UFC 3-130-03
16 January 2025

UNIFIED FACILITIES CRITERIA (UFC)

ARCTIC AND SUBARCTIC FOUNDATIONS FOR FREEZING AND THAWING CONDITIONS

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ARCTIC AND SUBARCTIC FOUNDATIONS FOR FREEZING AND THAWING CONDITIONS

U.S. ARMY CORPS OF ENGINEERS (Preparing Activity)

NAVAL FACILITIES ENGINEERING SYSTEMS COMMAND

AIR FORCE CIVIL ENGINEER CENTER

Record of Changes (changes are indicated by **1**\ ... /**1**/)

Change No.	Date	Location

This UFC supersedes UFC 3-130-04, *Foundations For Structures - Arctic and Subarctic Construction*, and UFC 3-130-06, *Calculation Methods for Determination of Depth of Freeze and Thaw in Soil - Arctic and Subarctic Construction*, dated 16 January 2004.

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FOREWORD

The Unified Facilities Criteria (UFC) system is prescribed by MIL-STD 3007 and provides planning, design, construction, sustainment, restoration, and modernization criteria, and applies to the Military Departments, the Defense Agencies, and the DoD Field Activities in accordance with USD (AT&L) Memorandum dated 29 May 2002. UFC will be used for all DoD projects and work for other customers where appropriate. All construction outside of the United States, its territories, and possessions is also governed by Status of Forces Agreements (SOFA), Host Nation Funded Construction Agreements (HNFA), and in some instances, Bilateral Infrastructure Agreements (BIA). Therefore, the acquisition team must ensure compliance with the most stringent of the UFC, the SOFA, the HNFA, and the BIA, as applicable.

UFC are living documents and will be periodically reviewed, updated, and made available to users as part of the Military Department's responsibility for providing technical criteria for military construction. Headquarters, U.S. Army Corps of Engineers (HQUSACE), Naval Facilities Engineering Systems Command (NAVFAC), and the Air Force Civil Engineer Center (AFCEC) are responsible for administration of the UFC system. Technical content of UFC is the responsibility of the cognizant DoD working group. Defense Agencies should contact the respective DoD Working Group for document interpretation and improvements. Recommended changes with supporting rationale may be sent to the respective DoD working group by submitting a Criteria Change Request (CCR) via the Internet site listed below.

UFC are effective upon issuance and are distributed only in electronic media from the following source:

- Whole Building Design Guide website https://www.wbdg.org/dod.

Refer to UFC 1-200-01, *DoD Building Code*, for implementation of new issuances on projects.

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TABLE OF CONTENTS

FIGURES

TABLES

CHAPTER 1 INTRODUCTION

1-1 BACKGROUND.

The field of Arctic and Subarctic engineering, also known as cold regions engineering, covers a wide range of multidisciplinary topics and principles. Unique issues exist in the planning, design, construction, and operation of infrastructure and facilities in Arctic and Subarctic regions. Among them are permafrost, seasonal ground frost heave and thaw settlement, extreme low temperatures, high wind loads, heavy snow loads, and remote construction sites. Additionally, the implications of the rapidly changing climate in Arctic and Subarctic regions exacerbate these unique challenges.

The Unified Facilities Criteria (UFC) Arctic and Subarctic series includes five volumes that summarize relevant information and the most feasible approaches and solutions for planning, design, construction, and maintenance of infrastructure and facilities in the Arctic and Subarctic areas of the globe.

1-2 NEED FOR SPECIAL APPROACHES.

A defining characteristic of the Arctic and Subarctic in the context of this UFC is the presence of permafrost in soil and rock, as described in Chapter 2 of this UFC and in UFC 3-130-01. One definition of Arctic and Subarctic used by the Arctic Council, an intergovernmental group, includes permafrost and nonpermafrost areas located north of 51° N latitude, including most of Alaska, Greenland, and Iceland, as delineated on the “Geographical Coverage” page of the Arctic Monitoring & Assessment Programme website (www.amap.no/about/geographical-coverage). More broadly, principles described in this UFC apply to areas below the Arctic Circle, based on extreme cold weather and environmental characteristics like flora and fauna.

Frozen soil exhibits unique characteristics because of the ice within its interstitial spaces and the massive ice features that may be present in permafrost. The presence of ice introduces an important variable that can make material properties sensitive to changes over time. As a result, foundation design must consider factors such as variability in ground temperature (both seasonally and over the design life of a facility); ice content and heterogeneity, which affect material behavior under loading and produce additional variability within the frozen soil or rock matrix across a site; and pore water salinity, which changes the freezing point and affects a variety of material properties. Site development, changes in vegetation, and climate must also be considered because they affect permafrost conditions at a project site.

1-3 REISSUES AND CANCELS.

This document supersedes and cancels inactive UFC 3-130-04 and inactive UFC 3-130-06, dated 16 January 2004.

1-4 PURPOSE AND SCOPE.

The Arctic and Subarctic UFC series provides technical guidance and available technical requirements for planning, design, construction, and maintenance of DoD facilities worldwide for all Service elements in Arctic and Subarctic environments. These guidance and technical requirements are based on the International Building Code (IBC) and the requirements in UFC 1-200-01. The UFC 3-130 series covers many aspects of Arctic and Subarctic engineering, with the specific exception of pavements, which is incorporated in the UFC 3-250 and UFC 3-260 series, as discussed in UFC 3-130-01, paragraph 1-6.3. In addition to this volume, there are four other series volumes:

- UFC 3-130-01, *Arctic and Subarctic Engineering*. UFC 3-130-01 serves as an introduction to the Arctic and Subarctic UFC series.
- UFC 3-130-02, *Arctic and Subarctic Site Assessment and Selection*. UFC 3-130-02 provides applicability and technical guidance for geotechnical site assessment for the Arctic and Subarctic environment conditions.
- UFC 3-130-04, *Arctic and Subarctic Buildings*. UFC 3-130-04 includes building design in the Arctic and Subarctic areas.
- UFC 3-130-05, *Arctic and Subarctic Utilities*. UFC 3-130-05 provides criteria and guidance for the design of utility systems for military facilities in Arctic and Subarctic regions.

This UFC addresses foundation planning, design, construction, and maintenance issues pertinent to the Arctic and Subarctic that are related to the technical disciplines of geotechnical engineering, engineering geology, and construction engineering for buildings (vertical structures) and facilities such as roads and airfields (horizontal structures). Careful planning and consideration of both current site conditions and the changes in those conditions that may occur over the life of a project are essential when designing foundations in the Arctic and Subarctic. In addition to unique physical considerations (such as the difference between saline and nonsaline permafrost, variations in ice content within the soil, and geomorphic features such as ice wedges), the designer must also consider how conditions might change over time due to factors such as the following:

- Site development affecting ground thermal conditions and drainage
- Adjacent structures altering snow accumulation and shade sites
- Surface drainages that might change course over time
- Changes in climate affecting ground freezing and thawing

1-5 APPLICABILITY.

This UFC follows the same applicability as UFC 1-200-01, paragraph 1-3, for those geographic locations in Arctic and Subarctic regions worldwide.

1-6 GENERAL BUILDING REQUIREMENTS.

This UFC is an integrated part of the Arctic and Subarctic UFC 3-130 series. Use the other documents in this series in conjunction with this UFC to address construction aspects unique to cold regions. See UFC 3-130-01, Chapter 2, for the definitions of Arctic and Subarctic. This UFC modifies and supplements the criteria found in the core UFCs. Utility provider's or installation-specific requirements must be considered.

1-6.1 Geotechnical and Foundation Engineering.

Conventional foundation practice must be modified and adapted for use in Arctic and Subarctic regions to account for extremely low temperatures and unique ground conditions, such as permafrost, seasonal frost heave and thaw in soils, and climatic changes affecting ground conditions over time (for example, permafrost degradation and slope erosion and instability).

The designer of record (DoR) must also comply with the following UFCs, except when cold regions requirements dictate otherwise:

- UFC 3-220-04FA, *Backfill for Subsurface Structures* (Army and Air Force only)
- UFC 3-220-05, *Dewatering and Ground Control*
- UFC 3-220-08FA, *Engineering Use of Geotextiles* (Army and Air Force only)
- UFC 3-220-10, *Soil Mechanics*
- UFC 3-220-20, *Foundations and Earth Structures*

These documents present regulatory and industry standards that must be considered. They include general requirements that are applicable to foundation systems and are therefore not specifically covered in this document. Other (USACE) Engineering Manuals (EM), such as EM 1110-1-1804, *Geotechnical Investigations*, and EM 1110-2-2906, *Design of Pile Foundations*, may also contain general criteria not specifically covered in this UFC.

1-6.2 Structural.

Use UFC 3-301-01, *Structural Engineering*, and UFC 3-301-02, *Design of Risk Category V Structures, National Strategic Military Assets*, as needed for design and analysis of DoD buildings and other DoD structures assigned to Risk Category V for national strategic military assets (see UFC 3-301-01, Table 2-2).

1-7 LEVEL OF CONSTRUCTION.

See UFC 1-200-01, paragraph 1-3.2, for the definitions of permanent construction, temporary construction, and facilities in support of military operations.

1-8 CYBERSECURITY.

All control systems (including systems separate from an energy management control system) must be planned, designed, acquired, executed, and maintained in accordance with UFC 4-010-06, *Cybersecurity of Facility-Related Control Systems*, and as required by the system's individual service implementation policy.

1-9 BEST PRACTICES.

Much of the state of practice for cold regions engineering, planning, design, and construction is not codified. Lessons learned and the experiences of the facility installation engineering staff are invaluable and may help to avoid potentially costly or catastrophic infrastructure failures. Appendix A presents general guidance on best practices for accomplishing certain foundation design and engineering services in extreme Arctic and Subarctic environments.

The DoR must review and interpret this guidance as it conforms to criteria and contract requirements and apply the information according to the needs of the project. If a best practices document guideline differs from any UFC, the UFC takes precedence. The DoR must submit a list of any best practices guidelines or requirements not discussed in a UFC that are being used for the project, along with documentation sufficient for review and approval prior to incorporation within the design, to the Government Project Manager.

1-10 GLOSSARY.

Appendix B contains acronyms, abbreviations, and a glossary of terms used in this document. See UFC 3-130-01 for definitions of additional terms.

1-11 SUPPLEMENTAL RESOURCES.

Appendix C contains a list of supplemental sources for information on subjects related to cold regions engineering, design, and construction. These resources are valuable tools for the civil engineer and contain additional information on topics pertinent to and affiliated with construction of foundations in the Arctic and Subarctic. See UFC 3-130-01 for additional resources for cold regions engineering.

1-12 REFERENCES.

Appendix D contains a list of references used in this document. Unless otherwise specified, the most recent edition of the referenced publication applies.

CHAPTER 2 PLANNING AND DESIGN

2-1 INTRODUCTION.

This chapter describes general factors to consider during planning and initial selection of the foundation concept and highlights some unique issues associated with foundations in the Arctic and Subarctic that should be considered.

