregation	Yes, in mineral sediments under peat
Thermokarst lakes (accompanied by palsas and cryogenic hummocks)	All formations, especially fine and peaty	Peat Clay silt Sand	Discontinuous and widespread Discontinuous and dispersed Sporadic	n/a	n/a
Polygons with ice wedges	Tills Sand from fluvial terraces Uplifted coastal sand Sedge peat bogs	Peat Fine to coarse sand	Continuous	Corner ice Interstitial ice in polygons	Yes, in corner patterns
Polygons with soil corners	Tills (on ridges and drumlins) Fluvioglacial deposits (outwash plains and deltas)	Heterometric and coarse sandy-gravelly deposits	Continuous Discontinuous and widespread	Interstitial ice	No
Low-centre mudboils	Tills Diamicts (uplifted foreshore flats) Often associated with soil corner polygons and gelifluction lobes	Heterometric sandy-gravelly deposits with a fraction of very fine sand or silt	Continuous Discontinuous and widespread	Interstitial ice A little segregation ice	No
Raised-centre mudboils	Deposits marins and lacustres (common on cryogenic hummocks)	Fine sand and clay silt	Continuous Discontinuous and widespread Discontinuous and dispersed	Segregation	Yes
Striated soils	Tills Slope deposits	Rubby deposits with fine matrix	Continuous	Interstitial	No
Gelifluction lobes and tables	Tills Marine sands Slope deposits	Heterometric deposits with sand or silt matrix	Continuous Discontinuous and widespread Discontinuous and dispersed Sporadic	Interstitial	No
Thufur	Tills and diamictos on low poorly drained terrain	Heterometric deposits with sand or silt matrix	Continuous Discontinuous and widespread	Interstitial	No
Seasonal hummocks with ice nodes and icing	All types of deposits	All granulometries and all organic soils Near streams and location of springs	Continuous Discontinuous and widespread	Intrusive (significant, rapid swelling in winter, subsidence in summer)	Yes
Ejection blocks or mounds	Rock (favourably cracked)		Continuous Discontinuous and widespread Discontinuous and dispersed	Intrusive? Segregation?	?

TABLE 5.4 SUMMARY: LINKS BETWEEN UNCONSOLIDATED DEPOSITS, PERIGLACIAL FORMS AND ICE CONTENT IN PERMAFROST

5.2 PERMAFROST DISTURBANCES: CAUSES, MECHANISMS, PREVENTIVE APPROACH IN CONSTRUCTION

5.2.1 Introduction

The causes of geomorphological instability, topographic disturbances and permafrost degradation with an impact on the natural terrain or the integrity of human structures are rooted in a very simple principle. As the preceding chapter shows, in the natural environment, permafrost is above all a climatic phenomenon and its stability depends on its thermal regime. Since the water it contains is constantly below 0°C, it is frozen. Only the active layer thaws in summer and refreezes in winter. The soil-ice mix that constitutes permafrost is in principle a very solid substrate, capable of bearing very heavy loads.

Any change occurring on or near the surface of the land is likely to change the thermal regime at the permafrost table (i.e. the interface between the active layer and the permafrost). For example, a rise in average annual temperature at the surface, whether concentrated in one season or spread throughout the year, will trigger a thickening of the active layer through thawing of the permafrost immediately below, thereby melting the ice it contains. If such an increase permanently raises the surface temperature above 0°C, the permafrost will automatically deteriorate and may even disappear.

Conversion of the ice into water upon melting triggers compaction of the soil surface. This compaction will vary with the ice content as well as the method and speed of meltwater drainage. If drainage is poor, as is often the case, because the subsoil remains frozen and impermeable, the high water content in the soil, which sometimes exceeds its natural porosity, eliminates its bearing capacity. This makes the soil muddy or increases interstitial pressure to the point where it exceeds its shear strength and may even cause landslides on slopes.

In brief, permafrost deterioration always starts with a thermal cause. The causes of thermal disturbance of the surface may be:

- climatic;
- geomorphological and ecological;
- indirectly human;
- directly human.

The resulting disturbances will take different forms and processes depending on the nature of the surface deposits thawing and the slope of the land.

Finally, it must be kept in mind that in environments with permafrost, there are particularly dynamic disruptive processes involving water circulation, which is both a vector for heat and agent for erosion. Water running freely in contact with permafrost transfers heat to the latter; in this situation, the localized thawing process (thermo-erosion) can be very fast.

Moreover, the water that oozes up to the soil surface—for example, from the still unfrozen active layer in early winter or from a pocket of unfrozen soil (called talik)—freezes very quickly in the extreme cold and triggers the formation of ice layers that may be accompanied by strong pressure.

Preventing thermal destabilization of permafrost in the construction sector relies in large part on the use of appropriate backfill concepts for transportation infrastructure and building foundations. However, given the fact that the northern environment is very dynamic, the risks associated with the appearance of active processes in the land must also be considered in land development.

The various permafrost disruptions therefore are reviewed here based on their climatic, ecological and human causes. The dynamic processes associated with water runoff in the soil and on the surface are discussed. Finally, we comment on the human causes linked to construction of infrastructure and buildings.

5.2.2 Climatic disturbances

When the climate changes, the permafrost thermal regime adjusts to the new conditions. The depth of the active layer diminishes in periods of cooling and, conversely, increases in periods of warming. The temperature profile adjusts accordingly. Before the start of the 20th century, climate changes were attributable to natural causes (e.g. variations in solar activity or circulation of ocean currents). Between the end of deglaciation in northern Québec (some 8,000-7,000 years ago) and approximately 3,000 years ago, the paleoclimatic indexes obtained from lake sediment cores and stratigraphic and pollen analyses in peat bogs indicate a fairly hot climate. Later, the climate fluctuated, cooling over the long term until the latest cold period, called the “Little Ice Age.” This period, probably the coldest in the latest millennia, generally extended from the mid-14th century to the end of the 19th century.

During that period, permafrost temperatures cooled, as documented by geophysicists through digital analysis of thermal profiles deep in the rock (Chouinard et al., 2007). It was also during this period that a large number of palsas formed (see section 5.1).

Early in the 20th century, the climate began to warm around the globe, but always with variations. This warming may have been caused in large part by industrial activity on the planet, especially the growing use of responsible for an increase in greenhouse gases.

The climate data from Environment Canada stations in northern Québec show that temperatures slowly declined after the late 1940s, but with interannual variations until 1992. Since that date, the climate has shifted to a completely different regime as the land has undergone unprecedented warming (Figure 5.38). Figures 5.39 and 5.40 show the thickening of the active layer that occurred in the 2000s in various soil types in a few Nunavik communities.

Table 5.5 summarizes the known climate changes that have had documented effects on permafrost for the past 3,500 years or so.

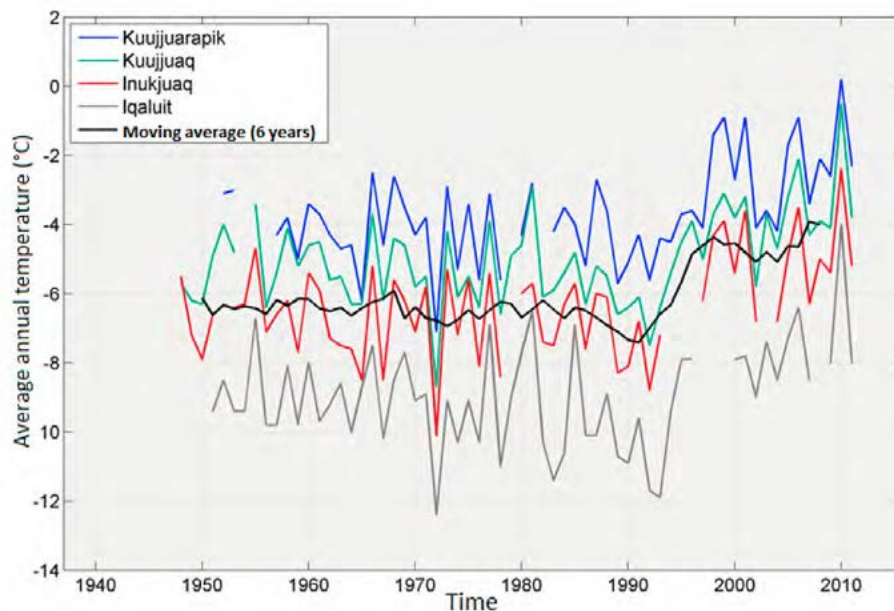


FIGURE 5.38: CHANGE IN AVERAGE ANNUAL TEMPERATURES IN NUNAVIK AND AT IQALUIT IN NUNAVUT BETWEEN 1948 AND 2011 (SOURCE: ENVIRONMENT CANADA).

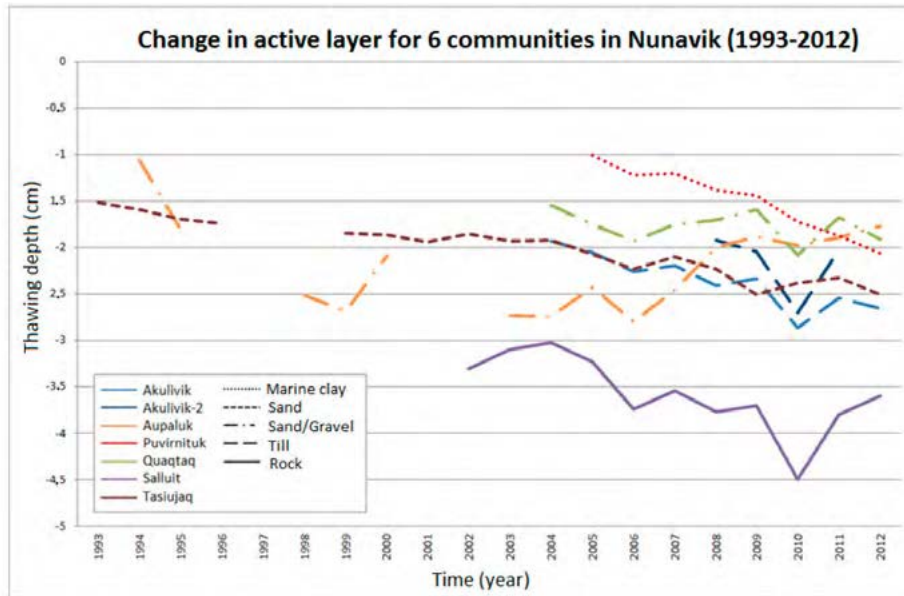


FIGURE 5.39: THICKENING OF THE ACTIVE LAYER IN THE 2000S IN VARIOUS SOIL TYPES IN A FEW NUNAVIK COMMUNITIES.

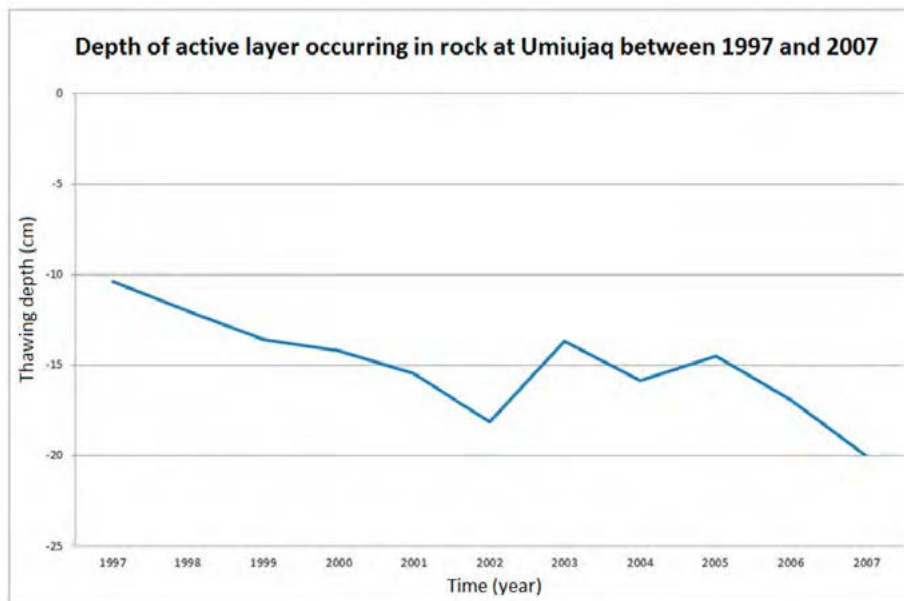


FIGURE 5.40: THICKENING OF THE ACTIVE LAYER IN ROCK AT UMIUJAQ BETWEEN 1997 AND 2007.

PERIOD	CLIMATE	VEGETATION	ICE WEDGE ACTIVITY
1950 to 1992	Cooling	Sedge and moss	Gradual reactivation of ice wedges
1900 to 1950	Hot	Sedge and moss	Cessation of activity
1500 to 1900	Cold	Moss Eolian activity Slope process	Activity intense
1030 to 1500	Cooling	Herbaceous Eolian activity Slope process	General increase in activity
140 to 1030	Generally hot and humid	Sphagnum	General decline in activity Alternating activation and deactivation
-1400 to 140	Generally cold and dry	Sedge Eolian activity	Generally active Formation of low-centred polygons

TABLE 5.5: GENERAL CLIMATE PERIODS DETECTED THROUGH ICE WEDGE ACTIVITY AND PALEOECOLOGICAL INTERPRETATIONS. THE TIME SCALE IS NOT LINEAR (ADAPTED FROM KASPER AND ALLARD, 2001).

What disturbances of the permafrost in Nunavik can we associate with recent climate warming? The comparative mapping (of old and recent aerial photographs) of palsas, lithalsas and thermokarst lakes between Kuujjuarapik and Inukjuak reveals a gradual disappearance of permafrost in the discontinuous zone since the late 1950s, with the speed of deterioration growing in the past 20 years.

Moreover, landslides at random locations in the active layer are partly attributable to warming. Thus, L'Hérault (2009) showed that strike-slip slides of the active layer have tended to occur in late summer of warmer-than-average years, when the active layer thaws more deeply than in previous years. Thawing reaches the particularly thick layers of segregation ice in the permafrost table, effectively increasing interstitial pressure just at the thawing front, which then provides an ideal landslide plane (Lewkowicz and Harris, 2005).

Other causal factors, however, may enter into play, such as increased water content due to snow accumulation on roadsides. At the very least, the risk of landslides increases as the active layer expands and is more pronounced in warmer years.

Figure 5.41 shows the expected temperature increases in northern Québec based on the output of climate models produced by the Ouranos consortium.

These increases will cause a decline in freezing indexes and an increase in thawing indexes. In the natural environment, the gradual disappearance of permafrost will continue in the discontinuous zone.

In the continuous zone, the thickness of the active layer will continue to grow, causing compactions of the land surface, and temperatures in the actual permafrost will rise, thus approaching the fusion point.

In the built environment, thickening of the active layer will trigger compactions, for which buildings must be prepared. Otherwise, they will have to be moved. The risk of landslides in ice-rich soils such as marine clay will increase, even on very gentle slopes.

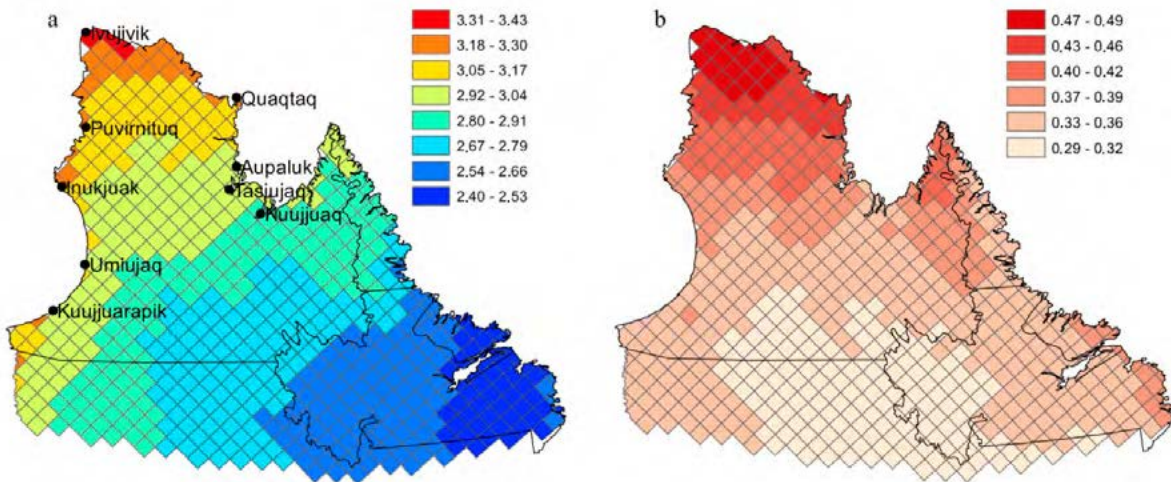


FIGURE 5.41: A) PROJECTED CHANGES IN AVERAGE ANNUAL AIR TEMPERATURE (°C) OUT TO 2050 BASED ON SIX OUTPUTS FROM THE CANADIAN REGIONAL CLIMATE MODEL (CRCM) AND B) THEIR STANDARD VARIATIONS (FROM BROWN, R. ET AL., 2012).

5.2.3 Geomorphological and ecological disturbances

This category includes the natural processes that occur without necessarily involving climate change or the impact of human activity. However, a meteorological event such as a rapid winter thaw, heavy rains or a heat wave can trigger these processes. These may be spontaneous and very fast, that is, catastrophic, or slower, resulting in particular from changes in vegetation. The primary types of disturbances are listed below:

- Fast processes
 1. Landslides of the “active layer strike-slip” type
 2. Thermal erosion
 3. Formation and collapse of icings and seasonal frost blisters (ice-core hummocks)
 4. Wet snow avalanches
- Slow processes
 5. Gelifluction
 6. Differential snow cover and shrubification
 7. Formation of thermokarst lake

“Active layer strike-slip” landslides (Figures 5.42 and 5.43) occur when the thawing front advances rapidly in an active layer that contains a great deal of ice. Specifically, however, they tend to occur toward the end of an especially warm summer when the thaw penetrates deeper than in previous years, thus melting ice lenses previously formed at the permafrost table. The movement is usually fast, just a few minutes. This type of slide most often starts at the top of the slope and bulldozes the active layer as it slides to the bottom of the slope along the very ice-rich permafrost front. The slide may continue a little farther after the exposed walls collapse. These slides occur in soils very rich in ice, such as marine clay or tills. The combined triggering factors are:

- An abundance of ice at the base of the active layer or in the upper part of the permafrost;
- The angle of the slope; risk rises with the slope, although this type of slide can occur on slopes as gentle as 2° to 4°;
- Local soil temperature higher than in surrounding soil, due for example to the presence of greater snow accumulation;
- High water content in the active layer following concentration of surface runoff;
- A rapid thaw during a warm summer in addition to a heat wave at the end of the season.

Ground conditions in fact are already present in the environment. The risk of a slide rises with sustained and higher summer temperatures. In 1998, three slides of this type occurred in the Salluit Valley, including one on the edge of a residential neighbourhood under construction (Figures 5.42 and 5.43).



FIGURE 5.42: AN ACTIVE LAYER STRIKE-SLIP SLIDE AT SALLUIT IN 1998 RESULTED IN ABANDONMENT OF DEVELOPMENT OF THE NEW RESIDENTIAL NEIGHBOURHOOD AND THE MOVING OF SOME TWENTY RECENTLY INSTALLED HOMES.



FIGURE 5.43: ACTIVE LAYER STRIKE-SLIP SLIDE AT SALLUIT ON AUGUST 22, 2010. WE SEE THE STRIKE-SLIP FAULT IN THE ACTIVE LAYER AND THE NEWLY EXPOSED ICE-RICH PERMAFROST. THE PLANT COVER AND ACTIVE LAYER SLID TO THE BOTTOM OF THE SLOPE. AT THE RIGHT, THE DOTTED LINE INDICATES A SIMILAR STRIKE-SLIP FAULT SLIDE THAT OCCURRED IN 2005.

Thermal erosion is a destructive process that can be very fast. It creates ravines, tunnels or erosion of banks triggered by the flow of free water directly over exposed permafrost. This exposure may result from any number of causes, such as a landslide, excessive erosion by a stream during heavy rain, massive water infiltration into an open frost crack at an ice corner, sudden drainage of a lake by an erosion channel, or permafrost erosion along a river bank. Sometimes, when it affects ice corners, thermal erosion creates tunnels under the land surface.

The process therefore occurs naturally where permafrost is rich in ice and where series of tundra polygons are present. The times of year posing the greatest risk are during the spring thaw, when large amounts of water are running under the surface of the still-frozen tundra, and during intense rains in summer. With climate change, such episodes are likely to become more frequent.

Icings or ice domes (naled, aufeis) are layers of ice that form on the soil surface, or in the bed of a watercourse or lake. They are the product of runoff that freezes as it spreads in the open air in winter. Underground runoff can occur in the active layer or through taliks (unfrozen area) in discontinuous permafrost zone. Ice domes may be up to several metres thick and extend over several hundred square metres. These layers of ice melt late in summer. They form domes when the water pressure continues to build under the first layer of ice already formed. These domes crack under pressure and new layers of water spread across the surface, causing the ice dome to spread and thicken. The process often occurs in river beds that maintain a small flow under their ice cover in winter.

Seasonal hummocks with an ice core (frost blisters, pingoes, hydrolaccolithes) form in a very similar way except that the water flowing in the soil, generally in the active layer, concentrates in a specific place and forms a lens trapped in winter under the surface of frozen soil, caught between the permafrost and the surface of the active layer that is refreezing. This frozen soil swells and cracks under hydraulic pressure. When the water lens freezes, it becomes the ice core of the hummock. These inflows of water that continue through part of the winter form layers of massive ice or mega-pure ice lenses (> 1 m). This intrusive ice is distinct for its crystalline structure in vertical prisms. Since it forms under the surface, the ice is covered by a mineral and/or organic layer. This layer is often ruptured and the ice is directly visible in spring in the cracks and many small land slumps. All this ice normally melts over the summer, but sometimes persists more than a year. The rapid formation, in a single winter, of seasonal frost blisters, and the hydrostatic and cryostatic pressure they generate as they grow, heaves up thick layers of soil, which rupture and dislocate during the thaw.

Ice domes and seasonal frost blisters reform at roughly the same location each year, at the foot of slopes, in wetlands along watercourses and at the site of springs and seepages in summer.

Avalanches are not a phenomenon associated with permafrost. There are two general types—snow avalanches and wet avalanches—which can also be called slush avalanches. The slopes where snow avalanches might occur have already been indexed in the territory of Inuit communities in Nunavik, following the fatal avalanche that occurred in Kangiqsualujjuaq on December 31, 1998. The foot of banks in the Salluit Valley therefore has been zoned “at risk of avalanche.”

Slush avalanches generally occur in torrential ravines or corridors running down mountainsides. They usually occur during a fast spring thaw or heavy rain, which greatly increases the water content of heavy drifts. In turn, drifts sometimes retain large amounts of meltwater upstream before they collapse catastrophically. The resulting rapid runoff consists of a mix of water, snow, mud and blocks of rock with strong erosive force. This type of avalanche took out a portion of the Baie Déception road on May 15, 2005 (Figure 5.44).



FIGURE 5.44: SLUSH AVALANCHE THAT TOOK OUT A PORTION OF THE BAIE DÉCEPTION ROAD ON MAY 15, 2005.

Thus, a geomorphological analysis of the risk of a snow or wet avalanche must be conducted when building infrastructure or homes in valleys and areas in Nunavik with steep terrain.

Gelifluction consists of a slow downward slide of the soil surface on slopes in areas where frost is active. This is actually summer creep of the thawed surface of the soil across the underlying soil that remains frozen. The presence of frost under the surface, whether permafrost or the active layer that has not fully thawed, prevents deep percolation of rainwater and promotes water saturation of the thawed layer to the point where it becomes plastic or semi-fluid. During the summer thaw, oversaturated sediments begin to creep down slopes. Fine-matrix soils (silt and clay) at a slope of 5° to 20° are the most sensitive, although noticeable movements have also been recorded on much gentler slopes ($\approx 1^\circ$). The organic matter of soil surface horizons also provides colloids (fine organic particles) that promote water retention and make the soil plastic. The rate of creep down slopes depends on the conditions specific to each site (slope, texture, penetration speed of the thawing front, variations in soil water content along the slope, etc.), but usually is about three or four centimetres a year and rarely exceeds 15 cm. A stretching and alignment of structured soils as alternating mud boils and plant cover is usually observed parallel to the slope as these are stretched by gelifluction.

The most frequent forms are gelifluction layers or lobes (see Figure 5.35, section 5.1.9.4). These present a fairly uniform surface of varying slope and an abrupt front usually 50 to 150 cm high. A cross section at the front of a layer often reveals overlaid paleosoils (see Figure 5.36, section 5.1.9.4). The presence of these forms thus is a sign of slow but persistent slope instability. To the best of our knowledge, no study has established the structural risk or the forces that gelifluction may exert on buildings or infrastructure.

The associated differential snow cover and shrubification constitute an ecological process closely linked to the morphology of the land and the compaction caused by thawing of permafrost ice. Snow actually plays a major role in the evolution of periglacial environments. Under the effect of wind, it is very unevenly redistributed across the land surface. Flat or convex landforms without shrub or tree cover remain almost totally devoid of snow because they are scoured by the wind, which erodes and redistributes the snow on the ground. By contrast, sites sheltered from deflation (depressions, slopes, copses) can often accumulate several decimetres or even metres of snow. This snow cover plays a major role in the thermal profile of the soil surface (see preceding section). For example, throughout virtually all of Nunavik, snow accumulation exceeding one metre, especially at the start of the season, insulates the soil surface in winter to the point that the annual thermal regime is at or above 0°C, thus thawing ice in the permafrost. On soils with excess ice content, thickening of the active layer as a result of warming caused by snow cover triggers compaction and thus the formation of depressed land in which a greater amount of snow will accumulate in subsequent winters, creating a feedback loop that hastens the process.

The impact of climate warming on vegetation is an additional accelerating factor. The deeper snow cover in the depression protects shrub seedlings (willow, dwarf birch, alder, spruce) from freezing and desiccation caused by winter cold, while longer, warmer summers promote plant growth. The vegetation grows denser and higher. These groves slow the wind speed and retain more snow in winter. Differential snow cover and shrub or even tree cover is now having a major impact on permafrost degradation in the discontinuous zone (Figure 5.45).

Once permafrost starts to deteriorate, land drainage becomes poor and the soil becomes saturated with water. This water in the active layer (which deepens over time) takes much longer to freeze again in winter because of its extensive latent heat of fusion (see section 5.1.4). This delay prevents recooling of the thermal profile in the permafrost, which then warms up in a few years and approaches the fusion point.

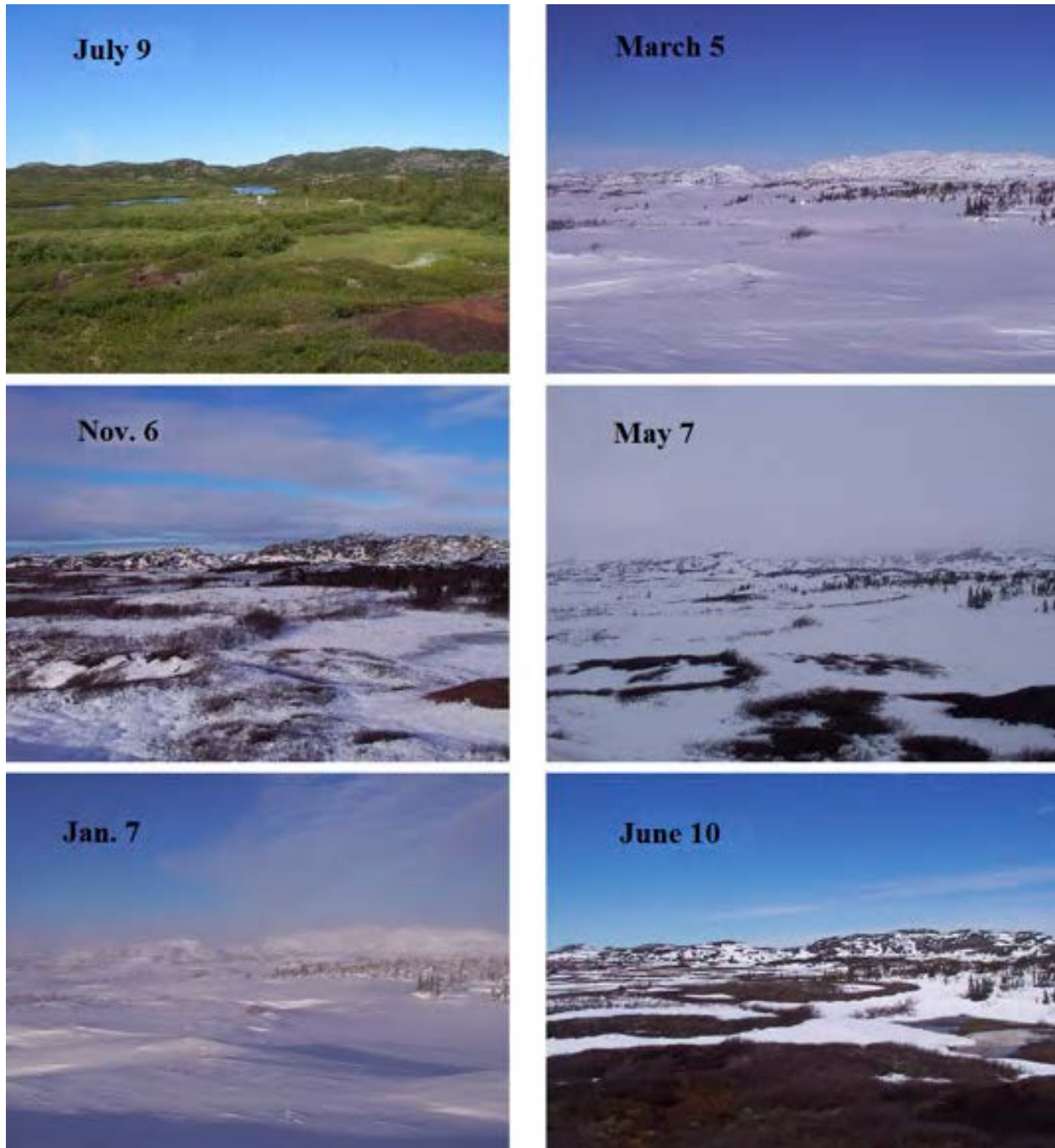


FIGURE 5.45: SEQUENCE OF SIX PHOTOS SHOWING DIFFERENTIAL SNOW COVER IN A DISCONTINUOUS PERMAFROST ZONE FROM JULY 2003 TO JUNE 2004. ON JULY 9, A LITHALSA (BEARING A WEATHER STATION) IS SURROUNDED BY SHRUBS AND WETLANDS FREE OF PERMAFROST. ON NOVEMBER 6, THE FIRST SNOW COVERS THE LANDSCAPE. IN WINTER, WINDS REDISTRIBUTE THE SNOW (VISIBLE IN THE COMET-TAILED DRIFTS) AND THE DAMP DEPRESSIONS ARE FILLED WITH SNOW. ON JUNE 10, THE LITHALSA SUMMITS ARE EXPOSED BY THAWING, BUT THE DEEP DRIFTS MELT LATE IN THE DEPRESSIONS WITHOUT PERMAFROST.

The formation of thermokarst lakes results from differential snow cover in the permafrost degradation sequence. When the depressions caused by compaction become deep enough in the land, drainage diminishes and they ultimately retain stagnant water. In winter, this water slows the refreezing of the soil. In summer, it absorbs solar radiation, sometimes becoming much warmer than the atmosphere. This heat is transferred to the permafrost, which then deteriorates, followed by compaction, and the lake grows deeper and spreads. Once it becomes deep enough (e.g. more than ≈ 1.5 m), the bottom no longer freezes in winter and the temperature rises significantly above 0°C throughout the year. A talik develops under the surface. As the thermokarst lake deepens, its surrounding slopes become steeper and subject to active layer slip-strikes and small landslides. As it continues to expand, it becomes a small lake and the banks start to erode under the effect of waves. As a result of this chain of geomorphological and thermal processes, some 50 percent of the permafrost existing in 1950 in the discontinuous zone east of Hudson Bay has now disappeared, replaced by hundreds of thermokarst lakes (see Figure 5.28, section 5.1.9.1).

5.2.4 Disturbances of indirect human origin

The impact of interventions and construction of infrastructure on the land are subject to the same principles related to the thermal regime and permafrost degradation as the natural environment. Permafrost is affected by construction and the presence of infrastructure where these create:

- conditions favourable to landslides or increased risk of a slide;
- new conditions favourable to thermal erosion;
- conditions favourable to the spread of subterranean water on the surface or to flooding by watercourses, even very small ones;
- conditions suitable to differential snow cover and shrubification, ultimately producing thermokarst.

Landscapers and builders must consider risk factors such as slush avalanches in their environment, and learn to deal with gelifluction on affected slopes.

5.2.4.1 Landslides

Human interventions likely to increase the risk of landslides are those that destabilize the land through excavation or fill in ice-rich soils, due to thermal degradation of exposed permafrost.

Except where necessary or for unavoidable reasons, adding fill to level land must always be avoided in permafrost unconsolidated deposits. Before depositing fill, builders must have excellent knowledge of the ice content of the permafrost to be excavated, because the stability of the new artificially created slope is dependent on this factor.

For example, a cut in an ice-poor gravel or sand deposit may have no consequences, but in ice-rich marine clay or till, slope stabilization work may prove difficult and above all, costly.

In natural talus, the factors that contribute to triggering active layer strike-slip slides are slope, liquidity limit of the thawed material, water content of the active layer, and interstitial pressure near the thawed/ frozen soil interface, which is the interface between the active layer and permafrost at the end of summer. The following main indirect human actions increase the risk:

- Increased water content in the active layer, for example, following diversion of upstream drainage, runoff from a culvert or retention through a damming effect, such as depositing road fill on a slope;
- Increased water content and depth of thawing of the active layer; excessive snow accumulation often results from construction of infrastructure (fill or building) that generates differential snow cover, or from snow clearance operations;
- Application of overload caused by fill or an invert installed on a slope; however, as long as the permafrost is maintained under the invert or fill and under the foot of the fill, the land will remain solid; overload begins to have an effect when the active layer deepens and becomes saturated with water when the permafrost thaws;
- Creation of a cavity or ravine by thermal erosion, in which the destabilized slopes will then continue to deteriorate until they trigger landslides.

5.2.4.2 Thermal erosion

The human cause of thermal erosion most often observed in the tundra is rutting caused by vehicles or machinery. In the presence of permafrost, surface water actually runs off primarily in the form of thin layers and thin streams of water. Sometimes this becomes concentrated in “watertracks” in which the water runs off by seepage in the active layer in summer and on the surface, especially during the spring thaw.

Tundra vegetation and organic matter in the active layer easily absorb the low kinetic energy of this surface runoff. However, once channelled into a rut, the rills concentrate their energy and erode the frozen soil. One or more ravines can quickly form when the heat of the moving water (carried by convection) is transferred to the permafrost, in which the ice melts very quickly. A system of thermal erosion ravines can develop catastrophically in just a few hours and have a destructive effect on the land.

This case can be amplified in the presence of a series of ice corners, the thawing of which can quickly give rise to chaotic topography. The energy produced by water running out of culverts under all road fills must also be monitored and dispersed if necessary, to avoid the formation of thermal erosion cavities or plunge pools and accelerated gullying (Figure 5.46).



FIGURE 5.46: THERMAL EROSION AND PLUNGE POOL IN A FORMER RUT CAUSED BY MACHINERY PASSING OVER THE TUNDRA.

5.2.4.3 Seasonal icing and frost blisters (ice-core hummocks)

Two aspects of icing and formation of intrusive large ice lenses in the soil must be considered. First, these must be avoided when planning land development or construction. Second, one should avoid triggering these processes because they usually become uncontrollable and cause serious damage to roads and buildings.

The simplest way to detect places affected by water seepage is to observe terrain in winter or, better, at the start of spring when surrounding snow has already largely melted, revealing the ice.

Since these ice forms essentially reappear in the same place each winter, they leave traces in summer: muddy terrain saturated with water, small hummocks of vegetation half submerged and still showing remains of ice, cracks in the plant cover, and stones dislodged from their original place in the soil.

Making cuts in slopes poses the greatest risk of triggering icing. This operation can actually expose seepage areas in the active layer that were previously invisible on the surface.

This can even occur in rock where water flowing in joints and fractures between the refrozen surface and the permafrost table can be released. This water may even be found at a certain artesian pressure, depending on the topography. Once the winter runoff and icing have started, on a road for example, they become very difficult to contain and control due to the complexity of subsurface runoff, which follows local variations of thickness in the active layer, relief and topography of the rock below unconsolidated deposits.

5.2.4.4 Differential snow cover

Snow accumulation at the foot of road and airport runway fill, at the edge of inverts, in ditches and on the downwind side of buildings is probably the main indirect impact of human actions on permafrost destabilization. The formation of snow banks is linked to winds, which redistribute the snow that has fallen on the ground, against topographic obstacles, especially road fill, in cleared sections and on the downwind side of buildings. As just one of many examples, Figure 5.47 shows the effect of fill at the Tasiujaq airport during its construction in 1989 and a dozen years later.

Aside from the depressions containing water at the foot of the fill, shrubbery colonization of the snow-covered band parallel to the runway is obvious. During geophysical surveys in 2004, and validation core drilling in 2009, it was found that the permafrost had thawed to a depth of seven to eight metres under the snow-covered area, resulting in major compaction on the runway shoulders, which thus required renovation work.

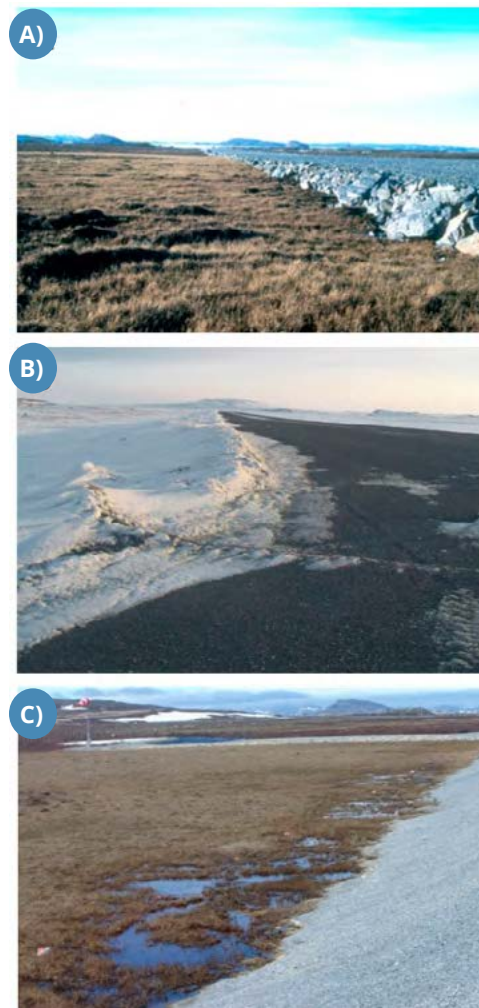


FIGURE 5.47: IMPACT OF SNOW COVER AGAINST FILL ON THE TASIUJAQ RUNWAY. A) CONSTRUCTION USING FILL OVER THE TUNDRA IN 1989. B) SNOW ACCUMULATION AGAINST THE FILL (>2 M THICK). C) THERMOKARST LAKES AND START OF SHRUBBERY COLONIZATION IN 2004.

Similarly, in residential developments built on permafrost, the benefit of buildings raised above the ground, on trestles or piles, extends beyond their immediate stability. The passage of wind under buildings prevents snow accumulation in the area, thus helping to preserve permafrost stability and prevent compaction, creation of depressions and formation of standing water.

The other cause of differential snow cover that damages permafrost is localized piling of snow from snow removal operations, for example, along roads (Figure 5.48) or in snow depots on soils sensitive to thawing. Snow piled by machinery has a much higher density than fresh snow, giving it greater thermal conductivity, so we can assume it does not insulate as well as natural snow drifts.

Of course, the large amount of snow usually piled cannot fail to reduce winter heat loss from the underlying soil. Add to this the large amount of water released into the active layer when this snow thaws, which will slow refreezing in subsequent winters, increasing the risks of thermal erosion and increasing the risk of landslides.



FIGURE 5.48: LARGE ACCUMULATION OF SNOW AGAINST FILL ON THE AIRPORT ROAD AT SALLUIT IN MAY 2011. THE ROAD HAD TO BE REBUILT IN 2012 TO REPAIR THE DAMAGE CAUSED BY PERMAFROST DETERIORATION.

As noted in the introduction, problems of drainage, water accumulation and soft soils along the edge of infrastructure and buildings are usually caused upstream by warming of soil temperature, thus by a thermal impact. Compaction and poor drainage reflecting this thermal impact generally take a few years to become visible. Differential snow accumulation is the main cause of local thermal impact.

5.2.5 Direct human disturbances

Direct human disturbances are those in which heat generated by a structure or industrial activity is transferred directly to the permafrost, causing thawing of the permafrost that supports the structure responsible for this deterioration. This may involve industrial activities such as a mining operation in permafrost or passage of an underground pipeline that is moving warm fluid. In construction, the main direct impact is heat transfer from a heated building to the underlying permafrost.