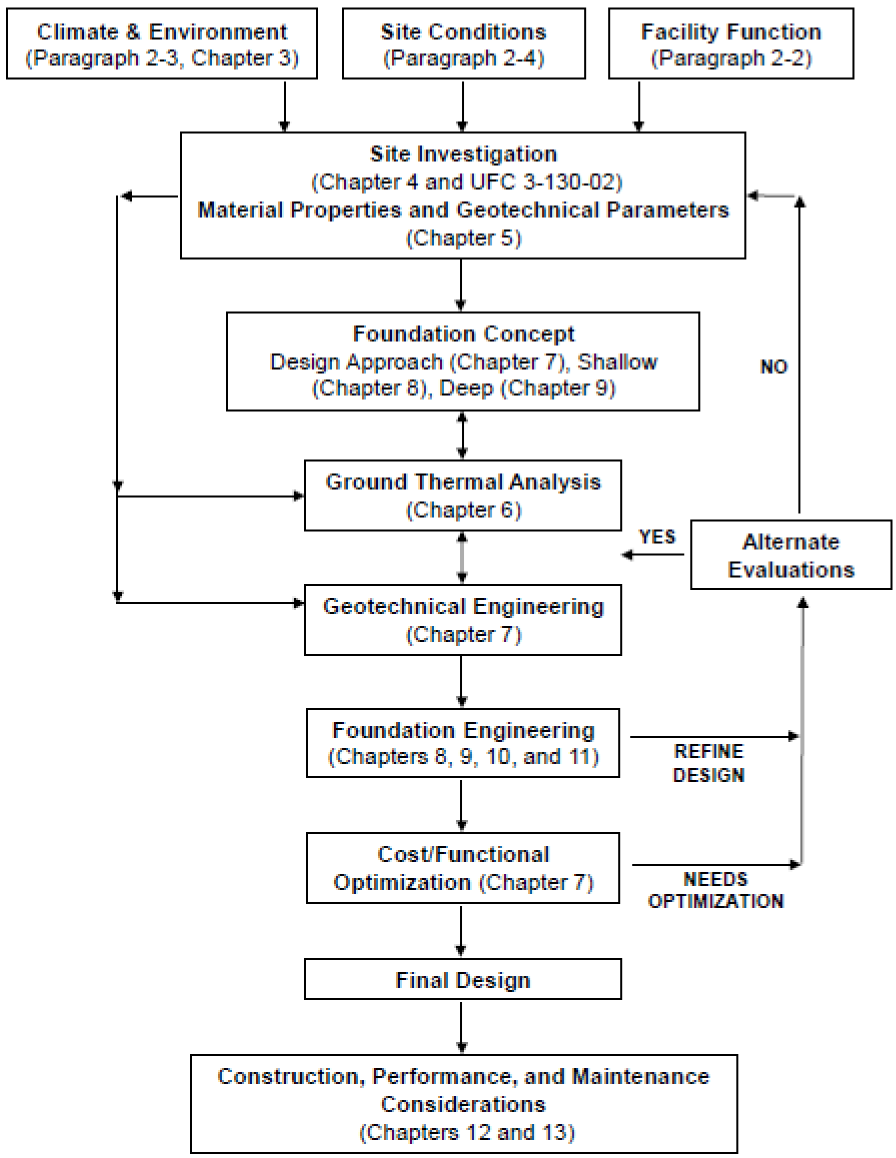
The planning, design, construction, and maintenance of foundations in the Arctic and Subarctic are affected by the unique conditions found in these regions, including the presence of permafrost and deep seasonal frost, extreme air temperatures, and sensitive environmental conditions. Complex supply and construction logistics associated with remote locations add to these challenges. Planning and formulating the foundation concept is an important first step in the design process. Figure 2-1 illustrates general steps to follow when evaluating foundations. As shown in Figure 2-1, facility function, site conditions, climate, and environment need to be considered early in the process because these considerations influence the geotechnical design parameters, the site investigation approach (see UFC 3-130-02), and the laboratory testing approaches. Figure 2-1 also shows how subsequent steps may provide feedback loops, leading to further iterations of site characterization and design before a final solution is selected.

2-2 FACILITY FUNCTION AND OTHER PLANNING CONSIDERATIONS.

The facility function helps define the level of site investigation required and relates to design loads and design life, with mission-critical facilities and life safety concerns typically having more stringent design criteria. Design life is an important consideration because, as noted in paragraph 1-1.2, frozen ground is subject to changes in behavior over time that may be the result of many factors. Changes in frozen ground behavior may include the following:

- Thaw settlement due to warming ground temperatures;
- Seasonal frost heave due to freezing of frost-susceptible soil;
- Changes in active layer depth due to changes in surface conditions;
- Differences in response to load duration and type (such as creep under long-term loads or loss of adfreeze strength due to vibratory loading);
- Changes in soil response because of frost heave; and
- Changes in material properties, depending on factors such as duration of load, change in ground temperature, change in surface conditions, or the duration of load and type of loading.

Figure 2-1 Arctic and Subarctic Foundation Evaluation Process



2-2.1 Approvals and Permits.

See UFC 3-130-01, paragraph 1-13, for the general approval and permit processes for Arctic and Subarctic construction.

2-2.2 Risk and Resilience.

See UFC 3-130-01 and UFC 2-100-01, *Installation Master Planning*, for a discussion of risk and resilience. The concepts of reliability-based design are incorporated into industry standard documents such as American Society of Civil Engineers (ASCE) Standard 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Risk assessment and infrastructure vulnerability or resilience assessment are emerging topics for cold regions engineering, and guidance is limited. However,

Figure 2-1 illustrates a feedback loop showing how a design evolves as different factors are considered.

2-2.3 Planning and Logistical Considerations.

In the Arctic and Subarctic, foundation systems are often significant cost items affected by facility use and operational constraints. For example, hangars must have at-grade access for aircraft and require special foundation systems to control potential differential movement between the structure and the apron, whereas one- or two-story buildings may be more easily elevated to decouple heat flow from the building into the underlying soil and ensure permafrost preservation. See UFC 3-201-01, *Civil Engineering*, to conduct a preliminary analysis of the existing conditions at the site; this might include conducting a geotechnical site investigation or a topographic survey and documenting environmental considerations. See UFC 3-130-02 for site analysis topics specific to the Arctic and Subarctic. Installation-specific design preferences and standards may also apply. These installation-specific issues must be considered with input from responsible engineering and operations personnel as part of the system design analysis.

2-2.3.1 Remote Site Logistics.

Military installations in the Arctic and Subarctic are frequently in remote locations and may only be seasonally accessible. Remote site logistics must be considered because these will differ with location and may include seasonal restrictions on access to some sites due to shipping arrival and departure restrictions caused by sea ice and weather and mobility changes that occur as the ground freezes and thaws. Construction schedules may dictate procuring materials up to 12 months in advance or prepositioning equipment and materials because of seasonal restrictions on access. Careful planning is required to establish and maintain construction schedules. Project design teams should be consulted early in the planning process to help identify project criteria with significant logistical impacts.

Modular construction techniques and prefabricated elements are important for military construction because these facilities may need to be expediently constructed in all seasons. Where road or airfield access was possible, truck- and airlift-capable modules have been used successfully in Alaska to expedite the construction of facilities. Additionally, large sealift modules weighing greater than 5,000 short tons (4,500 metric tons) have been used to deploy complex facilities when there were limited windows of operation. If heavy modules are to be moved, it is critical to design roads and module offloading facilities to accommodate loads imposed by self-propelled module transporters used to move heavy modules. Bridges for river crossings are especially important during module movement, and local ground conditions or other logistical considerations will dictate the locations of suitable crossings.

2-2.3.2 Personnel and Equipment.

Personnel and equipment requirements must also be considered. The efficiency and productivity of personnel and equipment are reduced when working in low temperatures, and the combination of wind and blowing snow can create major construction and operational problems even when the total precipitation is low. Equipment often requires winterization to ensure proper operation during periods of very low air temperatures. Logistics may not allow properly sized equipment to be used, thereby constraining the earthwork and foundation construction. See UFC 3-130-01 for additional resources on personnel and equipment operations.

2-2.4 Foundation Materials.

Specific materials, such as low-temperature steel or cement and grout formulated for placement at freezing temperatures, are often required for constructing Arctic and Subarctic foundation systems to ensure proper performance. In addition, earthworks may require nonfrost-susceptible soil (NFS). Specialized cold regions building design criteria and guidance are fully discussed in UFC 3-130-04.

2-3 CLIMATE AND ENVIRONMENT.

Climate and environment are two major elements to consider when planning projects and selecting foundation alternatives in the Arctic and Subarctic. For general information on environmental conditions, see UFC 3-130-01, reports such as *Permafrost and Related Engineering Problems in Alaska,* by Ferrians et al., and other supplemental references listed in Appendix C.

2-3.1 Climate Models and Predictive Tools.

Climate refers to the average weather conditions described statistically over periods of months to years, while *weather* refers to short-term variations in the state of the atmosphere (for example, wind, air temperature, cloudiness, and moisture) that occur over a period of minutes to about 15 days.[1] Climate-related inputs have traditionally been estimated by interpolating datasets that are often limited. While using historical data may be appropriate for estimating conditions in the next 10 to 20 years, observed trends suggest that these data may be less suitable for predicting climate more than 30 to 40 years in the future. Therefore, current practice is evolving toward using global climate models (GCM) to understand both the magnitude and uncertainty of possible changes. Chapter 3 and paragraph A-5 contain further discussion of the application of GCMs and climate modeling.

In addition to GCMs, there are predictive tools, such as the Scenarios Network for Alaska + Arctic Planning (SNAP) tool that was created by the University of Alaska Fairbanks and is available on their website (www.uaf-snap.org). SNAP is based on an average of five GCMs and can be used to facilitate estimating factors such as future air temperature and precipitation when a full analysis of GCM models is not warranted due to limitations in scope, schedule, or budget. Considerable judgement is required when selecting climate inputs for use in design, whether from specific tools or GCMs. Limitations and assumptions built into models must be understood before adopting the results as a basis for design.

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[1] *Glossary of Permafrost and Related Ground-Ice Terms*, Harris et al.; *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms*, van Everdingen.

2-3.2 Environmental Considerations.

Paragraphs 2-3.2.1 through 2-3.2.4 describe aspects of the environment that can affect site conditions over the life of the project. These elements are also significant factors in ground thermal analyses (see Chapter 6) and are used to forecast the depth of seasonal frost penetration and changes in ground temperature over the life of the project.

2-3.2.1 Vegetation.

The presence or absence of vegetation on a site affects the surface energy balance and ground thermal regime in complex ways.[2] For example, vegetation provides shading that helps keep solar effects low in summer, but it can also enhance snow accumulation that insulates the ground surface, thereby reducing winter cooling. Figure 2-2, which is based on a study of permafrost dynamics near Fairbanks, Alaska, illustrates the effects of vegetation on the depth of the active layer and the top of permafrost.

2-3.2.2 Air Temperature.

In the Arctic and Subarctic, air temperatures have been increasing and are expected to increase further, based on both observed trends and future projections. Air temperature is an important driver of changes in ground surface temperature and, thus, is a factor in the design of shallow and deep foundation systems and passive refrigeration, such as thermosyphons. GCMs tend to have a higher level of agreement (less uncertainty) regarding future air temperature than other environmental parameters. See UFC 3-130-01 for additional information.