Compaction caused by thawing of the permafrost, usually differential, that is, of unequal amplitude over space, results in structural damage to and deformation of buildings, occasionally making them unusable, and only fit for demolition (Figure 5.49).



FIGURE 5.49: SALLUIT FIREFIGHTERS' GARAGE. BUILT IN 2003 ON A CONCRETE SLAB, IT HAD TO BE DEMOLISHED AFTER THE FLOOR SANK ABOUT 0.50 M DUE TO THAWING OF THE PERMAFROST UNDER THE FOUNDATION.

This is why many technological approaches in construction on permafrost are described in the following sections. However, all focus on a single goal: in one way or another, they keep annual average soil temperature below 0°C. The only other solution is to build only on rock or unconsolidated deposits known with certainty not to contain excess ice and to have good drainage when they thaw. In light of ongoing climate warming, the best option is that which guarantees total safety and long service life of buildings.

5.2.6 Conclusion on permafrost concepts

In the construction of buildings, residential complexes and urban or transportation infrastructure, the most important consideration is adequate knowledge of the soil or unconsolidated deposit and its geotechnical properties. An even more important requirement, however, is adequate knowledge of ice content and the thermal regime of the permafrost. This knowledge cannot be acquired solely by excavating the active layer. Core drilling is necessary and the temperature of the permafrost must be measured. In light of climate warming, this information will assist decision making to ensure the stability of construction as long as possible. Knowing the thermal regime and ice content is essential if a decision is made, prior to building, to conduct predictive calculations and digital simulations, which must be validated by measurements.

The first principle is not to trigger a direct or indirect impact on the thermal regime of the permafrost. A direct impact under a building will result in serious damage over a period of two to four years.

An indirect impact, for example, the appearance of new drifts, will take longer to occur, causing damage or involving natural risks, but the spatial spread of this impact might compromise long-term viability of the community in this location. Construction and development where permafrost is present, including the choice of foundation type, therefore must be carried out with long-term prevention in mind.

5.3 GENERAL CONSIDERATIONS ON FOUNDATIONS

The role of a foundation is to transfer and distribute loads from a building to the soil and to maintain stability of the structure throughout its service life. Through the simple fact that a foundation rests on soil, good knowledge of the geotechnical characteristics of the soil is vital to properly assess the mechanical properties and other factors that might affect foundation durability. Designing and building a foundation in a permafrost zone poses a serious challenge due to the number of factors to be considered, which differ in nature and intensity from those in areas without permafrost (Johnston, 1981).

In permafrost areas, the surface soil is subject to the effects of seasonal freezing, in which the successive phase changes reduce the soil's resistance and trigger several processes. These include frost heaving and differential compaction, which can affect foundation stability and cause serious damage to the structure (Phukan and Andersland, 1978). The simple conversion of interstitial water into ice during the freezing process induces an increase in soil volume of 9 percent, almost half of which translates into vertical uplift (Sanger and Sayles, 1979). This uplift increases when the soil characteristics as well as the hydraulic and thermodynamic conditions promote the formation of ice lenses. Under this surface layer of soil lies a layer of permanently frozen soil (permafrost), with mechanical characteristics very closely linked to its thermal state. Interactions between geological, geomorphological, hydrological and climatic processes within a periglacial environment define the geotechnical and cryostratigraphic characteristics of permafrost. Thus, permafrost consists of a complex assembly of solid particles, air and ice in various forms (interstitial, in segregation, intrusive and massive) that reflect the specific conditions present when it was initially formed (epigenetic phase) and over the course of its development (syngenetic phase).

In Nunavik, many problems involving the foundations of community buildings have led to demolition or relocation of the building, or a change of its initial use. In most cases, these problem foundations were built over ice-rich permafrost without conducting a prior study of the soil. That study focuses specifically on identifying problem sites and recommending an acceptable technical approach to ensure stability and sustainability of the structure. The costs incurred by preliminary studies, detailed site surveys and geotechnical follow-up during construction represent a small fraction of the investment necessary for building new housing. Note that construction costs as well as living costs are much higher in Nunavik than in Québec's temperate zones due to the limited availability of human and material resources. Consequently, the risks of instability of foundations built on permafrost must not be under-estimated. Sound knowledge of the physical characteristics of a building site in a permafrost zone is vital for designing optimized structures adapted to the site conditions.

The mechanical conditions of permafrost are thermodependent, which means that soil temperature influences bearing capacity, adherence strength due to freezing, and creep rates. Areas where permafrost is discontinuous and warm (annual average soil temperature above -2°C) pose serious challenges for engineering foundations, due to very poor soil strength, high creep rates and limited thermal resilience following changes in the land and climate. Although just as complex, areas where permafrost is continuous and cold (annual average soil temperature below -2°C) provide better resistance values and creep rates, but remain sensitive to thermal disturbances despite greater thermal and mechanical resilience.

5.3.1 Freezing action and foundations

The effect of seasonal freezing within the active layer can subject foundations and any other structure to considerable uplift forces and destructive movements, making this a serious consideration in the design of foundations for unheated or slightly raised buildings, bridges, and transmission and communication towers (Johnston, 1981).

Frost heave consists of soil expansion due to the formation of ice lenses when soil refreezes at the start of winter. In a permafrost zone, frost heave is limited to the surface layer of the soil, which is subject to the annual freeze-thaw cycle (active layer). The amplitude of frost heave depends on soil type and availability of water. In general, a thicker active layer also increases the potential for soil uplift through the increase in water quantity and duration of refreezing. Under optimal conditions for frost heave, in the presence of soil sensitive to unconfined freezing, fed by water and subject to cooling that promotes freezing, there is no limit, in theory, to frost heaving. It is common to see soil surface uplift of a few centimetres, even about 15, during the freezing season. The recent use of teledetection techniques that take radar images of a given areas at different times to measure differential soil surface movements (DInSAR, InSAR) can quickly assess frost heave gelivity of surface deposits. Such measure-

ments, recently taken in Nunavik (May, 2011; Eppler et al., 2015) and Nunavut (Short et al., 2012; Leblanc et al., 2015), suggest seasonal movements with a potential amplitude of more than about 10 centimetres in any location, depending on the type of deposit and local drainage conditions.

At time of refreezing, the uplift forces that develop in the soil as ice lenses form can lift structures buried in or resting on the active layer. Uplift forces caused by freezing that develop within frost-susceptible soil are transferred to foundations in two ways: by base force acting on the base of the footing when ice lenses form, and by adherence force acting instead on the foundation walls (Johnston, 1981). The amplitude of the uplift forces that develop during ice lens formation in frost-susceptible soil is difficult to assess due to the many parameters to consider, such as overload, foundation load, soil type, soil temperature variation over time and depth, refreeze rate, availability of water, foundation surface type, foundation placement method, and rate and duration of loading. As soon as uplift forces due to freezing exceed the load applied to the foundation by the weight of the building, uplift occurs. In extreme cases, uplift forces of 1,000 kPa may develop under a footing and adherence forces due to freezing of almost 500 kPa have been measured along steel piles (Penner and Goodrich, 1983). During thaw, rapid thawing of lenses that have formed under the foundation may significantly reduce soil bearing capacity if the water released by the thaw cannot be effectively drained. In these circumstances, the foundation soil bearing capacity is greatly diminished, which promotes deformation under the infrastructure load.

Surface frost heave can seriously affect foundation integrity as shown in Figure 5.50 A) where the on-grade slab of an unheated building shows central arching of about 30 centimetres. After lifting over the winter, the foundation often cannot return to its initial position during the thaw and thus is gradually expelled from the active layer over the years. One of the clearest examples of the effect of frost heave on foundations, regularly observed in areas where permafrost is present, is the gradual expulsion of footings for fenceposts when these are sunk into the active layer (Figure 5.50 B). An example of skewing of surface foundations on an invert consisting of frost-susceptible material is shown in Figures 5.50 C) and D). The technical report (Journeaux Assoc., 2014) states that ice enrichment of partially frost-susceptible fill was promoted by percolation of surface water from sporadic spills that occurred during filling of the drinking water tank and by the lack of eavestroughs on the roof.

It has been demonstrated in the laboratory and in the field that the amplitude of frost heave can be reduced by increasing load on the soil (CRREL, 1974). In foundation design, the reductive effect on frost heave of adding an invert composed of non-frost-susceptible material can add a certain load to the soil, and also limit the amplitude of frost penetration into the natural terrain under the invert. It should be noted that in a permafrost zone, the addition of a layer of material over the natural land surface generates a readjustment of the soil's thermal regime that raises the permafrost table. This rise is proportional to the thickness of the layer of added material, but must be thicker than one metre, because with less than this, the change in surface conditions can neutralize the rise in the permafrost table, or even drive it deeper. Given this thermal readjustment, all or part of the initial active layer will become syngenetic permafrost and, during the process, the formation of ice lenses can produce frost heave. For this reason, it is preferable to build inverts one year in advance to allow them and the thermal regime to stabilize. To avoid the formation of ice lenses within fill through percolation of surface water in the soil, it is important to take precautions to allow effective drainage of foundations and remove water as much as possible. Conscientious snow management and the addition of a spill guard for drinking water tank fill hoses can reduce the risk of frost heave, especially in partially frost-susceptible fill.

The use of insulation can also considerably reduce penetration by the freezing front under unheated infrastructure as well as heated, raised structures with a ventilated space. The insulation thickness required is determined by the region's freezing index. Protection against frost is most effective when insulation is placed at a shallow depth, usually between 20 and 30 cm under a soil layer. Depending on the type of foundation used, several precautions can reduce the effect of frost on foundations; a few of these are shown in figure 5.51.

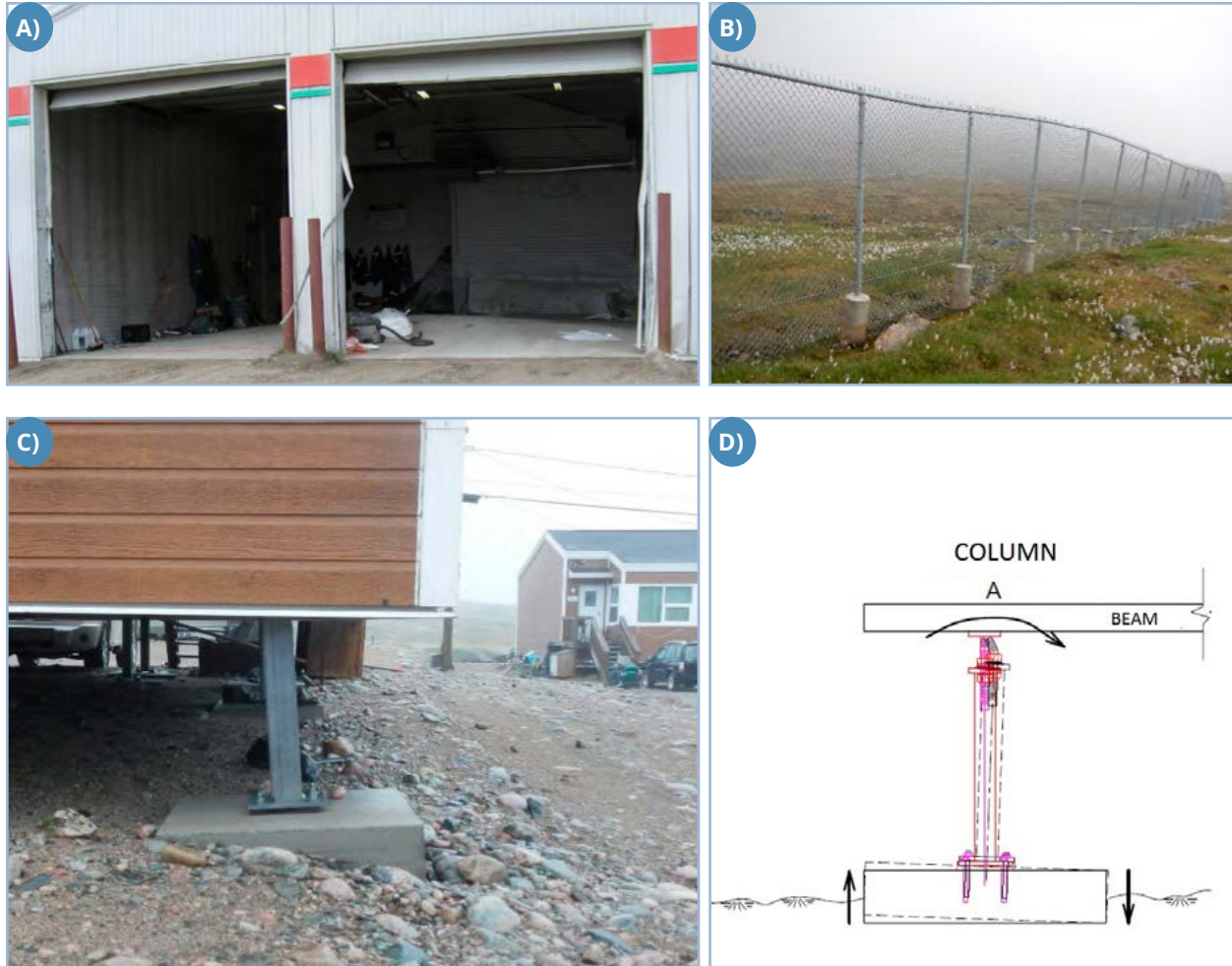


FIGURE 5.50: A) FROST HEAVE OF THE SLAB ON GRADE OF AN UNHEATED BUILDING FOLLOWING THE FORMATION OF SEGREGATION OR INJECTION ICE, AT PANGNIRTUNG, NUNAVUT. B) FROST HEAVE OF FENCEPOST FOOTINGS AT PANGNIRTUNG, NUNAVUT. C) INWARD SKEWING OF A FOUNDATION FOOTING CAUSED BY WATER SATURATION OF PARTIALLY FROST-SUSCEPTIBLE FILL COMBINED WITH THE FROST EFFECT. D) TYPICAL SKEWING MOTION OF FOUNDATION FOOTINGS (FROM JOURNEAUX ASSOC., 2014).

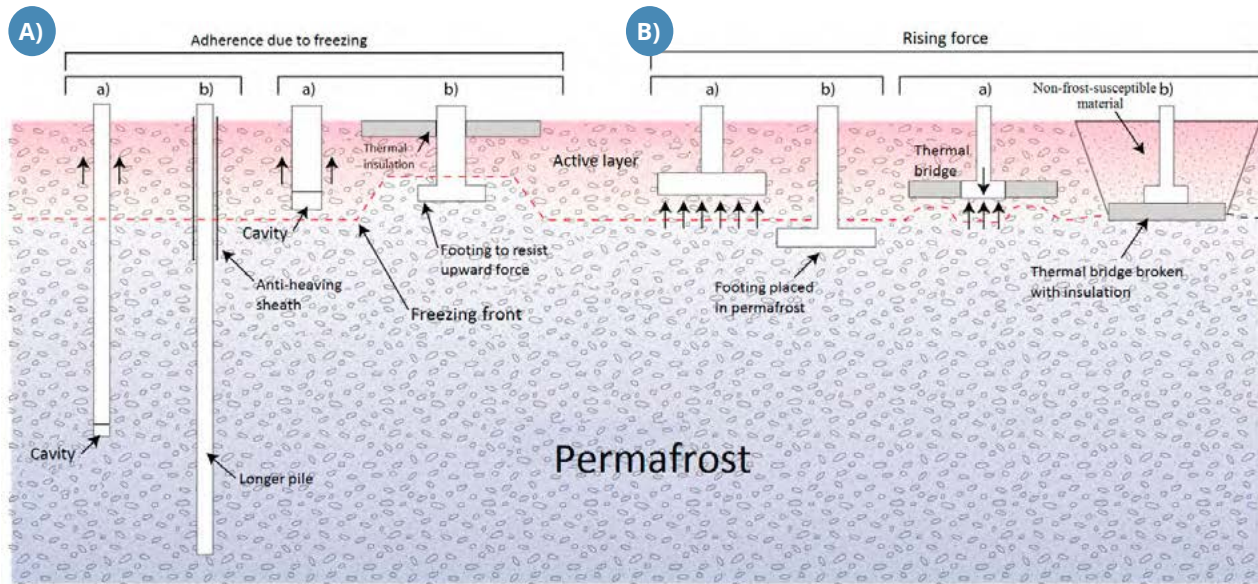


FIGURE 5.51: A) EXAMPLES OF THE FROST EFFECT ON CERTAIN FOUNDATION TYPES AND B) PROTECTIVE MEASURES.

5.3.2 Mechanical behaviours of permafrost

Permafrosted soils consist of a complex amalgam of soil of variable textures, ice in various forms and air bubbles, the mechanical properties of which are not easily estimated. Frozen soil generally provides excellent support for foundations due to the presence of ice in the pores, which creates bonds between the particles (Phukan and Andersland, 1978). In soils containing excess ice, however, deformation of the soil by creep under the foundation footings or accumulation of excess water at the thawing front can cause many problems. When soil is subjected to demand, that is, when a load is applied to the surface, such as that of a structure or fill, the subsequent vertical deformation is called compaction. As soon as a foundation and its load are placed on the soil, several phenomena occur in the short term and others begin to develop over the longer term. Soil compaction is often critical in a foundation project and can be broken down into several types of deformation, some reversible and others permanent.

1. The instant elastic deformation that corresponds to soil deformation linked to elastic deformation of the soil skeleton, ice, unfrozen water and gases (reversible)
2. Instant plastic deformation due to collapse of the structure of unsaturated frozen soil under load (irreversible)
3. Slow deformation by primary consolidation triggered by expulsion of part of the air and unfrozen water contained in pores under a pressure gradient (irreversible)
4. Slow deformation by secondary consolidation (creep), which corresponds to movement of solid particles governed by runoff from ice within the pores (irreversible), developing after primary consolidation

All these sources of deformation contribute to soil compaction under a given constraint, and the scope of each depends on the soil characteristics (granulometry and soil density), temperature and live load, variables that define the resistance behaviour of frozen soils. For example, shear strength of well compacted coarse-grained soil is determined by the angle of friction between particles and by its dilatancy. When the soil is frozen, its shear strength increases through intergranular bonds provided by the interstitial ice (grain cementation). However, this increased shear strength from ice reaches its peak at soil saturation and then declines when the soil becomes over-saturated with ice. In these conditions, the forces no longer apply to the mineral skeleton (reduced internal friction), but instead to the ice. Thus, the mechanical properties of the ice will determine soil shear strength, which is usually reduced due to its propensity for creep. Under constant pressure, the phenomenon of soil creep

induces deformation closely linked to the duration of the process. The creep rate in turn will be influenced by the ice content, soil temperature and live load. Under excessive load and after a certain time, soil may deform at a sustained rate until it reaches the breaking point (Johnston, 1981).

Under low constraints, ice-poor soils, in which grain-to-grain contact is possible, tend mainly toward primary creep, in which the resulting deformation will gradually stop. In the case of ice-rich soil, the intergranular contact that generates internal friction disappears, thus promoting deformation at a constant rate under low or moderate load. This type of soil tends more quickly toward secondary creep. Under high constraints, this soil type will shift rapidly to accelerated creep, without clearly distinct primary and secondary phases, and will break after a very short time. The constraint under which a sample break occurs within a few minutes defines the material's short-term resistance value. The constraint for which creep rates decelerate to zero after a certain time is called long-term resistance. In frozen soils with high ice content, long-term resistance is only possible when they are confined. Without confinement, they continue to deform indefinitely.

For frozen soils, the effect of temperature and time on soil strength and mechanical behaviour adds another dimension to design and remains vital in assessing the load that can be applied to the foundation. Temperature directly influences the mechanical behaviour of frozen soils through its consequences on the amount of unfrozen water and the strength of the bonds forged between particles by interstitial ice. In general, lowering the temperature increases soil resistance (Figure 5.52). However, the influence of temperature on resistance of frozen soils is not uniform and also depends on the type of material. For example, an increase in the strength of sand based on lower soil temperatures will occur very quickly and plateau as soon as the unfrozen water has been totally frozen. For silt and clay, soil acquires strength more gradually due to the proportion of unfrozen water that remains despite cold temperatures. The consolidation of frozen soils by expulsion of unfrozen water can be substantial in areas where the permafrost is warm and the material is likely to contain a significant portion of unfrozen water (silt and clay). Aside from temperature and the type of material, resistance of frozen soils will also be affected by salinity.

The term “bearing capacity” refers to the load that can be carried by the foundation soil, for which deformation and compaction will be limited and will not affect use and stability of the structure. As noted earlier, permafrost sensitivity to creep varies based on the soil characteristics (granulometry and soil density), temperature and live load. For ice-rich permafrost, major deformation through creep and compaction can occur, making foundation design even more complex, when choice of a durable solution can prove expensive or even impossible. Thus, the major issue in designing foundations resting on permafrost lies in choice of the site, therefore in characterization of the existing permafrost conditions and assessment of their thermodependent mechanical behaviour, which is transitory and changing.

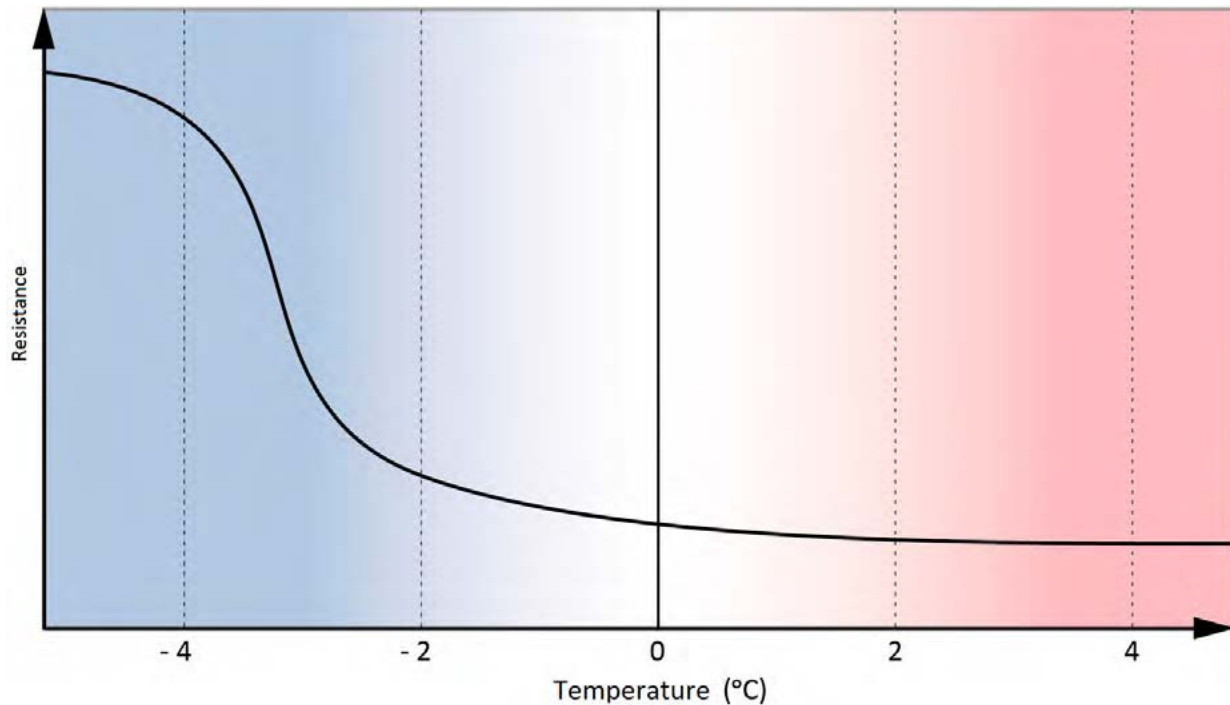


FIGURE 5.52: SCHEMATIC REPRESENTATION OF PERMAFROST RESISTANCE BASED ON TEMPERATURE.

5.3.3 Compaction and consolidation upon thawing

When permafrost melts, thawing of the ice produces a quantity of water that frequently exceeds the absorptive capacity of the soil skeleton. The direct consequence of this condition is an increase in interstitial pressure, which reduces the effective constraints, and inevitably, the soil's shear strength. The phase change for the ice as well as the expulsion of excess water in the soil trigger a change in soil volume that manifests in vertical deformation called compaction. The ability of permafrost to serve as foundation soil depends on its sensitivity to thawing, that is, the amplitude of compaction that occurs upon thawing, and its strength in the frozen and unfrozen state. Compaction and consolidation of ice-rich soils upon thawing can result in serious soil deformation, causing considerable damage to infrastructure. Many examples of damage to structures caused by such soil deformation have been reported in Nunavik and Nunavut. Thawing of permafrost is triggered by the structure itself (heated building), by changes in local environmental variables (snow cover, water accumulation, surface conditions) or by increased air temperature. Heated structures with a slab-on-grade foundation resting on ice-rich permafrost are especially likely to trigger such deformation if no special measure is taken to mitigate the thermal impact of the infrastructure on the soil (e.g. foundation with thermosyphons) (Figure 5.53).

When undrained saturated soil with constant water content freezes, it swells in volume equivalent to that associated with the phase change of interstitial water contained in the pores, approximately 9 percent. When it thaws, the soil will return to its initial volume and consolidate further if conditions allow the water to drain. This situation applies essentially in coarse soils where the ice segregation process is very limited. For fine-grain soils, slow and gradual penetration of the thawing front as well as constant water feed promote the formation of segregation ice. In such conditions, the water content of frozen soil often exceeds its water content in unfrozen and normally consolidated state. Consequently, when this type of soil thaws, major compaction occurs, essentially broken down into three parts: 1) compaction linked to phase change of the ice; 2) consolidation of soil under its own weight; and 3) consolidation of soil under the applied constraint. Compaction generally predominates when ice is present in segregated form (lenses) whereas consolidation predominates in the presence of interstitial ice.

In extremely ice-rich soils where ice lenses or massive ice occurs, compaction values can be roughly estimated through visual assessment of the thickness of ice lenses or the layer of massive ice. However, it is better to assess soil compaction and consolidation upon thawing in the laboratory using an undisturbed cylindrical sample taken from the permafrost in compliance with the ASTM D2435/D2435M standard. A thawing compaction and conso-

validation test is shown in figure 5.54. A small change in volume occurs in frozen state when constraint is applied (point a to point b). These are instant elastic and plastic deformations of the soil skeleton, ice, unfrozen water and gases. Following this, in thawing conditions, a large change in volume attributable to the phase change from ice to water, to drainage of excess water and to soil consolidation under its own weight will occur (point b to point c). The soil will then consolidate further, based on the overload applied, until it achieves a state of balance (point c to point d). The number of samples to be taken and tests to be conducted to accurately assess the compaction and consolidation parameters will depend on heterogeneity of the soil, ice distribution along the soil profile as well as size and function of the building. The purpose of these tests is to determine the total compaction values for the permafrost on which the structure rests, and if necessary, assess the amplitude of soil deformations resulting from thawing.

A few consolidation tests have already been conducted in Nunavik by researchers from Université Laval (Leroueil et al., 1991), but these have been limited to a single material (clay silt) collected in a single community (Kangiqsualujuaq). In recent years, however, in a geotechnical characterization initiative for permafrost conditions encountered in Nunavik, many consolidation tests have been conducted on a considerable number of samples covering the primary geological materials (gravel, sand and gravel, silt and clay), deposit types (glacial, marine glacial, coastal, alluvial, colluvial, organic and other sediments) and permafrost conditions (ice content, cryostructure, temperature, etc.) (L'Hérault et al., 2012; 2013, 2014; 2015). These results have shown that in certain communities, the probability of having to build on ice-rich soil is very high. Fine-grain marine sediments, colluvial deposits and certain tills are likely to contain large amounts of ice. Within a given surface geological unit, ice content varies greatly over space, both laterally and vertically, along the soil profile. In general, ice concentrations are highest in depressed, poorly drained areas and are stratigraphically concentrated in the top few metres of permafrost. It is also in these first surface metres of permafrost that the thermal impact caused by infrastructure or climate changes will be greatest.



FIGURE 5.53: SERIOUS DEFORMATION AND DAMAGE CAUSED TO SLAB-ON-GRADE FOUNDATIONS BY COMPACTION AND CONSOLIDATION AT TIME OF THAWING OF ICE-RICH PERMAFROST. A) HEATED WAREHOUSE AT PANGNIRTUNG, NUNAVUT. B) SLAB OF FORMER FIREHALL IN THE MUNICIPALITY OF SALLUIT, NUNAVIK. C) FORMER MUNICIPAL GARAGE OF THE MUNICIPALITY OF TASIUJAQ, NUNAVIK.

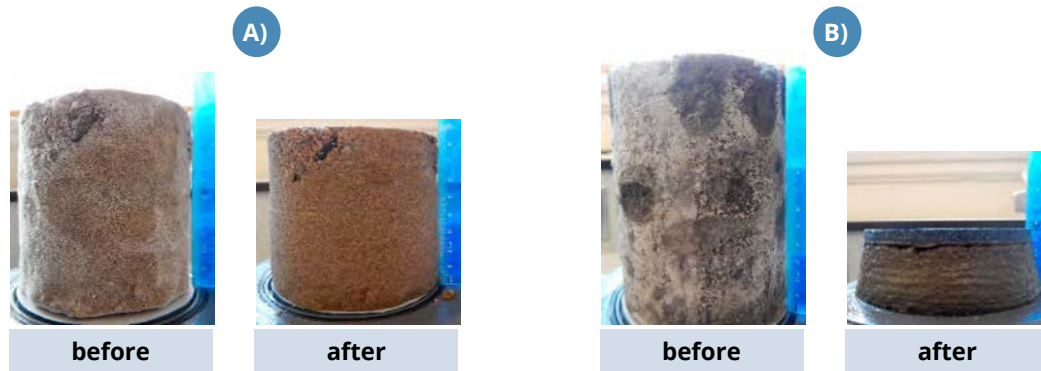


FIGURE 5.54: A) POOR IN ICE AND B) RICH IN ICE SUBJECT TO THAWING CONSOLIDATION TESTS (FROM L'HÉRAULT ET AL., 2015).

5.3.4 Thermal impacts of foundations on permafrost

As noted earlier, soil temperatures and the presence or absence of permafrost are the result of the interaction of a host of climatic (air temperature, solar radiation), environmental (vegetation, drainage) and geological (thermal properties of materials, geothermal flows) variables. For a given site, the soil's thermal regime reflects a transitional state of balance between intrinsic environmental conditions and climatic conditions. This transitional balance is definitely fragile and can tip rapidly toward thermal conditions favourable or unfavourable to the maintenance or even development of permafrost. Among the factors likely to disrupt the thermal balance of permafrost, development of land for construction and the presence of infrastructure definitely must be considered. Since they alter the initial conditions of surfaces, soils and the environment, these factors trigger a thermal change in the permafrost, an essential parameter in assessment of the thermal-dependent mechanical behaviours of frozen soils. When designing a foundation system, it therefore is vital to ensure that the building's thermal footprint is minimized, to preserve a thermal regime amenable to maintaining the permafrost, especially if this is unstable when it thaws. The compaction generated by thawing of permafrost can have catastrophic consequences on building integrity.

The amplitude of the thermal disturbance of permafrost caused by infrastructure depends on structure size, temperature inside the building, presence and thickness of insulation on the soil, presence or absence of a ventilated space, addition of a layer of material on the natural soil, and the thermal properties of the underlying natural soil (Figure 5.55). Permafrost generally thaws when a sufficient amount of heat is transferred to the soil. This situation occurs regularly when a heated building rests directly on the soil. This is precisely the type of foundation for which the largest number of ruptures have been recorded in Nunavik and elsewhere in the Canadian Arctic. Under this type of foundation, the thawing front will penetrate the soil at a sustained rate unless precautions are taken to reduce these heat transfers, for example, by using a ventilated foundation (natural or forced) or a cooling system (such as thermosyphons). Note that drinking or waste water tanks resting directly on the soil also risk disturbing the thermal balance of the soil by promoting its warming. In practice, these tanks are installed inside the thermal envelope of buildings, but they could also be placed on solid rock or a raised structure.

Allowing or even increasing the release of heat contained in soils (cooling) is a principle that may prove necessary for construction or rehabilitation of certain foundations resting on permafrost susceptible to thawing. The most economical, effective and common solution is to limit heat transfer between the building and the soil by raising the structure to create a ventilated space under the building. The passage of air extracts heat and limits snow accumulation. In addition, the shadow effect created by the building protects the soil surface from direct solar radiation, which helps preserve the permafrost. When the building cannot be raised, there are other techniques for evacuating heat, including thermosyphons and naturally or mechanically ventilated ducts. The experience acquired in Nunavut, the Northwest Territories and Nunavik shows that extreme caution is required when the effectiveness of the techniques used relies on human intervention or mechanically activated components. These crucial mechanisms for building stability must be maintained. For these reasons, only so-called passive technology, based on the thermosyphon principle, are recommended when constructing a new building. However,

they are used only very rarely in small residential buildings due to their fairly high cost. Although based on a so-called passive principle, thermosyphons also require periodic inspection. In particular, temperatures under foundations must be monitored and the system must be checked for potential gas leaks. These technologies are explained in greater detail in section 5.5 on foundation types.

Insulation is often used in a structure to limit thermal transfers between the structure's floor and the foundation soil. It also reduces heating costs and ensures occupant comfort. The most commonly used insulation materials are extruded polystyrene or expanded polyurethane panels. The choice of insulation material will depend on the required specifications for insulating properties, bearing capacity under static and dynamic load, and durability. Note that the addition of insulation reduces and delays, but does not prevent, heat transfer from the building to the soil. For this reason, preserving the permafrost under a heated building cannot depend solely on insulation. When the insulation material is buried under the surface in a humid environment, it can rapidly lose its insulating properties, by absorbing this humidity, as well as its strength, through physical alteration caused by repeated freeze-thaw cycles. To avoid such problems, insulation material is often buried within well drained, non-frost-susceptible granular fill placed on the natural soil surface (Figure 5.55 B).

The design must include a buffer zone where the insulation extends beyond the infrastructure perimeter to limit the impact of the edge effect on foundation performance associated with snow cover, wind and solar radiation (CAN/CSA-S500-14 standard). In fact, fill can absorb a substantial amount of heat through solar radiation, which can result in thermal deterioration of the permafrost and cause deformation in the fill. This thermal deterioration is especially serious in fill talus, where the granular material becomes too thin to ensure a transition with the natural terrain. The deterioration is even worse when a deep layer of snow accumulates and insulates the soil surface in winter (Figure 5.56). Once the deterioration process has begun, the environment changes and promotes positive feedback. This is usually followed by a deepening of the active layer which, following compaction to an extent dependent on the consolidation coefficient for the thawed permafrost, results in a depression where water accumulates in spring when the snow melts, and in summer. This water captures more solar radiation than the original plant-covered surface, which promotes warming of the surface and the soil. The following winter, the depression may receive a larger amount of snow, with an amplified insulation effect due to deeper snow cover, and so forth. In Nunavik, this precarious thermal situation at the foot of fill, caused by modification of local environmental factors such as snow cover and drainage through the simple presence of infrastructure, is the source of most deformations (compaction, creep) observed on the edge of fill.

During design, therefore, it is necessary to anticipate possible permafrost degradation on the edge of fill. One necessary precaution is to provide a sufficiently wide invert around the infrastructure to ensure that permafrost deterioration around the fill edge cannot affect stability of the structure. Lowering the slope of fill talus (1V:6H) and good planning of drainage ditches can reduce the potentially harmful thermal impact of snow and water accumulation at the foot of fill. In brief, regular monitoring of terrain conditions on the edge of fill is essential to quickly rectify factors that might promote permafrost degradation and thus avoid a worsening of the situation that could compromise the stability of the permafrost under the fill.

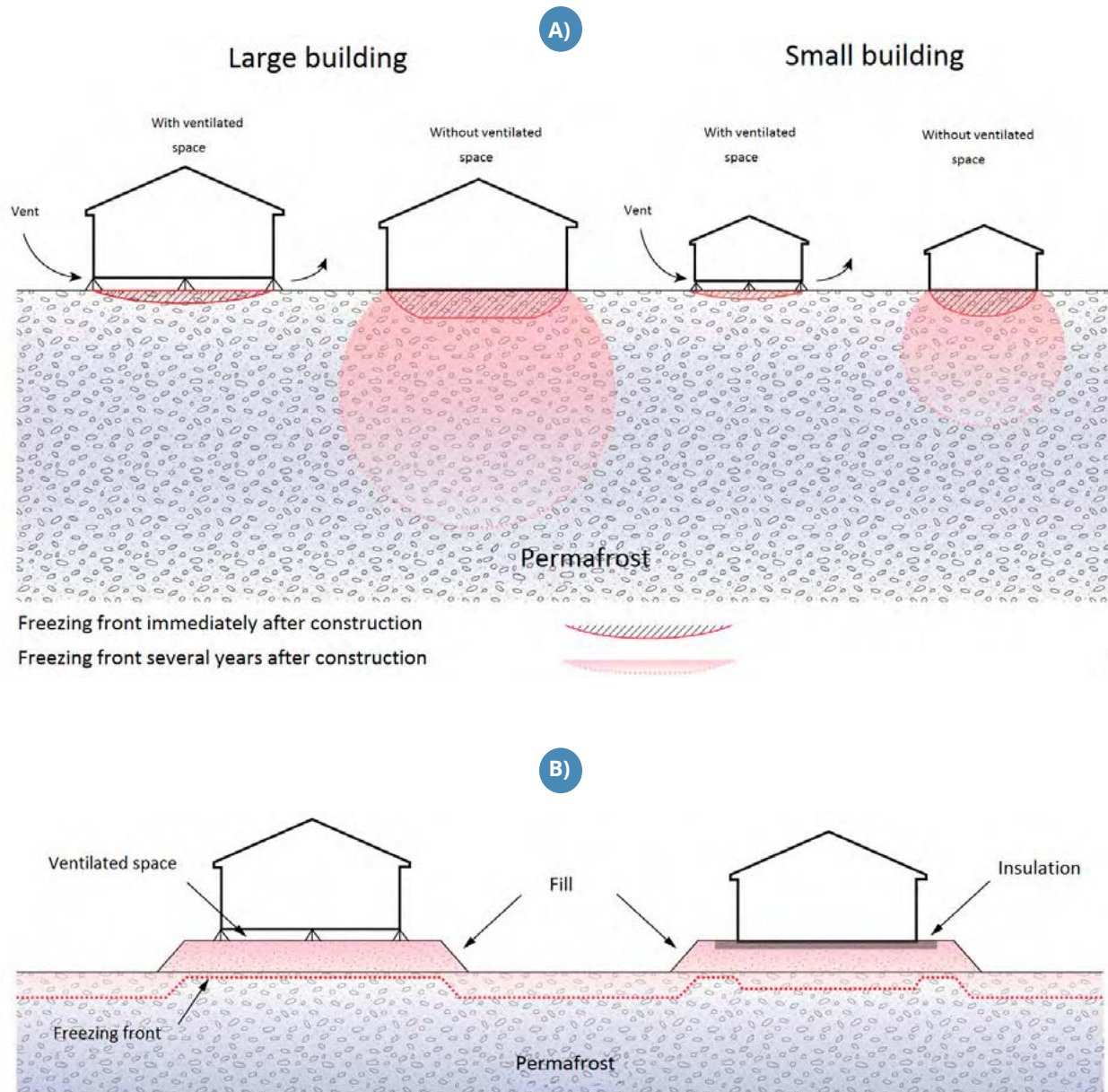


FIGURE 5.55: A) POSITIONS OF THE THAWING FRONT UNDER HEATED BUILDINGS BASED ON THEIR SIZE, FOUNDATION TYPE AND TIME. B) TWO TYPES OF FOUNDATION SYSTEMS RESTING ON GRANULAR FILL.

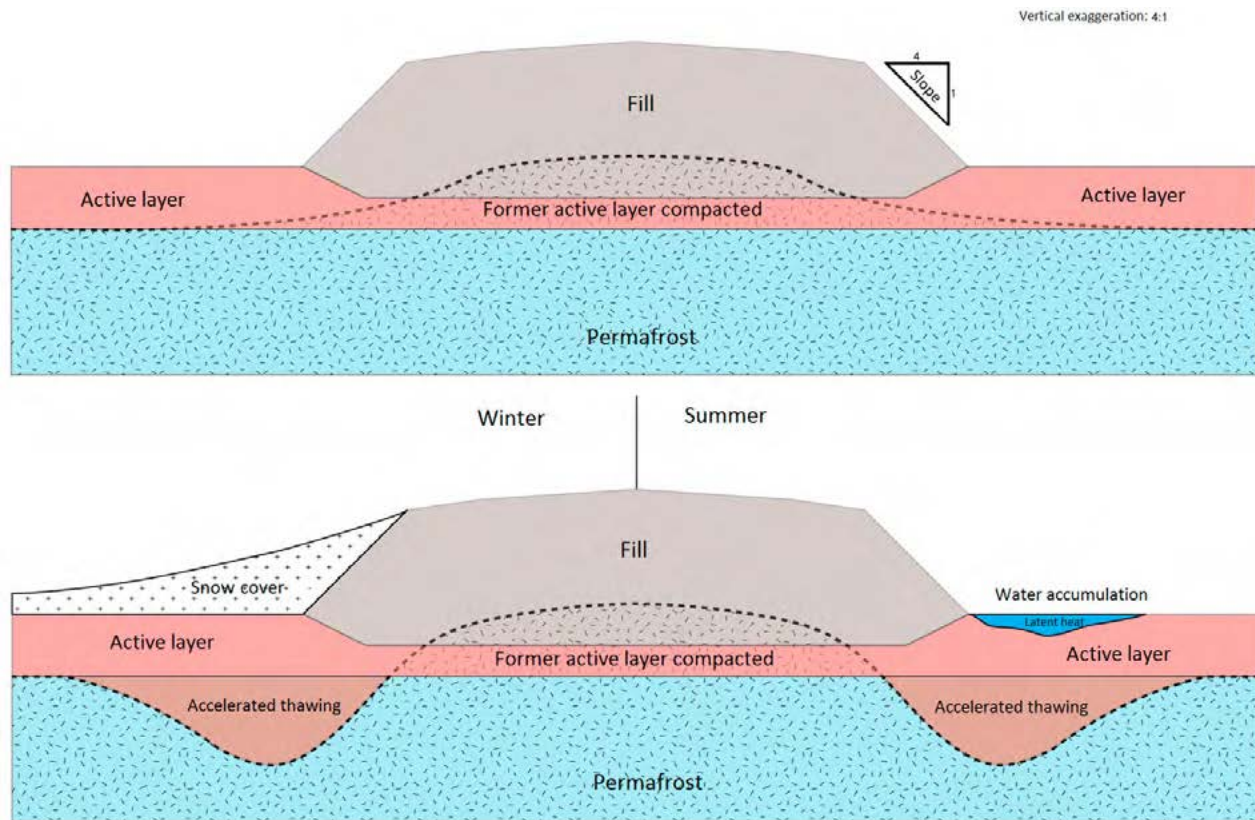


FIGURE 5.56: ANTICIPATED THERMAL READJUSTMENT OF PERMAFROST AFTER PLACEMENT OF FILL WITHOUT AND WITH SNOW AND WATER ACCUMULATION AT THE EDGE OF THE FILL (FROM L'HÉRAULT ET AL., 2012).

5.3.5 Impact of climate change on permafrost

Given the thermodependency of the mechanical properties of permafrost as well as the occurrence, amplitude and pace of certain processes that develop (e.g. creep), it is imperative when designing a foundation on soil sensitive to thawing to consider future climate change and its impact on the soil's thermal regime. An increase in soil surface temperatures caused by disturbance of surface conditions or a change in climate will automatically trigger warming of the permafrost. In areas where soils are ice rich, the foundations of buildings and infrastructure will be subject to greater compaction and previously stable steeply sloped lands could become unstable.

Many studies on climate change in northern regions cite rising air and soil temperatures over the past 30 years in the western Arctic and more recently in Nunavik (Osterkamp and Romanovsky, 1999; Chouinard et al., 2007; Akerman and Johansson, 2008; Smith et al., 2010). Meteorological data recently compiled for northern Québec show rising average temperatures in most Nunavik communities since the watershed year 1994. With increased average air temperatures in northern Québec, the thermal regime and dynamics of permafrost have changed (Smith et al., 2012) and several studies are already reporting direct consequences of this warming on northern communities and environments (ACIA, 2007).

Over the long term, rising air temperatures will trigger a decline in the thickness of permafrost from above and below. The thickness of the active layer will generally increase in step with the rise in air temperatures. As the thawing front extends to greater depths, differential compaction linked to thawing of ice-rich horizons in the permafrost, as well as breaks of the active layer in favourable locations are likely to occur. It is important to note that permafrost will react to climate change at different rates between sites due to variability in time and space of the thermal properties of materials, local environmental conditions and climate. One thing is certain, warming of the thermal regime of permafrost appears inevitable. Designers therefore must deal with the presence of permafrost

in transition, likely to suffer a loss of bearing capacity and risks of instability in response to climate change.

To this end, digital modelling exercises can be conducted to simulate coming thermal changes in permafrost (higher soil temperatures, thicker active layer, formation of taliks, etc.) in response to climate change. This type of exercise can rely on climate change assumptions for which future climate projections are generated using complex physical models. These model outputs are plausible representations of future climate consistent with greenhouse gas emission assumptions and current knowledge of their effects on climate (ACIA). These climate projections have been used for a few years now as inputs in geothermal simulation models designed to simulate changes in the thermal regime of permafrost (Sazonova and Romanovsky, 2003; Zhang et al., 2008; Alfaro et al., 2009; L'Hérault et al., 2012; 2014; 2015). Note that despite their ability to adequately simulate a soil's thermal response to a climatic phenomenon, geothermal models remain a schematization of a reality in which the stratigraphy and thermal properties of their defining soils are highly simplified. This simplification of reality, in which the attribution of thermal properties of soils is based on laboratory measurements and theoretical calculations and in which integration of spatial and temporal variability of local climatic and environmental variables (precipitation, runoff, snow cover) is very limited, adds much uncertainty. All digital modelling results therefore must be considered with caution. Despite the uncertainty attached to such exercises, they can in fact anticipate the potential thermal reactions of permafrost in response to climate change and assess the possible future impact on the stability of infrastructure over its service life.

For Nunavik, six air temperature outputs from the Canadian Regional Climate Model (CRCM) are available for conducting digital permafrost modelling exercises out to 2050. The results for the optimistic (AEV) and pessimistic (AHA) CRCM scenarios represent roughly the two climate extremes for all available data. The climate data feeding the two CRCM series used come from two different global models. The AEV series, piloted to its lateral limits by the CGCM3 model, presents the coldest projections and is considered an optimistic scenario. Conversely, the AHA series, piloted to its limits by the ECHAM5 global model (Max-Planck Institute), constitutes the warmest CRCM output (pessimistic scenario). figure 5.57 shows an example of the different climate outputs for the Tasiujaq area. For Nunavik, all the CRCM series used to drive the geothermal models project an average increase in air temperatures of about 3°C out to 2050 (Table 5.6). However, this increase will not be uniform across the territory. Three temperature change zones have been established by Barrette et al. (2013). These are the northern zone (Quaqtaq, Ivujivik and Puvirnituk), central eastern Nunavik zone (Tasiujaq, Aupaluk and Kuujuaq) and the Hudson Bay region (Kuujuarapik, Umiujaq and Inukjuak) for which annual average temperatures are expected to increase respectively by about 3.2°C, 2.8°C and 3°C by 2050. For each of the 14 Nunavik communities, the changes in annual average air temperature out to 2050 based on six CRCM simulations (°C) are shown in table 5.6. On a seasonal basis, this projected rise in air temperatures results in a sharper temperature increase in winter (from 2.8 to 4.6°C) than in summer (from 1.5 to 2.1°C). Note that with climate change, quantity of precipitation (rain and snow) and the wind regime are also likely to change. These climatic variables must be assessed and considered where necessary when designing a foundation system.

When the climate model outputs are used as inputs in geothermal models or for sizing foundation systems, it is important to remain cautious when interpreting and assessing the scope of results. It has been shown that CRCM data have a cold bias and must be corrected. Since it is very difficult to assess the number of climate processes occurring in the Arctic due to low weather station coverage and reliability, it is also hard to gauge the precise reasons that may explain this bias. However, some possibilities that come to mind are poor knowledge of the climatology of northern regions as well as poor intake of certain physical processes intrinsic to the model. Of the many methods for eliminating this data bias, that described by Salzman et al. (2007a and b) has been used with success in several permafrost geothermal modelling exercises in Nunavik (Barrette, 2010, L'Hérault et al. 2012; 2014 and 2015) and is preferred over others due to the simplicity of its use.

The degree of permafrost sensitivity to anticipated climate warming is determined primarily by its temperature and ice content. The safest approach for building and maintaining infrastructure resting on permafrost is definitely to choose areas where permafrost conditions have little or no sensitivity to thawing. Poor foundation design, disregarding the impact of infrastructure on location environmental factors (snow cover and drainage) or a surprising development in climate warming beyond the range established by climate scenarios will then have limited consequences. If this is not possible, the CAN/CSA-PLUS-4011-10 standard presents an interesting risk management approach based on permafrost sensitivity at the construction site (temperature, type of material, ice content, etc.), resilience of the foundation type and consequences of a potential rupture in the building on public

safety, quality of life, the environment and the economy within a community. This type of risk analysis is necessary when selecting a site and designing foundations. It helps determine the level of detail required for geothermal site investigation as well as the complexity of the foundation system needed to guarantee structural stability of the infrastructure facing climate uncertainty. At the community level, this analysis supports planning of infrastructure development for trouble-free, durable facilities on permafrost in the context of climate change. For Nunavik in recent years, potential construction maps based on permafrost conditions and slopes have been produced for each community (Allard et al., 2010, L'Hérault et al., 2012 and Carbonneau et al., 2015). Although these maps are no substitute for geotechnical studies, they remain a useful tool to assist planning in the pre-project preliminary phase.

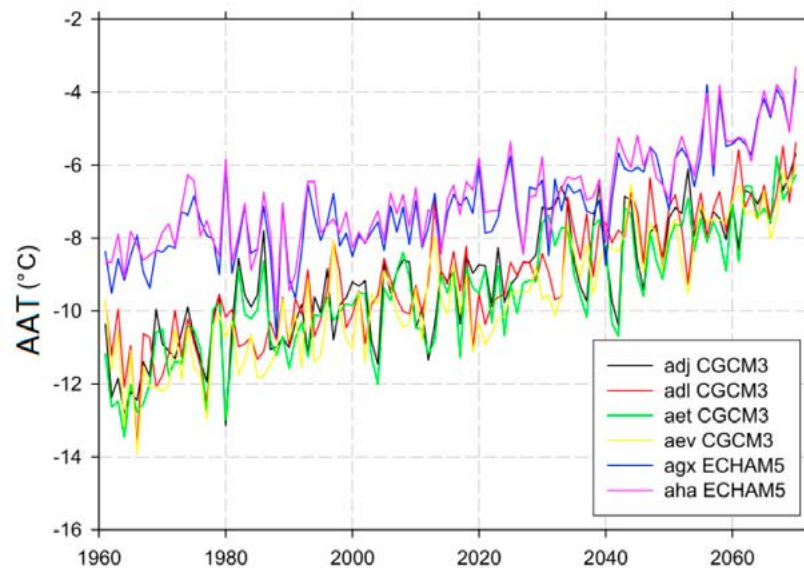


FIGURE 5.57: THE SIX CRCM OUTPUTS FOR AIR TEMPERATURES BETWEEN 1961 AND 2070 FOR THE TASIUJAQ AREA.

AIRPORT	CRCM (AEV OUTPUT)	CRCM (AHA OUTPUT)	AVERAGE OUTPUT
Tasiujaq	+2.4 °C	+2.9 °C	+2.7 °C
Quaqtaq	+2.5 °C	+3.4 °C	+3.0 °C
Akulivik	+2.8 °C	+3.6 °C	+3.2 °C
Salluit	+2.7 °C	+3.7 °C	+3.2 °C
Puvirnituq	+2.7 °C	+3.5 °C	+3.1 °C
Kangirsuk	+2.5 °C	+3.4 °C	+2.9 °C
Inukjuak	+2.7 °C	+3.2 °C	+2.9 °C
Moyennes	+2.6 °C	+3.4 °C	+3.0 °C

TABLE 5.6: PROJECTED AIR TEMPERATURE CHANGES OUT TO 2050 FOR SELECTED NUNAVIK COMMUNITIES.

5.4 DESIGNING FOUNDATIONS ON PERMAFROST

Construction of building foundations in permafrost zones requires knowledge and techniques that must be fully mastered. Conventional Québec techniques of laying foundation footings on the surface seasonal frost layer cannot be used in permafrosted unconsolidated deposits. It becomes impracticable to rely on soil located under the frost base because this can go down hundreds of metres. When permafrost is frozen, its base is generally stable. However, thawing can cause serious compaction problems and thus cause major structural and architectural damage. Compaction can be substantial, on the order of several hundred millimetres. For example, ice-rich permafrost (let's say 20 percent above natural porosity) can subside by about 100 mm if it thaws only down to 500 mm. The seriousness of the situation when thawing extends deeper or occurs in soil with a much higher ice content is easily imaginable. Building costs in Nunavik are very high, so there must be assurances that foundations and buildings will remain functional throughout their anticipated service life. Several cases of serious deterioration of foundations have been documented. Most of the time, problems arise when foundations rest directly on ice-rich permafrost, which thaws due to heat transfer from the building to the soil. Other factors can also contribute to permafrost thawing and thickening of the active layer, especially poor surface drainage, adverse snow cover conditions, denaturalization of the surface layer, and rising air temperatures.

The best approach to designing and building foundations on permafrost will be dictated by the type of structure to be built, the logistical constraints, detailed site conditions and potential impact of the infrastructure on its environment (drainage, snow cover, soil temperature, permanent load, etc.). The approach generally will be dictated by one key factor, whether the foundation soil is stable or unstable in thawing. In the case where foundation soil is stable when thawing and consists of a well drained non-frost-susceptible material containing very little ice, the conventional approach to designing a foundation system can be used, as described in the Canadian Foundation Engineering Manual (CFEM, 2013). However, despite material stability, there must be assurance that it contains no excess ice of external origin such as buried glacier ice, injection ice or corner ice, that it will not settle excessively due to low soil density and that it is not lying on a layer of material sensitive to thawing that could thaw during the service life of the structure.

In places where permafrost might be sensitive to thawing, it is advised that the foundation be designed to preserve the initial conditions of the soil's thermal regime and ensure that it is not disturbed during construction. To this end, there are various foundation types depending on the building's function, the soil's thermal and geotechnical characteristics as well as environmental, technical and logistic constraints. During construction of the foundation, good practices advocate drainage control to avoid any water accumulation or runoff and minimize disturbance of the plant cover on and around the construction site. If work cannot be performed in winter, vegetation can be preserved by covering it with a layer of non-frost-susceptible granular material to be used as a work surface. Note that it is practically impossible to restore surface conditions once fill has been placed, so the work surface must form an integral part of the concept as a permanent component.

If the soil's initial thermal regime cannot be preserved, it is possible to thaw and consolidate the soil or excavate and replace inadequate soil (frost-susceptible and ice-rich) with appropriate material. Note that this type of procedure requires time, good planning, is more expensive and applies only to certain specific cases. For example, this procedure can be considered in the discontinuous permafrost zone, when the permafrost is not very thick, or in the continuous permafrost zone, when the ice-rich deposit is thin, superficial and resting on substrate stable under thawing. If disturbance of the thermal regime is unavoidable, but the amplitude of anticipated compaction over the service life of the building is deemed acceptable, the use of adjustable or monocoque foundations combined with a periodic levelling maintenance plan may be considered, but there are still special cases that must be meticulously assessed. In general, designs that allow thermal degradation of permafrost are used where the permafrost consists of stable material under thawing, the amplitude of anticipated compaction is factored into the design of the foundation type, or the building will be temporary.

The design process to be described in section 5.4.1 applies solely to the specifics of foundations built on permafrost; it does not replace the CFEM conventional process that essentially covers soil and rock mechanics regardless of technical and logistical considerations that apply to permafrost and the specific geographic context of Nunavik. The process proposed in this guide complies to some extent with the main stages necessary in foundation design for temperate climate (CFEM, 2013), but has been adapted to incorporate the specifics of arctic and subarctic climates as well as permafrost. In this respect, the following works on engineering in cold regions, to name only the main ones, have been consulted.

- *Geotechnical Engineering for Cold Regions* (Andersland and Anderson, 1978)
- *Permafrost: Engineering Design and Construction* (Johnston, 1981)
- *Arctic and Subarctic Construction Foundations for Structures* (USA Department of the Army and the Air Force, 1983)
- *Frozen Ground Engineering, 2nd Edition* (Andersland and Ladanyi, 2004)
- *Canadian Foundation Engineering Manual, 4th edition* (CES, 2013)
- *International standards* (ASTM, CSA, CAN/BNQ)

5.4.1 Design approach for foundations on permafrost

In permafrost zones, it is less common to face bearing capacity problems for small buildings, because as long as the soil remains frozen, it generally provides acceptable bearing capacity. Problems generally arise when ice-rich soil thaws because it loses almost all its bearing capacity. For this reason, when designing a foundation on permafrost, it is essential to consider the rheological aspects, that is, assess the effect of a load on the foundation soil as well as the thermal aspects, given that the mechanical behaviour of frozen soil is thermodependent. Thus, foundation design in cold regions requires a sound assessment of the geotechnical characteristics of the foundation soil and the amplitude of current and future temperature changes in the surface and deep soil, to accurately assess potential soil deformation on a seasonal, interannual and multiannual basis. Given that the term permafrost refers to a transitory state of thermal balance of the soil with the climate, surface conditions and thermal properties of the materials in place, and that this thermal state defines its mechanical properties, assessing it requires a slightly different approach from that normally used in a non-permafrosted zone.

During construction planning, it is important to determine whether the study site is located in a permafrost zone sensitive to thawing, to study the foundation soil conditions and to allow for factors likely to alter the site's thermal balance. If the permafrost in the study area is ice rich, the wisdom of choosing another site must be considered. The foundations chosen must be sturdy, adapted to the site conditions and planned with sufficient safety margins to provide the expected level of service for the full service life of the work, considering the impact of climate warming on depth of the active layer and temperature of the permafrost.

Sound construction planning is the key to success of a project located in a permafrost zone. During this process, the anticipated performance and suitable approach are defined based on the various factors likely to influence the sizing and selection of foundation type best suited to a given site and project. In various situations, this process may differ due to the project needs, but essentially comes down to four phases: feasibility study (project definition and preliminary site assessment), preliminary design, final design and execution (Figure 5.18).

The feasibility study is essential to any project, but especially so when the designer is unfamiliar with the area, which is not developed or documented, or in the case of a major project. The purpose of this phase is to conduct a comprehensive assessment of the distribution of the geological materials and their geotechnical characteristics, and detect the presence of dangerous conditions or severe constraints that might compromise stability of the infrastructure and user safety, or incur major costs to make the site conditions acceptable. Following this study, high-risk sites may be abandoned, forcing project officials to seek a site with more favourable conditions. For poor-quality sites, the feasibility study may propose optimal use of the site to avoid the most problematic areas and thus reduce construction costs. Depending on the nature of the project, sites unsuited to construction will not have the same characteristics. It is usually the information gathered on site characteristics (environmental, rheological, thermal and climatic conditions) that dictate the need to conduct a thorough, detailed study, and the tools and methods to be used. If this study discovers no severe constraint, a preliminary design, accompanied by a cost estimate, can be produced.

The preliminary design phase starts when the building site, size and live load are defined. This phase consists of selecting the most economical foundation type and size that provide a reasonable margin of safety in the event of soil break under the anticipated live load. In many projects, especially smaller structures, the feasibility and preliminary design phases are often combined.

In problematic areas, if the preliminary design leads to solutions that are too expensive or technically unacceptable, alternate solutions must be considered. During this repetitive process, the designer may have to change the foundation type, location or dimensions, alter the structure or foundation soil, or plan construction stages that favourably affect site behaviour, to cut costs while ensuring stability of the structure. Additional information is often necessary to improve design criteria, which may require a thorough site assessment. This may involve drilling to take undisturbed core samples, geophysical surveys, laboratory analyses, geothermal simulations to assess deformation linked to thawing, compaction and consolidation likely to occur under the anticipated live load and during the service life of the structure. If the alternate solutions considered fail to meet the project requirements, the site initially chosen ultimately may be abandoned. In this case, the new site will also have to be surveyed.

During the execution phase, especially construction of a deep foundation, conditions may be encountered that were overlooked by the detailed study. More thorough soil analyses might then be required to provide relevant information to validate the final design, which may have to be changed in light of these new data. It is also during this phase that instrumentation will be installed to monitor parameters deemed important for performance and stability of the structure. These sensors may serve as an alarm system to prevent potential failure of the foundation. They may also be thermistor cables—to monitor the thermal regime in the soil and assess the performance of a cooling system—or pressure, soil movement or water-level sensors.

It is important to note that foundation design remains a repetitive process during which the foundation parameters are modified until a satisfactory safety margin is obtained. Thus, as understanding of the site's behaviour improves, the design criteria are likely to change.

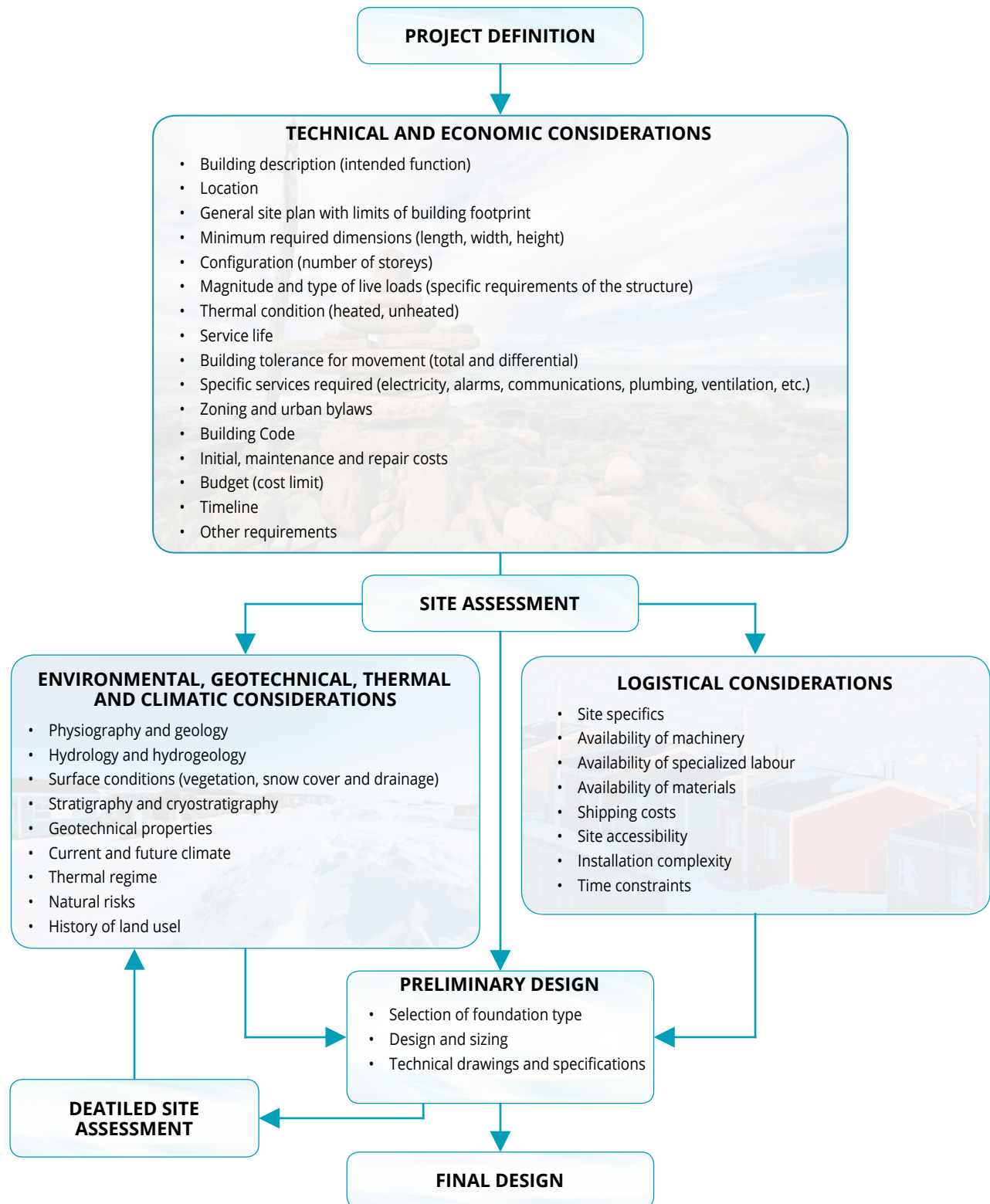


FIGURE 5.18: APPROACH TO DESIGNING FOUNDATIONS RESTING ON PERMAFROST.

5.4.2 Project definition (technical and economic considerations)

The first stage in designing a foundation system on permafrost consists of defining the project and its requirements (technical characteristics) based on the client's needs. At this stage, the client's needs in terms of building function, dimensions, configuration and location are conceptualized by an architect and an engineer responsible for providing the preliminary sketches of the building. The technical information emerging from this process allows the engineer to note geotechnical shortcomings that must be remedied, a stage that precedes the choice of foundation type and size. The necessary information to design the foundation system will be compiled in a preliminary survey, and completed if necessary during a fairly detailed survey of the project site, based on the quantity and quality of information available, complexity of the structure to be built and physical characteristics of the environment (geotechnical properties, drainage, topography, etc.). To provide the engineer with a good understanding of how the structure will influence the environment, the following issues must be addressed and resolved during the project definition process.

- Building description (planned function)
- Location
- General site plan with limits of building footprint
- Minimum required dimensions (length, width, height)
- Configuration (number of storeys)
- Magnitude and type of live loads (requirements specific to the structure)
- Thermal status (heated, unheated)
- Service life
- Building tolerance for movement (total and differential)
- Special services required (electricity, alarms, communications, plumbing, ventilation, etc.)
- Zoning and bylaws
- Building code
- Initial, maintenance and repair costs
- Budget (cost limitations)
- Timeline
- Other requirements

5.4.3 Site assessment (geotechnical study)

Early in the design process, once the project has been defined and its requirements determined, the developer must conduct a project site assessment. The purpose of this stage is to gather the information needed to characterize the site's geotechnical, hydrological and environmental conditions. This stage is vital to ensure that the building's design, construction and maintenance reflect the site's specific conditions. The site assessment must be conducted by engineers and professionals with solid expertise in permafrost.

Site assessment is generally conducted in two stages: the preliminary survey and the field exploration. The preliminary survey consists of gathering and reviewing the available information about the site, while the field exploration validates this information and completes it as necessary by conducting field work. This last stage implies a visit to the site to assess its geotechnical conditions, which may require surveys, excavations, drilling with or without sampling, and geophysical surveys. It is also during the field visit that information on the behaviour of structures next to the site or information from local experience may be compiled. The scope of the site assessment is determined by the site's complexity (e.g. variability of underground conditions and sensitivity of soils to thawing), project type (e.g. size, service life, live load, tolerance for movement, etc.) and quantity and quality of

information gathered during the preliminary survey. Consequently, the need to conduct drilling and geophysical surveys, their number, spacing and depth, sample collection, in situ tests and laboratory analyses depend on the combination of the project and the site as well as the resulting challenges. An experienced geotechnician must determine the scope of this assessment and supervise the work.

It must be noted that foundation design is a repetitive process. The preliminary survey defines the main site characteristics, with certain limitations, and some of these may require modification of the preliminary foundation concept, or even abandonment of the site. Based on the concept and the information gathered, the geotechnical engineer is able to adapt the investigation program to focus the exploration work to complement rather than seek information already known.

Site assessment studies are more complex in a permafrost zone than a temperate region. Studying the thermal regime is just one example of the specifics that must be considered by designers. The presence of ice in the frozen soil or fractured rock, combined with the effect of thawing and freezing, can considerably affect the properties of materials and cause compaction and uplift far beyond what a conventional building can tolerate. At time of writing this guide, a standard for geotechnical studies of building foundations constructed in a permafrost zone (CAN/BNQ 2501-500) was being developed. The following sections review the key points of these studies.

5.4.3.1 Preliminary survey

The purpose of a preliminary survey is to compile the latest local information on environmental conditions (climate, drainage, topography, vegetation) and the physical characteristics and properties of soils to draw up as accurate a profile as possible of the conditions encountered on the project site. A preliminary survey determines the issues and challenges to be addressed to carry out the project and assess the requirements and needs that must be considered during the site assessment. The focus at this stage is on defining the project and site specifics, especially in light of the type of construction planned, the likely construction period, the behaviour of adjacent structures, information from local experience, observation of existing buildings and the visible nature of surface rock, as well as reviewing the other information available.

First, it must be determined as quickly as possible whether the construction site is located in an ice-rich permafrost zone or in a stable zone, consisting of rock or ice-poor soils. Slope gradients, a condition favourable to development of slope processes (landslide, gelifluction, avalanche, etc.), and the proximity of watercourses (risk of erosion, thermal erosion and flooding) are factors that must be considered in assessing the location of a new building.

The preliminary survey must cover the following factors.

Environmental, rheological, thermal and climatic considerations (Section 5.4.3.3)

- Local climatic conditions
 - o Air temperature (annual and monthly average temperature, freezing index, thawing index, etc.)
 - o Precipitation (solid and liquid)
 - o Wind (speed and direction)
- Surface conditions
 - o Vegetation
 - o Snow cover
 - o Surface drainage
- Physiography and geology
 - o Topography, site orientation and slope
 - o Hydrology
 - o Geomorphology
 - o Geology of surface deposits
 - o Geology of basement rock
 - o Hydrogeology
 - o Seismic activity
- Permafrost
 - o Soil temperatures
 - o Description of frozen soils
- History of soil use
- Climate projections
 - o Air temperature
 - o Precipitation
 - o Wind

Logistical considerations (Section 5.4.3.4)

- Site specifics
- Availability of machinery
- Availability of skilled labour
- Availability of materials
- Transportation costs
- Site accessibility
- Complexity of siting
- Time constraints

To conduct the preliminary survey, a host of resources are now available. These include satellite images, aerial photographs, LIDAR surveys, digital elevation models, topographic maps, geology and surface geology, avalanche risk and mass movement maps, flood zones maps, permafrost and vegetation, geophysical surveys, technical documents, geotechnical reports, scientific articles, community development plans, information on historic use of existing lands, spatial databases on soil temperature and data on climate and hydrology. Various organizations across Canada gather data on permafrost distribution, characteristics and temperature. In Nunavik, data related to permafrost are more detailed for regions where vast geotechnical studies have been conducted during major projects, but are often fragmented and dispersed for regions where there has been little or no industrial development. For any project, the provincial and federal government databases (MERN, MFFP, MTMDET, MAMOT, MSP, MDDELCC, NRCan, StatCan, GSC, etc.) are suitable sources. Many other organizations that gather, receive or manage data on permafrost can also be contacted. These include the Kativik Regional Government, northern research institutes (Centre for Northern Studies), universities, Ouranos and engineering consulting firms specializing in geotechnical aspects.

5.3.4.2 Field exploration

Sound knowledge of building site conditions in a permafrost zone is essential to support the choice of foundation design and size. Quite often, a meticulous documentary study of these conditions is insufficient. A field exploration is then important to properly document the geotechnical, rheological and thermal conditions that will ensure satisfactory performance of the structure throughout its service life.

The purpose of field exploration is to characterize the geological environment and determine the spatial distribution and thickness of all soil and rock types in the area that influence the proposed construction, the surface and underground drainage conditions with their seasonal variation, and the physical and geotechnical properties of soils and rock formations. Natural risks must also be assessed, such as slope instability (landslide, falling rocks, gelifluction, avalanche, etc.), active or potentially active faults, seismic activity in the region, exposure to submersion (flooding) or erosion, land movements (compaction, subsidence and uplift), as well as soil response to a change in initial (natural) conditions triggered by work on the land (overload, discharge, excavation) or new construction, and the quality of materials to be used (fill, concrete, etc.).

During the field exploration, the structure's lateral and vertical soil influence zone must be determined, as well as the influence of environmental factors that can affect the structure. The area covered by the investigation will depend on the building's size, load, foundation type (surface or deep) and soil conditions. The field exploration may include the following work: an investigation of the subsoil by drilling, excavation and/or geophysical methods, soil or rock sampling, in situ or laboratory tests to determine the geotechnical properties of materials, and installation of characterization instrumentation as well as tracking of certain variables (soil temperature, water level, interstitial pressure, etc.). In general, the field exploration must include at least three drillings to a depth well beyond the active layer to provide details on the geotechnical characteristics of the permafrost. Based on these drillings, it is possible to determine soil stratigraphy and take samples of each layer encountered, to document the subsurface conditions and the associated geotechnical properties. Geotechnical properties such as soil granulometry, water or ice content, density, consistency, strength and thermal conductivity can be determined in compliance with the various standards in force. To complete and extend the drilling observations, the field exploration may rely on geophysical methods (resistivity surveys, georadar surveys, electromagnetic prospecting, seismic reflection surveys). The exclusive use of geophysical methods to deduce the stratigraphy and geotechnical conditions is not recommended. During field exploration, certain aspects may have to be documented to ensure an appropriate, optimized design of the foundation system. These include the following aspects

- Stratigraphy and cryostratigraphy
 - o Type and thickness of deposits
 - o Cryostratigraphy (ASTM D4083)
 - o Depth of rock
 - o Water table
 - o Maximum thawing depth

- Thermal regime of soil
 - o Soil temperature based on depth (minimum, maximum, average)
 - o Amplitude of temperatures by depth (minimum, maximum, average)
 - o Thickness of the active layer
 - o Surface temperature
- Geotechnical properties of materials
 - o In situ soil density (CAN/BNQ 2501-058, CAN/BNQ 2501-060, ASTM D1556)
 - o Apparent density (ISO 17892-2, ASTM D7263)
 - o Density of solid particles (CAN/BNQ 2501-070)
 - o Water/ice content (CAN/BNQ 2501-170, ASTM D2216)
 - o Salinity (ASTM D4542)
 - o Granulometry (ASTM D6913)
 - o Plasticity (CAN/BNQ 2501-090, CAN/BNQ 2501-092, ASTM D4318)
 - o Soil classification (ASTM D2487)
 - o Strength (ASTM D7012., ASTM D7300, ASTM D5731)
 - o Freezing adherence strength (ASTM D5780)
 - o Quality of rock (ISO 14689-1, ASTM D6032)
 - o Compaction and consolidation (ASTM D2435)
 - o Sensitivity to freezing and thawing (ASTM D5918.)
 - o Creep (ASTM D5520)
 - o Thermal properties (ASTM D4611, ASTM D5334)

5.4.3.3 Environmental, geotechnical, thermal and climatic considerations

5.4.3.3.1 Surface geology, geomorphology, stratigraphy, cryostratigraphy and geotechnical properties

The nature of the soil is definitely one of the most important factors to consider before building a new foundation in a permafrost zone. Adequate knowledge of the spatial distribution and thickness of unconsolidated deposits, their geotechnical characteristics as well as the depth separating them from the rock is essential to assess the future performance of a building's foundation. In a permafrost zone, the surface geological units are not just simple solids, but complex assemblies of particles of various compositions, forms and sizes containing a proportion of air and water in solid and liquid form. This distinctive assembly determines the structural characteristics and thermodependent geotechnical properties of the permafrost. Whether a marine clay deposit, glacial till, other unconsolidated deposit or even fractured rock, ice-rich permafrost can be problematic for foundations. Thermal disturbance of this type of permafrost, whether by construction activities, the building itself, modification of site conditions or local environmental factors (snow cover, drainage, etc.) and warming air temperatures can cause considerable compaction. In general, there are two main classes of permafrost conditions: deposits that remain stable when thawing (rock and deposits containing little or no ice) and deposits that are unstable when thawed (quaternary deposits with fine granulometry containing a lot of ice). During site assessment (geotechnical study), it is important to determine whether the permafrost on the planned site for a building is stable when thawing, as this is a major parameter that will influence the structure's design criteria and long-term performance. Ice-rich areas therefore must be identified in the preliminary survey and identification must continue if necessary during a field exploration phase. During field exploration, existing soil stratigraphy and cryostratigraphy can be speci-

fied, in addition to determining certain geotechnical parameters, through in situ or laboratory measurements, deemed relevant for designing the foundation system.

Ideally, the chosen site will be characterized by the presence of shallow solid rock or a deposit with low ice content, often consisting of sand and gravel. Even in the presence of rock, it is important to pay special attention to open discontinuities that may fill with water in the active layer and heave blocks of rock under the effect of frost. In the case of sites with ice-rich soils, special precautions must be taken to keep the soil frozen if the building cannot be erected on a site where the deposit is not sensitive to thawing. Yet where possible, this latter site should be given priority.

Over the past five years, exhaustive maps of permafrost conditions, developed for communities in Nunavik, have been produced by the Centre for Northern Studies (Allard et al., 2010; L'Hérault et al., 2013; Carbonneau et al., 2015). The maps available cover built-up areas, areas planned for expansion and well beyond to give decision makers a wider vision of the territory. Note that due to the great horizontal and vertical spatial variability of ice content within a given geological surface unit, the available maps of permafrost conditions are primarily a planning aid and not a substitute for pre-project geotechnical studies. Many studies, specifically those of transportation infrastructure built on permafrost by the MTMDet, also contain much useful information on surface geology, geomorphology, stratigraphy, permafrost conditions and geotechnical properties observed in Nunavik villages (Allard et al., 2006; L'Hérault et al., 2012; 2014; 2015).

5.4.3.3.2 Current and future local climatic conditions

Climate data such as air temperature provide important information for designing foundation system technical parameters, as well as useful information for planning work, such as the best time for performing certain work or installing foundation components. Annual average air temperature generally declines as latitude or elevation increases. For example, the climatic norm for 1981 to 2010 is -5.4°C in Kuujuaq (N $58^{\circ}06'$) and -9.3°C for Iqaluit (N $63^{\circ}45'$) (Environment Canada, 2015). In Nunavik, the coldest air temperatures are measured in the centre of the Ungava peninsula, partly due to the region's altitude but also to its distance from the coast. The topographical effect on air temperature is also observed within a community. For example, the air temperature at Salluit airport is generally colder by one degree Celsius than that measured in the valley, barely two kilometres away.

Many parameters can be calculated from a continuous series of daily air temperatures (ADAT), especially the following.

- Minimum and maximum annual average air temperature
- Minimum and maximum monthly average air temperature
- Start, length and end of frost season
- Start, length and end of thaw season
- Freezing degree days (freezing index)
- Thawing degree days (thawing index)

The design freezing index recommended by the American Society of Civil Engineers (ASCE) for foundation design is the average of the freezing index for the three coldest winters over the past 30 recorded years. The same principle applies for the design thawing index, using the average thawing indexes for the three warmest summers. When data are only available for a shorter period, the United States Army Corps of Engineers suggests the method described by Linell et al. (1973), which also uses the coldest winter over the past 10 years.

In addition to temperature data, precipitation records also provide some details on local climate that are relevant to foundation system design. Snow accumulations and distribution on a site are parameters that must be considered in the design, because they can directly or indirectly affect performance of the foundation system by placing overload on the structure and altering the thermal regime of the permafrost. In Nunavik, snow accumulations formed by wind can quickly become problematic and even disastrous for building foundations. Due to their insulating properties, early snow accumulations at the start of the winter season hinder refreezing of the active layer near foundations and are likely to cause warming of permafrost temperatures. The dynamics of site snow cover can also have consequences for building function and maintenance operations.

To accurately assess snow cover dynamics on a construction site, it is recommended that the preliminary survey view aerial photographs of the site in spring and interview staff members of the community's public works department who handle snow clearing operations or any other person able to provide details on this subject. For areas where snow cover is deemed a critical parameter and for which little information is available, the detailed site assessment phase must include a field visit in the spring to determine seasonal snow distribution patterns. To allow for the effect of snow load on the structure, the designer may refer to the Canadian standard CAN/CSA-S502-14, Managing changing snow load risks for buildings in Canada's North. For planning drainage, the designer may refer to Canadian standard CAN/CSA-S503-15, Community drainage system planning, design, and maintenance in northern communities.

The wind regime must be considered not only for its impact on the structure, but also for snow distribution on the ground. Long periods of continuous wind and extended winter seasons are factors that increase the amount of snow that accumulates in the lee of buildings, on the side away from the wind (Figure 5.59 A). The wind frequency diagram is a graphic tool that shows the wind direction and average strength in a given location (Figure 5.59 B). Direction may be strongly influenced by site topography and the presence of surrounding obstacles. In Nunavik, winds of very high speed must be expected. For example, episodes of violent winds with measured speeds exceeding 100 km/h are frequent in Salluit (Allard et al., 2010). Wind pressure on buildings must be factored into foundation design. When using piles, for example, wind bracing must be provided for the exposed portion to ensure adequate lateral rigidity. For surface foundations on an invert, it may be necessary to secure the building to the foundation system or even secure it to the ground with anchors inserted into the granular fill.

Designers must exercise judgment in the selection of design indexes, especially when the period covered by available data is short. For most Nunavik communities, climate data series are discontinuous or too short to calculate normal climate values. Caution therefore is required when using average data because in practice, good statistical representation of climate requires about 30 years of observation. Despite these fragmented data, reconstituted climate data can be obtained from reanalyses (NARR and CFSR), which provide an acceptable estimate of climate parameters around the world, with maximum spatial resolution of 38 km x 38 km. Although the reanalyses incorporate observed data and provide a fairly realistic portrait, there may be significant differences between the parameters measured and those reconstituted, in brief, inherent uncertainties in representation of current climate. Despite these uncertainties, reanalyses are an indispensable tool for studying climate in areas where fragmented measurements cannot specify certain climate parameters.

Anticipated climate changes in Nunavik will result in increased air temperature and precipitation, but will also affect the length of the freezing and thawing seasons as well as the frequency and intensity of extreme climatic episodes (storms, heavy rain, windstorms, blizzards, etc.). Although uncertain and unpredictable, these anticipated climate changes must be considered in foundation design. On this point, designers may refer to the climate projection data published in the Canadian Regional Climate Model (CRCM) (Ouranos). The Canadian technical guide Infrastructure in permafrost: A guideline for climate change adaptation (CAN/CSA-PLUS-4011-10) provides an interesting framework, shown in figure 5.60, for factoring climate change into the process of designing infrastructure resting on permafrost.