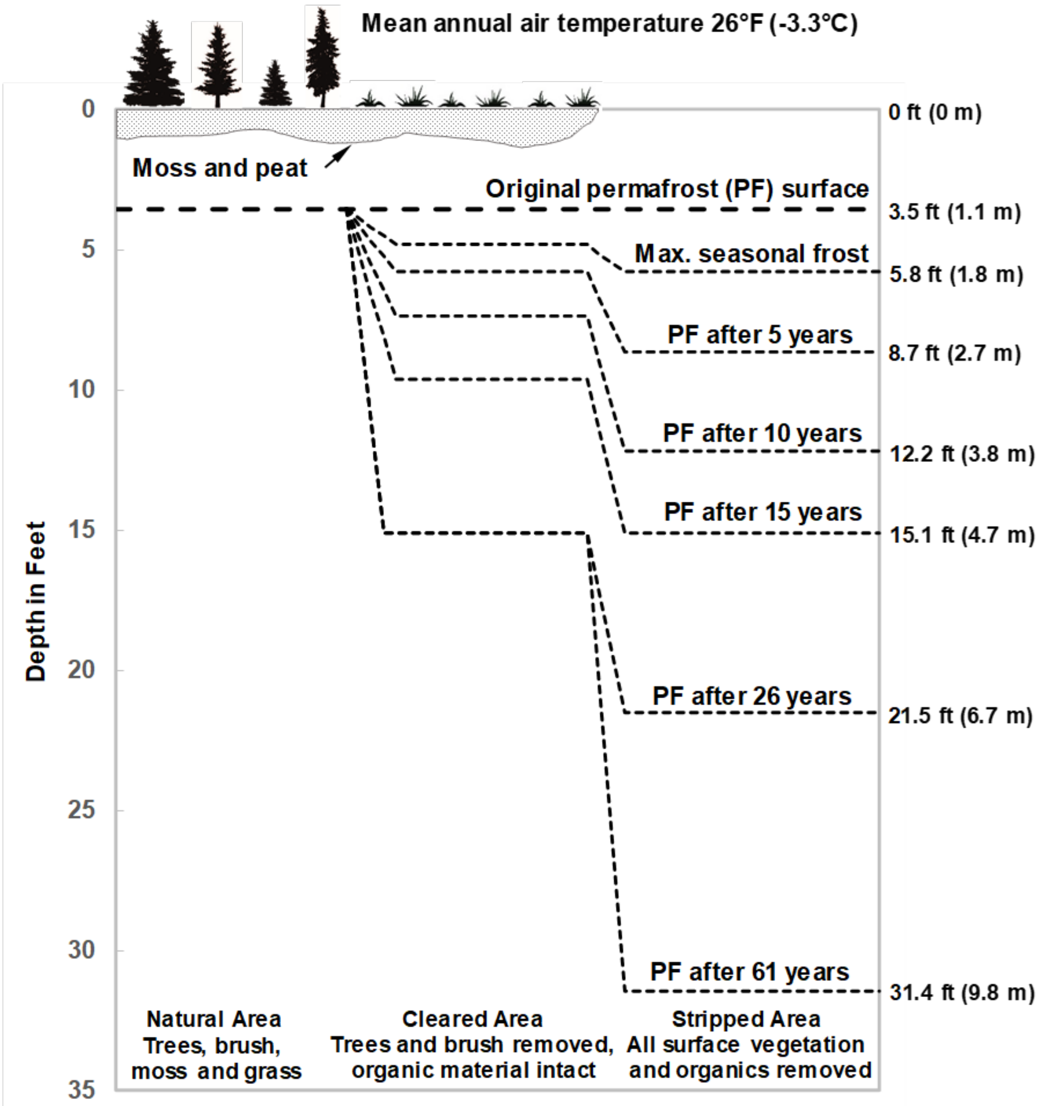
2-3.2.3 Precipitation.

2-3.2.3.1 Effects.

Precipitation in the form of rain or snow can alter ground conditions. Snow insulates the ground surface, locally affecting ground temperature and the depth of the active layer in permafrost areas. Changes in precipitation can also lead to alteration of drainage patterns and saturation in subsurface materials. In seasonal frost areas, increased saturation can lead to increased frost heave and to soil strength changes that affect the performance of horizontal structures. Developing appropriate design criteria for precipitation and runoff may require considering future conditions, which can be predicted using GCMs. However, judgment must be used when interpreting predictions of future precipitation because these often involve a greater amount of uncertainty than temperature predictions (see paragraph 3-3.2).

[2] “Permafrost and Terrain Conditions at Northern Drilling-Mud Sumps: Impacts of Vegetation and Climate Change and the Management Implications,” Kokelj et al.; “Ground Temperatures and Permafrost Warming from Forest to Tundra, Tuktoyaktuk Coastlands and Anderson Plain, NWT, Canada,” Kokelj et al.

Figure 2-2 Permafrost Degradation and Vegetation Effects



Source: "Permafrost Dynamics at the Fairbanks Permafrost Experimental Station Near Fairbanks, Alaska," by Douglas et al., Figure 9. Reproduced with permission of the International Permafrost Association.

2-3.2.3.2 Volume and Runoff.

Precipitation volume and patterns of runoff are changing due to changes in climate. These changes influence the design of drainage and hydraulic structures in various ways:

- They exacerbate permafrost degradation, requiring relocation of drainage structures.
- They can affect both surface water and groundwater flow, creating design issues such as increasing aufeis and thermo-erosion of permafrost.

- Increased surface water flow may cause flooding if culverts are not appropriately sized to accommodate increasing flows over time.
- An increase in ponded water intensifies the degradation of permafrost and increases the total depth of thawed soil and the formation of taliks.
- Changes in drainage pathways can lead to increased pore pressures, in turn reducing slope stability and altering the seismic hazard, because shallow surface slope failures may increase if these materials become saturated, and the potential for liquefaction may increase with changes in saturation.

Chapter 11 presents additional drainage considerations.

2-3.2.3.3 Snow Accumulation.

The accumulation of snow around structures must be considered during design. Blowing snow that can cause snow drifts influences the orientation of the facility and the type of foundation that is selected. Specialized modeling may be required to understand snow accumulation patterns for complex structures or for sites with multiple components or terrain variation. See UFC 3-130-01 for information on snow drifts.

2-3.2.4 Wind.

Wind affects surface energy balance and knowledge of wind speed may be required for some analyses of ground freezing. See UFC 3-130-01 for a discussion of snow drifting, wind, and wind chill. Buildings must be designed to ensure snow does not accumulate beneath elevated structures or create drifts that impede access. Deep snow drifts, especially at the margins of work pads and embankments, can affect the thermal balance and result in unanticipated accumulations around buildings.

2-4 SITE CONDITIONS.

Subsurface conditions at sites in the Arctic and Subarctic may be underlain by continuous or discontinuous permafrost or may be seasonally frozen (absent of permafrost). Each of these conditions poses unique challenges for the foundation designer that require some level of site investigation and field testing, coupled with laboratory testing, to determine appropriate geotechnical properties. Ground temperature monitoring, as discussed in UFC 3-130-02, must be considered at sites in permafrost areas. As illustrated in Figure 2-1, the design properties selected will also be influenced by the climate, environment, and facility type or function. Chapter 4 provides further details on site conditions.

2-4.1 Permafrost.

The presence of permafrost is a significant factor to consider when designing foundations; the effects of thawing, creep under sustained load, and changes in strength parameters due to changes in ground ice content and temperature must be considered. The engineering parameters of frozen ground include soil type, soil or rock temperature, moisture (ice) content, saline content, bulk unit weight, unfrozen moisture content, and structure of ground ice. Chapter 5 presents a general discussion of the material properties of frozen ground.

Although ground temperature is used to define permafrost, for engineering purposes ice content and thaw stability are of critical importance when discussing frozen ground. Figure 2-3 and Figure 2-4 illustrate the change that can occur when frozen ground containing excess ice undergoes a phase change from the frozen to the unfrozen state. Note the loss of structure and the production of excess moisture as free water.

Figure 2-3 Frozen Silt with Excess Ice

Figure 2-4 After Thawing (Settlement and Strength Loss)

2-4.1.1 Standard Terminology and Classification.

For definitions of terms describing frozen ground for engineering purposes, see UFC 3-130-01 and ASTM International (ASTM) Standard D7099, *Standard Terminology Relating to Frozen Soil and Rock*. ASTM D7099 references other documents, such as *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms,* by van Everdingen, and *Glossary of Permafrost and Related Ground-Ice Terms,* by Harris et al., that include terminology for permafrost, ground ice, and cryogenic processes.

During site investigations, frozen soil and rock must be classified according to ASTM D4083, *Standard Practice for Description of Frozen Soil (Visual-Manual Procedure)*, in addition to standard logging procedures. This standard describes the classification of important conditions such as ice bonding and the presence of excess ice.

2-4.1.2 Ground Temperature—Seasonal Change.

Ground temperatures change seasonally in the Arctic and Subarctic. Therefore, seasonal freezing and thawing are design considerations in both the Arctic and Subarctic. Additionally, when permafrost is present, variations in ground temperature with depth must be considered during foundation selection and design. The behavior of frozen ground is both temperature and time dependent, and properties such as adfreeze strength can change from strong to weak depending on the season and loading conditions.

Ice strength is a function of temperature and applied stress. In general, the mechanical properties of frozen ground, such as stiffness, improve or increase as ground temperatures decrease. Stiffness dramatically decreases when soils, and the ice within them, change from frozen to thawed. Therefore, it is beneficial to prevent frozen ground from warming and, in some cases, to cool the ground through a combination of refrigeration and insulation. However, the magnitude and duration of load application are also significant because ice in the foundation materials will creep over time.

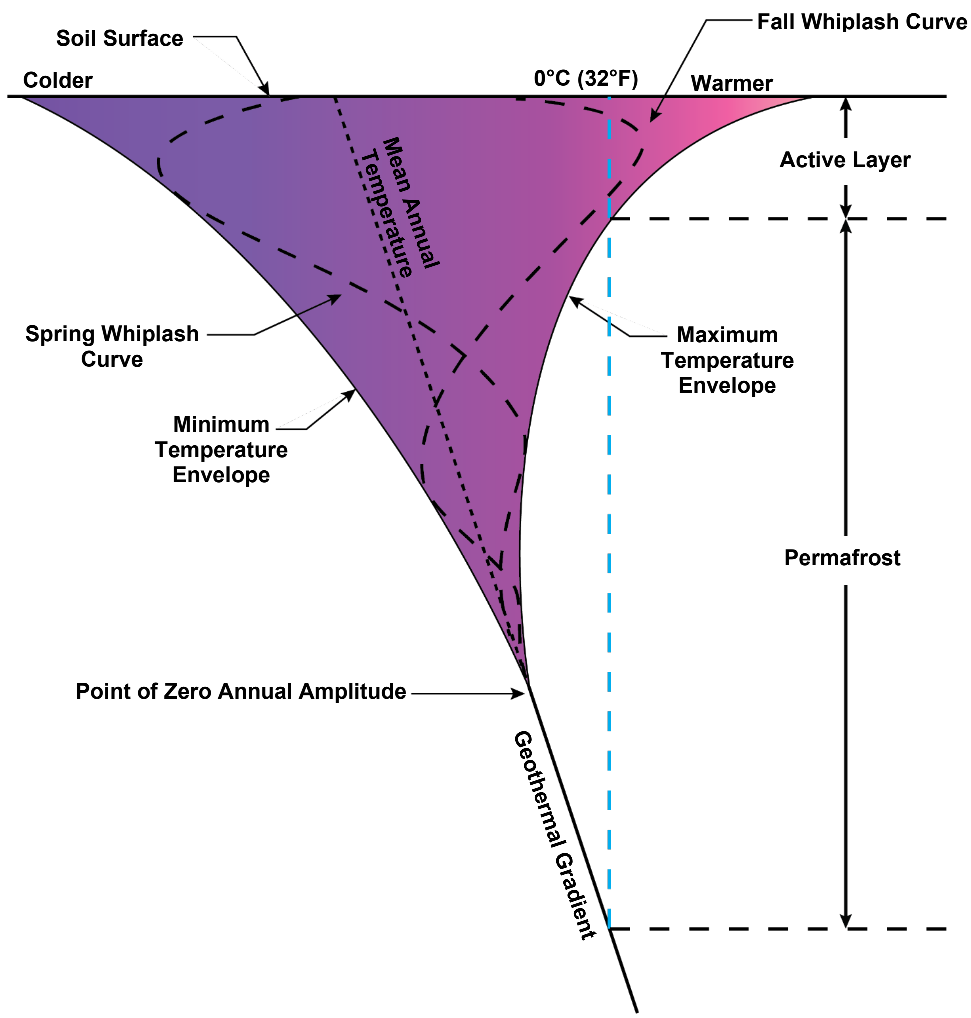
2-4.1.3 The Trumpet Curve.