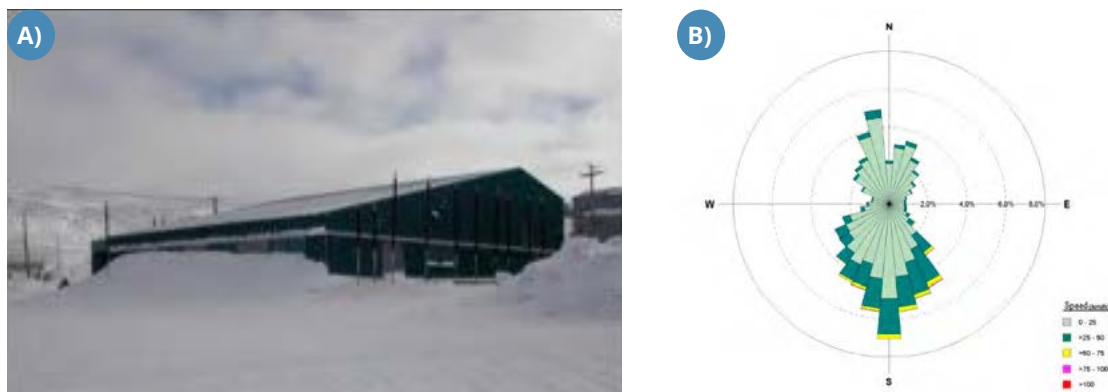


FIGURE 5.59: A) MAJOR SNOW ACCUMULATION NEAR A BUILDING. B) WIND DIAGRAM AT THE SILA STATION IN SALLUIT VALLEY (FROM ALLARD ET AL., 2010).

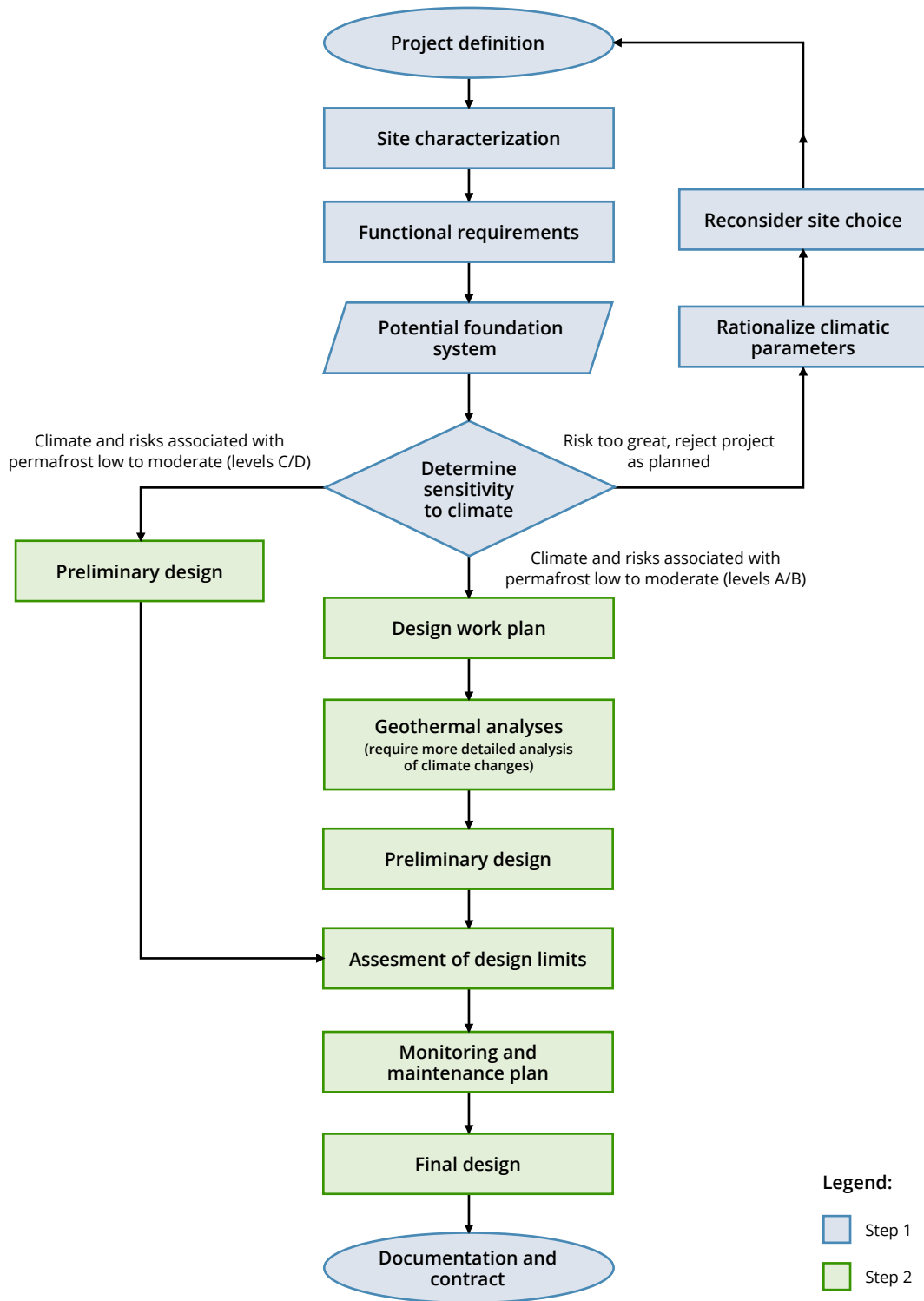


FIGURE 5.60: FLOW CHART FOR DESIGNING INFRASTRUCTURE ON PERMAFROST ALLOWING FOR CLIMATE CHANGE (FROM CAN/CSA-PLUS-4011-10 TECHNICAL GUIDE, 6/01/2010. ISBN (S): 9781554914081, P. 112, PRODUCT CODE: 2420571).

5.4.3.3.3 Permafrost and the thermal regime of soils

Permafrost distribution is influenced by various factors, primarily of a climatic but also geological and environmental. In Nunavik, permafrost is divided into various zones based on its distribution: continuous, abundant discontinuous (≥ 50 percent), dispersed discontinuous (< 50 percent) and sporadic. This distribution is consistent with a south-north gradient on which permafrost appears sporadically in the most southern villages (e.g. Kuujjuarapik) and progressively occupies all the territory except areas under bodies of water and major rivers. Thus, except for the village of Kuujjuarapik, where permafrost is sporadic, the probability of having to build on permafrost in Nunavik is very high. The permafrost distribution map produced by Allard et al. (2013) provides general information that must be validated by assessment studies in the field before erecting new buildings.

The presence of permafrost is closely linked to air temperature. In theory, an annual average air temperature at or below the freezing point (0°C) is one of the required conditions for the presence of permafrost. In practice, however, this is rarely the case due to the influence of surface conditions on temperature at the surface of the soil, that is, at the permafrost peak. For example, air temperature measured about 1.5 m above the ground is usually colder than that measured at the surface, especially in winter due to the insulating effect of snow. For this reason, it is preferable to use surface temperatures for a summary assessment of the possible occurrence of permafrost as well as its thickness and temperature.

Using the ground surface temperature instead of air temperature incorporates the influence of various factors such as net radiation, vegetation, snow cover, relief and the thermal properties of the soil, on heat transfer between the atmosphere and the ground surface. Depending on surface conditions, the difference between air temperature and that at the ground surface is sometimes quite large. This difference justifies determining and integrating these so-called “limiting” conditions into permafrost thermal regime modelling exercises. The schematization and integration of these conditions poses a considerable challenge due to their spatial and temporal variability as well as the shortage of in situ measurements available (type of vegetation and depth of snow cover). Nevertheless, for design or digital simulation purposes, surface temperatures are routinely estimated by an empirical coefficient called the “n-factor” (Johnston, 1981), defined as the ratio of surface temperature to air temperature. Use of such a coefficient simplifies complex heat transfers between the air and the ground surface. For example, as the coefficient approaches 0, the surface conditions mitigate thermal exchanges between the atmosphere and the ground surface. Conversely, if this factor is greater than one, the surface conditions amplify these exchanges.

For a given site, n-factors are generally calculated on a seasonal basis to obtain an n-factor for the freezing season (n_f) and another for the thawing season (n_t). To determine the value of the seasonal n-factors, air temperature and ground surface temperature must be measured simultaneously during several winter and summer cycles. For sites where such measurements are unavailable, n-factors taken from the literature (Andersland and Ladanyi, 2004) may be used (Table 5.7). It is also possible to roughly estimate surface temperature using an approximate relationship suggested by Smith and Burgess (2000), which indicates that annual average temperature at the ground surface (AAS) is generally about 4.5°C warmer than the annual average air temperature (AAAT). Despite this, these estimated values must be used with caution because the associated uncertainties can result in oversizing or undersizing the foundation system.

SURFACE CONDITIONS	N-FACTOR (N_f)	N-FACTOR (N_T)
Snow (on the surface)	1.0	n. a.
Surface cover free of snow or ice	0.9	n. a.
Sand and gravel	0.9	2.0
Peat	0.5	1.0
Mineral soil surface	0.33	1.22
Gravel (probable values in northern conditions)	0,6-1,0 0,9 - 0,95	1,3 – 2
Asphalt paving (probable values in northern conditions)	0.29 - 1.0 or more 0.9 - 0.95	1.4 – 2.3
Concrete paving (probable values in northern conditions)	0.25 - 0.95 0.7 - 0.9	1.3 – 2.1

TABLE 5.7: N-FACTOR VALUES IN FREEZING SEASON (N_f) AND THAWING SEASON (N_T) BASED ON SURFACE CONDITIONS (FROM ANDERSLAND AND LADANYI, 2004).

Trumpet diagrams provide an excellent graphic representation of the thermal profile of soils based on depth. The illustration and characteristics of this diagram are shown in section 5.1.3 of this chapter. This type of diagram is especially useful for foundation designers. In particular, it provides a graphic presentation of the thermal characteristics of permafrost in its natural state (temperature range, thickness of the active layer, thickness of the permafrost, etc.). Based on calculations of the thermal regime, it can present the soil temperature profile at the end of a building's service life and, if necessary, during the transitional phases. This tool should be used as often as possible.

There is general acceptance that soils are frozen once the temperature drops below 0°C. However, special caution is necessary when soil temperatures approach this value. In the case of marine clay, where salinity is high, the temperature sometimes must drop to -2°C for the soil to freeze. Permafrost with a temperature close to 0°C must be carefully studied, because very minor warming may have a considerable effect on its mechanical properties. Figure 5.22 in section 5.1.8.4 shows the extent and altitude of marine invasion in permafrosted regions of northern Québec and defines the coastal area where fine granulometry marine deposits are often found. Near the freezing point, care must also be taken with the accuracy of the measuring devices used. Sensors with an accuracy of about 0.1°C are recommended.

5.4.3.3.4 Vegetation

Vegetation and surface condition also play a considerable role in the thermal regime of permafrost as well as the thickness of the active layer. The presence of dry organic soil acts as insulation, significantly moderating heat transfer between soils and the air. When thawed and dry, organic soil can provide an insulation value comparable to that of batt insulation (fibreglass). The presence and thickness of these materials therefore directly influences the thickness of the active layer and soil temperatures. For example, at the southern limit of the discontinuous permafrost zone, permafrost usually is present only where peat or organic soils are found on the surface, or at high altitudes.

Disturbance of plant cover quite often triggers thermal deterioration of the permafrost (warming of the thermal profile and expansion of the active layer). Many studies, including those by Linell (1973) and Douglas, Jorgenson et al. (2008), clearly illustrate the thermal disturbance of permafrost in response to removal of surface organic soil cover.

5.4.3.3.5 Topography

For technical, logistical and geotechnical reasons, topography remains a key factor to consider in design. Site accessibility, highly dependent on topography, can restrict the type of foundation by limiting use of the machinery needed to move materials and install foundation system components. In addition, not all types of foundations have the same ability to adjust to uneven topography. For example, on steeply inclined terrain, the amount of gravel needed to lay the granular fill required for certain foundation types could be very large, posing a risk of higher construction costs, a delayed work schedule and depleting local supply of granulates. For sloped sites characterized by ice-rich permafrost, instability of thawed slopes and limited ability to terrace the land without disturbing the permafrost also constitute limiting factors that must be carefully assessed in the design process. In a permafrost zone, flat valley bottoms are usually poorly drained and ice rich. These areas, which look technically and logistically interesting, must be the subject of a detailed geotechnical study to ensure that the drainage and geotechnical conditions will not compromise stability of the infrastructure.

Note that topographical factors such as slope orientation and gradient play an important role in the climate dynamics of certain regions. These factors have a thermal (alteration of the radiation balance) and dynamic (alteration of air flow) balance (Choisnel, 1987). The intensity of direct solar radiation received on a surface is inversely proportional to the angle of incidence of the solar radiation on this surface. The intensity of this radiation therefore is greatest if it strikes the surface at a perpendicular angle, and least when it is parallel to that surface. Consequently, the orientation and inclination of slopes play an important role in climate dynamics in mountainous areas at various times of day and in different seasons of the year. By altering certain climatic parameters, topography influences permafrost conditions at the local level. For example, the active layer is generally thicker below a surface with southern exposure than one facing north. This effect varies by site latitude and time of year and day. The beneficial thermal effect on permafrost of shadows cast by surrounding peaks must also be considered.

The interaction of dominant winds with topography also plays a decisive role in snow distribution patterns. For example, in Nunavik, snow tends to accumulate in places where the energy to move it is reduced, as in shallow fractures of the basement rock, depressions, small irregularities in the relief and cuts. Due to the insulating properties of snow, formation of these drifts influences the thermal regime of permafrost, which is much warmer here than at a site with little or no snow cover. Thus, a design based on soil temperatures measured beyond the site, in an area without the same topographical characteristics (orientation, slope), or without considering the influence of topography on exposure to solar radiation and on snow cover may lead the designer to underestimate soil temperatures and thereby compromise stability of the design.

5.4.3.3.6 Drainage

Designs must pay special attention to surface drainage to ensure good foundation performance. Defective drainage and the presence of accumulated water are the source of many problems of poor foundation performance observed in Nunavik. Water accumulation and infiltration in soils below foundations increase the thawing depth. When this thawed soil is ice rich, compaction can quickly become extensive and significantly reduce bearing capacity. Such problems have been noticed in various types of foundations, especially for buildings installed on a slab on grade, piles with capacity dependent on adherence in frozen soil and even foundations built on conventional tripods or piles on footings resting on granular fill.

Generally, there are very few ravines in areas with permafrost. In the spring thaw and major rainstorms, water runs off in thin sheets across the surface of the tundra. On slopes, runoff occurs in parallel but diffuse channels where soil humidity is concentrated and where water migrates slowly, partly on the surface and partly through upper horizons of the active layer. The water in these damp channels carries heat by convection, so when infrastructure (e.g. fill) is placed on top of this, subsidence usually occurs with the passage of water. Managing this diffuse surface drainage and humid channels requires avoiding, as much as possible, cutting through them with linear infrastructure such as roads. When they must be crossed, very careful planning of the location, profile and form of culverts is vital. Digging ditches in natural terrain to channel water that, when concentrated and filled with kinetic energy, seriously increases the risks of causing thermal erosion, must also be avoided whenever possible.

Regardless of the source, water accumulation near foundations poses a serious risk of disturbing their future performance. The thermal conductivity of water is about 16 times greater than that of air. At the same temperature as air, water therefore can thaw permafrost much faster, explaining why it absolutely must be avoided near foundations. Saturation of granular fill resulting from poor drainage can also radically reduce the bearing capacity of these soils and cause skewing of the footings (Figure 5.50 C).

Water accumulation inside buildings on a slab on grade can very easily accelerate compaction of the underlying soil. In a heated garage for sewage trucks at Salluit, water from thawing snow clinging to the trucks was removed through a floor drain. This water, warmed by the heated indoor space, accelerated the thawing of the ice-rich permafrost under the building's slab and also accumulated on the floor slab. A large and problematic counter slope developed in the drain pipe in the year following construction of the building and the layer of granular soil under the slab became saturated with high-energy water that caused the rapid thawing observed. A sinkhole reaching 800 mm developed at the centre of the building (N. Journeaux).

Spills of drinking and waste water also cause certain problems. In the example of the Salluit biodisk, the tank trucks in front of the building pumped waste water into the tank inside the building housing the waste-water treatment system. These pumping operations caused spills of lukewarm and saline water on the ground. The water ran off across the surface before infiltrating along the piles that relied for their strength on adherence in a saline and "lukewarm" ice-rich soil. Thawing of this soil resulted in compaction of about 80 mm.

5.4.3.3.7 Natural vagaries

Nunavik is the site of active processes such as river crests, coastal submersions, ice jams and break-ups, flooding, slope movements (rock falls, landslides, gelifluction, avalanche, etc.), periglacial processes and extreme climatic phenomena (wind storms, blizzards, etc.). These processes represent random natural events the past occurrence of which and risk of recurrence on a project site must be assessed.

For example, in sloped areas where permafrost is ice-rich, rapid penetration of the thawing front to depths greater than those of previous years thaws the ice in the soil, thus releasing large amounts of water likely to increase interstitial pressure at the interface between thawed and frozen soil (L'Hérault, 2009). The special climatic conditions encountered in 1998, 2005 and 2010 increased instability of the active layer and fostered the occurrence of this type of mass movement in the Salluit Valley on slopes as gentle as four degrees (Figure 5.61 A). Gelifluction, a gradual or even imperceptible slope movement linked to freeze-thaw cycles, is common on slopes covered with till (Figure 5.61 B). On rocky slopes, mechanical alteration of the rock by frost riving fosters rockfalls.

The formation of seasonal hummocks with ice cores (frost blisters) is a phenomenon that occurs only in permafrost zones and is fairly common in Nunavik villages and elsewhere in the Arctic. For example, at Kangiqsualujjuaq, two frost blisters recently developed next to the airport access road and one damaged an electrical pole next to the road (Figure 5.61 C). At Kangiqsuaq, the hydrological situation promotes recurring formation of frost blisters in the sandy deposits south of the village and along the rock face (Figure 5.61 D) (Carbonneau et al., 2015). Although less frequent, the formation of icing (aufeis) on the soil surface by successive freezing of upwelling underground water in winter is also a phenomenon specific to the subarctic and arctic environment that must not be overlooked when assessing random natural events. The surface layer of ice resulting from this process can reach several metres thick and cover large areas. At Quaqtaq, for example, the formation of icing near the former COOP store is a recurring event in winter.

Although not linked to the presence of permafrost, areas at risk of avalanche must be considered when determining construction sites. On January 1, 1999, for example, nine people perished in an avalanche at Kangiqsualujjuaq. Following this catastrophe, the Ministère de la Sécurité publique (MSP) commissioned a study on avalanche risks (NGI, 2000) which found seven villages in Nunavik at risk. Several avalanche corridors have been established and maps have been drawn to identify the problem areas. Although most of these corridors are free of housing or other construction, some buildings did have to be moved.

In Nunavik, tides can be very high. At Tasiujaq (Baie-aux-Feuilles), for example, high tides can reach more than 15 m, among the highest in Canada. During the ebb or falling tide, river runoff speeds can be very high and increase erosion of the substrate and concave banks, especially at the sharpest bends (Figure 5.61 E). Erosion at the base of the talus on a concave bank destabilized the banks of a Kugluk River at Salluit, deforming the surface, which altered drainage conditions and aggravated erosion of part of the fill upstream, thus destabilizing a foundation support (Figure 5.61 F). To avoid such situations and anticipate or prevent erosion of banks, a more thorough hydraulic assessment may prove necessary. The formation of ice jams, promoted by environmental characteristics such as riverbank ice, local geomorphology (geomorphological restriction of the river bed) and convergence of currents, can cause serious flooding and exert major erosive action by moving ice. For example, major ice jams, ice breakups and floods have occurred in the community of Kuujuaq, carrying away homes and raking the banks and beds of watercourses as they passed (Bleau, 2012). An interview with village elders can provide valuable information on past events of this nature.

Flood and coastal zones exposed to erosion are also factors to consider when planning construction of new buildings. In periods of high tides and major low pressure centres, the combined action of waves at high water levels contributes to erosion of banks (Savard et al., 2016). Buildings located in these zones may be destroyed or seriously damaged (Figure 5.61 G and H). Shore and riverbank areas normally should be avoided unless clearly located outside flood zones and banks provide sufficient natural or mechanical protection against erosion risks.



FIGURE 5.61: A) BREAK OF THE ACTIVE LAYER AT SALLUIT. B) GELIFLUCTION LOBES ON THE SHORE OF HUDSON STRAIT. FROST BLISTERS C) ALONG THE AIRPORT ACCESS ROAD AT KANGIQSUALUJJUAQ AND D) SOUTH OF THE COMMUNITY OF KANGIQSUJUAQ. TALUS ERODING ON CONCAVE BANKS OF THE E) BÉRARD RIVER AT TASIUJAQ AND F) KUUGULUK RIVER AT SALLUIT. NOTE THE SUBSEQUENT SINKING AND EROSION OF THE INVERT THAT AFFECTED A FOUNDATION FOOTING AT SALLUIT. G) AND H) EXCEPTIONALLY HIGH WATER LEVEL, COASTAL SUBMERSION AND EROSION AT SALLUIT (NUNATSIAQONLINE, 2010).

5.4.3.4 Logistical considerations

A frequent problem that arises in communities is lack of adequate labour, construction materials and equipment to perform the necessary work for a project (excavation, compaction, drilling, granulates, etc.). These logistical constraints have an impact on the cost of the project. It therefore is vital to consider this when choosing a foundation, because even though one type of foundation may be technically and economically ideal for the conditions encountered on the construction site, this may not be the best logistical solution.

5.4.3.4.1 Availability of labour, machinery and materials

Construction in the North usually entails hiring skilled and unskilled workers who are supervised by the contractor coordinating the various project construction stages and ensuring compliance with the quality of work and the project requirements. In the project feasibility study, labour needs must be carefully assessed, because labour is often limited, especially in small isolated communities. When skilled labour must be hired, these workers often must be housed on site, which considerably increases project costs. For a long time, building housing in Nunavik was limited to installing prefabricated units, which required very few local resources (labour and materials). Although still common for small buildings, this practice is less frequent for large projects or when site access is a problem and requires construction performed on site. Where little or no skilled labour is available, prefabricated structures easily assembled on site by local workers with minimum supervision remain a valid option.

Some necessary site preparation work (excavation, compaction, drainage, etc.) and placement of foundations requires specialized machinery (rock drills, cranes, etc.) that may not be available on site. Most communities have heavy machinery consisting of loaders, trucks, mechanical shovels, bulldozers, graders and compactors but their number is limited and the short construction season means that equipment in high demand is not readily available. Specialized machinery such as rock drills, cranes and platforms is not available in all communities, so its movement must be arranged as required. For availability and location of heavy machinery, with or without an operator, check with the land corporation, municipality or rental companies.

Construction materials such as lumber, metal and brick are not readily available in most communities. In Nunavik, most communities are located above the tree line, and for those near the line, forests are sparse and trees have limited potential in terms of quantity and quality to provide structural lumber. Rock, granulates (quarry stone or gravel) and sand are the only construction materials available in most communities. However, their availability in sufficient quantity and acceptable quality for the intended use must be ensured. The main sources of gravel granulate are fluvioglacial, alluvial and foreshore deposits. Many of these deposits may contain large amounts of fine particles and thus require washing and screening to meet requirements. An inventory of granulate resources in each community is now being compiled and the results are available from the Ministère de l'Énergie and des Ressources naturelles (MERN). In some communities, nearby sources of granulates have been totally or virtually depleted, while potential sources are too far away or subject to environmental considerations that limit their use. For this reason, a growing number of communities plan to operate quarries to produce granulates. This operation is more expensive, however, significantly increasing the price of the material. Depending on the quality of the rock on site (igneous, metamorphic or sedimentary), use of granulates may be limited to a small number of applications to avoid certain problems (disintegration of granulates under load, gelifraction, compaction, alcali-granulate reaction, etc.).

5.4.3.4.2 Shipping materials and equipment

Moving materials in Nunavik communities is a decisive factor in the selection of a foundation system. Overall, there are very few suppliers of construction materials in these communities. Thus, materials such as lumber, steel and cement must be imported. Their handling and shipping costs can amount to approximately 20 percent of the construction costs, or more if shipping must be by air. Logistical costs vary by foundation type and on-site availability of materials and equipment needed for construction.

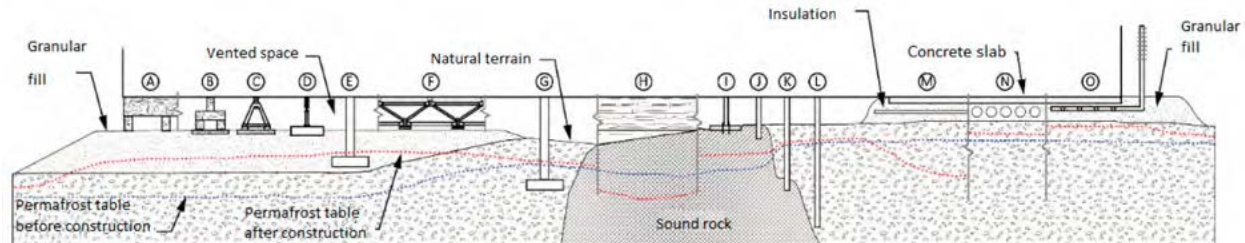
Due to the lack of road connections between northern communities and with the South, shipping of construction materials represents a major constraint in seasonal planning of construction, due to its impact on the project cost as well as the timeline. Currently, the most economical mode for materials is by sea, which is limited to a short period during the year (June to November). Two major shipping companies currently serve Nunavik, NEAS and Desgagnés. Frequency of arrivals in communities, which varies from year to year based on demand, ranges from two to four a year. Larger communities such as Inukjuak, Salluit, Kuujuaq and Puvirnituk, have more frequent service. Despite the increase in marine services, the space available remains limited and may quickly become unavailable, depending on planned construction and the quantity of consumer goods ordered by the community. It therefore is crucial to reserve the necessary space for shipping construction materials and machinery as early as possible. Note that due to the presence of ice and variable weather conditions, delivery delays are common and can significantly delay planned construction. To limit the potential impact of delivery delays, the common practice is to plan construction work one year in advance to ensure that when work is scheduled to start, materials and equipment are already on site. As a last resort, contractors can always turn to air transportation for delivery of small materials, but weight and size restrictions as well as high costs must be considered. Nunavik has a network of quality airports that can accommodate Dash 8 aircraft adapted to gravel runways, as well as daily commercial flights between communities and with the South, essentially operated by Air Inuit and First Air (Kuujuaq). Two runways in Nunavik can currently accommodate larger aircraft (Boeing 737): Puvirnituk and Kuujuaq.

Access to certain sites within a community is sometimes difficult due to the lack of roads, or rough terrain and difficult soil conditions (e.g. poorly drained area on sensitive permafrost). For these reasons, moving equipment to a construction site must be carefully planned and may require certain precautions such as transportation by air or in winter to avoid disturbing the land. Site access may limit the choice of foundation type due to restricted availability of materials and equipment necessary for construction that stays within the initial budget. Winter movement may sometimes be beneficial but can also make certain construction activities more complex or even impossible.

5.5 FOUNDATION TYPE

Depending on soil type, a structure's permanent load and potential excess loads, there are various foundation types suited to cold regions and permafrost zones. The simplest foundation types are normally used for small, unheated buildings. The design of heated or larger buildings often requires special care which, depending on the soil type, may complicate selection of the foundation system. In the literature, the foundation types used in a permafrost zone fall into three major categories: surface foundations, deep foundations and foundations with a heat extraction system. For each category, the main foundation types used for construction of houses and other buildings on permafrost are shown in figure 5.62 and will be described in the next section. The anticipated costs, benefits, drawbacks and suggested uses for these foundation types are shown in Table 1 of Appendix XVI.

In Nunavik, the foundation types for residential buildings erected in recent decades have remained virtually the same. For the most part, these are wood frame buildings resting on a steel frame with a surface foundation system (tripods with adjustable jacks) over granular fill. Commercial or institutional buildings are equipped with foundation systems ranging from simple (slab on grade or foundation wall on a footing) to complex (ventilated slab on grade or with thermosyphons), depending on the permafrost conditions encountered and their sensitivity to thawing. For example, the foundation system for Salluit's municipal swimming pool, resting directly on rock, contains no mechanism for preserving the permafrost despite the structure's heavy permanent load. This is not the case for the new municipal garage build on sensitive permafrost, which has a slab foundation with thermosyphons.



SURFACE FOUNDATIONS		DEEP FOUNDATION	FOUNDATION WITH HEAT EXTRACTION SYSTEM
with granular fill	without granular fill		
- Joists at grade level (A) - Beams on footings (B) - Piles or tripods with adjustable jacks, on footings (C and D) - Pile on embedded footing (into fill) (E) - Rigid three-dimensional foundation (F) - Foundation walls on continuous footing - Slab on grade (M)	- Pile on embedded footing (in natural soil) (G) - Foundation walls on continuous footing on rock (H) - Pile and footing on rock (I) - Piles embedded in rock, near the surface (J)	- Point-bearing piles (K) - Adherence and point-bearing piles (L)	- Ventilated invert (N) - Slab on grade with thermosyphons (O) - Thermal piles

FIGURE 5.62: TYPES OF FOUNDATIONS THAT CAN BE USED IN PERMAFROST ZONES

5.5.1 Granular fills

Granular fill is not a foundation type strictly speaking, but instead must be considered an essential component of certain foundation systems. It is often used for sites where foundation soil conditions are extremely poor. In addition to providing a level surface, use of fill essentially preserves the temperature of the underlying permafrost. When the soil surface is raised, the thermal regime adjusts and the permafrost table rises into the former active layer, ideally up into the fill. In this way, seasonal freeze-thaw cycles are limited to the fill. To limit any potential movement linked to the seasonal frost heave process, the fill must be thick enough and composed of non-frost-susceptible material (sand, sand and gravel, gravel or crushed rock). Ideally, the invert should be set in place one year before construction starts on the building to allow the thermal regime to readjust (rise in the permafrost table). When preparing fill over permafrost, it is usually best to backfill the land without removing the vegetation and surface layer of organic soil. Removing or disturbing this organic insulating layer, especially at the start of the warm season, contributes to thickening of the active layer, which is undesirable, especially when the upper part of the permafrost is ice rich. In some cases, when the permafrost is stable when thawed, it may be necessary to completely remove the organic surface layer or localized pockets of organic soils before starting construction of the granular invert, to avoid excessive compaction under the buildings.

The bearing capacity of the fill will depend on the quality of the material used (strength when not frozen and degree of compaction). For fill normally compacted by truck or a bulldozer with tracks, the acceptable load may be as little as 75 kPa, but can reach more than 250 kPa for carefully controlled and tested fills (AGRA Earth & Environmental Limited, 2000). The thickness of the granular fill between the base of the footing and the underlying natural soil must be enough to reduce the concentration of live loads on the natural soil to acceptable values while controlling the amplitude of freeze-thaw cycles to limit deterioration of the permafrost. The thawing amplitude can be easily estimated using the simple Stefan or modified Berggren equation (Aldrich and Paynter, 1966). Normally, fill thickness must be 1.5 times greater than the maximum thickness reached by the active layer.

To prevent potential deterioration of the permafrost, it is important to limit any addition of heat that may come from the building. Where possible, the building should be raised above the ground. The space under the building floor is usually 500 to 1000 mm high, to promote air movement that evacuates any heat coming from the floor. Note that the building's shadow effect considerably cools surface temperatures under the building in summer, which can be almost 50 percent lower (Bouchard, 2005).

For heated buildings on a slab, precautions must be taken to limit heat transfer from the building to the permafrost. Depending on the permafrost characteristics, these precautions may range from simple placement of insulation under the slab to installation of a passive or mechanical heat extraction system. Use of extruded rigid polystyrene insulation in some cases can improve the performance of foundations. For example, in a building resting on a slab on grade, insulation reduces thermal heat exchanges from a building to the soil to limit the thermal footprint on the permafrost (Figure 5.55 B). In some cases, however, it may also restrict heat extraction from the permafrost to the atmosphere in winter, thus limiting the permafrost's ability to cool down. Thermal analyses are then required to justify the use of insulation and, of necessary, to position materials correctly. Under the CAN/CSA-S501-14 standard, Moderating the effects of permafrost degradation on existing building foundations, the use of insulation may be considered in areas where annual average soil temperatures are below -4°C , but should be considered with caution and based on the recommendations of a professional in the case of permafrost with an annual average temperature between -4°C and 0°C . Good practice suggests installing insulation at the end of winter rather than in summer or fall, to reduce the risks of trapping heat beneath it and avoid delaying refreezing of the active layer by several months (Johnston, 1981). Depending on the air temperature, the required thickness of insulation will vary from 50 to 100 mm. The pressure applied to insulation must not exceed 40 percent of its compression strength to avoid polystyrene creep.

Here are a few design recommendations.

- Finished surfaces of granular fill must be profiled to promote rapid evacuation of melt water and precipitation to surrounding drainage systems. The minimum recommended slope for these finished surfaces is two per cent.
- A platform at least three metres wide should be preserved around the building to ensure stable circulation of vehicles and avoid rutting in the natural soil near the building.
- To obtain adequate drainage and optimize the use of granular resources, it is recommended that drainage and grading plans be drawn up before proceeding with construction of inverts for house footings. The goal is to effectively integrate surface runoff evacuation to depressions alongside streets or, if necessary, to new ditches built on lot perimeters.
- Ideally, ditches must be profiled with fill materials to avoid excavating and exposing the permafrost and must have a slope that promotes rapid runoff. To the extent possible, and to reduce the risks of talus instability, drainage ditches must be located far from the foot of fills when the site consists of unconsolidated deposits sensitive to thawing. Placement of fill on a gentle slope can be a possible solution in this case.
- To spread local differential movements over the surface of fill, it can also be reinforced with rows of biaxial geogrids. This solution simply seeks to lessen the amplitude of highly localized compaction and must not be used for anticipated compaction in an area of a few metres. Reinforcement with biaxial geogrids can, however, increase the bearing capacity of a work area that is too soft.
- In partially frost-susceptible fill, the addition of a waterproof membrane in the upper layer may reduce soil movements associated with the formation and thawing of seasonal ice.

Granular inverts must be placed methodically and with caution to limit potential thermal disturbance of the permafrost. It therefore is important to avoid disturbing the surface vegetation layer with machinery, so as not to affect the thermal and structural properties of the natural soil under the new fill. To this end, no motorized vehicle able to damage the plant and organic layers should move directly on the land surface before the invert is installed. The goal is to maintain the insulating properties of these surface materials and the integrity of the natural drainage while avoiding the creation of low areas that might accumulate surface water and thus promote thermal deterioration of the underlying permafrost. The following approach is suggested.

- Before authorizing movement of trucks and heavy equipment on wheels, place a layer of compactible, non-frost-susceptible materials 600 mm thick, pushing them ahead with a bulldozer. This precaution spreads the equipment loads over a wider bearing surface and ensures stability of the underlying natural soil layer.
- Place fill materials over the initial layer and then in successive layers about 400 mm thick. Cover this with a thin traffic layer of crushed stone up to 20 mm calibre; when a smaller calibre is not available, dynamited stone with a calibre up to 600 mm may also be used, and covered with a layer of crushed stone with a calibre up to 150 mm and the traffic layer (Figure 5.63 A). Between each layer of different materials, the granulometry of granulates must comply with the filters law to avoid any migration of particles into voids left between pebbles in the underlying layer.
- Densify each layer surrounding buildings (at least eight passes) and the area located immediately under the building (at least 12 passes) using a heavy vibrating compactor. Quality control of these materials and their placement by a certified laboratory is recommended. If resurgence of water is observed on the surface, immediately stop vibration to avoid destabilizing the underlying soil layer and the appearance of soft areas.
- A hardpan of pit run or other type of coarse rock may also be placed over talus of granular fill to protect it from erosion.

A few examples of granular inverts illustrating the recommendations made above are shown in figure 5.63 B and figure 5.64.



FIGURE 5.63: A) EXAMPLE OF SLIGHTLY SLOPED GRADING WITH TERRACED INVERTS. B) STRUCTURE OF FILL WITH VARIOUS CALIBRES OF GRANULAR MATERIALS.

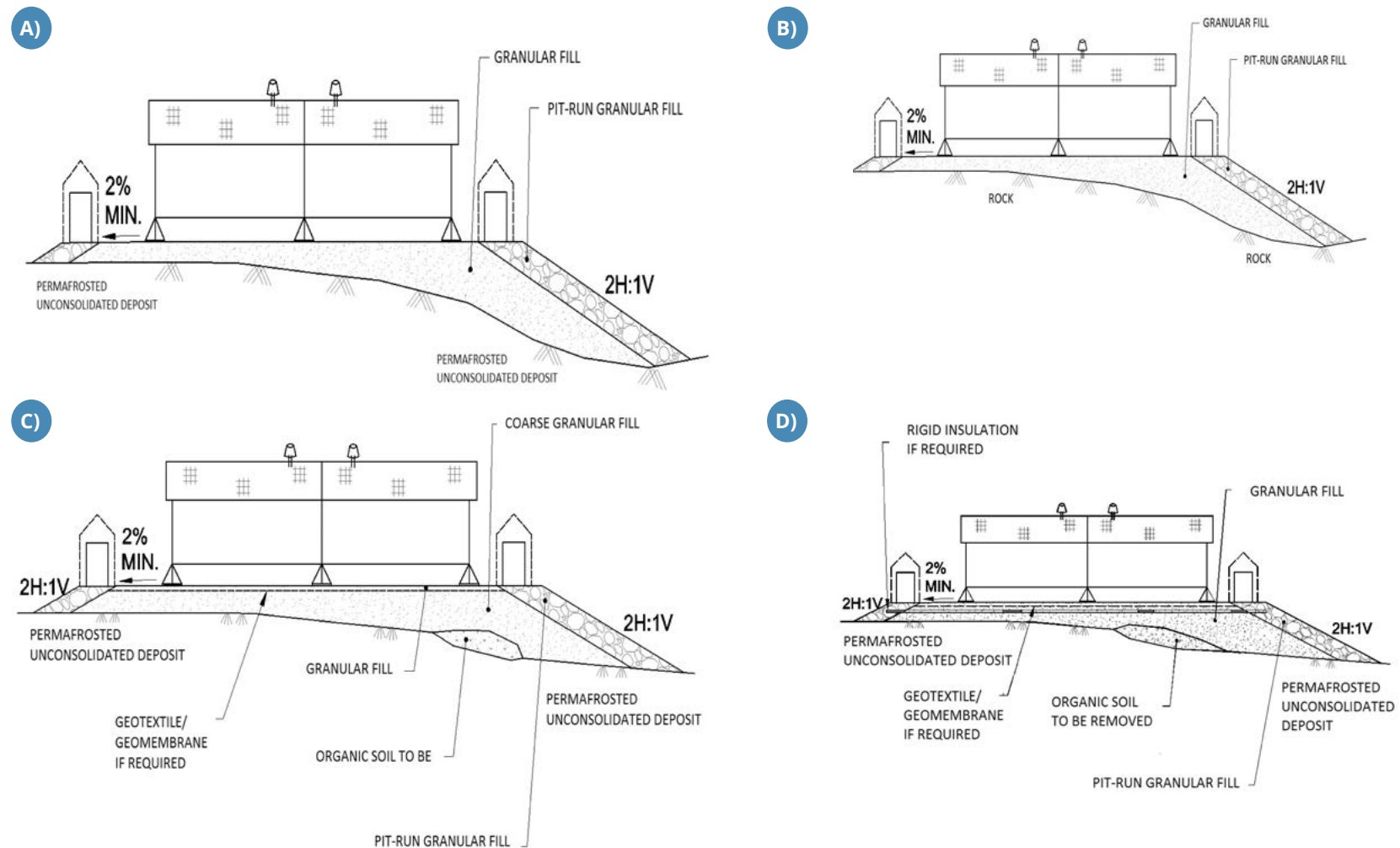


FIGURE 5.64: GRANULAR FILL PLACED A) ON AN UNCONSOLIDATED PERMAFROSTED DEPOSIT OR B) ON ROCK. GRANULAR FILL PLACED ON AN UNCONSOLIDATED PERMAFROSTED DEPOSIT WITH THE PRESENCE OF LOCALIZED ORGANIC SOILS C) WITH POSSIBLE USE OF A GEOTEXTILE OR GEOMEMBRANE AND D) WITH POSSIBLE USE OF A GEOTEXTILE OR GEOMEMBRANE AND RIGID INSULATION.

5.5.2 Surface foundations with or without granular fill

Surface foundations, regardless of the materials used (lumber, metal, concrete, etc.) or their geometry, transfer loads from the structure directly to or slightly below the ground surface. This type of foundation is generally used in the presence of a surface soil layer with the required bearing capacity, and where the characteristics of the construction site and building load and overload do not require a deep foundation. There are two main categories of surface foundations, those resting directly on the soil surface and those slightly embedded in the upper part of the permafrost. Depending on the ability of the natural soil to bear the building load and overload, granular fill is commonly used, into which the permafrost will rise and envelop the foundation.