A trumpet curve like that shown in Figure 2-5 is often used to depict the range of ground temperatures that occur at depth over time. The Figure 2-5 curves are generalized and trumpet curves will differ at each site depending on site conditions and the site's location within the Arctic and Subarctic. Trumpet curves are useful for illustrating important features that are commonly referred to in literature and in engineering documents, such as the following:

- Active layer: The zone of seasonally unfrozen ground extending to some depth below the ground surface in permafrost areas, or the depth of seasonally frozen ground in nonpermafrost areas.
- Whiplash curve: Ground temperature at a given moment; in aggregate, these form the trumpet curve.
- Trumpet curve: The envelope of ground temperature bounding all whiplash curves. The shape and limits of the trumpet curve may shift right or left depending on ground temperature and with time at a given site in response to changes in ground temperature.
- Point of zero annual amplitude: The point where the average ground temperature does not change seasonally.

The zone within 1 ft to 6 ft (0.3 m to 1.8 m) below the base of the active layer is sometimes referred to as the *transient layer*. The transient layer is not defined by its thermal state but is instead characterized as an ice-rich zone that acts as a thermal buffer to protect the underlying permafrost due to its relatively higher ice content and the significant heat needed to thaw this layer.[3] This layer can thaw partially or completely when the active layer deepens due to factors such as climate change or site development, resulting in significant thaw settlement. In areas where permafrost has been degraded, the transient layer may not be present.

Figure 2-5 Trumpet Curve Bounding Changes in Ground Temperature with Depth



2-4.1.4 Sources of Ground Temperature Data.

Direct measurement of ground temperature is preferred during the definition of site conditions, which will support the final design. During planning, site-specific data may not be available, and in this case, reference data can sometimes be obtained from other sites that are part of a global permafrost monitoring network and from UFC 3-130-01. Predictive tools, such as the Permafrost Temperature Tool from the University of Alaska Fairbanks Geophysical Institute Permafrost Laboratory, are also being developed to

[3] “The Upper Horizon of Permafrost Soils,” Shur; “The Transient Layer: Implication for Geocryology and Climate-Change Science,” Shur et al.

facilitate assessment of ground temperatures within 3 to 6 ft (1 to 2 m) of the ground surface. Synthetic ground temperature profiles can also be generated using numerical modeling, but reference data are still needed for calibration of these models (see Chapter 6).

2-4.1.5 Permafrost Distribution and Extent.

Gathering sufficient baseline data about site conditions in permafrost areas, including ground temperature, the heterogeneity of ice content, and soil and rock types, is an important aspect of early development planning. This is discussed further in UFC 3-130-02. It is important to consider the vertical extent of permafrost present at a site and to understand the ground temperature profile at a given location when planning projects. In the absence of site-specific data, refer to UFC 3-130-01 and to regional maps produced by regional governmental agencies or to other information in technical literature that can provide context that may be useful for estimating baseline conditions for planning studies.

The depth of permafrost exceeds 1,000 ft (305 m) along the Arctic coast of North America, and average ground temperature may be approximately 19°F (−7°C), while further south or in areas such as the Yukon-Kuskokwim Delta and interior Alaska, permafrost is discontinuous or sporadic, with ground temperature warmer than 28°F (−2°C). At a regional scale, climate is the main factor controlling permafrost distribution. At a local scale, permafrost conditions are also related to the local terrain and geological history. The permafrost–terrain relationships in the zones of discontinuous permafrost are generally more complex than those in the continuous zone.[4] Permafrost in the discontinuous zone is also typically warmer and more sensitive to factors such as terrain, vegetation, climate, and site development. The presence of ice-rich or saline permafrost at relatively shallow depths (<50 ft [15 m]) will also affect the overall performance of foundation systems.

2-4.1.6 Submarine Permafrost.

Special attention is required when designing infrastructure or utilities, such as pipelines or subsea cables, at the transitions between onshore and offshore permafrost areas. Historic sea level changes around coastal areas have resulted in nearshore areas where soil salinity may cause unique foundation engineering concerns. In these areas, the permafrost soil may be unbonded because the soil salinity can exceed that of seawater (which freezes at approximately 28.4°F [−2°C]). In these areas, it may be necessary to add additional cooling (such as passive thermosyphons) to foundation systems, especially in transition areas crossed by pipelines and other utilities.

2-4.1.7 Soil Salinity.

Soil salinity is an important material property to define during site investigation because it affects both ice bonding and soil strength. Depending on the depositional history at a site, it may be a significant design consideration, resulting in unfrozen moisture content,

[4] *The Periglacial Environment*, French.

brine pockets, and the presence of soil that behaves as if it is unfrozen. Paragraph 5-3.1 presents an additional discussion of soil salinity and its effect on material properties.

Saline permafrost is found in coastal areas of the Arctic that were submerged during periods of sea level rise and marine sedimentation and in areas, such as around Hudson Bay, that have experienced isostatic uplift. Saline soil is also found in permafrost areas with limited precipitation and relatively dry climates, such as the Tibetan Plateau.[5] For engineering purposes, salinity values are typically reported as concentrations in parts per thousand (ppt), with values greater than 10 to 12 ppt being high enough to influence mechanical behavior. Values up to 30 ppt are not uncommon, but higher concentrations, such as 80 to 100 ppt, also occur and are of particular concern because of the reduction in shear strength and the increased creep rate associated with frozen saline soil (see paragraph 9-5.3.4.2).

2-4.2 Seasonal Frost When Freezing Index Greater than 4,500°F-Days.

2-4.2.1 IBC and SEI/ASCE 32.

Section 1809.5 of the *International Building Code* (IBC) addresses frost protection of shallow foundations and requires, with limited exceptions, that the foundation extend below the frost line; be constructed in accordance with SEI/ASCE 32, *Design and Construction of Frost-Protected Shallow Foundations*; be erected on “solid rock”; or bear on soil that is permanently frozen. However, as noted by SEI/ASCE 32, it “applies to buildings on potentially frost susceptible ground with slab-on-ground or suspended floor foundations” but “does not apply to buildings on permafrost, to areas with mean annual outdoor air temperatures less than 32°F (0°C), or to areas with air-freezing indexes greater than 4,500°F-days (60,000°C-hr).”

The limitation on the applicability of SEI/ASCE 32 precludes its use in most of Alaska and other Arctic and Subarctic areas. The concepts outlined in this guidance can still be applied but require an extension to colder climates, such as in *Frost Protected Shallow Foundations (FPSF) for Interior Alaska Freezing Indices Between 4,000 and 8,000 Degree-Fahrenheit-Days: A Research Report,* by Perreault. In the absence of local building codes or other guidance, the DoR must be familiar with and apply fundamental principles related to permafrost and cold regions ground engineering, and perform thermal analyses when appropriate, to show that the design will not be affected by the freezing of foundation soils.

2-4.2.2 Floor Insulation.

Building foundations often incorporate floor insulation to enhance energy efficiency. Floor insulation in proximity to foundation elements reduces heat flow to the foundation soils, which may increase insulation requirements for shallow frost-protected foundations, even in areas where SEI/ASCE 32 is applicable. Areas with high heat flux, such as vehicle entrances and personnel doors, are especially susceptible to frost

[5] *Geocryology: Characteristics and Use of Frozen Ground and Permafrost Landforms*, Harris et al.

penetration below foundation elements and may require additional thermal analysis. Frost effects on foundations are discussed further in Chapter 7 through Chapter 9.

2-4.3 Topography and Slope Geohazards.

Topography and slope orientation affect permafrost distribution and properties, due mainly to the absorption of solar radiation. In general, the effect will be greater in areas of discontinuous permafrost. For instance, in the discontinuous permafrost zone, frozen ground is more common on north-facing slopes, where absorption of solar radiation is lower; the active layer on north-facing slopes is also generally thinner than on south-facing slopes. Higher levels of solar radiation absorption also occur due to reflection from the walls of buildings.

Slopes in permafrost areas can migrate downslope over time due to the force of gravity and depending on ground ice content, active layer moisture, and ground ice temperature. Some common slope movements that constitute geohazards and associated foundation engineering issues that must be considered when planning a project are discussed in paragraph A-7 and in other publications, such as in Chapter 25 of *Landslides: Investigation and Mitigation,* by Turner and Schuster, and in *National Assessment of Shoreline Change—Historical Shoreline Change Along the North Coast of Alaska, U.S.–Canadian Border to Icy Cape,* by Gibbs and Richmond.

2-4.4 Earthwork (Cut and Fill).

Development in the Arctic and Subarctic changes the local thermal regime in ways that may cause long-term degradation of permafrost or initiate changes in ground conditions that could affect foundation support and site stability. In general, unless engineering measures are implemented to mitigate thawing, earthwork leads to increased permafrost degradation due to changes in the surface energy balance. Earthworks may also modify the flow of surface water in ways that could lead to ponding at the toe of slopes or concentrate drainage along ditches that will enhance permafrost degradation if the drainage crosses ice-rich areas. In addition, cut slopes will expose underlying permafrost due to the removal of protective vegetation, which will lead to thawing and may initiate slope instability.

2-4.5 Surface Water Bodies.

Surface waters are often underlain by thawed zones, especially if they do not annually freeze to the bottom. Foundations and embankments located near lakes can be affected by degrading permafrost around the water body. These thawed zones are most significant when routing linear structures.

2-4.6 Site History.

An understanding of the changes in vegetation that may have occurred or been initiated by events such as wildfires, earthwork, or site development helps engineers determine appropriate foundation types.

2-4.6.1 Wildfire.

Wildfires occurring in areas of permafrost, including on tundra terrain, can trigger permafrost degradation with an increase in the active layer.[6] Primarily a concern during site selection, permafrost in areas that have had wildfires is likely to be different than in surrounding unburned areas. For instance, the insulation properties of burned vegetation are lower than for living vegetation, and, as a result, this change in insulation property can trigger a deepening of the active layer, an increase in permafrost temperature, and the melting of ground ice.

2-4.6.2 Past Development.

Past development and use of a site may affect permafrost conditions and is therefore an important consideration. While development is often easy to identify in the Arctic, in the Subarctic, where vegetation is more abundant, past use may not be evident, even though the past use may have already begun a process of long-term changes in the ground thermal regime.

2-4.6.3 Adjacent Structures.

It is important to consider the location of a facility and the effect it may have on other structures in the area. Adjacent structures in the Arctic and Subarctic can be affected by seemingly minor shading that locally changes environmental conditions and soil temperatures, changes in wind patterns and snow drifting that result in increased thawing, or changes in drainage that affect surface water and groundwater movements. Snow drifting may also affect building egress and increase snow removal requirements.

[6] “The Response (1958–1997) of Permafrost and Near-Ground Temperatures to Forest Fire, Takhini River Valley, Southern Yukon Territory,” Burn.

CHAPTER 3 CLIMATE

3-1 INTRODUCTION.

Climate is a key consideration for Arctic and Subarctic ground engineering projects because temperature, precipitation, and wind regimes can affect the thermal conditions of permafrost and partially frozen ground (see paragraph 2-3). Climate change has the potential to alter existing conditions in ways that may affect foundation design. It is important to understand how future climate projections can be considered for assessments of frozen ground to improve the resilience of foundation designs.

This chapter discusses the potential impacts of climate change on key climate variables associated with foundation engineering and outlines a strategy for using future climate projections to inform designs.

3-2 CLIMATE CHANGE CONSIDERATIONS.

Climate projections may be used to gain valuable insights on the magnitude and uncertainty of projected changes in climate from a range of GCMs and emissions scenarios. General information and a summary of the overall climate projection trends can be found in UFC 3-130-01.

The effects of climate change and site development are especially important considerations that must be addressed in design and construction planning to ensure that designs are resilient and adaptable. The following effects may need to be considered:

- Changes in ground ice temperature due to rising air temperatures.
- Changes in liquefaction potential that may occur due to ground thawing, whether natural or because of site activities.
- Changes in drainage requirements during the life of the facility that may occur due to changes in precipitation associated with changing climate in the Arctic and Subarctic. For example, increased precipitation may require larger-than-normal drainage structures or the incorporation of resilient design features that allow easy adaptation in the future. These changes may include shifts in natural drainages, increased flow, or changes in erosion-control requirements.
- Changes in coastal erosion processes are especially important in areas where changes in sea ice extent are creating longer open water seasons and increased thawing of coastal permafrost.

3-2.1 Global Climate Models.

As of 2024, future climate conditions are typically projected using GCMs that involve the mathematical representation of global land, sea, and atmospheric interactions over a long period of time. These GCMs were developed by various government agencies, but they share a number of common elements described by the Intergovernmental Panel on

Climate Change (IPCC). Climate projection data are available from over 30 GCMs in reports available from the IPCC (see paragraph A-5.1).

3-2.2 Downscaling Climate Data and Sources.

The climate projection resolution of GCMs is generally too coarse for direct use in foundation engineering applications because they do not resolve weather and extreme weather patterns or climatology at local scales. Rather than use GCM output directly, there are different options for analyzing climate projections at a regional scale. Downscaling methodologies incorporate region-specific information in various ways to improve the representation of climate and the temporal and spatial resolution of GCMs. Downscaled climate model outputs are available from a variety of sources, depending on the region being considered. Review available downscaled future climate data sources to select appropriate climate model outputs to inform foundation designs. To estimate climate change effects using downscaled future climate data, compare a long-term average future period, which will vary depending on the type of project and its design life, to a long-term modeled baseline period. See paragraph A-5.2 for data and resources available as of 2024.

3-3 KEY ENVIRONMENTAL PARAMETERS.

The following key parameters, estimated using downscaled GCM output, are used to inform foundation engineering design in a changing climate:

- Air temperature: Increasing air temperature will influence ground temperature. This will result in thawing of permafrost, thereby affecting ground engineering designs that assume frozen ground.
- Precipitation (rain and snow): Precipitation in the form of rain and snow will both remove heat from and insulate the ground. Changes in precipitation patterns and related consequences (such as water ponding or increased drainage) can be important design considerations when evaluating uncertainty in long-term performance.
- Wind: Projected changes in wind speeds affect surface energy balance and are especially important to consider when evaluating the performance of passive thermosyphons when selecting appropriate boundary conditions for thermal models (see paragraph 6-4.2).

Using a multi-model ensemble of climate projections, changes in the key environmental parameters may be estimated across a set of climate models and emissions scenarios to gain an understanding of the magnitude and uncertainty of projected changes from an established modeled baseline period. Paragraphs 3-3.1 through 3-3.3 describe considerations when using climate projections for this set of key environmental parameters.

3-3.1 Air Temperature.

In the Arctic and Subarctic, air temperatures are expected to increase and be more variable, given both observed trends and projections. GCMs tend to have a higher level of agreement (less uncertainty) for air temperature than for other environmental parameters. In addition, it may be necessary to consider uncertainty in air temperature projections for some foundation engineering designs. For example, thermosyphons may need to be sized to take advantage of short periods of colder-than-average temperatures rather than using annual averages that include periods when the thermosyphons may not be effective due to warm air temperatures.

SNAP downscaled climate projections include multiple climate models and emissions scenarios, including representative concentration pathways (RCP)4.5 and RCP6.0 (moderate emissions) and RCP8.5 (high emissions). See paragraph A-5.1 for discussion of RCPs. Using SNAP's set of downscaled climate projections, the mean annual temperature in Fairbanks, Alaska, under RCP4.5 is projected to increase by 4.7°F (2.6°C) in the near term (2030–2039) and by 7.6°F (4.2°C) in the longer term (2090–2099) relative to historical climate conditions under RCP4.5. Under RCP8.5, a mean annual temperature increase of 5.4°F (3.0°C) in the near term and 22.3°F (7.0°C) in the longer term are projected. With a wide range of possible future temperatures, uncertainty may be considered to inform foundation engineering design based on the design lifespan and level of risk involved.

3-3.2 Precipitation (Rain and Snow).

Precipitation changes surface and subsurface water flows related to the drainage and degradation of frozen ground and also insulates the ground when in the form of snow; hence, it is a significant design consideration. While climate models tend to have greater agreement regarding projected changes in temperature, projections of precipitation often involve a greater amount of uncertainty due to the finer spatial and temporal resolutions involved in the physical processes that are being modeled.

Using downscaled climate projections from SNAP, annual total precipitation for Fairbanks, Alaska, is projected to increase by 18% in the near term (2030–2039) and by 25% in the long term (2090–2099) under RCP4.5. Under RCP8.5, an annual total precipitation increase of 18% in the near term and 52% in the long term is projected. With a wide range of future total precipitation amounts (along with mean air temperature), more precipitation may be projected, with a greater portion falling as rain. The timing and magnitude of snow depth may also change, depending on how precipitation and temperature amounts are projected to change seasonally and the uncertainty across climate models and emissions scenarios. These changes in climate may be considered for engineering foundation design because they may affect permafrost depths and the underlying soil thermal properties.

3-3.3 Wind.

Wind affects the surface energy balance and must be considered when evaluating model inputs, such as n-factors, that are used to predict changes in the depth of thaw or in other boundary conditions noted in paragraph 6-4.2. Wind is also a significant factor when evaluating the performance of passive thermosyphons. Wind and related icing also have a significant effect on horizontal loadings and can result in harmonic motions that are accounted for in the IBC and other building codes. Historically, global wind speeds have been decreasing; however, in recent years, wind speeds have begun to increase.[7] Like precipitation, model agreement is typically low for wind speeds due to the finer spatial and temporal resolutions involved in the physical processes that are being modeled.

The community wind tool provided by SNAP provides historical and projected wind speeds for several Arctic communities. For Fairbanks, Alaska, this tool demonstrates that wind events above 7 mph (11.3 kph) may become more common in the future. This is especially true for durations of 12 hours or less and for wind events of 11.5 mph (18.5 kph) or less. More detailed information regarding projected wind speeds can be obtained from downscaled datasets such as the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). Extreme wind speeds are generally not well represented by climate models.[8] Projected wind speeds may be an important consideration for engineering foundation design because more frequent wind events may increase blowing snow, which can form drifts that insulate the ground and lead to increased thawing and can cover foundation elements that should remain exposed. Conversely, more frequent wind events may increase ground heat loss through convection, which may be beneficial to cooling and to the performance of foundation systems.

3-4 CLIMATE UNCERTAINTY.

3-4.1 Climate Projections.

When using climate projections, it is important to understand the limitations and assumptions built into the models before adopting the data as a basis for design. Because climate models generally provide outputs in a coarsely gridded (greater than 60 mi [100 km] grid resolution) format, differences can be expected when comparing to point observations, especially for climate variables that differ on finer spatial and temporal scales (for example, precipitation and wind). When using climate projections to inform design, use downscaled climate model output to better capture site-level conditions (see paragraph 3-2.2).

3-4.2 Use of Multiple Models.

Due to differences in future climate scenarios (RCP versus shared socioeconomic pathways [SSP], as discussed in paragraph A-5.1), climate model structure, parameterization, and initialization, an ensemble of climate projections must include different representations of both current and future climate for a given location. Because no one model or climate scenario can be viewed as completely accurate, the IPCC recommends that climate change assessments use as many models and climate scenarios as possible, or a “multi-model ensemble” (see page 79, *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Stocker et al.). For this reason, the multi-model ensemble approach is used to delineate

[7] “A Reversal in Global Terrestrial Stilling and Its Implications for Wind Energy Production,” Zeng et al.
[8] “Evaluating Wind Extremes in CMIP5 Climate Models,” Kumar et al.

the probable range of results and better capture the actual outcome (an inherent unknown). Percentiles may be used to express the distribution of future climate projections while also considering each of the models in the multi-model ensemble. The selection of which percentile to use should be based on the balance between the conservatism of the geotechnical engineering inputs used for design and the consequential risks. For example, projections at the 50th percentile represent the median projections, while the projections at the 95th percentile represent an outcome where 95% of the projections are at or below this value.

3-5 CLIMATE AND CONTINUAL IMPROVEMENT.

The *Guide on Climate Change Adaptation for the Mining Sector*, prepared by Golder Associates, provides a stepwise approach to incorporating climate change adaptation into decision-making processes to increase climate change resilience at mine sites. This document is not specific to Canada and can be applied globally. The document provides a three-stage framework for incorporating climate change in decision making:

- Assessing climate risk. This assessment must include use of DoD-specific tools as applicable to the project type.
- Developing adaptation pathways.
- Implementing adaptation pathways.

In this iterative three-stage process, each stage of the cycle should be reevaluated based on the outcomes of previous stages, updates to climate projections, and changes to infrastructure. Reevaluation is based on the results of monitoring and surveilling the adaptation pathways and whether established triggers or thresholds were met. For example, the need for reassessment will arise when there are updates to the climate projections or changes to the infrastructure or operations of the mine component. The reassessment can be included as part of existing continual improvement processes.

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CHAPTER 4 SITE INVESTIGATIONS

4-1 GENERAL.

Requirements and guidance regarding site assessment, characterization, and monitoring for Arctic and Subarctic construction are presented in UFC 3-130-02. Additional general site investigation criteria are provided in UFC 3-201-01 and UFC 3-220-01, *Geotechnical Engineering*. See paragraph A-2 for additional resources.

4-2 INVESTIGATION APPROACH.

4-2.1 Scope.