Where appropriate, surface foundations should include adjustment devices (jacks) to adapt to soil movements or at least provide the option of levelling the building if necessary (addition of wooden beams). This device has the advantage of compensating for differential compaction likely to occur in areas where permafrost is ice rich. The ability to make an adjustment of 100 to 150 mm is normally considered acceptable. To provide access for personnel responsible for adjusting foundations, the minimum height of the ventilated space should be 500 mm. A greater height, up to 1200 mm, improves access and provides a thermal break between the heated building and the underlying soil.

Some foundations have a metal structure for transferring the load to a limited number of bearing points and levelling the floor if necessary (three-dimensional foundations with multiple bearing points). This type of foundation, successfully used in the Canadian Arctic but very little in Nunavik, is normally used for small buildings of one or two storeys.

5.5.2.1 Beams at grade level

Beams at grade level consist of concrete or laminated wood footings laid longitudinally under the structure and resting on granular fill (Figure 5.65). Contrary to a foundation with individual footings, the beams at grade level provide a greater bearing surface and thus are less likely to skew. However, this type of foundation is vulnerable to differential compaction because of its adjustment limitations. Placing three or four parallel rows of beams under the structure ensures a certain degree of flexibility and strength compared with use of a single continuous beam placed on grade around the perimeter. This type of foundation may not raise the building far enough above the ground to ensure effective ventilation, which limits its use with heated buildings, but it can still be suitable for unheated structures that may have to be moved (McFadden, 2000).

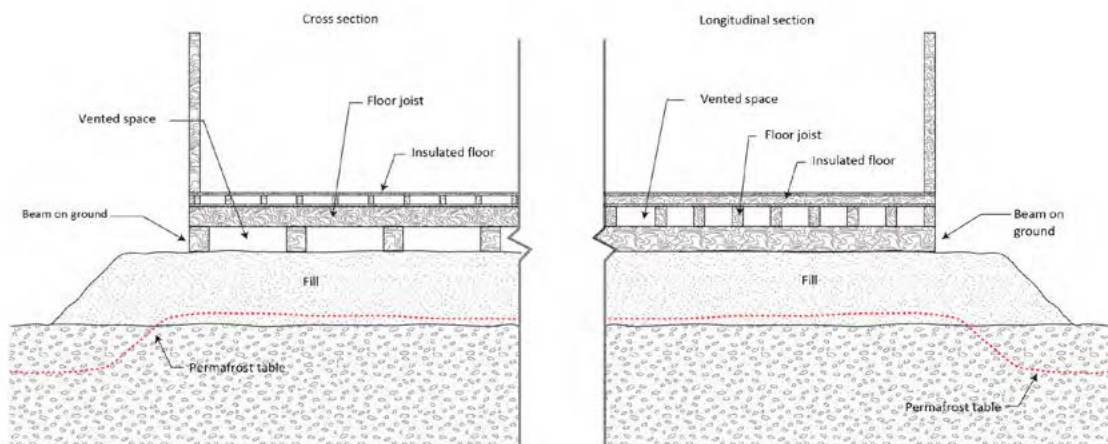


FIGURE 5.65: CROSS AND LONGITUDINAL SECTION VIEW OF A SURFACE FOUNDATION DESIGN WITH BEAMS AT GRADE ON GRANULAR FILL.

5.5.2.2 Beams on footings

Beams on footings are one of the most commonly used foundation type in continuous and discontinuous permafrost areas. This foundation type involves placing alternating layers of wood framing on a footing resting on granular fill, a rock outcrop or any other deposit with the necessary characteristics of bearing capacity and gelivity (Figure 5.66 A). The structure's primary beams are supported at regular intervals, usually every two and a half to three metres, by layers of stacked timbers to achieve the required height, generally one metre, to create sufficient air space under the building and avoid transferring heat from the building to the underlying soil (Figure 5.66 B). A suitable height between the building and the soil also facilitates its levelling using a pair of additional beams if needed. It is recommended that this foundation type be fastened to the main beams with metal brackets or another type of fastener (Figure 5.66 A). In some communities, cables secure the structure to the ground with anchors embedded in granular fill. The use of treated lumber is recommended for foundation components in direct contact with the soil (footing) or that might be exposed to water or snow.

This foundation type essentially is used on soils with low bearing capacity and for small buildings that pose little risk of damage from a reasonable amount of movement (CMHC, 94-214). Long used in Nunavik due to the small amount of material needed and the simple installation, this type of foundation is gradually being replaced in new home models by piers or tripods on a footing with adjustable jacks (Section 5.5.2.3).

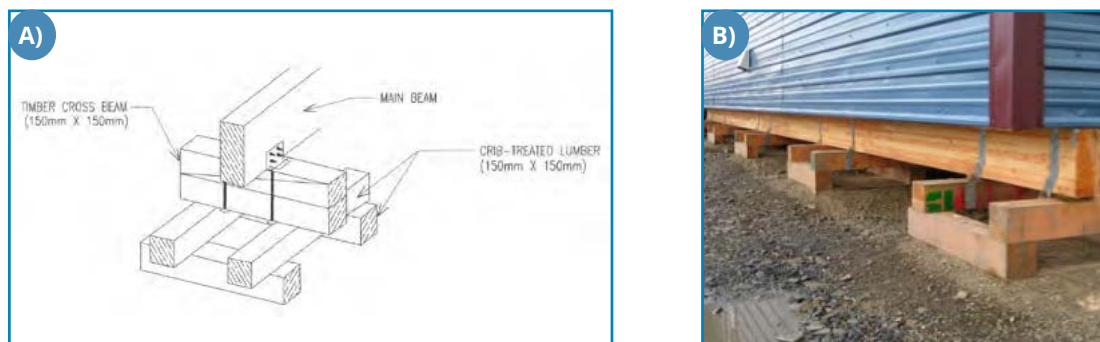


FIGURE 5.66: A) SURFACE FOUNDATION SYSTEM COMPONENTS USING TIMBERS (MODIFIED FROM AGRA EARTH & ENVIRONMENTAL LIMITED 2000. B) MAIN BEAM OF THE ELEVATED STRUCTURE SUPPORTED AT REGULAR INTERVALS BY TIMBERS ([HTTP://WWW.CCHRC.ORG/](http://www.cchrc.org/)).

5.5.2.3 Piles or tripods with or without adjustable jacks on footings

This is the foundation type now most commonly used in Nunavik for residential buildings of one or two storeys, with piles and tripods of different forms and configurations. The structures most commonly used are tripods (Figure 5.67 A and B) or square or cylindrical piles (Figure 5.67 C et D) resting on footings. The footings are individual or combined, depending on whether they are supporting one or several piles and their size allows good distribution of the building's load over the soil to prevent the foundation from sinking. In a permafrost zone, the use of individual footings is preferable, since these pose less risk of damaging the foundation in the event of differential movement (CMHC, 94-214). Footings may rest directly on the surface of the natural soil if it is deemed adequate, but most often bear on non-frost-susceptible granular fill. Footings may also be embedded into the soil at shallow depths to rest on the upper part of the permafrost or be fully embedded. Tripods usually are made of metal, while lumber, concrete or steel are commonly used in the fabrication of piles. For the footings, treated lumber is an excellent choice of material when this rests on the surface of well drained granular fill, especially since the thermal properties of wood restrict heat transfer to the soil. When they are embedded under the surface, footings are often made of concrete. In this case, it is important to ensure that the concrete is of good quality and reinforced with steel.

This foundation type generally provides excellent performance. The clear space under the building allows the wind to sweep out the snow and stop heat transfer from the house to the permafrost. This approach usually provides good results under almost all soil conditions. However, use of this foundation type can require a large amount of granular material, especially on sloped terrain. Normally, supports for these structures, in the form of steel trestles or piers, supported by square timbers or a concrete footing, can be built at reasonable cost.

Use of this type of surface foundation is desirable for sites with little ground movement, but with proper, regular maintenance (levelling), this type of foundation adjusts to most differential movements that may occur. This type should be used where the owner and occupant are able to maintain the foundation if necessary. Installation is simple and does not require specialized machinery, only the heavy machinery usually available in Nunavik villages. However, its effectiveness is largely dependent on the quality of the granular fill.

Although a rare occurrence with this foundation type in Nunavik, it may be necessary in areas with seismic activity or strong winds (e.g. Salluit) to stabilize the structure against horizontal loads using braces placed between the piles (McFadden, 2000). For buildings with a small load and overload, the structure should also be secured to the ground with cables and anchors.

5.5.2.3.1 Footing resting on the ground surface or slightly embedded

When this type of foundation rests on or is slightly embedded in compacted and well drained granular fill, the acceptable pressure constraints depend on the strength in unfrozen state of the type of material used. For example, the thickness of the granular fill between the base of the footing and the underlying natural soil must be such that the concentration of live loads on the natural soil is reduced to acceptable values, while controlling the amplitude of thawing to limit deterioration of the underlying permafrost. Given that this foundation type rests on the soil surface rather than being embedded in the permafrost, the risks of seasonal ground movements linked to frost heave may require regular adjustment of the foundation in fall and spring. To offset this risk in areas where the material making up the active layer before construction is frost-susceptible, placement of fill is recommended using non-frost-susceptible material deep enough to draw the permafrost up to its base and thus limit the freeze-thaw cycles.

In places where the rocky substrate is exposed or at shallow depths under unconsolidated deposits (< 2 m), which is common in Nunavik, footings can be anchored directly in the rock (Figure 5.68 A). Anchoring foundations directly in the basement rock significantly increases their bearing capacity while ensuring resistance to lateral stress and uplift. In general, granitic rock is more solid than sedimentary rock, but the capacity of the rocky substrate must be accurately assessed before construction, failing which, estimates of bearing capacity must remain conservative. Some rocky outcrops may present an advanced degree of alteration in which many vertical and horizontal cracks allow water to infiltrate and freeze, forcing frost heave of rocky blocks under certain conditions. This active periglacial process affecting many rocky outcrops in Nunavik communities (L'Hérault et al., 2013) can significantly alter the capacity of rocky substrate. It should be noted that certain types of rocks are more sensitive to physical disintegration resulting from freeze-thaw cycles due to their stratified structure, as in the case of Kangirsuk and Kangiqsujaq.

5.5.2.3.2 Embedded footings resting on or in permafrost

Footings resting directly on or slightly embedded in permafrost are fairly common in the Arctic. There are several ways to install this type of foundation. The first is to excavate the natural soil through the active layer down to the permafrost table, and then embed the footing (Figure 5.68 B and Figure 5.69 A). If the active layer is not frozen, the walls of the excavation may be very unstable due to water seepage from the water table perched above the permafrost. The combined effect of water seepage and collapse of the excavation walls can alter the bearing capacity of the soil located under the footing. In this case, the excavation walls must be sloped out (1V:4H) and a pump must be used to keep the excavation dry. It is also advisable to excavate for and install the foundation footings one at a time, to limit the area and length of exposure of the permafrost. In areas where excavation of the active layer remains difficult despite these precautions, the footing can be embedded in fairly deep granular fill to raise the permafrost high enough to envelop the footing (Figure 5.69 B).

Timber or prefabricated concrete footings can be laid on a thin levelling layer directly on the frozen soil, but if the concrete must be poured in place, a layer of compacted granular material at least 300 mm deep or extruded polystyrene insulation 50 mm thick should protect the permafrost from the heat emitted by the concrete (AGRA Earth & Environmental Limited, 2000). The footing must never be placed directly on permafrost containing segregation ice. In this situation, the permafrost must be excavated and replaced with a layer of compacted granular material at least 30 to 60 cm deep as shown in figure 5.69 A. Placement of this compacted granular layer below the footing also reduces thawing of the permafrost caused by the heat emitted by the curing concrete. When installing this type of foundation, special attention must be paid to the temperature at which the concrete is poured. It must be neither too warm, to avoid melting the permafrost, nor too cold, causing it to freeze before it has time to harden. Based on the experiment conducted by Braun et al. (1979), concrete poured at temperatures between 15°C and 18°C will thaw the adjacent soil to an approximate depth of 0.5 and 1 times the thickness of the footing. When the ambient temperature is above 0°C, and to minimize thawing of the permafrost, it is advised to backfill the excavation as soon as the concrete is strong enough. Following this, insulation (peat or rigid insulation) is placed on the soil surface, and covered with granular fill if necessary, taking care to leave a clearance of about 500 to 1000 mm under the building. Compaction and uplift can occur during thermal readjustment of the soil after this type of foundation is installed. Several seasons may be needed to achieve a new balance.

For the embedded portion of a pile in the active layer, there is a risk of heaving due to adherence caused by frost (Figure 5.51 A). Necessary precautions therefore must be taken to limit soil adherence to the pile (Figure 5.51 B). To achieve this, the use of non-frost-susceptible material is recommended around the pile, which should then be covered with polyethylene sheathing or the equivalent (Figure 5.69 A). An adjustment system with jacks can also be incorporated into the foundation design to level the structure as necessary.

The benefit of embedding the footing in permafrost is its location below the seasonal freeze-thaw zone (Figure 5.69 C), where it rests on permanently frozen substrate. Successful use of this foundation type requires keeping the soil frozen under the footing and accurately assessing its bearing capacity and potential compaction linked to long-term creep of the foundation soil. The pressure limits acceptable for surface foundations embedded in permafrost are determined by the shear strength of the frozen soil based on duration and temperature. The excavation depth required to reach the permafrost table is highly variable between sites (intrasite variability), locales (locale variability) and villages (regional variability). For a given site and between sites, the active layer varies depending on the type of material in place, type of surface, topography, drainage and snow cover. There is general agreement that the active layer will be proportionally thinner as one moves north. For example, for a site with similar materials and surface conditions, the active layer will be thicker at Umiujaq than at Salluit. When designing this type of foundation, the depth it is embedded must factor in the thermal impact of the infrastructure and the new environmental conditions affecting the thermal regime of the soil (thickness of the active layer, soil temperatures at depth) as well as the anticipated impact of climate change. Several experiments conducted by Robinsky and Bessflug (1973) have demonstrated the effectiveness of using insulated footings for heated and unheated buildings to avoid penetration of thawing below the base of the footing.

Common practice suggests building foundations at the start of winter, when the active layer is thickest and the cold temperatures help refreeze the backfilled area (Phukan and Andersland, 1981). If installation is done in summer, the construction calendar must allow enough time for the soil around the footing and pier to refreeze.



FIGURE 5.67: A AND B) TRIPODS PLACED ON A TIMBER FOOTING WITH ADJUSTABLE JACKS, RESTING ON GRANULAR FILL (SOURCE: QUADRIVIVUM). C) PILE PLACED ON A CONCRETE FOOTING SLIGHTLY EMBEDDED IN GRANULAR FILL. D) PILE HEAD EQUIPPED WITH AN ADJUSTABLE JACK.

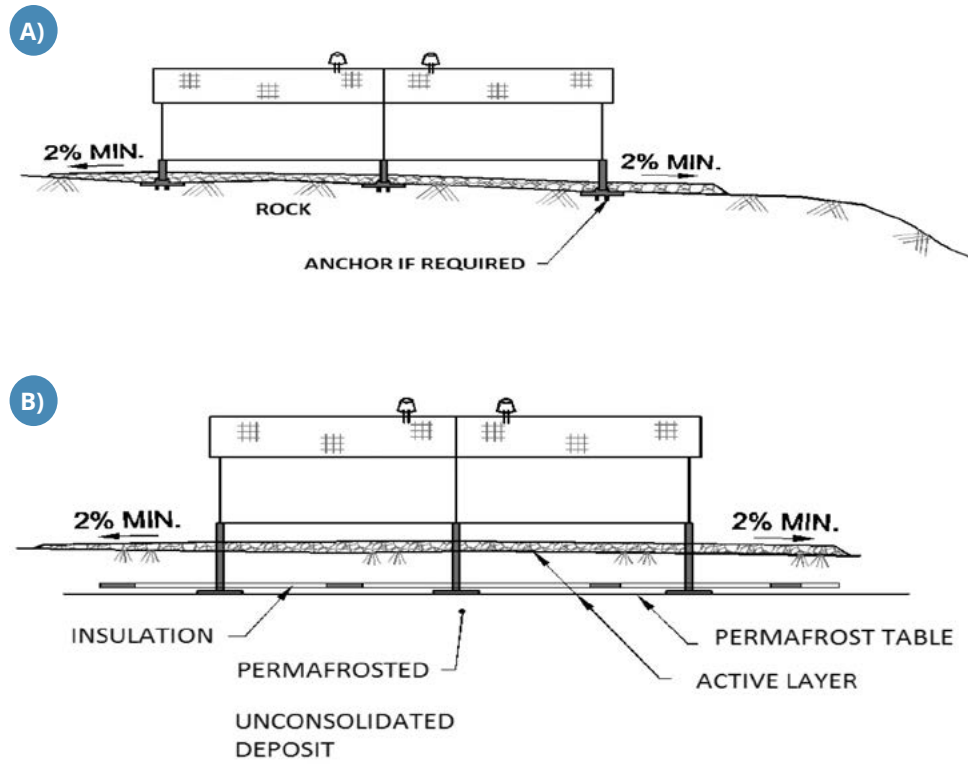


FIGURE 5.68: A) FOOTINGS RESTING ON ROCK SURFACE WITH ANCHORS IF REQUIRED. B) EMBEDDED FOOTINGS RESTING ON PERMAFROST, OR LIGHTLY ANCHORED IN THE PERMAFROST, WITH USE OF RIGID INSULATION.

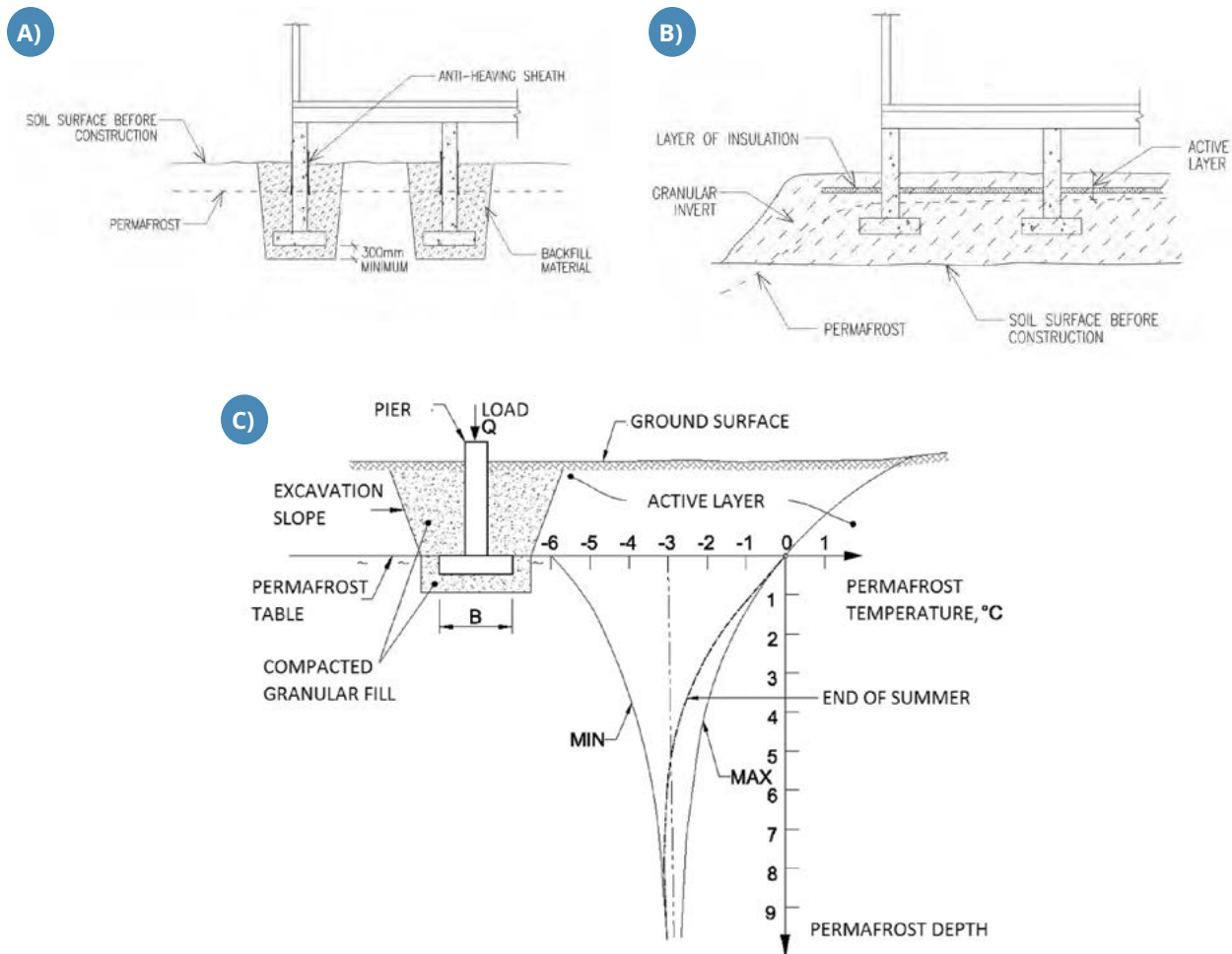


FIGURE 5.69: FOOTING EMBEDDED IN PERMAFROST A) IN NATURAL SOIL AND B) IN GRANULAR FILL RESTING ON THE SOIL SURFACE. C) CONCRETE FOOTING EMBEDDED IN PERMAFROST WITH MINIMUM AND MAXIMUM TEMPERATURE PROFILES IN THE SOIL (MODIFIED FROM LA CONCEPTION ET RÉHABILITATION DES INFRASTRUCTURES DE TRANSPORT EN RÉGIONS NORDIQUES 1983 NBR 123 DE BRANKO LADANYI, ISBN 2-550-25505-4). NOTE THAT IN THIS FIGURE, DEPTH 0 HAS ARBITRARILY BEEN SET AT THE PERMAFROST TABLE, NOT THE GROUND SURFACE.

5.5.2.4 Foundation wall on a continuous footing

Foundation walls on a continuous footing, used extensively in areas without permafrost, are a foundation type increasingly common in Nunavik and Nunavut to support large buildings that require good bearing capacity and where the rock is solid and at or just below the surface (Figure 5.70). This foundation type has the benefit of providing vacant space under the building (basement or crawl space) to accommodate mechanical components of the building. This space can also be outfitted for storage for use by the occupants. In a design of this type, small openings can be placed along the foundation to ventilate the crawl space and remove some of the heat (cold crawl space) (Johnston, 1981). A crawl space can also be ventilated with warm air from inside the building (heated crawl space) which is then exhausted through a chimney. In this case, insulation is used to cover the walls and floor of the crawl space (Andersland and Ladanyi, 2004). Construction of this type of foundation requires a source of suitable granulates for making concrete. It should be noted that this type of foundation is very sensitive to differential compaction and is likely to disturb the thermal regime of the soil if there is no cooling system (ventilated fill or thermosyphon). Thus, its use in a permafrost zone remains limited to sites where the soil is stable when thawed (unaltered rock outcrops, thick ice-poor granular deposits or thin cover over rock) and where soils are well drained. This type of foundation provides the benefit of adjusting to the topography of the rocky substrate even on a sloped site (Figure 5.70 C and D).

The choice of site for a house resting on this type of foundation must be carefully assessed to avoid fine, ice-rich soils that are sometimes found a few metres beneath a layer of sand and gravel. Despite its depth, this ice-rich soil is likely to thaw in a few years due to heat transfer from the building to the soil (Figure 5.55 A). This situation has been observed at Umiujaq in an area where houses with a basement were built on a sandy terrace a few metres thick, resting on a fine, ice-rich deposit.



FIGURE 5.70: A) AND B) FOUNDATION WALL ON A CONTINUOUS FOOTING RESTING ON A GRADED ROCKY SUBSTRATE AT KANGIQSUJUAQ, NUNAVIK. C) AND D) FOUNDATION WALL ON A CONTINUOUS FOOTING RESTING ON AN SLOPED ROCKY AT IQALUIT, NUNAVUT.

5.5.2.5 Three-dimensional foundations with multiple bearing points

Three-dimensional foundations with multiple bearing points are designed to remain rigid while accommodating major shifts or subsidence of soil, to prevent deformation of the building. This foundation type, developed in cooperation with the Canada Mortgage and Housing Corporation and the firm Triodetic Building Products Ltd., is based on the principle that a three-dimensional structure resting on three bearing points eliminates the problems caused by differential subsidence or by elevation of one of the three points, since they will always define the same plane. Any vertical displacement of one of these points will simply incline the plane, thereby allowing the structure to behave as a single unit. In other words, a local movement will affect the inclination plane of the overall structure rather than cause deformation at one specific point. The foundation plane can then be corrected if necessary with adjustable supporting plates, while limiting potential damage to the structure by this operation.

These foundations consist of a network or interconnected web of galvanized steel structural struts using hubs to form a three-dimensional structure (Figure 5.71 A). The hubs specially designed for this type of foundation can connect more than 10 struts at a single point (Figure 5.71 B). This structure is formed of an upper and a lower orthogonal grid of about one square metre braced with diagonal struts. The load and stress are distributed uniformly over this frame, which enhances structural integrity of the building. To ensure adequate rigidity under torsion, each grid is braced with horizontal struts. This rigidity ensures that by resisting multiaxial forces and rotation of individual struts, the structure acts like a floating slab. For this reason, there is no need to provide thick granular fill. The ground must be prepared with good surface drainage and suitable areas for access and traffic. For finer soils, geotextile may have to be laid on the ground before placing the fill.

Three-dimensional foundations are assembled on site and do not require a crew of skilled workers. Two people can usually erect the structure in a few days. This lightweight, compact system is delivered knocked down, to facilitate shipment by air or sea. For a structure 8.5 x 12.75 m (28 x 42 ft.), the weight of the structure, including floor joists, is approximately 4,500 kg with a volume of about four cubic metres, with no component longer than two metres (AGRA Earth & Environmental Limited, 2000).

Since 1985, this type of rigid three-dimensional foundation has been installed on about 800 housing units in northern communities and no performance problem has been noted to date (Triodetic). Monitoring of several hundred foundations of this type resting on various soils and in different surface conditions shows that initial and long-term movements of the structure have all remained within acceptable limits (Vangool, 1996). Based on the performance of this foundation type, service life is estimated between 70 and 80 years. A three-dimensional foundation with multiple bearing points provides great design flexibility for new projects or renovations, since there is no limitation on building size. This is a foundation type to consider, especially if availability of labour, materials and machinery is limited. One of the current limitations is that this foundation type is suited only to rectangular buildings. For the moment, there is only one structure with a three-dimensional foundation in Nunavik. It was erected in 2013 in the community of Akulivik (Figure 5.72 A and B) as part of a pilot project to assess applicability of various foundation types in Nunavik.

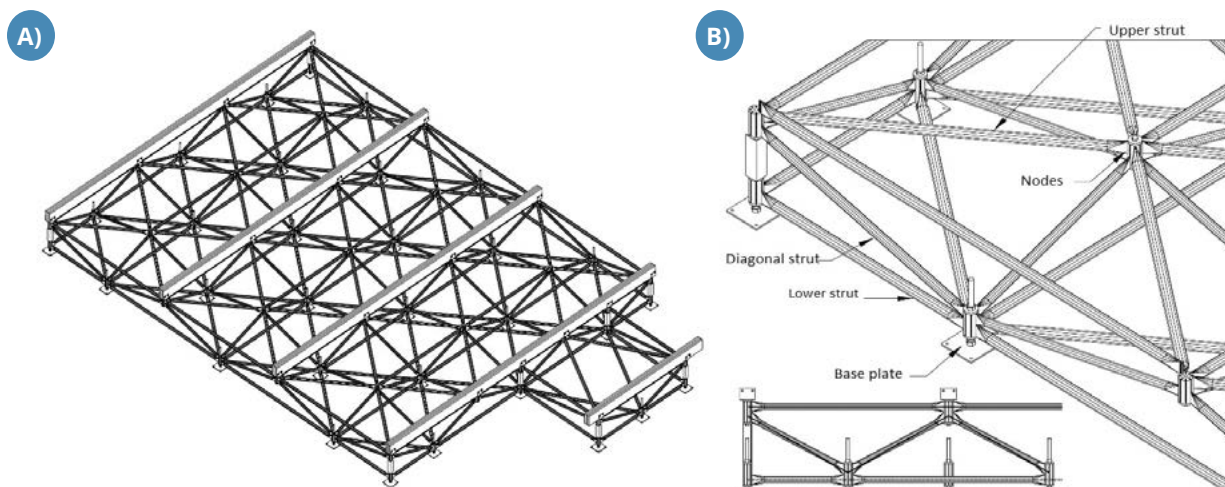


FIGURE 5.71: A) NETWORK OF GALVANIZED STEEL OR ALLOY STRUCTURAL STRUTS INTERCONNECTED WITH HUBS TO FORM A THREE-DIMENSIONAL STRUCTURE THAT ACTS LIKE A FLOATING SLAB. B) UPPER AND LOWER ORTHOGONAL GRIDS OF ABOUT ONE SQUARE METRE, INTERCONNECTED WITH DIAGONAL STRUTS. THE SPECIAL HUBS DESIGNED FOR THIS TYPE OF FOUNDATION CAN CONNECT MORE THAN 10 STRUTS AT A SINGLE POINT (MULTIPOINT FOUNDATIONS LTD. <http://multipoint-foundations.com/>, 10 DIDAK DR. ARNPRIOR, ONTARIO, CANADA, K7S 0C3. (613) 623 3434).

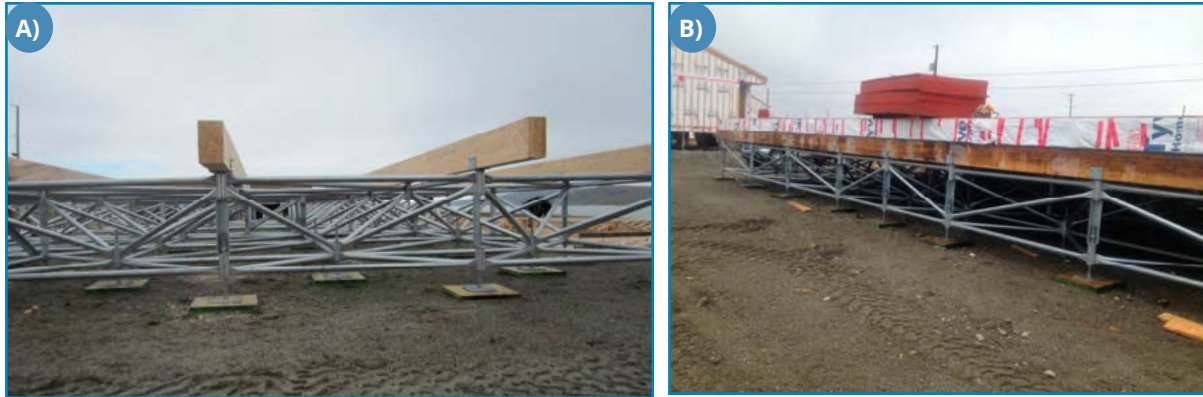


FIGURE 5.72: A) AND B) THREE-DIMENSIONAL FOUNDATION USED IN A PILOT PROJECT FOR HOUSING IN THE COMMUNITY OF AKULIVIK IN NUNAVIK (SOURCE: MAKIVIK, 2013).

5.5.2.6 Slab on grade

Concrete slabs on grade initially appear to be an excellent foundation option for houses and various other buildings such as garages, firehalls and warehouses. This foundation type usually provides an inexpensive, durable and smooth floor as well as structural support for heavy equipment. However, without a heat extraction technique under the slab (thermosyphon, ventilated fill, etc.), heat transfer from the building to the underlying permafrost can extend to significant depths (Figure 5.55 A). Given that the rigidity of this type of foundation allows for little soil movement, its use remains risky where permafrost is present and it should only be chosen after an exhaustive characterization of the study site. Major compaction can occur on ice-rich permafrost. In Nunavik, most serious foundation problems, those resulting in demolition or relocation of the building, or cessation of heating, are linked to heated structures on a slab on grade. A few examples of land development with a slab on or below grade are shown in figure 5.73. Ideally, this foundation type is suited to sites with solid rock near the surface. Slabs should also be reinforced with steel rebar to increase their rigidity and provide some resistance to differential movements that still might occur.

Eranti and Lee (1986) report a large number of breaks in this type of foundation for heated buildings where the permafrost protection strategy was limited to placing insulation under the slab. Thus, in addition to insulating the slab, foundations of this design often include a system for extracting heat lost from the building to limit permafrost thawing under the building. The systems most often used are ventilated fill or thermosyphons. These two systems are discussed in detail in section 5.5.4 on foundations with a heat-extraction system.

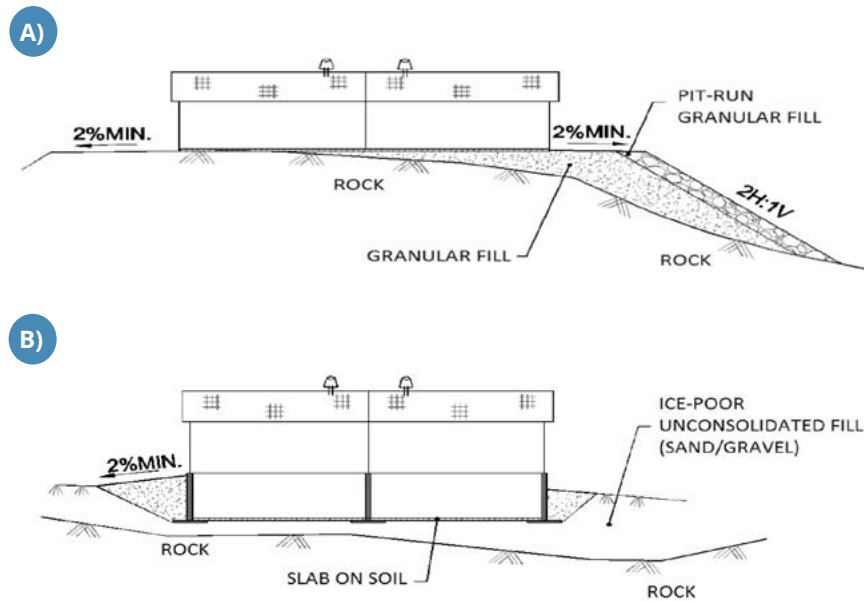


FIGURE 5.73: A) SLAB ON GRADE OVER A ROCK OUTCROP. B) SLAB ON GRADE WITH CRAWL SPACE OVER A THIN LAYER OF ICE-POOR UNCONSOLIDATED DEPOSIT ABOVE ROCK.

5.5.3 Deep foundations

Foundations on piles are widely used in permafrost zones. This type of foundation can support a wide range of structures, from a large heated building to a simple communications tower, even with heavy loads and unfavourable permafrost conditions (Johnston, 1981). This type of foundation, with a space for air circulation under the heated structure, has proved very effective, especially in areas where the permafrost consists of ice-rich sediments sensitive to thawing.

The purpose of this type of foundation is to transfer the structural load to a load-bearing layer at a greater depth, that will remain mechanically and thermally stable throughout the service life of the infrastructure. Based on site stratigraphy and the properties of the layers of material in place, the infrastructure's load will bear directly on the point where a solid soil layer is present (rock or dense, non-frost-susceptible granular material) or distributed along the pile using frost adherence forces. These two methods, which differ in how they distribute structural loads over the ground, define the two main categories of piles commonly used in a permafrost zone, point-bearing and adherence-bearing piles (Figure 5.74 A), and solely point-bearing piles (Figure 5.74 B).

Piles may be made of wood, concrete or steel. Selection of the pile material depends on several factors such as soil type and temperature, load to be supported, availability of materials and construction equipment, as well as shipping and installation costs. Tubular steel piles are the type most commonly used in Canada. They may have an open or closed end, depending on whether they are driven directly into the soil. The common practice, in Canada at least, is to drill a pilot hole slightly larger than the pile, insert the pile, and fill the space with a slurry of sand and water. Pile size and depth is determined by the foundation designer, based on the adherence strength required to support the live load from the structure and the anticipated uplift forces.

As shown by the few examples of land development with piles down to rock (Figure 5.75), use of this type of foundation can significantly reduce the quantity of granulate needed, especially on uneven terrain. Note that this foundation type does not eliminate the need to build a gravel driveway large enough to park residents' vehicles and accommodate deliveries of drinking water and heating oil as well as removal of waste water by truck. Installation of piles requires no excavation likely to destabilize the permafrost. However, some pile types do not allow levelling when necessary due to compaction or uplift. Simply installing adjustment screws on the head of each pile provides flexibility if the foundation shifts (Figure 5.76). Adjustable heads are recommended for adfreeze piles or those that cannot be embedded and anchored in quality rock, to allow for the small risk of movements during freeze-thaw cycles in the active layer.

5.5.3.1 Adherence and point piles

For this category, most of the bearing capacity of piles is obtained from the transfer of load to the adherence that develops between the lateral surface of the pile and the fill material used or the various soil layers drilled. In this case, a very small portion of the pile's bearing capacity is provided by the point bearing. To tap into adherence strength sufficient to support the structure and resist uplift caused by freezing, piles generally must penetrate the soil down to a depth of seven to ten metres (Torgersen, 1976).

Frost heave forces can be mitigated by ensuring that the pile section passing through the active layer is equipped with a sheath or covered with a smooth coating to reduce soil adhesion. Sufficient thickness of insulation or fill consisting of non-frost-susceptible material can be used to limit the amplitude of freeze-thaw cycles in the underlying frost layer and thus reduce seasonal movements. It is also possible to increase adherence between the soil and the pile by increasing surface roughness of the pile to be anchored in the permafrost (CAN/CSA-PLUS-4011-10 standard). There are many options to increase this adherence, including addition of steel collars along the pile and drilling holes for slurry migration inside the pile (Figure 5.77 A). The SHQ's new housing concept built in the community of Quaqtaq rests on piles to which steel collars have been welded and in which holes have been drilled to increase bearing capacity (Figure 5.77 A).

A foundation design using adherence and point piles must be very carefully assessed to allow for the many factors that can adversely affect performance, such as heat transfer to the soil by thermal bridging, water infiltration along piles, climate warming and the presence of saline permafrost. An exhaustive soil assessment study that specifically includes collection and analysis of samples and assessment of the thermal regime throughout the service life of the structure should be conducted.

To use this type of pile, the temperature of the permafrost ideally should be below -3°C , especially where the soil is saline. Permafrost salinity absolutely must be assessed in the site study because its presence complicates the design (CAN/CSA-PLUS-4011-10 standard). In Nunavik, several communities must deal with saline permafrost, because a large part of the coastal territory was previously submerged under the Tyrell Sea (Hudson Bay shore) or Iberville Sea (Ungava Bay shore).

5.5.3.2 Point-bearing pile

In this category, the structural load essentially is transferred by the pile point to a solid soil layer, which in many cases substantially increases the foundation's bearing capacity even if the surface soil is inadequate. This category of pile is considered only when it can reach rock or dense, non-frost-susceptible granular material (Johnston, 1981). Under the CAN/CSA-PLUS-4011-10 standard, the option of anchoring piles in rock is possible at depths of less than 10 m. However, in special situations and for economic reasons (e.g. building with a very live load and overload), it may be preferable to opt for piles bearing on rock rather than relying on adherence, even at a depth of more than 10 m. When the pile reaches the rock, it is common to embed it to a depth of about two metres to ensure that this rock is not simply a large block and that the pile end is resting on quality rock with little alteration. Low-temperature cement is then poured between the bore hole walls and the pile is securely sealed in the hole (Figure 5.77 B).

5.5.3.3 Installation method and considerations

There are several methods for installing piles. The best method depends on several factors, such as soil type and temperature, and availability of equipment on site. The most common methods include piles embedded in a pilot hole excavated with steam, hot water or an auger or rotary drill (water or air), and piles driven or vibrated directly into the soil. A combination of these methods is also possible. In areas where the permafrost is warm, the thermal destabilization that occurs when piles are embedded in a pilot hole excavated with steam or water considerably delays the return to initial thermal conditions. The same is true when piles are placed in a larger pilot hole that is then filled with slurry. In these circumstances, it may be necessary to use an artificial refrigeration system to promote refreezing and thermal stabilization of the bore hole and surrounding permafrost (thermopiles or thermosensors). In these zones, installing piles in the spring takes advantage of cold soil temperatures to accelerate refreezing around the pile and those avoid having to artificially refreeze the soil. Use of steam or water to drill the pilot hole is losing favour because it introduces large amounts of heat into the soil, which considerably delays refreezing of the piles and ultimately, the construction schedule. However, this may be an acceptable solution in places where the equipment needed to drill a pilot hole or drive piles directly is unavailable.

Most piles are now driven or vibrated directly into the soil, or placed in a pilot hole filled with slurry. These methods reduce thermal disturbance, allowing the soil to refreeze within days or hours of installation (Johnston, 1981). When piles are placed in a larger pilot hole, a mix of gravelly sand, sand, silt sand or silt with a water content between 6 and 15 percent is normally used as fill material. Cement can also be used. The mix temperature must be near the freezing point to promote rapid refreezing and should never exceed 4°C. During filling, special attention must be paid to avoid creating air bubbles between the pile surface and the walls of the bore. A ring-shaped space of at least 50 mm, but not exceeding 100 mm, between these surfaces facilitates filling operations and allows alignment of the pile when the hole is not perfectly plumb (Johnston, 1981). When the pilot hole is drilled deeper than planned, it may be filled with sand or fine gravel compacted to the desired level.

In fine-grained, plastic soils above -3°C, piles may be driven or vibrated directly into the soil. This operation considerably reduces thermal disturbance and refreezing occurs within minutes or hours of installation. The slurry must also be prepared. It is preferable to conduct this type of installation in summer when warmer soil temperatures promote better penetration. Once piles have been installed in pilot holes during the summer, special attention must be paid to avoid water infiltration into the hole and collapse of walls in the active layer. To accomplish this, surface tubing anchored in the permafrost may have to be installed. Gravel fill may also have to be laid to facilitate movement of the machinery and protect the natural soil surface.

It is vital to ensure that the soil around piles has fully refrozen and thermally stabilized before applying a load. Monitoring of soil temperatures is recommended at various depths along a few test piles. The instrumentation needed for this operation can also track long-term performance. Multiple factors determine soil refreezing time around a pile following installation: the soil's thermal regime; the pile installation method; the installation season (fall, winter, spring and summer); pile spacing; pilot hole diameter; and the temperature and thermal properties of the slurry (Figure 5.78). When piles are installed at the end of winter, refreezing of the permafrost around them occurs much faster than in late summer.

Uplift constraints that develop in the active layer during refreezing are transferred to adfreeze piles through adherence with the frozen soil. These constraints can be appreciable. Penner and Goodrich (1983) have calculated that they can reach up to 500 kPa on steel piles. The weight of a two-storey residential building is clearly not enough to resist the uplift forces exerted by an adfreeze pile in the soil. To counteract the uplift forces at work and achieve sufficient resistance, piles must be embedded and anchored in rock where possible. To limit soil action on the pile and thus reduce the risk of frost heave during refreezing of the active layer, it is recommended to supply a pile with a smoother finish or an anti-heave sheath in the section traversing the active layer. Addition of non-frost-susceptible fill can also help reduce potential displacements. Finally, to reduce heat transfer from adfreeze piles to the soil, it may be desirable to apply white paint to the section of piles on a building perimeter exposed to the sun.

In many communities in the Canadian Arctic, pile foundations are preferred although costlier than a surface foundation on an invert, due to the low maintenance required and the long-term performance (AGRA Earth & Environmental Limited, 2000). Despite the many benefits of this type of foundation, some design and placement difficulties remain. For example, the risks linked to poor design (incorrect assessment of depths, substrate bearing capacity, adherence strength, etc.) can result in damage to the structure. In addition, installation of this foundation type requires specialized labour and machinery not available in all Nunavik villages. If these must be brought in, this can considerably increase the project cost and delay the construction schedule. When the equipment and machinery are available, the cost per pile is about \$500 in Nunavut (Canadrill) and between \$700 and \$1,000 in the West (Tundra Drilling Services Ltd.). No drilling company is currently based in Nunavik. However, Makivik has a few pneumatic drills that move from village to village as needed. When present and available, this machinery can be rented with or without operators as was the case for construction of the Centre for Northern Studies research station at Salluit in 2010, which rests on a deep foundation consisting of six piles anchored in rock.

Deep foundations, such as steel piles anchored in rock, have been successfully used in Nunavik and Nunavut. These foundations are considered stable and require very little maintenance, and generally less granular material than building an invert. They can also raise heated buildings above the ground surface, thereby promoting scouring of snow by the wind and a better thermal break between the building and the underlying soil. This foundation type adjusts very well to uneven topography. For light residential buildings, tubular steel piles are the most common. These can be embedded in rock or embedded and anchored in basement rock to counteract uplift forces. When well designed, this foundation provides excellent bearing capacity and good long-term performance. Although piles for which bearing capacity is provided by adherence and point bearing have been described in this section, use of piles embedded or anchored in rock are preferable due to their resistance to tear out and their long-term stability, despite thermal changes to permafrost attributable to climate change. In fact, the CAN/CSA-PLUS-4011-10 standard states that piles anchored in rock are not affected by the soil's thermal regime and remain insensitive to thermal and mechanical changes triggered in permafrost by climate change.

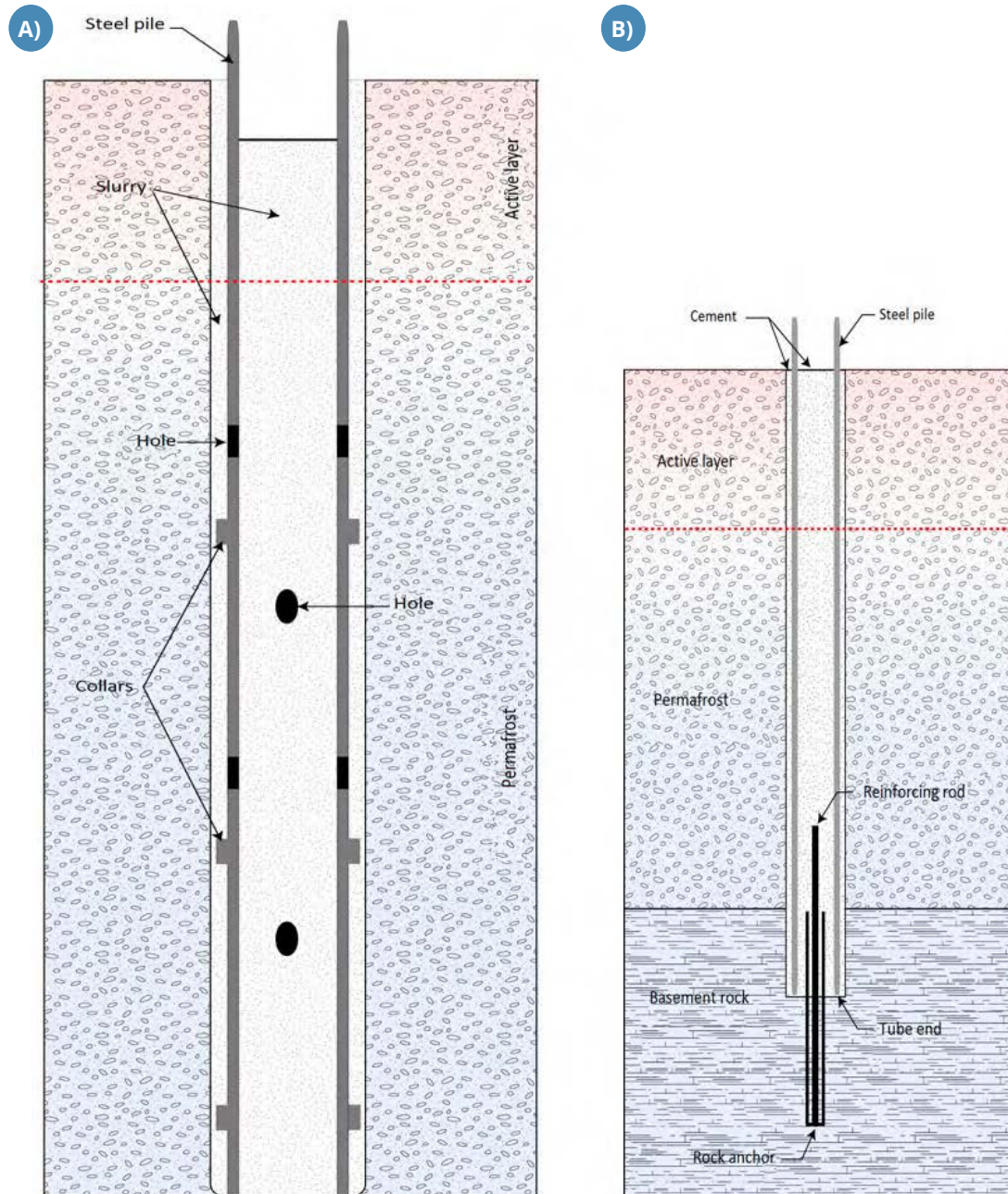


FIGURE 5.74: A) DRAWING OF AN ADFREEZE AND POINT-BEARING PILE. B) DRAWING OF A POINT-BEARING PILE ANCHORED IN ROCK.

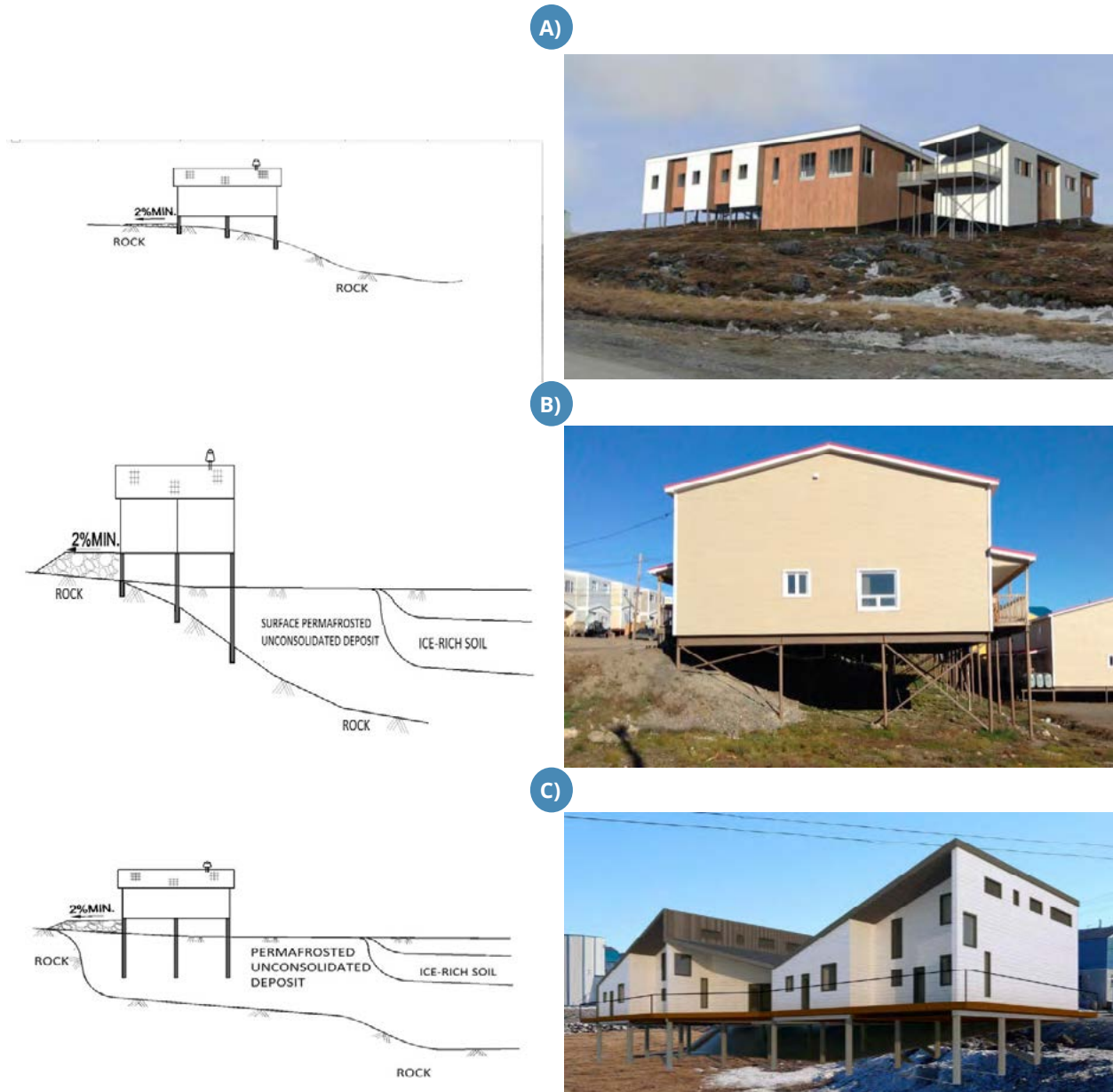


FIGURE 5.75: A) PILES EMBEDDED IN ROCK, WITH ROCK AT THE SURFACE. B) PILES EMBEDDED IN ROCK COVERED BY A THIN LAYER OF PERMAFROSTED UNCONSOLIDATED DEPOSIT. C) ADFREEZE AND POINT-BEARING PILES EMBEDDED IN DEEP PERMAFROSTED UNCONSOLIDATED DEPOSIT (SOURCE: M. BLOUIN, MB-A).



FIGURE 5.76 : A) ET B) TÊTES DE PIEUX AJUSTABLES (MENTION DE SOURCE : E. L'HÉRAULT, CEN, 2015). C) CONTREVENTEMENTS (SOURCE : N. JOURNEUX).



FIGURE 5.77: A) PILES TO WHICH STEEL COLLARS HAVE BEEN WELDED AND IN WHICH HOLES HAVE BEEN DRILLED TO INCREASE BEARING CAPACITY (SOURCE: G. ROBICHAUD, 2015). POINT-BEARING PILES USED FOR AN SHQ PROTOTYPE HOUSE FOUNDATION AT QUAQTAQ DURING B) SLURRY PLACEMENT AND C) ONCE CUT LEVEL WITH THE RIBBON JOIST ATTACHED (SOURCE: E. L'HÉRAULT, CEN, 2015).

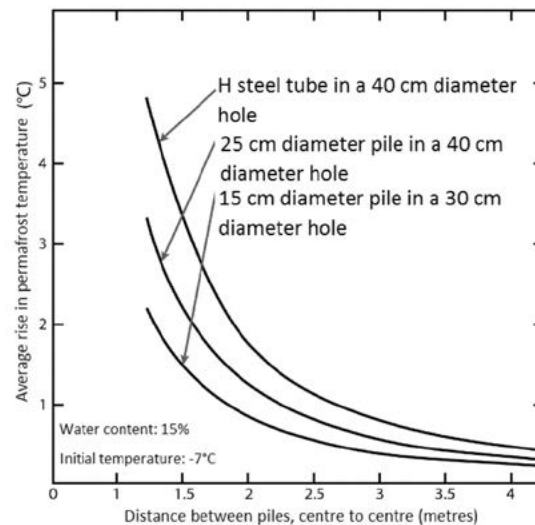


FIGURE 5.78: EFFECT OF HOLE DIAMETER AND PILE SPACING ON PERMAFROST TEMPERATURE (FROM « PERMAFROST: ENGINEERING DESIGN AND CONSTRUCTION » 1981 P.483 OF ASSOCIATE COMMITTEE ON GEOTECHNICAL RESEARCH OF NATIONAL RESEARCH COUNCIL OF CANADA, ISBN 0-471-79918-1).

5.5.4 Foundations with a heat-extraction system

5.5.4.1 Ventilated foundations

One of the most commonly used, effective and economical methods to prevent permafrost degradation under a heated building is a ventilated foundation (U.S. ARMY/AIR FORCE, 1983). This foundation type allows cold air to move freely or through a duct between the soil and the floor of a building in winter to extract heat and maintain cold conditions. In the design of many foundation types, both surface and deep, special attention is paid to maintaining sufficient air space between the soil and the building. When a large load will be applied to the building floor, as in the case of a garage, warehouse, hangar, electrical power plant or any other industrial building, a slab-on-grade foundation is often preferred because it distributes the load over the entire structure. Thus, unlike a foundation that uses individual footings, the risk of localized overload that might cause differential compaction is lessened. However, since this foundation type rests directly on the surface of granular fill, it does not allow heat extraction by air circulation and thus warms the thermal regime under the building and can even thaw the permafrost. This thermal disturbance of the permafrost will be even greater if the building is heated. It therefore is imperative to insulate and ventilate this type of foundation to limit heat loss from the building and subsequent thermal deterioration of the underlying permafrost.

A slab on grade provides several options for adequate ventilation under the building. However, these options are more expensive than simply raising the structure above the ground with piles or piles on a footing. In one of these options, horizontal ducts must be installed at regular intervals under the area covered by the slab, over the fill (Figure 5.79 A) or inside it (Figure 5.79 B). In this way, cold air entering and circulating through the duct gradually warms up as it absorbs part of the soil heat before it is vented at the other end. Even when wind conditions do not allow forced passage of air through ducts, air circulation occurs naturally due to the presence of a thermal gradient along the system that promotes convection. Air entering the duct must be cold enough for complete refreezing of the fill during the winter to preserve the underlying permafrost. The addition of chimneys can increase air circulation in the system through the phenomenon of thermal draft, but duct intakes and outlets must be located above the maximum snow cover level (Figure 5.79 C). Some systems use a fan to force air circulation into the conduits, but this addition increases the risks of breakdown likely to considerably reduce or even eliminate system performance. This type of system also must be closed in spring to avoid any addition of external heat during the summer season. Despite automation of the system opening and closing procedure, the risk of oversight remains high.

Ducts placed under the surface are more exposed to water and soil infiltration, which can seriously compromise system performance. Several experiments have shown that duct placement just below the soil surface and sloped to the surrounding terrain are preferable, to avoid water accumulation and promote drainage in the event of infiltration by snow, ice or water (U.S. ARMY/AIR FORCE, 1983).

Due to the many technical difficulties that can occur during construction and the high risks of malfunction (water, snow or soil infiltration, obstructed pipe), the Nunavut Good Building Practices Guideline (2005) does not recommend using naturally ventilated concrete slabs. When opting for a mechanical ventilation system, it must be recognized that this poses the same risks, plus a risk of mechanical breakdown and maintenance costs. The literature contains several examples of breaks in this type of foundation due to water infiltration (Bjella, 2010), but some foundations have demonstrated their effectiveness despite a few technical difficulties (Odom, 1983, cited in Clark [2007]). In discontinuous permafrost zones, this system can be insufficient to ensure complete refreezing of fill under a building.

If such a system is used, special attention must be paid to the following points during design.

- Ducts must have a large enough diameter to allow inspection and facilitate any necessary maintenance (unblocking) by maintenance staff.
- Fill must consist of non-frost-susceptible materials of sufficient thickness to ensure that freeze-thaw cycles remain within the fill.
- Ducts must be watertight to avoid any water infiltration.
- Chimney ends must be high enough to avoid being buried in snow drifts that often develop around buildings.
- If a check-valve system is installed, valves must be placed only in chimneys located on the upwind side of the building to allow convection flows even when check valves are closed.

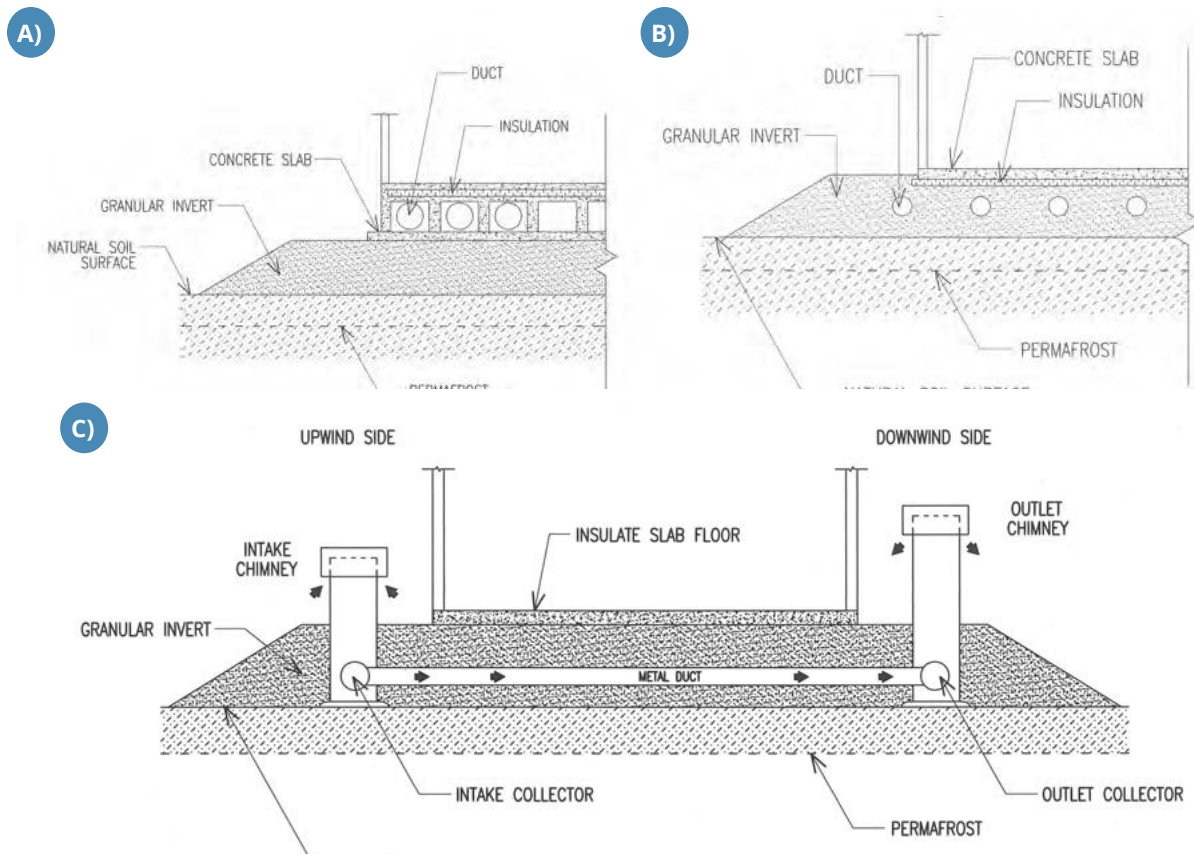


FIGURE 5.79: FOUNDATION VENTILATED USING HORIZONTAL DUCTS PLACED UNDER THE AREA COVERED BY THE SLAB A) ON GRADE OR B) EMBEDDED IN FILL. C) VENTILATED FOUNDATION WITH ADDITION OF CHIMNEYS WILL INCREASE AIR CIRCULATION IN THE SYSTEM THROUGH THE PHENOMENON OF THERMAL DRAFT (MODIFIED FROM JOHNSTON, 1981).

5.5.4.2 Thermosyphons

A thermosyphon is not a type of foundation, strictly speaking, but rather an addition to a foundation type that cannot be raised above ground for effective heat evacuation (e.g. slab on grade) or to thermally stabilize the soil to meet special technical specifications (thermopiles and thermosensors). The purpose of this cooling system is to ensure stability of freezing conditions under a building by keeping the soil temperature below 0°C. Thermosyphons are two-phase so-called passive cooling systems that do not require additional energy and do not contain any mechanically activated components. A thermosyphon consists of a closed, sealed tube capable of extracting heat from the soil and evacuating it to the atmosphere through the phase change from a liquid to gaseous state. In Canada, the two-phase liquid used is carbon dioxide.

The components of a thermosyphon are shown in figure 5.80 A. It essentially is a duct placed into the soil surface, called an evaporator, a vertical duct placed above the solid surface, called a conductor, a radiator installed at the upper end of the conductor, a filling valve and the liquid. The principle of heat exchange in a thermosyphon is shown in Figure 5.80 A. When the air is colder than the ground, vapour condenses in the upper part called the radiator. This reduces pressure in the tube and forces the liquid in the lower portion (evaporator, under the foundation) to boil and evaporate. The evaporation and condensation cycles extract heat from the soil when air temperature is below the freezing point. The system does not work in summer due to the lack of a temperature differential required for it to function. The temperature of frozen soil under the building therefore tends to rise gradually. To avoid complete thawing of the soil, the winter action of thermosyphons must offset the summer thermal gain. When climatic conditions do not provide a long enough operating period or the temperature differentials do not support efficient operation of the system, a hybrid system is recommended. This is equipped with a heat exchanger inside the radiator for connection to a cooling system. Use of a cooling system extends

the operating period of the system by ensuring the temperature differential needed for convection and thus extraction of heat from under the foundation. By artificially maintaining a cold temperature at the outlet, this type of system can increase the cooling rate even in summer. It can also achieve a state of thermal balance desired before building infrastructure when construction deadlines are short, or it can offset rising soil temperatures that are greater or faster than expected.

A thermosyphon works both horizontally, under a slab on grade, or vertically, serving as piles. Vertical and inclined thermosyphons use gravity to allow gases to migrate to the radiator and condense, before draining in liquid form to the lower end of the evaporator. Thermosyphons with horizontal loops instead use pressure differentials and slug flow of gas and liquid to bring gas to the radiator. Depending on the applications, thermosyphons can be configured in various ways. There are four main configurations: thermosensors (Figure 5.80 B), thermopiles (Figure 5.80 C), inclined thermosyphons (Figure 5.80 D) and thermosyphons in horizontal loops (Figure 5.80 E). Thermosensors are used to maintain frozen soil around piles or other foundation types and, contrary to thermopiles, bear no structural load. Thermopiles consist of piles with thermosyphon technology built in. For this application, the radiators are at the surface end of the pile in the ventilated space under the building. Their use can be effective when an active layer composed of frost-susceptible soils subject to swelling can cause uplift of conventional piles through adherence. Their use can also be beneficial in warm permafrost areas, where the potential for pile creep is high. Available information reports no thermal piles in Nunavik, and Holubec (2008) reports none in Canada, but thermal piles are widely used in Alaska. For example, from the early 1960s to 1975, 120,000 thermal piles cooled by thermosyphons were installed there to support the 1,300-km gas pipeline from Prudhoe Bay to Valdez.

Inclined and horizontal-loop thermosyphons essentially are used under concrete slabs or crawl spaces to evacuate heat transferred to the soil by the building. When thermosyphons are used under a slab or crawl space, the following components are added to the foundation system: compacted granular fill one to two metres thick, a bed and envelope of sand to protect the horizontal or inclined ducts and a layer of rigid insulation 100 to 200 mm thick. Note that the size and configuration of the various thermosyphon system components are interdependent. For example, an increase in capacity of the evaporator or radiator can reduce the thickness of insulation required under the foundation slab. An increase in insulation thickness under the foundation will reduce the required thickness of granular non-frost-susceptible fill. The main differences between the two configurations are pipe diameter (100 mm for inclined thermosyphons and 50 mm for horizontal-loop thermosyphons), angle of installation (flat or inclined) and pipe configuration (individual or loop). One drawback of inclined thermosyphons is that the evaporator must be installed with a slope between three and ten percent (Wagner, 2014), which requires special attention during placement and increases the installation costs. For larger buildings, the angle of installation necessary for proper operation of this system may require thicker fill, which increases the installation cost. Horizontal-loop thermosyphons are easier to install and can freeze 1.4 times more soil volume than inclined thermosyphons (Yarmak and Long, 2002). In the past twenty years, horizontal-loop thermosyphons have been used mostly in Canada (CAN/CSA-S500-14 standard); a typical installation under a slab on grade is shown in figure 5.81 Use of thermosyphons has been widespread in the Canadian Arctic and Alaska since the 1960s, in both continuous and discontinuous permafrost zones. Since 1985, more than a hundred thermosyphon systems have been installed in northern Canada (including ten or so in Nunavik) for industrial, commercial and institutional applications. Their use is much less common in residential construction. This type of system was recently chosen for corrective purposes to refreeze soil under concrete footings that have performed poorly (N. Journeaux) or for new slab-on-grade structures such as the air terminal at Kuujuaq airport (2006) (Figure 5.82) and the new Salluit municipal garage (2009) (Figure 5.83 A). Thermal soil monitoring under the foundation slab of the new Salluit municipal garage clearly demonstrates the effectiveness of the system installed (Figure 5.83 B and C).

Quite recently, the reliability of this technology and its performance in the context of climate change have been assessed by Holubec (2008). Despite the system's proven reliability, certain shortcomings in site selection, design, assessment of anticipated climate warming, construction, performance monitoring and maintenance can seriously compromise its performance and trigger compaction capable of significant damage to a building. Several examples of failure of this foundation type are occasionally documented in the literature. To guide the design, installation and maintenance of such systems more effectively, a standardization initiative has led to the CAN/CSA-S500-14 standard, *Thermosyphon foundations for buildings in permafrost regions*. Reference should be made to this standard when considering a foundation equipped with this type of system.

Thermosyphons are designed to preserve rather than create permafrost and thus should not be used in areas with a large amount of surface water or the presence of heavy underground runoff, which are significant heat sources. Installation of thermosyphons should only be considered if the permafrost on which the foundation will rest is unstable when thawed. A site where the permafrost is stable when thawed, such as a rocky substrate or ice-poor coarse deposit, does not need this protection method. Thermosyphons should not be used for unheated structures, unless they rest on warm permafrost and no other option for limiting thermal disturbance of the permafrost triggered by construction and the presence of the new infrastructure is practical. The liquid coolant must not pose a potential risk for stability of the permafrost or for the environment in the event of a leak. It is recommended that loops be isolated to limit spills and keep remaining thermosyphons operational. It is also recommended that radiators be protected from any damage that might be caused by vehicle movements and snow clearing operations. It is vital to keep radiators distant from any heat source from the building, such as ventilation outlets. It is also recommended that thermosyphons be equipped with temperature sensors to monitor system performance and quickly detect any breakdown that might compromise foundation stability. The CAN/CSA-S500-14 standard suggests preparing the site—that is, installing the fill, evaporators and insulation—in late spring or early summer to preserve cold temperatures in the soil. Because it requires that construction material already be on site, this strategy requires careful planning if materials must be brought in by sea. Once site preparation is completed at the end of the summer, construction should not start until the soil has completely refrozen, during the winter.

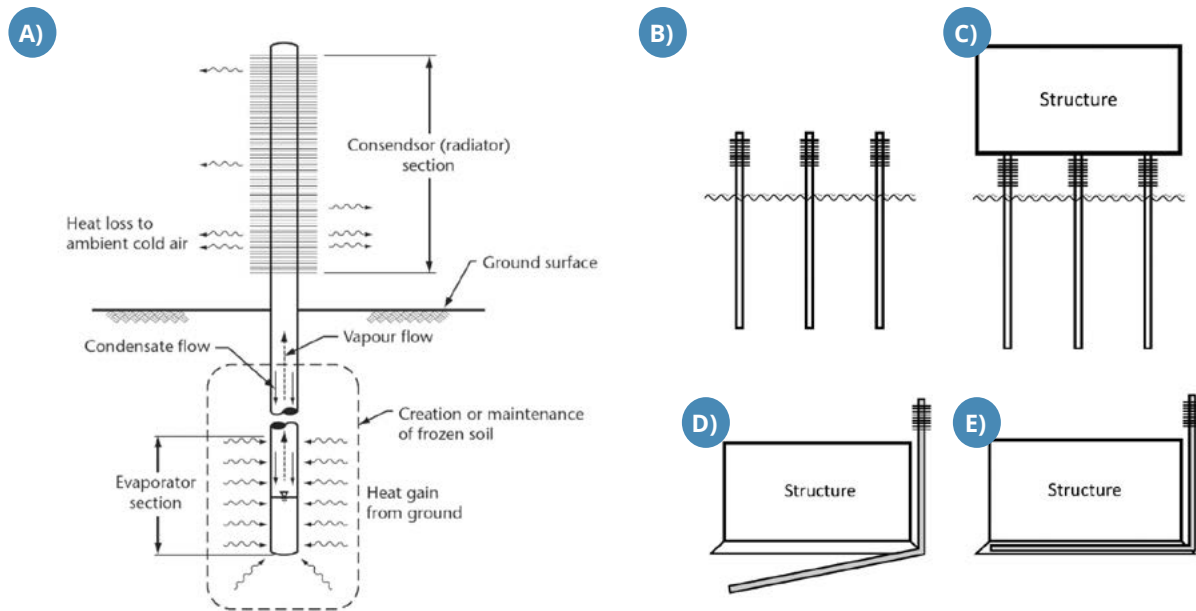


FIGURE 5.80: A) COMPONENTS AND HEAT EXCHANGE PRINCIPLE FOR A THERMOSYPHON (MODIFIED FROM CSA PLUS 4011-10 AND REPRINTED WITH PERMISSION OF DON HAYLEY). VARIOUS THERMOSYPHON CONFIGURATIONS AND THEIR NAMES: B) THERMOSENSORS, C) THERMOPILES, D) INCLINED THERMOSYPHONS AND E) HORIZONTAL-LOOP THERMOSYPHONS (FROM CAN/CSA-S500-14 STANDARD « THERMOSYPHON FOUNDATIONS FOR BUILDINGS IN PERMAFROST REGIONS » 2014 P. 44, PRODUCT CODE: 2423122).

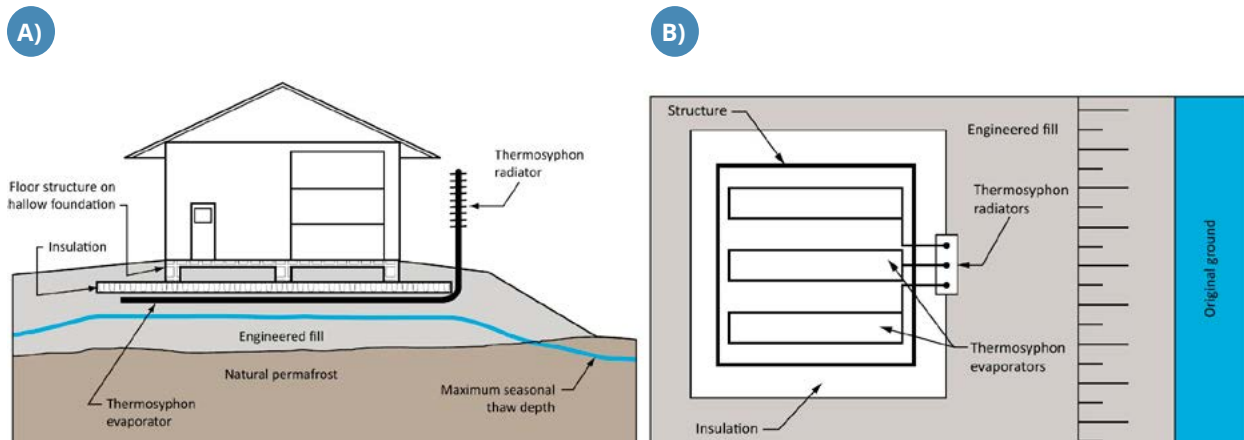


FIGURE 5.81: CROSS-SECTION (A) AND PLAN (B) OF A SLAB-ON-GRADE FOUNDATION EQUIPPED WITH A HORIZONTAL-LOOP THERMOSYPHON SYSTEM (FROM CAN/CSA-S500-14 « THERMOSYPHON FOUNDATIONS FOR BUILDINGS IN PERMAFROST REGIONS » 2014 NBR P. 44, PRODUCT CODE: 2423122).



FIGURE 5.82: THERMOSYPHONS FOR THE AIR TERMINAL AT KUUJUAQ AIRPORT IN NUNAVIK (SOURCE: CLAUDE LEPAGE).

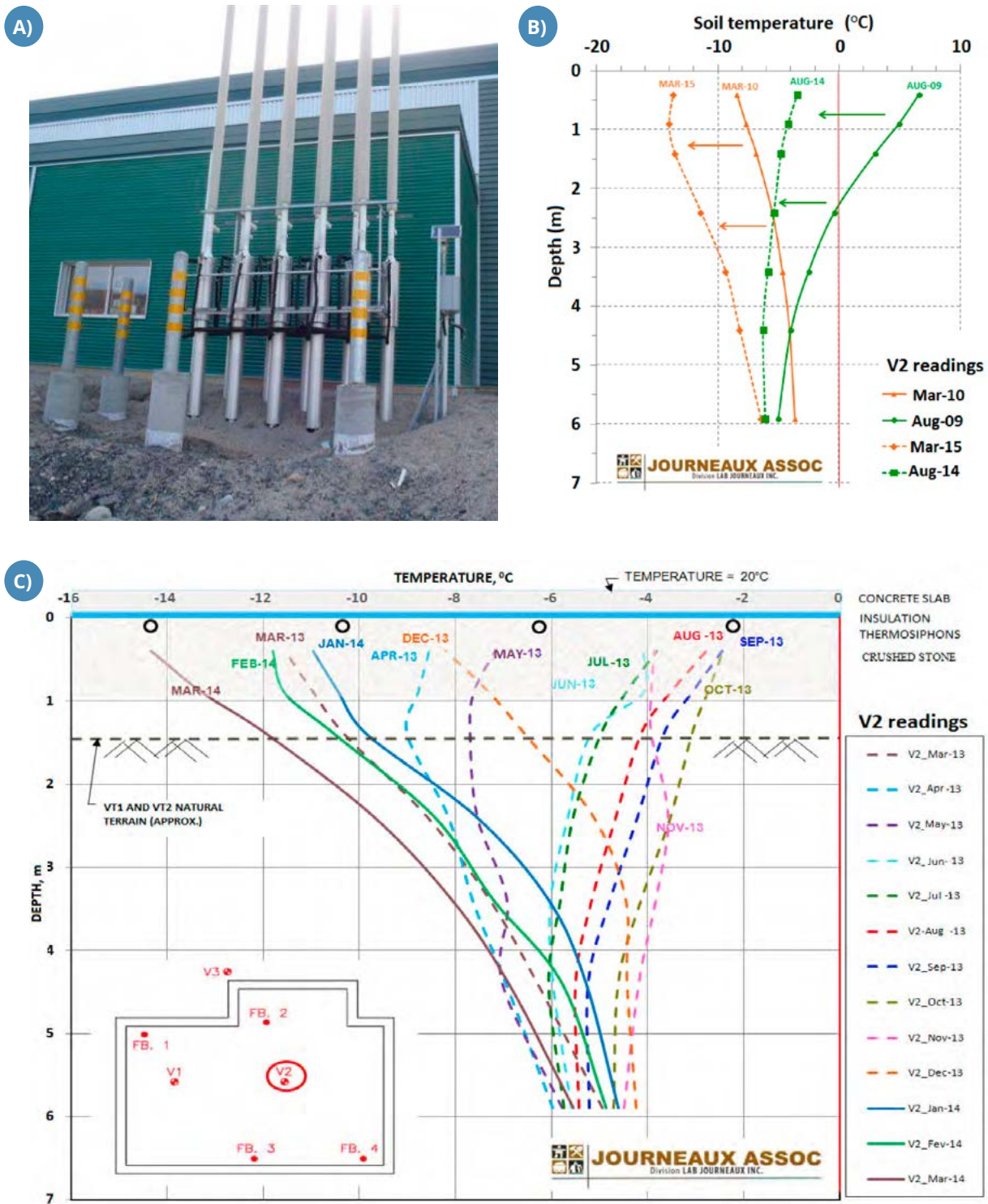


FIGURE 5.83: A) NEW SALLUIT MUNICIPAL GARAGE WITH SLAB ON GRADE AND HORIZONTAL-LOOP SYSTEM. THERMAL PROFILES MEASURED UNDER THE FOUNDATION AT THE LOCATION OF THE V2 THERMISTOR CABLE B) BETWEEN 2009 AND 2015 AND C) BETWEEN MARCH 2013 AND MARCH 2014, SHOWING THE COOLING OF THE SOIL SINCE INSTALLATION (SOURCE AND FIGURES: N. JOURNEAUX).

5.6 GROUND PREPARATION AND CONSTRUCTION MANAGEMENT

5.6.1 Seasonal planning of construction

Due to the geographic, climatic and geological specifics of Nunavik, seasonal planning of construction work must be studied in minute detail to capitalize on meteorological and geotechnical conditions suited to execution of the project. Good planning must maintain a balance among budget and time constraints, logistical constraints for shipping materials and accessing the site, and technical and performance constraints linked to the environment, which vary based on the work to be performed (excavation, filling, etc.) and elements of the building design (foundation type) (Figure 5.84). Maintaining a balance among the various constraints will dictate seasonal distribution of the type and quantity of work to be performed.

Nunavik's climate, characterized by a short summer and long, cold winter, poses a major challenge in seasonal planning of construction. Cold temperatures and short days in winter can severely affect, if not prevent, the execution of certain construction activities (reduced worker performance due to cold, technical difficulties, etc.). In turn, the presence of permafrost and its thermal fragility make winter construction beneficial in some regards. For example, when a watercourse or sensitive terrain must be crossed, construction of an ice road can facilitate access to the site while preserving the natural terrain. Placement of fill for use as an access road to the site or work surface can be avoided, thereby achieving considerable savings. During excavations, the risks of excessive thaw, slope destabilization and loss of permafrost bearing capacity, especially in fine, ice-rich soils, can make the installation of embedded footings difficult, if not impossible. In such cases, it may be preferable to excavate in early fall, when air temperatures are cold and thawing has reached maximum depth. As winter advances, cooling of soil temperature increases resistance, complicating excavation operations. Excavating frozen soil at cold temperatures can be compared to excavating concrete with low to moderate resistance.

The type of foundation selected can also influence seasonal planning, to avoid technical problems during placement or to improve foundation system performance. For example, piles are best installed in winter or spring to take advantage of optimal thermal stabilization of the soil around piles and avoid use of a costly cooling system, as much as possible. Moreover, to avoid certain complications, construction of concrete foundations poured in place in winter months requires additional material and human resources, which increases costs and execution time. An adapted design might then result in use of prefabricated concrete components (e.g. piles on individual footings). Where a foundation system requires fill, it is better to install this before the winter prior to construction of the building. This approach allows the thermal regime to attain its new state of balance, while leaving time for the active layer and fill to stabilize mechanically. Due to potential difficulties extracting granulates from borrow pits or meeting compaction requirements to ensure fill stability, fill construction in winter is not advised.