The scope of site investigations in areas characterized by permafrost or by freezing and thawing ground conditions must follow the approach outlined in UFC 3-130-02 and incorporate strategies and investigation techniques discussed in references such as *Cold Regions Pavement Engineering,* by Doré and Zubeck; *Permafrost Engineering Design and Construction,* by Johnston; and *National Standard of Canada CAN/BNQ 2501-500/2017: Geotechnical Site Investigations for Building Foundations in Permafrost Zones*, by Bureau de Normalisation du Quebec. In general, the scope of a field program should progress from broad (low resolution) reconnaissance that defines general conditions to site-specific (high resolution) investigations designed to address issues specific to the design. The actual level of investigation varies depending on the complexity of the project and may include multiple phases of field investigation.

Following initial site investigation, additional investigation may be needed to refine understanding of the subsurface conditions that are most important to foundation design and estimated construction costs, especially when foundation systems or subsurface conditions are complex. As data gaps are filled through investigation, knowledge of the site conditions will move from poor, to fair, to good or excellent, and both the site model and design will be refined.

4-2.2 Multi-phase Investigation.

The design of the Trans-Alaska Pipeline System is one example of a multi-phase investigation program. This very large project spanned many degrees of latitude and various types of permafrost and nonpermafrost terrain. Multiple site investigations were completed, beginning with early scoping and reconnaissance-level investigation, followed by site-specific investigations to generally confirm the conditions along the alignment, and other investigations to address design-specific concerns. The final level of characterization occurred during the construction process, when field design changes were made based on actual site conditions at each foundation. As the pipeline became operational, changes in terrain, drainages, and climate resulted in continuing changes to adapt to these changed conditions.

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CHAPTER 5 PROPERTIES OF FROZEN GROUND

5-1 INTRODUCTION.

This chapter provides an overview of testing that may be required to define mechanical properties of frozen and unfrozen ground used in geotechnical analyses for projects in the Arctic and Subarctic. Soil properties may either be measured as part of field investigations and laboratory testing or estimated based on correlations in the literature.

As for conventional foundation design, the level of effort expended to determine the properties of frozen ground will depend on the complexity of the project and the foundation engineering risk to be addressed. Frozen ground properties used in design may differ depending on ground temperature and may change over the life of the facility and duration of load.

5-2 LABORATORY TESTING.

Laboratory testing is an integral part of the overall site characterization processes outlined in Figure 2-1 and a necessary component of the design if site investigations are conducted. General requirements on laboratory testing are provided in UFC 3-201-01 and UFC 3-220-01, and applicable standards for many laboratory tests are published by ASTM. However, when using available data from the literature, it is important to validate the testing conditions to ensure the results are appropriate for use for a given site because, as discussed in MIL-STD-810G, *Department of Defense Test Method Standard: Environmental Engineering Considerations and Laboratory Tests*, test data should be representative of ground conditions at the site.

5-2.1 Index Testing.

Index tests provide important data on the fundamental characteristics of soil and rock materials. Frozen soil classifications must include the Unified Soil Classification System (USCS) symbol (ASTM D2487, *Standard Practice for Classification of Soils for Engineering Purposes [Unified Soil Classification System]*) and a description of the ice in the soil. For engineering purposes, a simplified visual method of characterizing the ice in frozen soil is described in ASTM D4083 and is summarized as a three-step process in Table 5-1. The classifications in ASTM D4083 are based on the size and morphology of ice and on the ice bonding and content as described in *Description and Classification of Frozen Soils,* by Linell and Kaplar, and *Guide to a Field Description of Permafrost for Engineering Purposes,* by Pihlainen and Johnston. The classifications used in ASTM D4083 can also generally be related to water transfer and freezing processes and to ice type, as discussed in *Permafrost Engineering Design and Construction,* by Johnston.

Table 5-1 Frozen Soil Classification Process

<table>
<tr><th>Step</th><th colspan="5">Process</th></tr>
<tr><td>1. Describe soil independent of frozen state</td><td colspan="5">Classify soil by the USCS</td></tr>
<tr><td rowspan="10">2. Modify soil description by description of frozen soil</td><td colspan="2">Major Group</td><td colspan="3">Subgroup</td></tr>
<tr><td>Description</td><td>Designation</td><td colspan="2">Description</td><td>Designation</td></tr>
<tr><td rowspan="3">Segregated ice not visible by eye</td><td rowspan="3">N</td><td colspan="2">Poorly bonded or friable</td><td>Nf</td></tr>
<tr><td rowspan="2">Well bonded</td><td>No excess ice</td><td>Nbn</td></tr>
<tr><td>Excess ice</td><td>Nbe</td></tr>
<tr><td rowspan="5">Segregated ice visible by eye (ice less than 25 mm thick)</td><td rowspan="5">V</td><td colspan="2">Individual ice crystals or inclusions</td><td>Vx</td></tr>
<tr><td colspan="2">Ice coatings on particles</td><td>Vc</td></tr>
<tr><td colspan="2">Random or irregularly oriented ice formations</td><td>Vr</td></tr>
<tr><td colspan="2">Stratified or distinctly oriented ice formations</td><td>Vs</td></tr>
<tr><td colspan="2">Uniformly distributed ice</td><td>Vu</td></tr>
<tr><td rowspan="2">3. Modify soil description by description of substantial ice strata</td><td rowspan="2">Ice greater than 25 mm thick</td><td rowspan="2">ICE</td><td colspan="2">Ice with soil inclusions</td><td>ICE+ soil type</td></tr>
<tr><td colspan="2">Ice without soil inclusions</td><td>ICE</td></tr>
</table>

Source: Adapted from ASTM D4083.

5-2.1.1 Frost Design Classification.

5-2.1.1.1 USACE System.

Table 5-2 presents the USACE frost design soil classification system from *Frost Action Predictive Techniques for Roads and Airfields, A Comprehensive Survey of Research Findings*, by Johnson et al. Frost groups are classified into eight categories, and three types of screening are used to determine frost susceptibility.

1. Soil types are determined based on the USCS, initially in the field.
2. The percentage of soil particles finer than the 8×10^{-4} in. size (0.02 mm) is determined based on measurement in the laboratory (ASTM D7928, *Standard Test Method for Particle-Size Distribution [Gradation] of Fine-Grained Soils Using the Sedimentation [Hydrometer] Analysis*).
3. Laboratory frost heave testing is performed to verify the estimated percentage estimated in step 2 (refer to paragraph 5-2.5 for a discussion of frost heave testing). Frost heave testing may not be performed on every sample and is optional, depending on project requirements.

5-2.1.1.2 Frost Heave.

Frost heave in soils occurs when soils freeze, but the extent of frost heave depends on soil type and the presence of contributing water through capillary rise determined through index testing.[1] For frost heave to occur, there must be what is sometimes referred to as the 3 Ws (water, wicking, and winter). Water must be available to create ice, wicking (capillary action) is required to bring water to the freezing front, and winter (freezing temperatures) is required to convert the water into ice. Reducing one or more of these conditions reduces the magnitude of heave or even prevents it.

5-2.1.1.3 Segregation Potential.

An alternative approach for estimating frost heave potential is to measure the segregation potential of the soil (see "Procedure for Determining the Segregation Potential of Freezing Soils," by Konrad). See paragraph A-2 for additional resources.

5-2.1.2 Pore Water Salinity.

5-2.1.2.1 Measurement.

For geotechnical engineering purposes, the salinity of pore water in permafrost soil is measured to estimate freezing point depression and unfrozen water content. ASTM D4542, *Standard Test Methods for Pore Water Extraction and Determination of the Soluble Salt Content of Soils by Refractometer*, is used to quickly estimate the soluble salt content of soils. However, electrical conductivity methods have also been widely used. Other methods have been developed for agronomy studies and are not necessarily appropriate for comparison to historical data or application to permafrost engineering problems. It is critical to understand the test method used when comparing test results from different sources.

5-2.1.2.2 Effects.

If saline conditions are identified at a site, the design must account for the behavior of the saline permafrost. Salinity in the pore water causes a freezing point depression, resulting in frozen soil that is weaker than nonsaline soil for a given ground temperature and load duration. Saline soil will also undergo higher levels of creep than nonsaline soil at the same stress level. The presence of pore water salinity may create permafrost that is not ice-bonded because of freezing point depression (the approximate freezing point depression in soil with 10 ppt pore water salinity is 1°F [0.56°C]). Typical sediments deposited in Alaskan offshore marine environments commonly have salinities that vary between 30 to 35 ppt. Salinity at this concentration in soil results in a freezing point depression to 28°F (−2.2°C), with the result that the sediment may be classified as permafrost, but because ice-bonded soil will not form at temperatures above the freezing point depression, the soil behaves as an unfrozen material. Pockets of high salinity can also form onshore and are not uncommon in coastal areas in northern Alaska.

[1] *Frost Susceptibility of Soil: Review of Index Tests*, Chamberlain.

Table 5-2 USACE Frost Design Soil Classification System

Frost Susceptibility[1]	Frost Group	Kind of Soil	Amount Finer than 0.02 mm (% by weight)	Typical Soil Type under USCS
Negligible to low	NFS	a) Gravels	0–1.5	GW, GP
		b) Sands	0–3	SW, SP
Possibly	PFS[2]	a) Gravels	1.5–3	GW, GP
		b) Sands	3–10	SW, SP
Low to medium	S1	Gravels	3–6	GW, GP, GW-GM, GP-GM
Very low to high	S2	Sands	3–6	SW, SP, SW-SM, SP-SM
Very low to high	F1	Gravels	6–10	GM, GW-GM, GP-GM
Medium to high	F2	a) Gravels	10–20	GM, GM-GC, GW-GM, GP-GM
Very low to very high		b) Sands	6–15	SM, SW-SM, SP-SM
Medium to high	F3	a) Gravels	>20	GM, GC
Low to high		b) Sands except very fine silty sands	>15	SM, SC
Very low to very high		c) Clays, PI > 12	--	CL, CH
Low to very high	F4	a) All silts	--	ML, MH
Very low to high		b) Very fine silty sands	>15	SM
Low to very high		c) Clays, PI < 12	--	CL, CL-ML
Very low to very high		d) Varved clays and other fine-grained, banded sediments	--	CL and ML; CL, ML and SM; CL, CH, and ML; CL, CH, ML and SM

Source: Reproduced from *Frost Action Predictive Techniques for Roads and Airfields, A Comprehensive Survey of Research Findings,* by Johnson et al., Table 1.

Notes:
1. Based on laboratory frost heave tests.
2. Requires laboratory frost heave test to determine frost susceptibility.

Abbreviations:
-- = none
C = clay
G = gravel
H = high plasticity
L = low plasticity
M = silt
NFS = nonfrost-susceptible
P = poorly graded
PFS = possibly frost susceptible
S = sand
USCS = Unified Soil Classification System
W = well graded

5-2.1.3 Bulk Unit Weight.

Bulk unit weight is determined from undisturbed samples (ASTM D7263, *Standard Test Methods for Laboratory Determination of Density and Unit Weight of Soil Specimens*).

In a design context, terms like *ice-rich* and *ice-poor* may be specific to a particular design methodology. For example, permafrost with excess ice is defined as ice-rich,[2] but it also can be described in terms of frozen bulk density,[3] with densities less than about 106 lb/ft^3 (1,700 kg/m^3) exhibiting ice-rich behavior in terms of pile design. Bulk density is also related to the relative compaction and thaw stability of in situ material and engineered fills.[4] Extensive studies of the placement and compaction of frozen soil have shown the difficulty in achieving commonly specified levels of compaction, which are required if there is the potential for the materials to thaw or creep under load.