Planning residential construction work over a period of two years usually provides definite advantages in the quality and stability of foundations. This timeline avoids problems associated with the logistical and technical constraints specific to Nunavik's geographic, climatic and geological constraints. The progress and efficiency of work during these periods will also depend on how site conditions have been factored into the designer's work. Poor planning or poorly adapted design can significantly increase project execution costs and delay work.

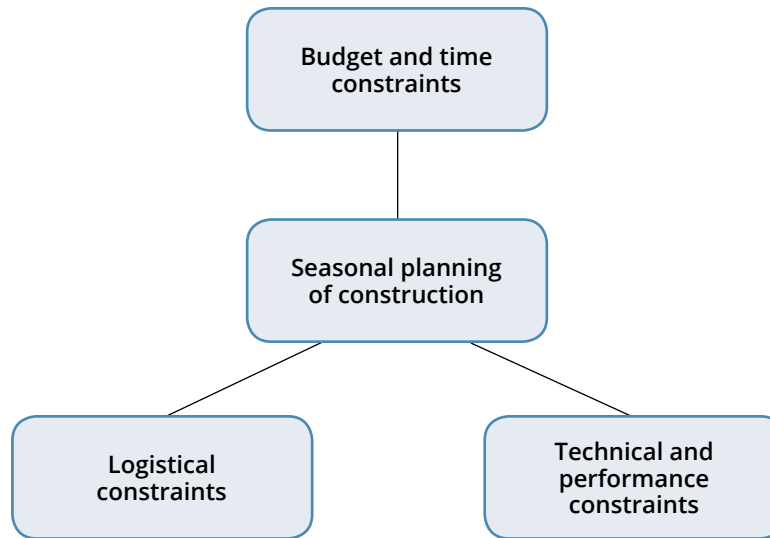


FIGURE 5.84: CONSTRAINTS TO BE CONSIDERED IN SEASONAL PLANNING OF CONSTRUCTION IN NUNAVIK.

5.6.2 Protecting the natural terrain

Residential construction often takes place in areas with organic soils on the land surface. This type of surface is susceptible to damage by moving equipment (Figure 5.85 A). Even shallow scars can channel natural runoff, thus accentuating the risk of water accumulation likely to result in permafrost degradation. Where possible, equipment should be used in late fall or in winter, when the ground is frozen. This precaution facilitates movement of machinery and reduces damage to the land surface. The granular invert construction method presented in section 5.5.1 also reduces degradation of the natural terrain. Placement of geotextile as a physical barrier between the natural terrain and materials also limits potential interaction between these two components to preserve their integrity (Figure 5.85 B). If an invert is placed in winter, snow cover must first be removed, exercising great caution in snow removal near the interface with the natural terrain. It is better to leave a thin layer of snow rather than risk destroying the vegetation and organic surface layer. A granular layer placed in winter, however, must not be too thick and materials must not be added until the trapped thin layer of snow has melted, to ensure good long-term performance of the fill.



FIGURE 5.85: A) DISTURBANCE OF LAND DURING INSTALLATION OF A PILE FOUNDATION AT PANGNIRTUNG, NUNAVUT (SOURCE: E. L'HÉRAULT, CEN, 2010). B) PLACEMENT OF GEOTEXTILE OVER NATURAL SOIL TO AVOID MIGRATION AND MIXING OF MATERIALS IN SITU WITH THOSE MAKING UP THE GRANULAR FILL, AT SALLUIT, NUNAVIK.

5.6.3 Layout of buildings and streets

In an urban development project in Nunavik, factoring in prevailing winter wind direction ensures optimal orientation of streets and buildings to reduce snow cover and promote permafrost preservation while reducing snow removal costs.

In a northern environment, distribution of snow cover is intimately linked to topography and plant structures. These local components influence wind dynamics, such as speed and direction, promoting or obstructing sedimentation and accumulation of snow scoured from the ground and carried by the wind. With strong winds in Nunavik, snow tends to accumulate in places where transportation energy is reduced, such as in shallow cracks in the basement rock, depressions and minor irregularities in the relief. In a built environment, the aerodynamics of infrastructure are added to topography as a factor controlling snow cover. Thus, regardless of the orientation of infrastructure, snow accumulation is to be expected in winter on the side of homes sheltered from prevailing winds (Figure 5.86). These snow accumulations take the form of comet-tail drifts with size more dependent on the aerodynamic characteristics of the site (interaction of building geometry with prevailing wind direction and speed in winter) than the total quantity of precipitation received. These accumulations can compromise the performance of foundations, because the insulating properties of snow limit extraction of heat accumulated in the soil in summer, a process essential to maintaining permafrost.

Foundations on trestles, which provide good clearance between the house and the ground, have demonstrated their effectiveness in reducing snow accumulation around and under the structure. Compared with foundations resting directly on the soil (concrete slab) (Figure 5.87 A and B), these raised foundations (trestles on an invert or piles) actually have a limiting effect on the components of wind dynamics such as speed and direction. This type of foundation therefore facilitates the movement of snow and reduces snow accumulation under and around the structure. The forced passage of wind through the confined space under the structure can even increase its speed (funnel effect) and capacity to carry snow. This accentuation of scouring under raised structures keeps the soil devoid of snow cover, thus keeping it cold and ensuring permafrost stability (Allard, Fortier et al., 2004; Bouchard, 2005). Foundation height is an important parameter to consider when assessing potential snow accumulation. Simulations on scale models in a wind tunnel, conducted by Sherwood (1967), have shown that a building raised two to four feet (500 to 1000 mm) above the natural grade considerably reduces snow drift formation. Winter field observations conducted in Nunavik and Nunavut communities confirm the effectiveness of raised foundations with ventilated space in reducing snow accumulation around buildings.

In addition to the influence of structure height on potential snow accumulation, it is also important to consider orientation in relation to prevailing winds. Where possible, the narrowest façade of buildings should face the prevailing winds. The snow accumulation area will then be reduced to the width of the structure (Figure 5.88 B). This principle also applies to parking and storage areas, which benefit from better wind scouring when their geometry presents a slim profile. It is also important to leave sufficient open space between buildings to avoid a build-up of drifts and allow for the passage of snow-clearing machinery if necessary. An example of the effect of building and street layout on the dynamics of snow cover is presented in figure 5.89.



FIGURE 5.86: GENERAL RELATIONSHIP BETWEEN INFRASTRUCTURE AND SNOW COVER IN BUILT ENVIRONMENTS (FROM BOUCHARD, 2005).

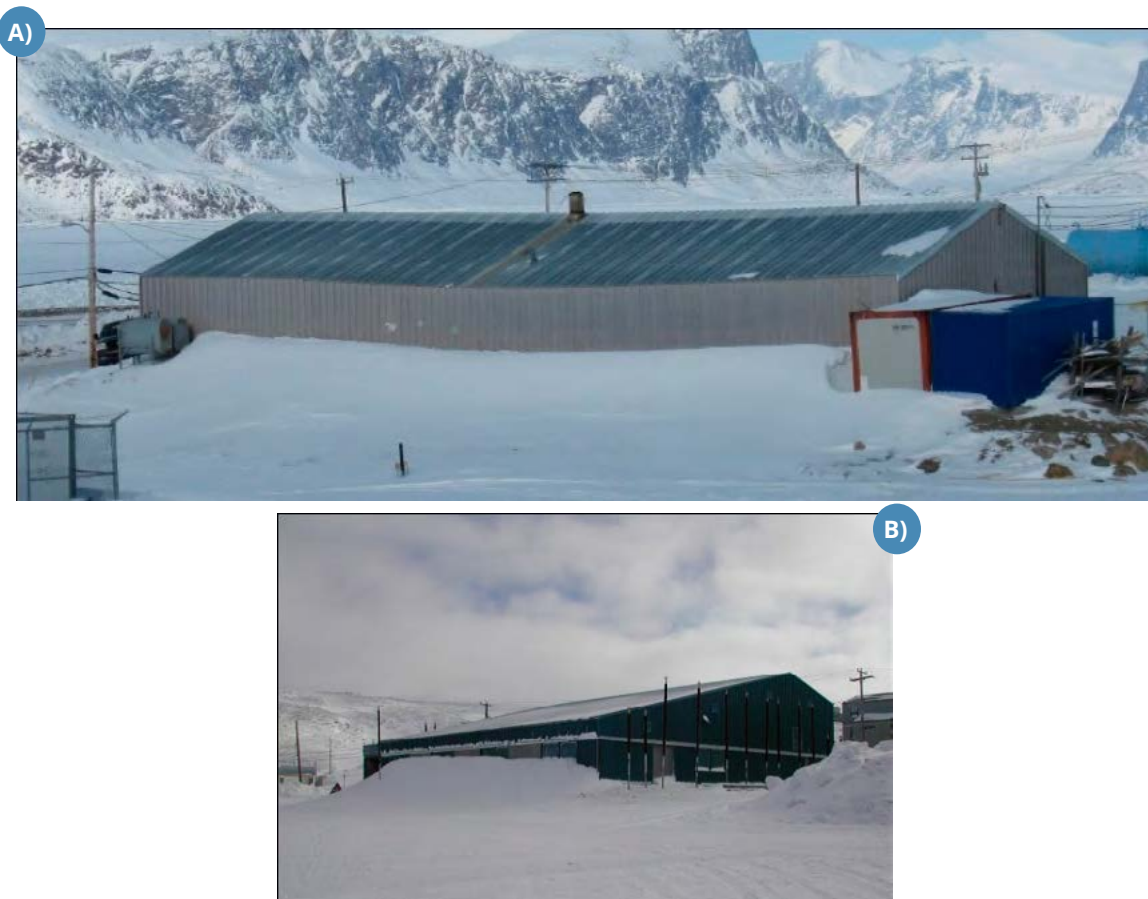


FIGURE 5.87: A) AND B) BUILDINGS WITH A FOUNDATION RESTING DIRECTLY ON THE GROUND, WHICH PROMOTES SNOW ACCUMULATION (SOURCE: E. L'HÉRAULT, CEN, 2010).



FIGURE 5.88: A) HOMES WITH THE LONG AXIS PERPENDICULAR TO THE PREVAILING WINDS. B) HOME WITH THE LONG AXIS PARALLEL TO THE PREVAILING WINDS (FROM ALLARD ET AL., 2010).

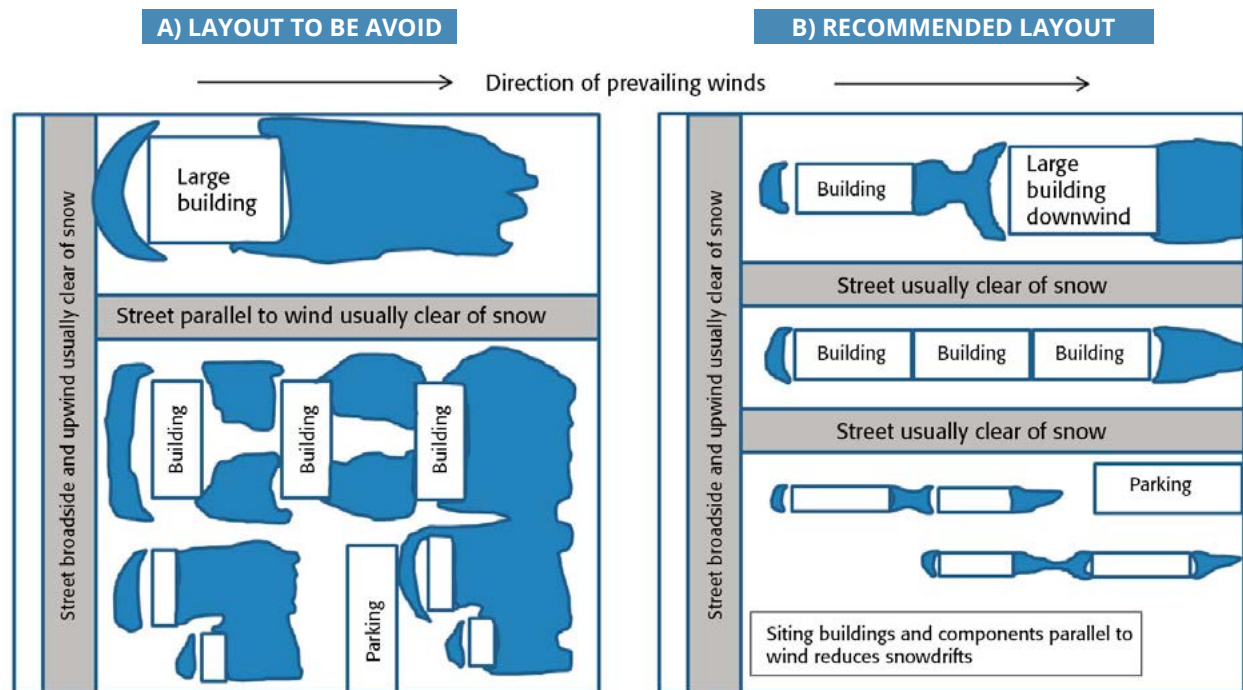


FIGURE 5.89: SNOW ACCUMULATION BASED ON PREVAILING WINDS AND BUILDING LAYOUT. A) LAYOUT TO BE AVOIDED AND B) RECOMMENDED LAYOUT (MODIFIED FROM RICE, 1996).

5.6.4 Site drainage

A well drained site facilitates site preparation operations (compacting, movement of workers and machinery) while ensuring good foundation performance in future. For this reason, the drainage plan for any new project should always be integrated into the community's plan. Once lots and buildings have been staked out as per the project plans, and before starting construction, qualified staff must visit the site to check the predominant geological, geotechnical and hydraulic components, validate the choices made during the site study and make any necessary changes to the drainage plan. When building on ice-rich permafrost, special attention must be paid to vehicle traffic, to avoid creating ruts that quickly channel surface runoff and would cause thermal destabilization of permafrost as well as rapid deterioration of the natural terrain (subsidence, creep, slide, etc.). This type of disturbance could complicate construction operations or even compromise stability of the infrastructure.

When preparing drainage plans, the natural surface water runoff axes must be considered. As a rule, the same runoff channels should be maintained because a balance has probably been achieved over the years, especially when runoff is constant. Altering runoff axes could cause rapid deterioration of ice-rich permafrost areas through thermal erosion. Talus must be profiled carefully in ditches based on the nature of the existing materials. For example, in fine sand, slopes of three horizontal units per vertical unit (3H:1V or 33 percent) may be required, whereas slopes of 1.5H:1V (67 percent) may be acceptable in a gravel deposit. Depending on water runoff speed and soil type, a ditch may have to be lined with rocks to prevent erosion. In areas where permafrost is ice rich, it is preferable not to excavate and opt instead for surface drainage using wide, shallow ditches. In these areas, placement of geomembrane in the bottom of a ditch or under a culvert can reduce surface water infiltration and limit thermal exchanges between the water and the permafrost.

As a rule, effect drainage carries water from its natural starting point to a collection point, open drain or ditch, ultimately taking it to a channel that leads the water to the discharge area. By ensuring that surface water runs off correctly, a good drainage system reduces surface accumulation and the water content of underlying soils. Special attention must be paid to drainage in the area directly around the building, where water gathers from a roof without gutters, from thawing of natural and manmade snow accumulations in spring, and spills occurring during filling of water tanks. For this reason, it is recommended that the land around buildings be graded at a slope of two to five percent to carry surface runoff water to the closest drainage ditch. Some experience has shown that without an adequate slope, saturation of granular fill with a high portion of silt or a mix of silt and clay can very quickly cause a loss of local bearing capacity, followed by rupture of the soil supporting the foundation. Where granular fill consists primarily of gravel and pebbles, saturation usually does not cause problems of lost bearing capacity. In the case of partially frost-susceptible fill, use of a geomembrane under the granular surface layer can serve as a water barrier to prevent infiltration into the underlying fill.

In Nunavik, shallow open drains often separate streets from houses. Vehicle traffic to access the building normally passes through these shallow, gently sloped drains without a problem. One example of optimal configuration of a drainage system carefully integrated into a residential development is shown in figure 5.90 A). At street intersections, prefabricated concrete gutters have been successfully used in recent years (Figure 5.90 B). These shallow drainage structures are easy to clean and maintain. The surface grate is simply lifted off so debris in the drain can be removed by hand. For maintenance and cleaning, and when thickness of the road fill allows, culverts at least 450 mm in diameter should be used instead of smaller culverts. In the case of culverts likely to be obstructed by ice, addition of a smaller-diameter culvert installed just above the main culvert can provide an overflow for heavy spring runoff to ensure adequate drainage. Ditches and culverts should be located in street or road rights of way and be properly maintained to avoid flooding and formation of pools of stagnant water as shown in figure 5.91.

To standardize the planning, design and maintenance of drainage systems in northern communities, a standard has recently been developed (CAN/CSA-S503-15), Community drainage system planning, design, and maintenance in northern communities. It includes a series of recommendations and requirements to ensure adequate drainage of surface water and preserve permafrost stability. These can be summarized as follows.

- Drainage ditches should not be excavated in ice-rich permafrost.
- The area under structures and within a perimeter of four metres around structures should be graded to facilitate rapid runoff of surface water away from the structure.
- During spring thaw, water should not accumulate under or immediately adjacent to a structure or foundation. Additional fill should be placed in some locations to facilitate better drainage.
- Downspouts on buildings and structures must be directed to splash blocks that empty onto natural soil at least four metres away from any structure. When there is no eavestrough, the grade in areas around the building should be sloped at least four percent away from the structure.
- New construction around existing structures or buildings that has a negative impact on the thermal regime of permafrost should be avoided.

This standard also addresses the challenges posed by climate change in the planning, design and maintenance processes for drainage systems. The anticipated general climatic instability, characterized by an increase in irregular events, some of which could be catastrophic, may result in more sudden, strong precipitation and greater accumulations of snow. These extreme climate events must be factored into the design of drainage around new buildings.



FIGURE 5.90: A) CROSS SECTION AND PLAN SHOWING THE BEST LAYOUT FOR A DRAINAGE SYSTEM CAREFULLY INTEGRATED INTO THE URBAN CONFIGURATION OF A COMMUNITY (FROM CAN/CSA-S503-15, « COMMUNITY DRAINAGE SYSTEM PLANNING, DESIGN, AND MAINTENANCE IN NORTHERN COMMUNITIES », 2015 P. 83, PRODUCT CODE: 2423574). B) SHALLOW CONCRETE GUTTER COVERED WITH A GRATE, SUCCESSFULLY USED AT STREET INTERSECTIONS IN NUNAVIK.



FIGURE 5.91: MAJOR WATER ACCUMULATION A) NEXT TO FILL AND B) IN A DRAINAGE DITCH (SOURCE: E. L'HÉRAULT, CEN, 2008).

5.6.5 Construction on organic soil

Accumulations of organic soil must be expected in all local depressions, on rock surfaces or undulating till as well as on more level surfaces such as damp areas on the surface of silt or clay plains. Thickness and resistance of organic soil layers must be measured to assess predictable differential compaction when placing fill and after building houses.

With this information, the thickness of the first layer of fill required to prevent rutting of this organic layer can be determined, along with the compaction method necessary to consolidate compressible peat under building footprints. The densification of all granular fill must be monitored. An experienced engineer will then be able to establish the weight, number of passes and speed of the compactor. Use of vibration must also be approved by an engineer, especially in the presence of clay or silt deposits sensitive to restructuring, directly under the layer of organic soil, or when a thicker, more saturated organic layer is encountered. With a prior study and suitable monitoring during work, it is often possible to build housing on this fill without causing differential compaction that harms the structure.

In the case of organic soils with very little resistance, difficult to excavate down to the underlying layer of materials with greater bearing capacity, pieces of dynamited rock may be buried to displace the problematic organic soil in the area subject to the loads transferred to the soil by the building.

It is also possible to use reinforcement methods for granular fill under buildings when differential compaction is expected. For example, installation of biaxial geogrids can augment fill rigidity and reduce uneven soil subsidence and differential compaction of footing drainage. This approach can be useful for very isolated compaction, but is not very effective if compaction extends over an area of a few metres.

In 2012, the geotechnical and geology section of the MTMDet published the document *Guide pour l'étude et la construction de remblais routiers sur tourbières*. This document contains much information that also applies to construction of buildings on peat bogs.

5.6.6 Construction near slopes

The presence of slopes is an important factor to consider when selecting areas for construction. In a permafrost zone, much gentler slopes than those normally considered stable in southern Québec may be subject to mass surface movements. Strike-slips of the active layer can occur in clay soils while gelifluction lobes can gradually form in ice-rich till. A technical notice published specifically for the village of Salluit by Journeaux (2010) recommends avoiding slopes exceeding five percent in clay soils and ice-rich till. Construction of steeper slopes must be subject to more thorough assessment that specifically studies the behaviour of the active layer when thawed, as well as the geotechnical properties of the deposit.

On sloped sites, all construction must start on low ground and work up toward higher ground, so the weight of the fill acts as a brace and increases stability of the slope by reducing downslope movements. Moreover, addition of a layer of material on the soil surface promotes raising of the permafrost table into the active layer and the fill, thereby improving resistance to rupture. In some cases, the addition of a geogrid at the bottom of the slope can resolve stability problems in the shoulder and top of the fill when creep occurs in the active layer during thawing.

During work, it is important not to damage vegetation, which has an insulating effect that preserves the permafrost and, to a lesser extent, increases shear strength through the root system (Andersland and Ladanyi, 2004). Drainage also must be controlled, to reduce interstitial pressure and help prevent landslides.

5.6.7 Managing granulates

In the past few decades, development in Nunavik and construction of new infrastructure has required the use of large quantities of granulates. Most northern villages have borrow pits for sand and gravel. Sustained demand, however, raises the issue of long-term availability of these resources.

In some communities, borrow pits near villages are gradually being depleted. In some cases, new quarries must be developed and operated where granulates are produced from existing rock. These materials must be dynamited and crushed to obtain the desired calibres, which is more expensive than extracting sand and gravel from borrow pits (Appendix XVI, Table 2). The Bureau de l'exploration géologique du Québec of the Ministère de l'Énergie et des Ressources naturelles (MERN) has recently begun work to find and characterize sources of granulates near northern villages. The results of these characterizations should be available as they are published on the MERN website.

Large quantities of materials are sometimes used to build granular inverts under buildings, especially where land is developed in sloped areas. In addition, construction of fills is so widespread that it now forms part of almost all projects, without necessarily assessing soil sensitivity or optimizing the volumes required. In Nunavik, many fills are very thick due to uneven topography on construction sites and the foundation type chosen. For example, figure 5.92 A) shows a granular invert at Salluit four to five metres thick in places. In this example, the design could have been optimized by choosing a foundation better suited to the topography, resting directly on rock, as shown in figure 5.92 B) and figure 5.92 C). The geometry, height and nature of fill materials should be dictated first by the geotechnical and drainage parameters, then harmonized with the earthwork and drainage plans for the area to be built.

Careful selection of materials could also contribute to sound management of granular resources. For example, it is not necessary to build the entire granular invert with the same materials. Those located outside the building footprint could be of lesser quality. In these locations, crusher or screening rejects (pebbles and blocks), silty sand or till could be used. However, the filters principle must be observed or a geotextile membrane must be installed to separate these materials from those of better quality used for the traffic layer at least 150 mm thick, normally consisting of sand and gravel. One example of materials discarded near an old crusher that would be quite usable for construction of granular inverts is shown in figure 5.92 D).



FIGURE 5.92: A) VERY THICK GRANULAR FILL ON SLOPED LAND AT SALLUIT, NUNAVIK. B) AND C) FOUNDATION SYSTEM ADAPTED TO THE TOPOGRAPHY, RESTING DIRECTLY ON ROCK AT IQALUIT, NUNAVUT. D) CRUSHER REJECTS USABLE FOR CONSTRUCTION OF GRANULAR INVERTS (SOURCE: N. JOURNEAUX).

5.7 MAINTENANCE, IMPLEMENTATION OF TECHNIQUES TO MITIGATE DETERIORATION OF PERMAFROST, AND POST-CONSTRUCTION MONITORING

In the years following construction of a structure and throughout its service life, routine, proactive measures are essential to preserve the permafrost around and under the structure, because stability of the foundation is dependent on this. Regular maintenance and monitoring reduce the risk of thawing permafrost and allow intervention if this occurs, to halt advance of the phenomenon and prevent deformation of the building before it is too late. This avoids costly repairs to the structure and mechanical components (electricity, heating, plumbing).

A standard now available was recently developed to structure monitoring and maintenance activities to moderate the effects of permafrost deterioration on the existing structure. The CAN/CSA-S501-14 standard, *Moderating the effects of permafrost degradation on existing building foundations*, proposes preventive and proactive measures to maintain permafrost around and under the structures of existing buildings. These measures form an integral part of a continuous maintenance process designed to maintain optimal site conditions to preserve permafrost (drainage and snow cover) and provide monitoring for quick detection of any signs of structural deterioration linked to the permafrost (Figure 5.93). Every building on permafrost should be inspected annually to detect any signs of deterioration. This inspection should form an integral part of a monitoring program headed by an engineer to check the building's structural integrity and detect any change in the thermal state of underlying foundation materials. This monitoring program should document any changes in signs of deterioration affecting the structure (cracks and deformations in the foundation, structure or visible structural components, the condition of doors and windows, damage to mechanical building components and any other interior surface damage), changes in deformation of the soil surface (compaction or heaving) and any change in site conditions, as well as any other indicator that might reveal a potential source of problems (drainage, snow cover, vegetation and lot layout). The information on the inspection sheet could be collated in a database to facilitate updates, consultation and dissemination of information.

The CAN/CSA-S501-14 standard also specifies steps to follow in assessing structures affected by permafrost degradation, to document the type and causes of the problem and apply appropriate corrective measures (Figure 5.93). For example, proper assessment can make the distinction between serious deterioration in buildings or structures caused by permafrost degradation and that resulting from seasonal frost movement in the ground. This distinction is crucial, because it guides the intervention strategy toward suitable mitigation measures. Note that the various strategies for mitigating permafrost degradation around and under existing structures proposed in this standard depend on the source of the problem (seasonal freezing or permafrost degradation), the foundation type and the site conditions. The main measures for mitigating permafrost degradation are shown in table 5.8.

When using a measure to mitigate permafrost degradation under and around a structure, it is important to maintain long-term monitoring to assess performance and make any necessary adjustments. For more complex foundation systems, such as thermosyphons, the monitoring program must be adapted to the recommendations of specialized suppliers in this field.

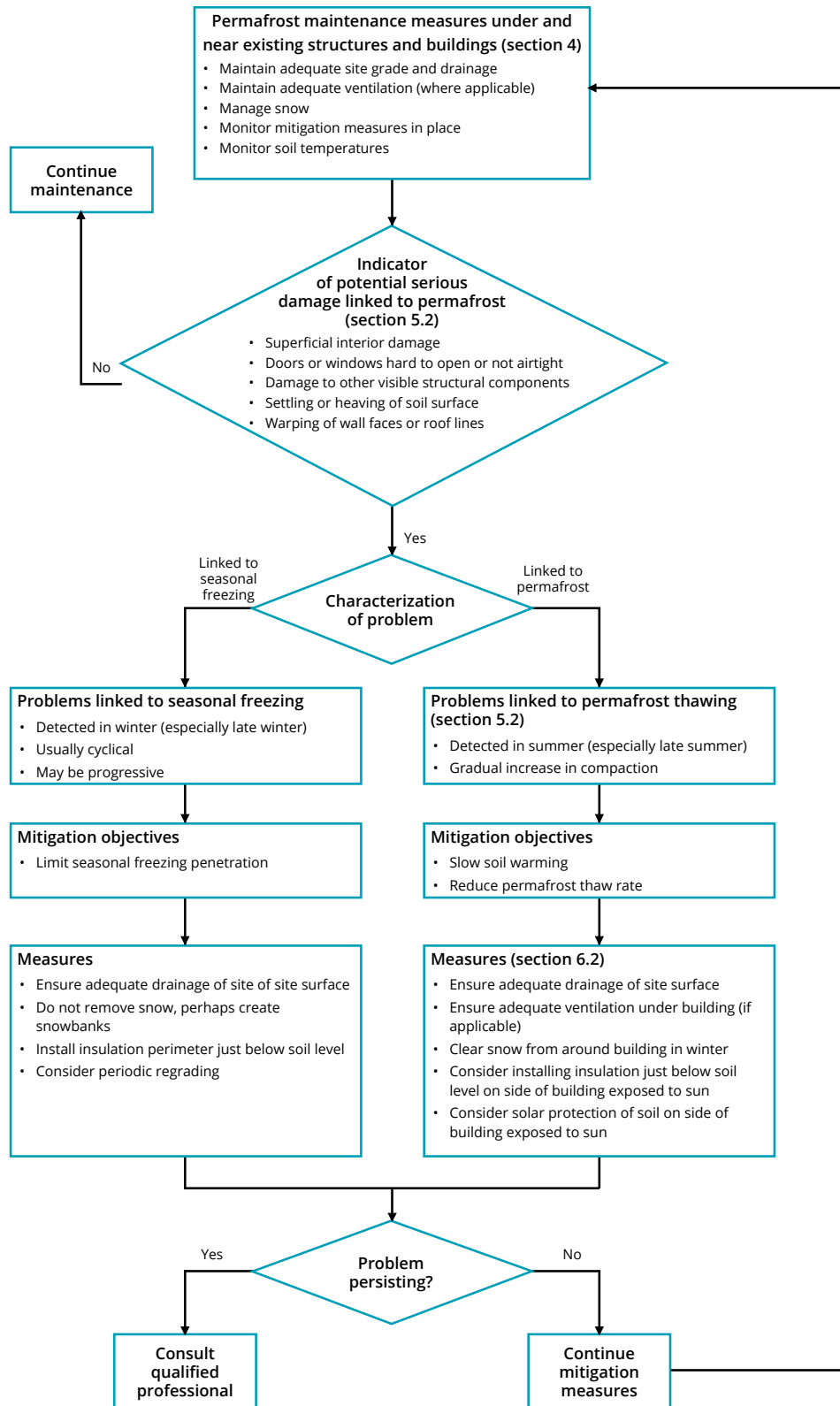


FIGURE 5.93: PERMAFROST MAINTENANCE MEASURES, MONITORING OF INDICATORS ATTRIBUTABLE TO POTENTIAL PERMAFROST DEGRADATION, CHARACTERIZATION OF THE PROBLEM AND IMPLEMENTATION OF APPROPRIATE MITIGATION MEASURES FOR THE SITE (MODIFIED FROM CAN/CSA-S501-14, « MODERATING THE EFFECTS OF PERMAFROST DEGRADATION ON EXISTING BUILDING FOUNDATIONS », 2014 P.55, PRODUCT CODE: 2423338).

MITIGATION TECHNIQUE	Surface foundations			Deep foundations	
	Surface footings	Buried footings	Slab on grade	Piles to promote freezing adherence	Cemented or peak-load piles
Solar protection – see section 6.3.1	Yes	Yes	Yes	Yes	Yes
Drainage – see section 6.3.2	Yes	Yes	Yes	Yes	Yes
Snow magagment – see section 6.3.3	Yes	Yes	Yes	Yes	Yes
Ventilation – see section 6.4.2	Yes	Yes	No	Yes	No
Soil insulation – see section 6.4.3	Yes	Yes	No	Yes	Maybe
Ajustment/levelling of existing foundation – see section 6.4.4	Yes	Yes	Maybe	Yes	Yes
Mecanical refrigeration – see section 6.4.5	Yes	Yes	Maybe	Yes	Yes
Thermosiphons – see section 6.4.5	Yes	Yes	Maybe	Yes	Yes
Replace foundation – see section 6.4.6	Yes	Yes	No	Maybe	Maybe

TABLE 5.8: APPLICABILITY OF VARIOUS TECHNIQUES FOR MITIGATING PERMAFROST DEGRADATION (FROM THE CAN/CSA-S501-14 STANDARD).

5.8 PLANNING VISION

Land development is subject to planning for areas reasonably suited to construction. Identifying these areas requires consideration of all the factors that can influence the performance of infrastructure. Construction of buildings and streets, drainage control and installation of utilities will require carefully ordered and planned engineering works to protect the permafrost. Buildings resting on different foundation types must not be placed too close to each other, especially where this could alter the thermal regime of permafrost under the adjacent building, a problem caused in many cases by poor planning of the drainage system and of snow accumulation. In brief, the following conditions must be met in built-up areas.

- The construction zone preferably should be located over good quality rock⁷ or on soil that is stable when thawed, for which compaction during thawing falls within acceptable tolerances.
- Slopes covered with unconsolidated deposits must be gentle enough to ensure long-term stability, considering all anticipated changes.
- Oversized fills and major earthworks should be reduced to a minimum, while excavation in ice-rich permafrost zones must be avoided.
- The area must be well drained and located outside flood zones or areas flooded by high tides and storm surges.
- Lot size and geometry must be sufficient for construction of the building while leaving adequate space around the structure for vehicle traffic.
- Sufficient clearance must be provided around areas sensitive to erosion or landslides, such as high river or stream banks, the base of potentially unstable slopes and the edges of water courses.
- Structures must be erected outside zones exposed to avalanches or any other potential natural risk.

7. Where such zones are scarce, local authorities can choose to reserve them for institutional, commercial or industrial purposes, to ensure the durability of large buildings and reduce their construction cost.

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APPENDIX I: ORGANIZATIONS AND AUTHORITIES FOR ANY CONSTRUCTION PROJECT IN NUNAVIK

I.1: FEES AND SERVICES PROVIDED

For more information on leasing/rental rates, services available, equipment rental, human resources or a specific community, please contact the northern villages and landholding corporations (contact information below).

NORTHERN VILLAGE	LANDHOLDING CORPORATION
AKULIVIK PO Box 50 Akulivik QC J0M 1V0 Tel: 819 496-2222 Fax: 819 496-2200	QEKEIRRIAQ LHC PO Box 59 Akulivik QC J0M 1V0 Tel: 819 496-2640 Fax: 819 496-2629
AUPALUK PO Box 6 Aupaluk QC J0M 1X0 Tel: 819 491-7070 Fax: 819 491-7035	NUNAVIK LHC PO Box 29 Aupaluk QC J0M 1X0 Tel: 819 491-7045 Fax: 819 491-7045
INUKJUAQ PO Box 234 Inukjuak QC J0M 1M0 Tel: 819 254-8845 Fax: 819 254-8779	PITUVIK LHC PO Box 285 Inukjuak QC J0M 1M0 Tel: 819 254-8101 Fax: 819 254-8252
IVUJIVIK PO Box 20 Ivujivik QC J0M 1H0 Tel: 819 922-9940 Fax: 819 922-3045	NUVUMMI LHC PO Box 157 Ivujivik QC J0M 1H0 Tel: 819 922-9944 Fax: 819 922-3045
KANGIQSUALUJJUAQ PO Box Kangiqsualujuaq QC J0M 1N0 Tel: 819 337-5270 Fax: 819 337-5200	QINIQTIQ LHC PO Box 160 Kangiqsualujuaq QC J0M 1N0 Tel: 819 337-5449 Fax: 819 337-5752

NORTHERN VILLAGE	LANDHOLDING CORPORATION
KANGIQSUJUAQ PO Box 60 Kangiqsujuaq QC J0M 1K0 Tel: 819 338-3342 Fax: 819 338-3237	NUNATURLIK LHC PO Box 39 Kangiqsujuaq QC J0M 1K0 Tel: 819 338-3368 Fax: 819 338-1071
KANGIRSUK PO Box 90 Kangirsuk QC J0M 1A0 Tel: 819 935-4388 Fax: 819 935-4287	SAPUTIK LHC PO Box 119 Kangirsuk QC J0M 1A0 Tel: 819 935-4269 Fax: 819 935-4440
KUJJUAQ PO Box 210 Kuujuaq QC J0M 1C0 Tel: 819 964-2943 Fax: 819 964-0734	NAYUMIVIK LHC PO Box 209 Kuujuaq QC J0M 1C0 Tel: 819 964-2870 Fax: 819 964-2280
KUJJUARAPIK PO Box 360 Kuujuarapik QC J0M 1G0 Tel: 819 929-3360 Fax: 819 929-3453	SAKKUQ LHC PO Box 270 Kuujuaapik QC J0M 1G0 Tel: 819 929-3348 Fax: 819 929-3275
PUVIRNITUQ PO Box 150 Puvirnituk QC J0M 1P0 Tel: 819 988-2825 Fax: 819 988-2751	DIRECTION GÉNÉRALE DU NORD-DU-QUÉBEC PO Box 151 Puvirnituk QC J0M 1P0 Tel: 819 755-4838 Fax: 819 755-3541
QUAQTAQ PO Box 107 Quaqtaq QC J0M 1J0 Tel: 819 492-9912 Fax: 819 492-9935	TUVAALUK LHC PO Box 102 Quaqtaq QC J0M 1J0 Tel: 819 492-9281 Fax: 819 492-9302

NORTHERN VILLAGE	LANDHOLDING CORPORATION
SALLUIT PO Box 240 Salluit QC J0M 1S0 Tel: 819 255-8953 Fax: 819 255-8802	QAQQALIK LHC PO Box 30 Salluit QC J0M 1S0 Tel: 819 255-8908 Fax: 819 255-8864
TASIUJAQ PO Box 54 Tasiujaq QC J0M 1T0 Tel: 819 633-9924 Fax: 819 633-5026	ARQIVIK LHC PO Box 52 Tasiujaq QC J0M 1T0 Tel: 819 633-5335 Fax: 819 633-5337
UMIUJAQ PO Box 108 Umiujaq QC J0M 1Y0 Tel: 819 331-7000 Fax: 819 331-7057	ANNITURVIK LHC PO Box 148 Umiujaq QC J0M 1Y0 Tel: 819 331-7831 Fax: 819 331-7832

I.2: FORMS AND CONSTRUCTION IN NUNAVIK

To obtain assistance when filling out application forms or obtain more information about construction in Nunavik, don't hesitate to contact the following people.

COORDINATOR, NUNAVIK LANDHOLDING CORPORATION ASSOCIATION	PO Box 179 Kuujjuaq QC J0M 1C0 Tel: 819 964-2925 Fax: 819 964-2613
URBAN PLANNER RENEWABLE RESOURCES DEPARTMENT, KATIVIK REGIONAL GOVERNMENT	PO Box 9 Kuujjuaq QC J0M 1C0 Tel: 819 964-2961 Fax: 819 964-0694 http://www.krg.ca

I.3: CLASS II AND III LAND LEASES

FOR THE REGION LOCATED EAST OF 76 DEGREES LONGITUDE

**MINISTÈRE DE L'ÉNERGIE ET
DES RESSOURCES NATURELLES
DU QUÉBEC**

**DIRECTION RÉGIONALE
DE LA GESTION DU TERRITOIRE PUBLIC**
837 Sacré-Cœur Blvd
Saint-Félicien QC G8K 1S7
Tel: 418 695-7877
Fax: 418 695-8133

FOR THE REGION LOCATED WEST OF 76 DEGREES LONGITUDE

**MINISTÈRE DES FORÊTS,
DE LA FAUNE ET DES PARCS**

**DIRECTION RÉGIONALE DE LA GESTION
DU TERRITOIRE PUBLIC**
1122 Highway 111 East
Amos QC J9T 1N1
Tel: 819 444-5641
Fax: 819 444-5837

A land lease application form can also be obtained from:

<https://mern.gouv.qc.ca/territoire/droit/formulaire-utilisation-terres-etat.html>

I.4: TO OBTAIN SPECIFIC INSTRUCTIONS FOR ALL LAND SURVEY WORK IN NUNAVIK:

**MINISTÈRE DE L'ÉNERGIE
ET DES RESSOURCES
NATURELLES (MERN)
BUREAU DE L'ARPENTEUR GÉNÉRAL
DU QUÉBEC
DIVISION DES TERRITOIRES
AUTOCHTONES ET DES FRONTIÈRES**

5700, 4th Avenue West, Suite F-310
Charlesbourg QC G1N 6R1
Tel: 418 627-6263
Fax: 418 643-6512
email: services.specialises@mern.gouv.qc.ca

For more information on the Bureau de l'arpenteur général du Québec, visit the Ministry's website:

<http://www.mern.gouv.qc.ca/information-fonciere>

I.5: TO OBTAIN CERTIFICATES OF AUTHORIZATION

**MINISTÈRE DU DÉVELOPPEMENT
DURABLE, DE L'ENVIRONNEMENT ET DE
LA LUTTE CONTRE LES CHANGEMENTS
CLIMATIQUES**
**DIRECTION RÉGIONALE DU
NORD-DU-QUÉBEC**

180 Rideau Blvd, 1st Floor
Rouyn-Noranda QC J9X 1N9
Tel: 819 763-3333
Fax: 819 763-3202

For more information on certificates of authorization from the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, visit the Ministry's website:

<https://mern.gouv.qc.ca/territoire/droit/formulaire-utilisation-terres-etat.html>

I.6: FOR CONNECTION TO THE ELECTRICAL AND TELEPHONE SYSTEM, CONTACT:

HYDRO-QUÉBEC

1 800 472-5103

BELL CANADA

819 773-5515

I.7: FOR MORE INFORMATION ON ARCHAEOLOGICAL SITES, CONTACT THE FOLLOWING ORGANIZATIONS.