5-2.2 Thermal Conductivity and Moisture Content.

Thermal conductivity is an important property used in ground thermal analyses. Thermal conductivity values are not constant but, rather, vary with moisture content, temperature, salinity, and soil types. Information on the thermal conductivities of ice-rich permafrost in frozen and thawed states is available in “Thermal Conductivity of Some Ice-Rich Permafrost Soils,” by Slusarchuk and Watson. Thermal conductivity is measured by laboratory testing or calculated based on empirical methods such as those developed in “Thermal Properties of Soils,” by Kersten, or *Thermal Conductivity of Soils,* by Johansen. Kersten’s results are not applicable to ice-rich soils. Generally, the Johansen method gives better results for soil saturation above 10%.[5] Errors have been corrected in the original translation of Johansen’s publication with respect to peat,[6] and this new version offers improvements to the method by accounting for natural and crushed base-course material and mineral composition.

In general, unfrozen water content will decrease as ground temperatures get colder and thermal conductivity increases. Unfrozen water content and thermal conductivity are especially sensitive to changes in low-salinity soil when ground temperatures are between 28°F and 32°F (−2°C and 0°C). As salinity increases in frozen soil, so does the unfrozen moisture content and the range of ground temperatures within which the effect on thermal conductivity is significant. However, unfrozen water content is not accounted for by Kersten. Thus, it is estimated the Kersten equations calculate values for thermal conductivity within ±25% of measured values, which is arguably less variation than the natural variance due to soil inhomogeneity.[7]

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[2] *Glossary of Permafrost and Related Ground-Ice Terms*, Harris et al.
[3] “Pile Design in Permafrost,” Weaver and Morgenstern.
[4] “Cold Regions Earthwork,” Tart.
[5]“ The Thermal Properties of Soils in Cold Regions,” Farouki.
[6] “A Generalized Thermal Conductivity Model for Soils and Construction Materials,” Côté and Konrad; “Thermal Conductivity of Base-Course Materials,” Côté and Konrad; “Estimating Thermal Conductivity of Pavement Granular Materials and Subgrade Soils,” Côté and Konrad.
[7] “The Thermal Properties of Soils in Cold Regions,” Farouki.

5-2.3 Advanced Testing.

Advanced testing is typically used to measure mechanical properties, such as creep, in uniaxial compression (ASTM D5520, *Standard Test Method for Laboratory Determination of Creep Properties of Frozen Soil Samples by Uniaxial Compression*) and shear strength under constant rate of strain (ASTM D7300, *Standard Test Method for Laboratory Determination of Strength Properties of Frozen Soil at a Constant Rate of Strain*). Other tests are used to measure unfrozen moisture content. For a general overview of frozen soils testing, see *Mechanical Properties of Frozen Soils,* by Zubeck and Yang, and Appendix C of *Frozen Ground Engineering,* by Andersland and Ladanyi.

Advanced testing of frozen soil requires specialized test apparatuses and is often conducted in a cold room to better control environmental conditions. Temperature control is an important consideration for advanced testing and may require multiple layers of insulation or circulating baths with precision controls. Samples must be maintained at an appropriate temperature that is representative of temperatures at the site. In addition, future changes in ground temperature may need to be considered in the design of the test procedures. Specialized considerations for handling and shipping frozen samples may be required.[8]

5-2.3.1 Thaw Strain.

5-2.3.1.1 Soil.

Thaw strain tests measure the total deformation that occurs upon thawing. This measurement can be a relatively simple test that provides useful index data indicative of the total settlement that may occur when frozen ground undergoes a phase change from frozen to unfrozen. Values of thaw strain can vary considerably, as shown in “Thaw Strain Data and Thaw Settlement Predictions for Alaskan Soils,” by Nelson et al., who discuss laboratory testing and report thaw strain of between 0% and 80% for a variety of soil types found in Alaska. When comparing reported values from the literature, it is important to understand the actual test setup and procedure used to measure reported values because there is no ASTM standard for this test. Figure 5-1 shows multiple thaw strain tests underway using custom fabricated equipment.

5-2.3.1.2 Rock.

Thaw strain and frost susceptibility in rock masses is related to the presence of frost-susceptible material and water within joints and infillings. If significant ice is present in a fractured rock mass, creep may also occur. Evaluation on a case-by-case basis is required.

[8] “Transportation, Preparation, and Storage of Freezing Soil Samples for Laboratory Testing,” Baker.

Figure 5-1 Thaw Strain Tests

5-2.3.2 Thaw Consolidation.

Thaw consolidation tests incorporate elements of thaw strain testing and measurement of conventional consolidation parameters after the sample has thawed. These tests measure initial strain as the sample thaws and then measure consolidation of the thawed material. For representative values determined during design and construction of the Trans-Alaska Pipeline, see “Thaw Strain Data and Thaw Settlement Predictions for Alaskan Soils,” by Nelson et al.

There is no ASTM standard for this test.[9] Hence, it is important to understand the actual test setup and procedure used to measure reported values.

5-2.4 Creep Tests.

The creep process depends on soil type, ice content, temperature, and pore water salinity; it also depends on loading rate and duration of load application. For testing procedure descriptions, see ASTM D5520 and other sources, including the following:

- *Creep of Frozen Soils*, by Sayles
- “An Engineering Theory of Creep of Frozen Soils,” by Ladanyi

[9] *Mechanical Properties of Frozen Soils*, Zubeck and Yang.

- "Uniaxial Compressive Strength of Frozen Silt Under Constant Deformation Rates," by Yuanlin and Carbee
- "In Situ Creep Properties in Ice-rich Permafrost Soil," by Savigny and Morgenstern
- "The Influence of Cryostructure on the Creep Behavior of Ice-Rich Permafrost," by Bray
- *Creep in Engineering Structures*, by Hult

Creep may occur at low stress levels. When ground temperatures are warm and conditions are ice-rich, the creep potential increases, with the result that creep may govern allowable loads and required embedment depths to limit structural deformation.

5-2.5 Frost Heave Test.

Frost heave testing is commonly conducted to understand changes in ground conditions that may occur along chilled gas pipelines or similar facilities. For structure foundations, it is preferable to mitigate potential frost heave, and this type of testing is generally not conducted. Mitigation of frost heave is discussed further in Chapter 7, Chapter 8, and Chapter 9.

Historically, the susceptibility of soils to weakening due to frost heave and thaw was measured using ASTM D5918, *Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils*, but this test method is now inactive. Frost heave testing has also been conducted by academic and industry staff using proprietary methods developed to measure specific aspects of frost heave.[10] Frost heave test data must be carefully evaluated when comparing historic data from different sources.

5-3 STRENGTH PROPERTIES AND CREEP.

In general, frozen soil has high shear strength under short-term loads, with maximum strength decreasing as temperatures warm. However, the presence of salinity will reduce the shear strength and creep behavior will affect allowable long-term design loads.

5-3.1 Saline Permafrost.

Salinity in permafrost soil has a significant effect on material properties, including reducing the freezing point (freezing point depression), increasing the unfrozen moisture content, and decreasing shear strength.[11] Creep and creep rate are also affected by saline conditions; hence, it is a very important parameter to define. The strength of frozen saline sand will decrease with increasing salinity and unfrozen water content, as it does in clayey soil.[12]

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[10] "Frost Heave Predictions for Alaskan Soils," Hazen et al.
[11] "Creep and Strength Testing of Frozen Saline Fine-grained Soils," Nixon and Lem.
[12] Ibid.

Details of the relationship between salinity and unfrozen water content in sand are described in “Shear Strength in the Zone of Freezing in Saline Soils,” by Chamberlain, “Salt Concentration Effects on Strength of Frozen Soils,” by Ogata et al., and “Strength of Frozen Saline Soils,” by Hivon and Sego. Sand strength is generally expected to be greater than the strength of clay for similar loading conditions, temperatures, and salinity. In addition, the freezing extent is also expected to be larger in sandy soil than in clayey soil for the same temperatures because of differences in the thermal conductivity and moisture content of the soil.

5-3.2 Creep in Frozen Soils.

Creep is a highly complex phenomenon that depends on soil type, ice content, temperature, pore water salinity, and the loading rate, magnitude, and duration of load application. However, in practice, creep effects are limited by controlling stress levels along a pile or below a foundation or by decreasing the ground temperature, which reduces the creep rate. Because creep is time, applied-stress, and temperature dependent, it is important to establish the service life and the acceptable total and differential settlement tolerances of structures and anticipated changes in thermal conditions because these will dictate allowable stress levels over time. Creep of footings is discussed further in paragraph 8-5.3.1 and creep for piles is discussed in paragraph 9-5.3.4.

5-4 PROPERTIES FOR ESTIMATING DYNAMIC RESPONSE.

Dynamic material properties are used to estimate the response of a foundation to loads, such as those due to seismic events or vibrations from reciprocating machinery, that may require consideration of small or repetitive strain. Properties can vary at a site and parametric analysis may be required to understand the effect on a foundation system. For example, the difference in the thickness and depth of organic soil across the site, or the presence of unfrozen zones, is a common variable that may warrant a parametric evaluation when evaluating site response. These properties will also vary with ground temperature. Testing may be conducted to estimate these properties, for both frozen and thawed conditions, using methods such as geophysical surveys like those discussed in UFC 3-130-02 or laboratory testing such as bender element tests (ASTM D8295, *Standard Test Method for Determination of Shear Wave Velocity and Initial Shear Modulus in Soil Specimens Using Bender Elements*). For more advanced projects, cyclic testing (such as triaxial, direct simple shear, or even centrifuge testing) can be performed; however, these methods are not typical for frozen soil.

5-4.1 Frozen Soil.

Shear wave velocities are expected to be higher in frozen soil than in thawed. In general, sites with fully frozen and bonded permafrost, and with temperatures colder than 25°F (−4°C), can be considered to have IBC Seismic Site Class B conditions unless shown otherwise by site investigation and testing. Warmer permafrost temperatures will result in lower shear wave velocities. Compressional (*p*) wave and shear (*s*) wave velocities (*Vp* and *Vs*) are measured in the field using seismic refraction survey methods, and variations of the surface wave velocities are determined using the multichannel analysis of surface waves, a seismic method that measures the shear-wave velocity distribution. Downhole methods, including those in ASTM D7400, *Standard Test Methods for Downhole Seismic Testing*, can also be used to measure *Vp* and *Vs*, which can then be used to calculate other properties used in dynamic analysis, such as Poisson's ratio (ν), shear modulus (G_{max}), and the impedance ratio (ζ).

Different methods may be used to measure *Vp* and *Vs*. For example, *Vp* and *Vs* were measured to a depth of 36 ft (11 m) at a site in the North Slope of Alaska[13] using three different seismic methods (such as cross-hole, downhole, and surface wave methods). The soil was well-bonded permafrost and included layers of sand and gravel with variable fines, a layer of organic silt, and a 10 ft (3 m) thick layer of massive ice. The different methods yielded *p*-wave velocities between 4,100 and 4,850 m/s and *s*-wave velocities between 1,800 and 2,200 m/s.

5-4.2 Thawed Active Layer and Underlaying Soil.