AVATAQ CULTURAL INSTITUTE

Inukjuak QC J0M 1M0
avataq@avataq.qc.ca (general information)
severian@avataq.qc.ca
(Archaeology Department)

**MINISTÈRE DE LA CULTURE ET
DES COMMUNICATIONS**
DIRECTION NORD-DU-QUÉBEC

19 Perreault Street West, Suite 450
Rouyn-Noranda QC J9X 6N5
Tel: 819 763-3517
Fax: 819 763-3382
dratnq@mcc.gouv.qc.ca

APPENDIX II: ADDITIONAL LAND SURVEY INSTRUCTIONS

The following instructions are provided for information purposes, as a complement to section 1.4.

Remember that it is essential to contact the Bureau de l'arpenteur général du Québec (BAGQ) at least 30 days before performing the work in the field to obtain land survey instructions. This step is necessary to submit the survey documents to the clerk of the Arpenteur général du Québec.

- The land survey plan must indicate the site (lot) where the structure will be built and especially the lot limits, measurements, area and the adjacent lots, and must be submitted to the clerk of the Arpenteur général du Québec.
- The clerk of the Arpenteur général du Québec acts as the single service point for submission of land survey documents, as a public register accessible to all. Only the BAGQ is authorized to issue certified copies of documents submitted to the clerk of the Arpenteur général du Québec. The BAGQ charges no fee to land surveyors for requests for specific land survey instructions.
- Following submission to the clerk of the Arpenteur général du Québec, the BAGQ forwards a certified copy of the document to the Kativik Regional Government's urban planner and to the appropriate landholding corporation.
- For all other private land survey work that does not create or alter a subdivision (e.g. location certificates), there is no requirement for submission to the clerk of the Arpenteur général du Québec. However, a certified copy of the document and a digital file must be submitted to the BAGQ by the land surveyor retained, to incorporate the information gathered in the field into the land surveys compilation map produced by the BAGQ's Division des territoires autochtones et des frontières.

APPENDIX III: DESCRIPTION OF PROJECTS SUBJECT TO AND EXEMPT FROM THE ENVIRONMENTAL ASSESSMENT PROCESS (FROM CHAPTER 22 OF THE JAMES BAY AND NORTHERN QUEBEC AGREEMENT)

Projects automatically **subject to** the environmental and social impact assessment and review procedure

1. Any mining operation as well as any significant addition to or transformation or modification of existing mining operations, but air and land reconnaissance, land survey, mapping and core sampling work is allowed without requiring an impact report.
2. The placement and use of large borrow pits, sand and gravel pits, and other quarries.
3. Energy production:
 - a. Hydroelectric power plants, nuclear facilities and related works
 - b. Storage tanks and water retention ponds
 - c. Transmission lines of 75 kV or more
 - d. Extraction and processing of energy resources
 - e. Thermal power plants fired by fossil fuel, with a capacity of more than three thousand kilowatts (3000 kW)

4. Tree-farming operations:
 - a. Major access roads built for forestry operations
 - b. Sawmills, pulp and paper mills or other facilities related to forestry activities
 - c. In general, any significant change in land use with a noticeable influence on an area exceeding twenty-five square miles (25 mi²)
5. Community and municipal services:
 - a. New and large sewage and waste water capitation and removal systems
 - b. Solid waste collection and disposal, including sanitary landfill and incineration
 - c. Proposed parks, ecological reserves or other similar land uses
 - d. New outfitter operations for more than thirty (30) people, including outpost networks
 - e. New towns, communities or municipalities, or significant expansion of existing sites
6. Transportation:
 - a. Access roads to communities and adjacent roads
 - b. Port facilities
 - c. Airports
 - d. Railways
 - e. Roadway infrastructure for new subdivisions
 - f. Pipelines
 - g. Dragging work to improve shipping

Projects automatically **exempt** from the environmental and social impact assessment and review procedure:

1. Any development within community boundaries that will have no direct impact on wildlife resources outside those boundaries.
2. Small hotels, motels, service stations and other similar construction alongside provincial and secondary highways.
3. Buildings constructed for housing, wholesale or retail businesses, garages, offices or craft work, and vehicle parking.
4. Thermal power stations fired by fossil fuel, with a capacity of less than three thousand kilowatts (3000 kW).
5. The following buildings:
 - educational institutions
 - banks
 - fire stations
 - property intended for administration, recreation, cultural activities, religious rites, sports and healthcare
 - property and equipment used for telecommunications.

6. Construction, modification, renovation, relocation or conversion to other uses of switching and transformer stations with a power of seventy-five kilovolts (75 kV) or less and energy transmission lines of seventy-five kilovolts (75 kV) or less.
7. Construction and extension of trunk pipelines with a diameter of less than thirty centimetres (30 cm) with a maximum length of five miles (5 mi).
8. Investigation, preliminary study, research, technical studies and surveys prior to any development, work or construction.
9. Tree farming operations where these form part of management plans approved by government, subject to the provisions of paragraph 23.5.34 of the James Bay and Northern Quebec Agreement.
10. Municipal streets and sidewalks built in compliance with municipal bylaws,
11. The operation and maintenance of roadways and roadway fittings.
12. Temporary facilities used for hunting, trapping, harvesting of wildlife resources, as well as outfitting services and camps for fewer than thirty (30) people.
13. Repair and maintenance of municipal works.
14. Extraction and handling of steatite, sand, gravel, copper and timber, for personal and community use.
15. Limited woodcutting for personal or community use.
16. Borrow pits for road maintenance.

The preceding provisions are not interpreted as restricting the requirements related to environmental impact assessment under the federal impact assessment and review process applicable to federal projects.

APPENDIX IV: RECAPITULATIVE TABLE OF REQUIRED AUTHORIZATIONS

The following table summarizes the authorizations issued by each organization.

ORGANIZATION	AUTHORIZATION	APPLICABLE FEES
VN	Development permit for projects on Class I lands	Administration fees
	Authorization to excavate natural materials from Class I lands	n/a
CF	Memorandum of understanding signed with the contractor on occupancy and use of Class I lands during construction	Rental costs during the construction period, which may differ from those outside the construction season
	Land leases for occupancy of Class I lands	Administrative and leasing fees
	Right to obtain gravel or other mineral materials from Class I lands	Compensation fees for extraction of minerals (price per tonne)
KATIVIK REGIONAL GOVERNMENT	Certificate of authorization for projects on Class II and III lands	n/a
MINISTÈRE DU DÉVELOPPEMENT DURABLE, DE L'ENVIRONNEMENT ET DE LA LUTTE CONTRE LES CHANGEMENTS CLIMATIQUES	Certificate of authorization for drinking water and sewage treatment and for waste disposal; Certificate of authorization to operate a new quarry or borrow pit	n/a
MINISTÈRE DE L'ÉNERGIE ET DES RESSOURCES NATURELLES	Land leases for projects on Class II and III lands and in NVs of Puvirnituq and Ivujivik	Administrative and leasing fees
BUREAU DE L'ARPENTEUR GÉNÉRAL DU QUÉBEC	Specific instructions for all land survey work on Class I lands and for all land survey work in Puvirnituq, Ivujivik and on Class II and III lands	n/a

APPENDIX V: NOVOCLIMAT PROGRAM

The following information is taken from the Transition énergétique Québec website.

Since 1999, Novoclimat has defined the **technical requirements** to be met when building a home or multiple-unit residential structure, to provide energy performance exceeding that required by the building code in force.

This program is gradually preparing the industry for a future upgrade of energy efficiency standards.

Novoclimat includes **training** and **certification** of construction contractors and ventilation specialists, **inspection** of homes during construction and **certification** of compliant housing units.

Finally, this program also includes payment of **financial assistance** to:

- Buyers and contractors for the Homes component;
- Developers for the Small Multi-unit Buildings and Large Multi-unit Buildings components.

This program has been officially extended to March 31, 2021. At the same time, Transition énergétique Québec has also removed the “2.0” reference and returned to the “Novoclimat” name for all components.

Since January 31, 2018, new technical requirements apply to all Novoclimat program components. These include but are not limited to the following major changes to the technical requirements:

- Removal of Part 4 – Complementary Optional Requirements;
- Addition of prescriptive requirements for achieving 20 percent energy savings despite removal of the complementary optional requirements.

A comparative table of the technical requirements in both versions of the program is available on the **Technical documents and forms** page of each component of the program.

APPENDIX VI: AIR LEAKS THROUGH THE ENVELOPE

Leaks generally occur through cracks and small openings in insulated windows, doors, walls, floors or roofs. Their extent depends on how the building is designed, the quality of materials, how they have been assembled and the difference in air pressure on both sides of the envelope.

Leaks through the envelope often cause the following problems: high heating costs, rotting or corrosion of materials due to water infiltration and the appearance of hidden mould due to condensation of humidity in internal components of the envelope.

The three primary mechanisms that allow the passage of air through a building's envelope are: the chimney effect, wind action and mechanical ventilation.

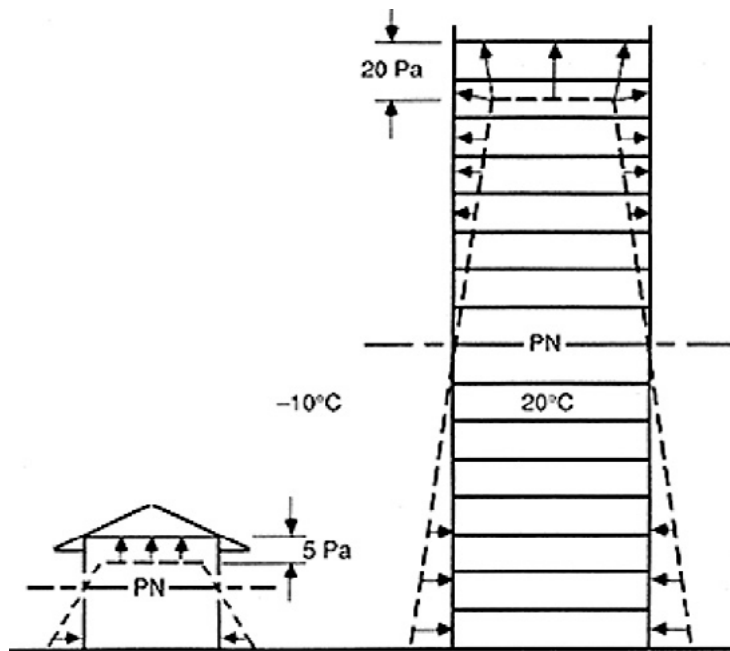


FIGURE VI.1: PRESSURE DIFFERENCES IN A BUILDING
SOURCE: NRC ARTICLE: "UNE DÉFINITION DE PARE-AIR," PRODUCED AS PART OF BUILDING SCIENCE INSIGHT 86

VI.1: CHIMNEY EFFECT

In multi-storey buildings, the chimney effect tends to cause exfiltration in the upper portions and infiltration in the lower portions. The higher the temperature, the less dense the air becomes, which explains why warm air is lighter than cold air. So warm air rises and this floatability exerts outward pressure on ceilings and the upper part of walls. Openings in the vapour barrier let hot, humid air escape under the roof and into the wall structure, where it cools and deposits humidity on cold interior surfaces of the roof or wall sheathing.

VI.2: WIND ACTION

Uncontrolled air currents through the envelope reduce the well-being of occupants and cause many

disorders. Wind blowing against a house produces positive pressure, pressing in the exterior face of the wall exposed to the wind and causing infiltration. The wind also produces negative pressure or depression on the other walls, causing exfiltration. This negative pressure draws indoor air to the outside through small openings and the humidity in this warm air condenses inside the wall structure, on cold components.

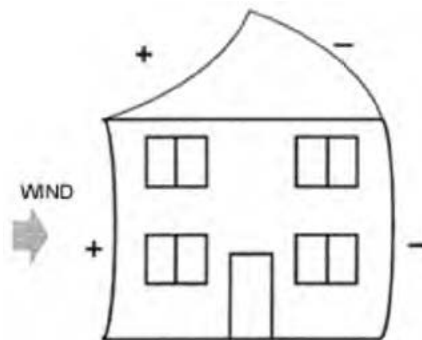


FIGURE VI.2: PRESSURE GENERATED ON A HOUSE BY WIND
SOURCE: NRC ARTICLE: "UNE DÉFINITION DE PARE-AIR," PRODUCED AS PART OF BUILDING SCIENCE INSIGHT 86

VI.3: MECHANICAL VENTILATION

Figure VI.3 shows the air flows entering and exiting a house that are necessary to use equipment such as the boiler, dryer and range hood.

While extraction ventilators reduce pressure inside a house by extracting air, poorly balanced mechanical ventilation systems, including fresh air ventilators, can generate positive pressure. Air and humidity then move outward and into the attic, where condensation can occur.

Careful design and construction are necessary to minimize air leaks and ensure water tightness as well as energy efficiency appropriate for buildings in Nunavik. To do this, managers, designers and builders must have a very thorough knowledge of air, water and vapour barrier systems.

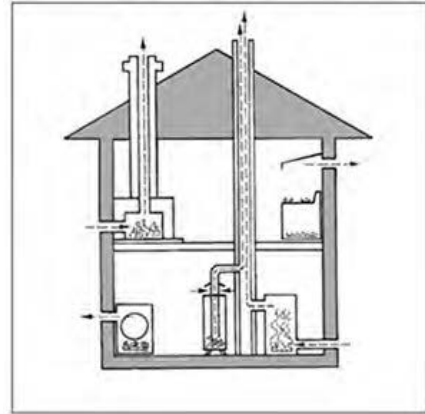


FIGURE VI.3: AIR ENTERING AND EXITING A HOUSE / SOURCE: NRC ARTICLE: « LE MÉCANISME DE VOTRE MAISON : VENTILATION ET CONTRÔLE DU FLUX D'AIR »

APPENDIX VII: MINIMUM PROPERTIES OF AN EFFECTIVE AIR BARRIER SYSTEM

VII.1: CONTINUITY

A continuous air barrier requires more than the lack of holes or flaws. A system that must act as an air barrier has to include suitable joint materials and sealing details to prevent any flows in the following meeting points: around doors and windows; at wall-roof, wall-foundation and wall-insulated floor junctions; around any architectural projections such as a porch, balcony or sun baffle; around electro-mechanical components such as wires, pipes and ducts crossing through the building envelope, etc. in brief, the winning solution is to ensure total continuity between all system materials to obtain an airtight "shell."

VII.2: STRUCTURAL STRENGTH

The component designed to serve as an air barrier must be able to withstand the excess pressure applied or must be protected with another suitable material. It must be resistant to the pressure or suction of the strongest excess wind loads without breaking or tearing away from its support. The air barrier must not rip off its support or fail due to creep under sustained pressure through draft, pressurization or extraction created by ventilators. The air break and its support must be rigid enough to resist movements. Thus, unless sandwiched between two rigid plates, an air barrier sheet must be strong enough to resist air pressure or depressurization, which is hard to achieve with thin membranes.

VII.3: LOW AIR PERMEABILITY

One essential characteristic of an air barrier is strong resistance to air flows. Since absolute air impermeability is rarely possible, or even necessary, air barrier materials will be required to provide low air permeability. For classification purposes, materials are rated with an index called the "air permeability rate" in private or government laboratory tests. In this regard, the Canadian Construction Materials Centre standard sets a maximum allowable rate of 0.02 L/s.m² at a pressure differential of 75 Pa. Note that this threshold is not very demanding since commonly used air barrier membranes sold in hardware stores achieve rates between 0.005 and 0.0017 L/s.m². In the air barrier/vapour barrier membranes category, extremely low air permeability rates can be attained, on the order of 0.0003 L/s.

VII.4: HIGH WATER VAPOUR PERMEABILITY (WHEN PLACED ON THE COLD SIDE OF INSULATION)

Permeability is the property by which a material allows water vapour to pass through it fairly easily: under a given humidity pressure, the higher a material's permeability, the more easily this occurs. This property can be illustrated as follows: greater permeability allows the material to “breathe” easily under humidity pressure. For classification purposes, materials are rated by an index called “water vapour permeability” in private or government laboratory tests. In this regard, the Canadian CCMC standard sets a minimum allowable rate of 170 ng/Pa.s.m² for an exterior sheathing membrane, equivalent to 3 US perm (1 US perm = 57.21 ng/Pa.s.m²). This threshold is not stringent at all since the commonly used membranes sold in hardware stores achieve test results between 7 and 30 US perm.

An air barrier system in which the primary barrier is on the cold side of the insulated component should have high water vapour permeability so any humidity that has crossed the interior vapour barrier can escape quickly through the envelope and thus minimize the risk of condensation on components inside the insulated wall.

VII.5: DURABILITY

Since the air barrier system materials are never visible and never exposed directly to foul weather, they are assured of extended durability if covered within the required time during construction. Durability of the barrier system as a whole thus is linked primarily to the sturdiness of the connecting or sealing components between the various air barrier membranes that make up the system: connection between two strips of the same membrane, connection between two different types of membrane (wall-ceiling, wall-floor, wall-opening, wall-projection and other junctions). Since most of these connections are made by adhesion or sealing, and since any assembly involving adhesion or sealing on the site requires great attention to detail to be reliable, a carefully made joint between the various components of the air barrier assembly will achieve the desired reliability for this building element. The following precautions therefore must be observed: clean surfaces, totally dry materials, controlled application temperature, compatibility between materials and products, sufficient overlapping of assembled, use of primer before adhesion, minimum application pressure, etc.

The environment to which the air barrier is exposed only briefly during construction may still adversely affect the durability of certain component materials. These must be adequately protected from foul weather, UV radiation and mechanical damage during construction.

APPENDIX VIII: WATER VAPOUR PERMEABILITY

The measurement of water vapour diffusion through a construction material is called “water vapour permeability.” The lower this permeability, the better the product resists the passage of vapour and the more effective it is rated as a vapour barrier. The common unit of measurement for permeability is the perm (US perm in North America): 1 US perm equals 57.2 ng/Pa.s.m².

Vapour barrier materials on the market are classified as type I, II or III based on their permeability as determined by the standard tests, with type I providing the best performance for containing water vapour:

- type I: less than 15 ng/Pa.s.m² (0.26 US perm),
- type II: between 15 and 60 ng/Pa.s.m² (0.26 – 1.05 US perm),
- type III: greater than 60 ng/Pa.s.m² and no more than 572 ng/Pa.s.m² (1.05 – 10 US perm).

The Construction Code requirements for vapour barrier materials differ depending on the climate zone, but in all cases, their permeability must be no more than 1.05 US perm (60 ng/Pa.s.m²), which requires at least a type II product. This value is not very restrictive since simple interior alkyd paint finishes on a gypsum panel can provide such protection. For example, the commonly used 0.15 mm thick polyethylene film provides a permeability of 0.03 US perm (1.6 ng/Pa.s.m²), which far exceeds the minimum standard and gives it a type I rating. In Appendix A, the Code's Building chapter provides a table with the water vapour permeability of common construction materials.

The Canadian General Standards Board has certified various vapour barrier products sold in the market, under the CGSB-51.33-M and CGSB-51.34-M standards, allowing them to display a certificate number as proof of compliance with the Code.

APPENDIX IX: INFILTRATION IN A CONSTRUCTION ASSEMBLY

Construction assemblies are naturally designed to prevent water and snow from penetrating into components of the envelope. However, precipitation driven by strong winds manages in some cases to penetrate the exterior cladding. The Code's Building chapter states that it is not necessary to totally eliminate all accumulations or prevent humidity at all costs from penetrating a construction assembly: wind-driven rain that penetrates the exterior cladding may not affect the long-term performance of the construction assembly, provided the dampness dries out or is released before it starts to degrade building materials. A design that allows fast drying of humid or damp materials therefore must form part of the design.

APPENDIX: RAIN SCREEN WALL

The "hidden protection" type of design is primitive and little used today, contrary to the much more popular "rain-screen" design type. The distinction between these two types of walls is explained in section A-9.27.2 of the Code's Building chapter. It states (section A-9.27.20) that the rain-screen wall type has three variants.

1. The "basic" rain screen wall, which requires no cavity behind the siding
2. The "draining" rain screen wall, in which the cavity behind the siding is open and ventilated using a support materials designed for this purpose
3. The "open" rain screen wall, the most common type, which includes a cavity 10 to 19 mm deep behind the siding, open and vented to the open air.

APPENDIX XI: DEGREE DAYS

Assessment of heating in "degree days" below 18°C in a given region or city measures annual energy expenditure calculated as follows: for each day requiring heating, the annual sum of the difference between the average daily temperature and the 18°C reference temperature. Schedule C of the Code's Building chapter presents a full table of these data for the primary locations in Quebec, including four villages in Nunavik: Inukjuak, with 9,050 dd, Kuujuaq with 8,650 dd, Kuujuarapik with 8,250 dd, and Puvirnituq with 9,200 dd.

APPENDIX XII: OTHER STANDARDS

Other energy efficiency standards that specifically govern building insulation may prove just as relevant for a northern climate, such as the Transition énergétique Québec (TEQ), Novoclimat Program for the "house and small multi-unit building" component or Natural Resources Canada's (NRCan) ENERGY STAR home certification program or the R-2000 certification program, also from NRCan. Since their application is optional, these standards are not shown in this guide. The TEQ and NRCan documentation still remains a valuable source of information, especially the Novoclimat publication that contains many practical tips and is extensively illustrated.

APPENDIX XIII: ENERGY STAR CERTIFIED DOORS AND WINDOWS

ENERGY STAR certified doors and windows are tested and certified by an independent accredited organization. Product are ENERGY STAR certified based on their U value (overall heat transfer coefficient) or their ER, which exceed the Construction Code requirements.

Map XIII.I shows the distribution of climate zones in Canada by colour code. Nunavik falls within zone D, which is 8,000 degree days and more.

The two following tables show the performance ratings for ENERGY STAR certified doors for each of the four climate zones determined for Canada. The U factor shown represents the measurement of the thermal transfer rate through the component. A low U value is desirable because it indicates low thermal loss in winter and low thermal gain in summer. The U is the mathematical opposite of the RSI thermal resistance value normally assigned to insulated walls. The energy performance rating (ER), represents the measurement of general energy performance for windows, incorporating heat loss through heat transfer, solar gain and heat loss through air leakage. The higher the energy rating, the better the window's energy performance in heating season..

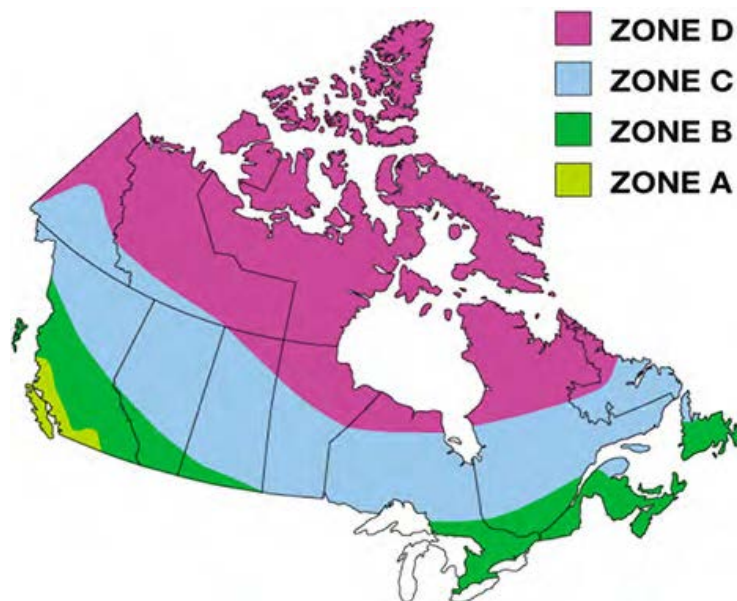


FIGURE XIII.I: CLIMATE ZONES IN CANADA / SOURCE: NATURAL RESOURCES CANADA

WINDOWS					
ZONE	Heating degree day scale	Compliance path			
		Energy efficiency rating (EER)	or	U factor	
		Minimum EER (no units) Maximum U factor 2,00 W/m ² •K (0,35 Btu/h•pi ² •°F)		Maximum U factor W/m ² •K (Btu/h•pi ² •°F)	Minimum EER (no units)
A	< = 3500	21	or	1,80 (0,32)	13
B	> 3500 to < = 5500	25	or	1,60 (0,28)	17
C	> 5500 to < = 8000	29	or	1,40 (0,25)	21
D	> 8000	34	or	1,20 (0,21)	25

TABLE XIII.1: ENERGY STAR WINDOW COMPLIANCE PATH

DOORS					
ZONE	Heating degree day scale	Compliance path			
		Energy efficiency rating (EER)	or	Facteur U	
		Minimum EER (no units) Maximum U factor 2,00 W/m ² •K (0,35 Btu/h•pi ² •°F)		Maximum U factor W/m ² •K (Btu/h•pi ² •°F)	Minimum EER (no units)
A	< = 3500	21	or	1,80 (0,32)	n/a
B	> 3500 to < = 5500	25	or	1,60 (0,28)	n/a
C	> 5500 to < = 8000	29	or	1,40 (0,25)	n/a
D	> 8000	34	or	1,20 (0,21)	n/a

TABLE XIII.2: ENERGY STAR DOOR COMPLIANCE PATH

APPENDIX XIV: INFILTROMETRY

XIV.1: INFILTRATION TEST

The infiltrometry test must be conducted by a specialist in this field, independent of any contractual link with the principals in the contract. This specialist must first close all exterior openings (windows, doors, ventilation dampers, plumbing drains, etc.) and check that interior doors are open, to allow the free movement of air. An infiltrometer is then installed in the entry door. This device is equipped with an airtight nylon fabric that seals the door opening with a frame that adjusts to the dimensions of the door and a fan. The device measures the pressure difference between the interior and exterior to determine how much air is entering the building.

The operator that searches for leaks to find the places where changes must be made to improve the building's airtightness. These changes can be made at little cost because the envelope is still accessible from the interior. Artificial smoke is used to detect the path of infiltration, an anemometer detects air movement in places where the air is filtering in, or infrared thermography makes the places cooled by infiltration visible.

A second infiltrometry test is conducted after the remedial work to determine the building's infiltration rate upon delivery. In new construction, the results should approach the values recommended by the Novoclimat energy efficiency program, shown in the attached Table XIV.1.

MAXIMUM ACCEPTABLE LEAKS ⁷					
Building type	CAH at 50 Pa	SFN at 10 Pa		TFN at 50 Pa	
Detached	1,5	0,75	1,08	0,57	0,11
Attached⁸ (e.g. semi-detached, row)	2,0	1,18	1,70	0,78	0,15

TABLE XIV.1: MAXIMUM ALLOWABLE AIR LEAKAGE, TABLE 2.2.2.1, FROM PAGE 19 OF THE NOVOCLIMAT PROTOCOL

A report of the results obtained on airtightness of the building must then be submitted to the owner's representative, and must cover at least the following points:

- General building and test conditions;
- Exterior walls;
- Attic;
- Doors;
- Windows;
- Airtightness;
- Recommendations.

7. Building airtightness is measured by an infiltrometry test performed under the CAN/CGSB2-149-10-M86 standard, Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method..

8. Applies only to buildings separated in more than one area by one common walls and subject to separate infiltrometry tests of these areas.

XIV.2: THERMOGRAPHIC ANALYSIS

The building envelope—the floor (exposed to the outdoor air as in raised buildings on pilings or adjustable jacks generally built in northern communities), walls and roof—must undergo thermographic analysis to observe variances that occur in thermal behaviour and detect any anomaly. This analysis should be conducted simultaneously on the exterior and interior surfaces of the building envelope.

Ideally, the thermographic analysis should cover both the qualitative and quantitative aspects, the first gathering information on the envelope components with unexpected or abnormal thermal behaviour, and the second examining the infrared radiation measurements to assess deficient thermal behaviour caused by defective profiles.



FIGURE XIV.1: INFRARED PHOTOGRAPH OF A HOME TAKEN IN WINTER. RED REPRESENTS WARM COMPONENTS, BLUE THE COLD COMPONENTS. / SOURCE: GOOGLE IMAGES

For prefabricated buildings fully assembled in a factory, the recommendation is to conduct as many tests as possible on site to measure insulation and airtightness. The builder can then make the necessary changes without delay and without incurring additional costs (shipping materials and travel and accommodation for specialized labour) to perform the work on site. Since the temporary preparation measures are not representative of actual conditions in Nunavik and the actual occupancy or usage of the building, the analysis should cover only the qualitative aspect. Another possibility for prefabricated buildings is to install the interior finish after thermographic analysis is performed on site, so the builder can make required changes before closing in the interior walls.

For buildings constructed directly in Nunavik and for those prefabricated in panels but assembled in Nunavik, thermographic analysis will be performed on site as soon as the suitable conditions are obtained. The minimum quantities of replacement materials initially specified in the construction contract (see section 3.2.4, Replacement of materials and products) can be used for immediate execution of the required remedial work, and subsequently replaced through annual procurement.

The contracts manager will simply have to deduct the cost of using these replacement materials from the payments due to the contractor performing the work. Here again, the analysis should focus on the qualitative aspect, although the quantitative aspect can provide valuable information on the actual performance of the facility and support the compilation of statistics for future follow-up, which provides crucial data in the event of a claim against the contractor performing the work.

In addition to constituting a valuable decision-making aid for construction contract managers when paying for work, production of a thermographic or infiltrimetry analysis report guarantees the quality of work and the expected performance for all components of the envelope. If the quality of work or the performance falls short of expectations, the contractor will then have no alternative but to make the necessary corrections.

APPENDIX XV: REVIEW PROPOSAL

We invite persons interested and wishing to participate in review of the *Guide to Good Practices* to submit proposed changes using this form.

Please indicate the section number in question and the page number: _____

Briefly describe the amendment, addition or deletion proposed: _____

State your reason for submitting this proposal (experience in the field, appearance of a new technology, other): _____

Name and occupation: _____

Organization or company: _____

Telephone number and email address: _____

Date: _____

Mailing address: _____

Please send your proposal to the following address:

Direction de l'expertise-conseil et du soutien à l'industrie
Société d'habitation du Québec
Jacques-Parizeau Wing
1054 Louis-Alexandre-Taschereau Street, 4th Floor
Québec QC G1R 5E7
lhn@shq.gouv.qc.ca

APPENDIX XVI: FOUNDATIONS

Tableau 1 : Comparaison entre les différents types de fondations.

Type of foundation		Cost \$ to \$\$\$	Avantage	Drawbacks	Suggested use and other notes
Superficial foundations	Granular invert	\$-\$\$	• Generally provides excellent performance when well designed and correctly installed • Effective for construction on warm and ice-rich permafrost • Proven, effective method locally well known • Requires machinery usually available in communities	• Cost rises greatly if it must be produced with crushed granulate or on steep slopes • Uses increasingly scarce natural granulate resources • If machinery is unavailable, mobilization can increase costs considerably • Frequent compaction problem in communities without a compacting roller	• In almost all situations, unless topography requires excessive amounts of granulate or if there is a shortage of granulate • Not a foundation system per se, must be combined with other techniques (see below) • Fill must be well compacted and correctly profiled on the surface to drain surface water adequately
	Beams on grade	\$	• Low cost • Provides greater bearing capacity than beams on footings, piles or tripods • Provides some flexibility for differential movements depending on beam configuration • Simple and easy to build • Does not require specialized labour or machinery • Building is easily moved	• Structure service life may be shortened due to potential movements • Subject to seasonal freeze and thaw movements • If beams are not suitably anchored, structure may shift and tip beyond foundation in strong winds • Cannot provide sufficient air space for effective heat and snow evacuation from beneath building • Requires a granular invert	• A configuration with three or four rows of parallel beams under the structure rather than a single continuous beam around the perimeter ensures greater flexibility and strength • Not recommended for heated buildings, but adequate for unheated structures and those that must be moved as required
	Timbers on footings	\$	• Low cost • Simple and easy to build • Does not require specialized labour or machinery • Easily adjusted • Provides ventilated air space under building • Building easy to move	• Structure service life may be shortened due to potential movements • Subject to seasonal freeze and thaw movements • If beams are not suitably anchored, structure may shift and tip beyond foundation in strong winds • Requires a granular invert • Requires regular levelling to reduce risk of damage to structure	• One of the most commonly used foundation types in continuous and discontinuous permafrost zones • Essentially used on soils with low bearing capacity and for small buildings that pose little risk of damage from a reasonable degree of movement • Long used in Nunavik due to the little material needed and simplicity of installation, but increasingly abandoned in favour of piles or tripods on footings with adjustable jacks • Use of treated lumber recommended for foundation components in direct contact with the soil (footing) and foundation should be secured to main beams using metal brackets or other type of fastener

Superficial foundations	Piles or tripods with or without adjustable jacks, on footings resting on grade	\$	• Low cost • Easy to build • Does not require specialized labour or machinery • Easy to level • Provides ventilated air space under building • Can be built with a single material (lumber, steel or concrete) or combination of materials • Building easy to move	• Structure service life may be shortened due to potential movements • Subject to seasonal freeze and thaw movements • If piles or tripods are not securely anchored, structure may shift and tip beyond foundation in strong winds • Requires a granular invert • Requires regular levelling to reduce risk of damage to structure	• May be used in most situations where construction of a granular invert is justified • Best known and most common foundation system in Nunavik • Excellent performance • Treated wood used as footing can be replaced with concrete poured in place or small prefabricated slabs
	Piles with or without adjustable jacks, on embedded footings	\$\$	• Resists lateral loads without requiring additional bracing • Affected little by seasonal freeze and thaw movements. • Easy to level • Provides ventilated air space under building • Can be built with a single material (lumber, steel or concrete) or combination of materials	• Requires excavation machinery • Long, delicate preparation and construction stages can delay progress • High risk of thermal disturbance of permafrost (permafrost exposure, thermal erosion) and unstable excavation walls • If no precautions are taken, this foundation type is subject to adherence frost heave acting on the portion of the pile passing through the active layer • Compaction and uplift can occur during thermal readjustment of soil after this type of foundation is installed. This readjustment can take a few seasons to achieve a new balance.	• Used fairly often in the Arctic • Common practice suggests building the foundation at start of winter, when the active layer is thickest and cold temperatures help refreeze back-filled area • Excavation and installation of foundation footings is advised one at a time to limit area and duration of permafrost exposure • In poorly drained areas, excavation walls must have a gentler slope (1V:4H) and a pump must be used to keep excavations dry. • In areas where excavation of the active layer is difficult despite these precautions, footing may be embedded in fairly thick fill to raise the permafrost enough to cover the footing
	Foundation wall on a continuous footing	\$\$	• Does not require specialized labour or machinery • Can bear heavy loads • Very stable bearing surface when system is well designed • Can be ventilated • Provides space under building for storage and installation of mechanical components	• Not adjustable unless it uses adjustable tripods or piers • Concrete quality must be monitored, which requires additional resources	• System recommended when loads are heavy • Suitable for footings resting on rock, non-frost-susceptible deposit or at a depth equal to or less than the expected permafrost table at the end of the building's service life • Can also rest on a full-size granular invert or one limited to the bearing area of the footing • May require excavation of a thin ice-rich deposit over rock and backfill

Superficial foundations	Slab on grade	\$\$	• Easy to build • Does not require specialized labour or machinery • Rigid structure reduces differential movements • Can support heavy equipment • Building can be heated if well designed	• Grading of land before installing slab may require excavation of rock • Large amounts of fill may be needed if land is sloped • Among the highest-risk foundation systems because there is direct heat transfer from building to underlying permafrost • Low tolerance for differential movement. • Foundation hard to releve	• Requires excellent-quality soil (rock or thin deposit of sand and gravel), because it can quickly become very problematic over ice-rich soil • Slab reinforcement recommended with steel rebar to increase rigidity and provide some resistance to potential differential movement • In addition to insulating the slab, design of this foundation type frequently includes a heat extraction system for heat from the building • In Nunavik, most serious foundation problems—those resulting in demolition, relocation or abandonment of the building—have involved heated buildings on slabs over ice-rich soil. Construction of residential buildings with a basement over ice-rich permafrost must be avoided. This type of foundation poses a high risk of problems.
	Three-dimensional foundation with multiple bearing points	\$\$\$	• Easy to build. • Does not require specialized labour or machinery • Rigid assembly that reduces differential movement • Minimal site preparation required • Reduced thickness of granular invert required • Ideal for renovation of existing buildings • Levelling is less frequent and less damaging to structure than with other adjustable foundation types • Building easy to move	• Costly to purchase • Specialized material not available locally • Interconnected structural members of foundation system limit access to mechanical components under building	• Used on soft ground susceptible to differential compaction • History of success in Canada's Far North • First system of this type in Nunavik built in 2013, performance to be monitored

Deep foundations	Adherence and point-bearing piles	\$\$-\$\$\$	• Resists lateral loads without requiring additional bracing • Easy to level if equipped with jacks • Provides ventilated air space under building • Can be built of different materials (lumber or steel)	• Requires detailed design and a site study • Requires specialized labour and machinery (drill and drilling) • Rusting possible	• Used when piles cannot be driven into rock • High-risk foundation technique in a context of climate warming, requires adjustable pile head and prior site study • Anti-heaving sheath recommended for portion of pile embedded in the active layer, or grease coating or polyethylene membrane
	Point-bearing piles	\$\$-\$\$\$	• Resists lateral loads without requiring additional bracing • Easy to level if equipped with jacks • Provides ventilated air space under building • Can be built of different materials (lumber or steel) • Piles are unaffected by freezing and thawing when well anchored in rock • Satisfactory reliability and performance in a context of climate change	• Requires specialized labour and machinery (drill and drilling) • Rusting possible	• Generally used when rock is less than 10 metres below the surface • Anchoring piles at least one metre in rock recommended to neutralize uplift forces generated by frost adherence in the active layer • Anti-heaving sheath recommended for portion of pile embedded in the active layer, or grease coating or polyethylene membrane • Adjustable heads recommended for piles embedded down to rock to absorb freeze and thaw movements

Foundations with heat extraction system	Ventilated foundation	\$-\$\$	• Effective • Economical • Easy to build • Does not require specialized labour or machinery • Simple principle	• Risk of infiltration when ducts are placed below the natural ground surface • Requires seasonal maintenance (closing check valves) • System must not allow complete refreezing of fill under building in discontinuous permafrost zones	• Used for buildings on a slab on grade • Ducts must be watertight and have sufficient diameter for inspection and maintenance • Chimney tops must be high enough to avoid being buried in snow drifts that often develop around buildings • If check valves are used, this system must be installed only on chimneys on upwind side of building to allow convection movement even when check valves are closed
	Thermosensor	\$\$\$+	• Satisfactory reliability and performance • Prove technology that keeps soil frozen around piles or other foundation type • System performance can be upgraded if necessary by adding a cooling system • Horizontal loop thermosyphons are easier to install than inclined thermosyphons and can freeze 1.4 times more soil volume.	• Very expensive and rarely used for residential buildings • More complicated design and construction require specialists • Requires a granular invert • Foundation difficult to relevel • Post-construction monitoring necessary (condition of thermosyphons and instrumentation) • Very few suppliers • May require regular maintenance if mechanical components are used to force convection (active system) • Inclined thermosyphons require special attention during installation to comply with the required installation angle and are less efficient than horizontal loop thermosyphons.	• Used to maintain frozen soil around piles or other foundation types Unlike thermopiles, thermosensors do not bear any structural load.
	Thermopiles	\$\$\$+			• Normally used for larger structures than residential buildings • Use may be interesting when an active layer of frost-susceptible soils subject to swelling can cause adherence heaving of conventional piles. Use may also be beneficial in warm permafrost areas with high potential for pile creep. • No examples of use of thermal piles in Nunavik or rest of Canada • Used extensively in Alaska
	Inclined thermsyphons	\$\$\$+			• Inclined and horizontal loop thermosyphons are used essentially under concrete slabs or crawl spaces to evacuate heat transferred to the soil by the building. • They should be used when a site could not be selected for construction of a concrete slab on conventional soil. • If a leak occurs, the fluid used must not degrade the permafrost and environment. • Loops should be able to be isolated as needed and radiators should be protected and located far from ventilation outlets.
	Horizontal loop thermosyphons	\$\$\$+			

Table 2: Relative purchase and installation costs of materials in Nunavik communities. These figures are provided as an indication only. They reflect prevailing costs at time of writing and must be validated for each community and each housing construction project. They may also vary significantly between northern communities depending on the quantity of materials needed for the project or on whether the equipment and other resources required are available locally.

MATERIAL	USE	APPROXIMATE COST (1)
Dynamited rock – pit run	Construction of granular inverts and roads	\$50/m ³
Natural sand and gravel from borrow pits	Construction of granular inverts and roads	\$30/m ³
Screened natural sand and gravel	Construction of granular inverts and roads	\$40/m ³
Pebbles and blocks, such as crusher rejects	Filling land beyond building footprint	\$25/m ³
Crushed stone up to 20 mm calibre	Construction of granular inverts and traffic layer of inverts and roads	\$100/m ³
Clean crushed stone	Drainage works	\$150/m ³
Excavation of unfrozen loose soils	Foundations, roads	\$15/m ³
Excavation of rock by dynamiting (large volumes)	Foundations, roads	\$40/m ³
Drilling	Installation of piles	\$1,000/pile in surface rock with pile embedded one metre into rock* \$1,800/ pile in shallow surface deposit, embedded one metre into rock*
Concrete	Foundations	\$2,000/m3 ³

* DEPENDING ON AVAILABILITY OF DRILLING EQUIPMENT. COSTS MAY VARY CONSIDERABLY IF MOBILIZATION OF SPECIALIZED LABOUR AND EQUIPMENT IS NECESSARY.

**BÂTISSONS
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