Particular attention must be given to the interface between the thawed active layer and the underlying frozen soil, where a large difference or variation in properties exists. The shear wave velocity in the active layer soil is expected to be 10 to 15 times less than the velocity in underlying frozen soil when the active layer soil is thawed. This difference results in a calculated value of G_{max} in thawed soil that is more than 100 times lower than G_{max} in the underlying frozen soil. Also, surface wave velocities in frozen soil have been shown to decrease significantly at temperatures warmer than approximately 30°F (−1°C).[14]

Guidelines for Estimation of Shear Wave Velocity Profiles, by Wair et al., provides a summary and comparison of several methods for estimating shear wave velocity. Additional methods and commentary regarding shear wave velocity estimates and considerations for vertical construction in thawed ground are provided in Section C20.3 of ASCE/SEI 7.

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[13] "The Measurement of Compressional and Shear Wave Velocities in Permafrost: A Comparison of Three Seismic Methods," Black et al.
[14] "Advances in Geophysical Methods for Permafrost Investigations," Kneisel et al.

CHAPTER 6 APPLICATION OF NUMERICAL MODELING FOR GROUND THERMAL RESPONSE

6-1 INTRODUCTION.

This chapter discusses the use of numerical modeling and the different approaches available to the designer, including the use of climate inputs discussed in Chapter 3. Geotechnical thermal analysis is a broad topic requiring an understanding of thermodynamic principles, heat flow in soils, climate science, and site conditions. General background can be found in several cold regions engineering textbooks and papers, such as the following:

- *Geotechnical Engineering for Cold Regions*, by Andersland and Anderson
- “Geotechnical Thermal Analysis,” by Zarling and Braley
- *Frozen Ground Engineering*, by Andersland and Ladanyi

Thermal modeling is considered fundamental for many projects because it is a useful tool for assessing ground temperature response to site development, such as the change to the depth of freeze and thaw and the potential for permafrost degradation and subsidence. It is also becoming more important due to climate change and its effect on ground temperatures. Numerical thermal modeling can also be complex due to the number of variables, including foundation geometry, climate, material properties, and ground temperature regime, that are included. Thermal modeling must be conducted by experienced practitioners and based on site-specific information and measurements.

6-2 HEAT FLOW.

Complex thermal models using finite element or finite difference methods are based on the first law of thermodynamics, which states that the total energy of a system is conserved unless energy crosses its boundaries. The rate of change in the stored thermal energy must equal the heat flux into the system minus the heat flux out of the system. Changes in thermal energy are associated with sensible heat (changes in temperature), latent heat of fusion (freeze–thaw), and latent heat of vaporization (vaporization and condensation). These parameters can be represented with one-, two- or three-dimensional (1D, 2D, or 3D) analyses in various finite element or finite difference methods like those noted in paragraph 6-3.

6-3 APPLICATIONS.

Ground thermal analyses are facilitated using computer programs. Available programs range from relatively simple programs that can calculate the depth of freeze and thaw using analytical methods to more complex software programs that use finite element or difference methods. There are several commercially available programs (as of 2024) that use finite element methods of analysis, such as TEMP/W by Seequent, RS2 by Rocscience, general programs such as Plaxis from Bentley, and various software products produced by Comsol.

Selecting the appropriate software tool for a given foundation design problem is an important consideration. For complex site conditions or geometry, fully coupled models incorporating seepage or airflow in porous media with thermal analyses may be used to understand ground temperature fluctuations in a dynamic environment. It is important to understand the internal calculations and assumptions inherent to each program and to consider comparing results from more than one software package and against known exact solutions. Sensitivity analysis is required, especially when modeling warm permafrost conditions (such as permafrost with ground temperatures warmer than about 30°F [−1°C]). It is also important to consider the properties of the soils being modeled. In many cases, it is best to focus on the foundation and then expand to a larger soil scenario so the final results portray the real thermal regime. Perform iterations including mesh refinement and time-step reduction to ensure the model results have converged on an acceptable solution. Additionally, some software may offer 3D analysis, which may prove very useful for complex geometries. It is critical that inputs to and results of 3D analysis be confirmed as realistic, which may require comparing them to output from other software products or 2D analyses with known solutions.

6-3.1 Depth of Freeze and Thaw.

For simple 1D scenarios, the active layer, depth of seasonal thaw (permafrost site), or depth of seasonal freeze (seasonal frost site) can be determined from field measurements or estimated using closed form equations such as the modified Berggren equation. The active layer thickness can be calculated by hand following UFC 3-130-05 or using software such as USACE's Pavement-Transportation Computer Assisted Structural Engineering software (PCASE).

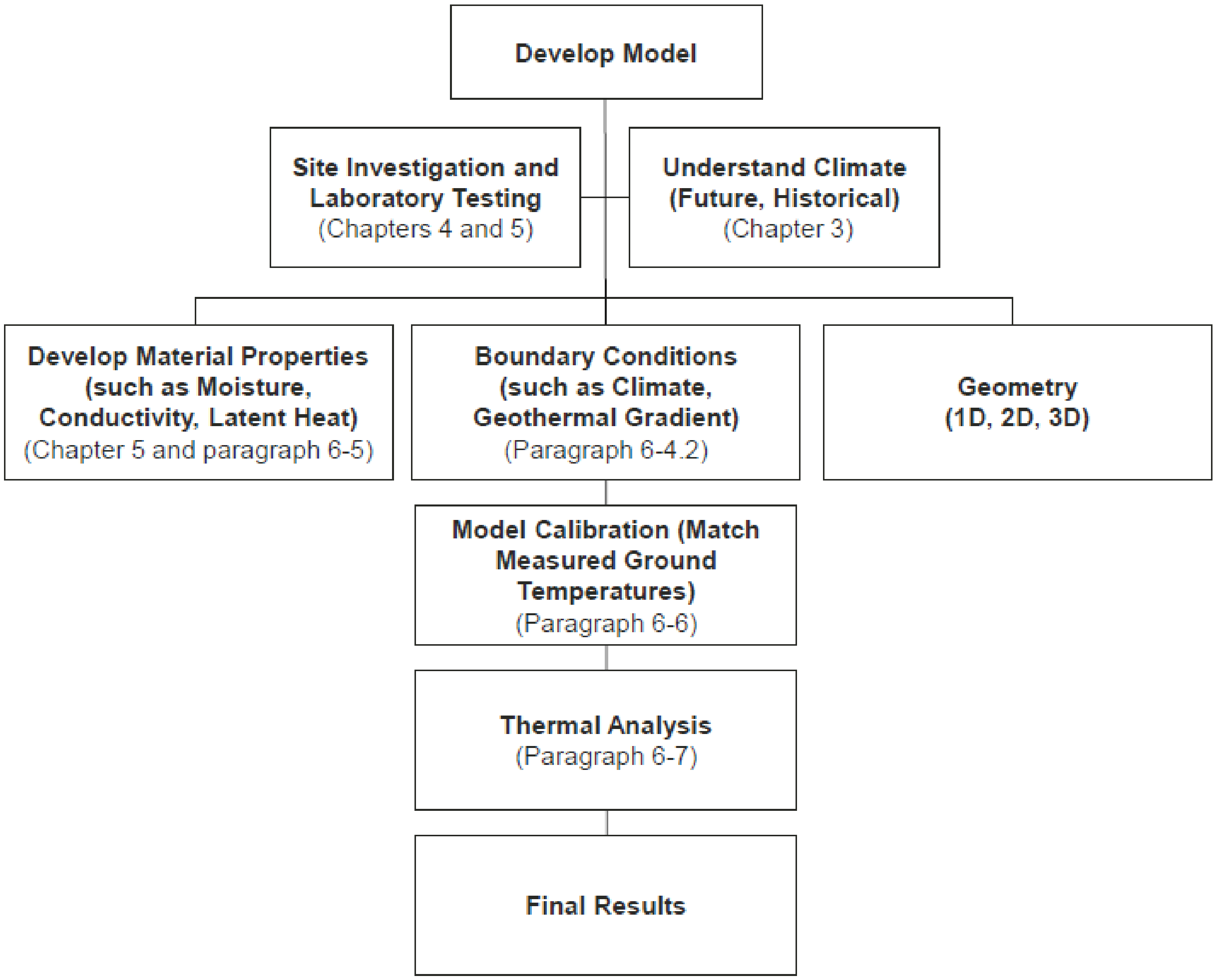
6-3.2 Permafrost Degradation and Subsidence.

Use thermal analyses to assess the effect of site development on ground temperature and the potential for permafrost degradation and subsidence. Methods for estimating potential thaw consolidation are outlined in "Estimating Thaw-Strain Settlement of Frozen Fill," by Crowther, and "Cold Regions Earthwork," by Tart. Projects with complex geometry may require the use of finite element analyses.

6-4 THERMAL MODELING PROCESS.

The process for developing an accurate thermal model relies on a comprehensive site investigation with ground temperature measurements, soil samples, subsequent laboratory analysis of the samples (soil type, dry unit weight, and moisture content are the minimum required), and good understanding of the climate. Thermal modeling is typically an iterative process to ensure the model matches site conditions. Figure 6-1 describes the steps of the thermal modeling process.

Figure 6-1 Typical Thermal Modeling Process



6-4.1 Geometry.

One of the first steps in numerical modeling is to define the geometry. Simple problems can be solved with a 1D model, but typical problems require a 2D model laid out with plan, profile, or axisymmetric views. In some instances, 3D analyses may be needed to accurately define foundation geometry. The mesh size must be considered when laying out the geometry. Areas with high temperature gradients require smaller mesh.

Circular structures, such as tanks and isolated piles, can be modeled symmetrically around the axis using 2D analysis to obtain 3D results from the model. This is done by modeling a vertical slice through the center of the tank or pile, including the area outside the structure, and revolving it around this central axis. For other structures, such as rectangular foundations, a vertical slice taken through the center of the foundation footprint, including the area outside the footprint, is the typical approach. The center axis is often a line of symmetry, which allows the modeled geometry to be reduced by one half. The boundary beyond the outside of the tank, pile, or foundation element must be far enough removed so that heat flow is 1D or vertical (zero heat flow normal to the boundary).

6-4.2 Boundary Conditions.

A number of boundary conditions, such as constant or varying temperature, heat flux, convective surfaces, and thermosyphons or other cooling systems, may be included in a typical thermal model. The ground surface boundary condition typically incorporates climatic variables to develop a relationship between air and ground temperatures. The bottom boundary uses a heat flux equivalent to the geothermal gradient at the site. The vertical boundary in a cross-sectional model must be a sufficient distance from the structure so that zero heat flux occurs across the boundary. The centerline of the structure may also be a zero heat flux boundary if the centerline is a line of symmetry. Boundary conditions at the ground surface depend on climate and other inputs that must be processed for use in thermal modeling. Two common approaches used in engineering analyses are highlighted in paragraphs 6-4.2.1 and 6-4.2.2. Thermal model results should be correlated with historical weather data and ground temperatures to calibrate the model before applying future climate projections for the thermal analysis.

6-4.2.1 The n-Factor Approach for Surface Boundary.

The n-factor approach uses a simplified empirical relationship (n-factor) between air and surface temperatures that implicitly includes factors such as net radiation, snow cover, soil thermal conductivity, latent heat, and surface vegetation. It is especially useful when only limited site data are available, but use of n-factors requires considerable judgement when selecting values and must be calibrated with historical ground temperatures.

The freezing and thawing n-factors are the ratio of the surface freezing or thawing index to the air freezing or thawing index, respectively. Tables of typical n-factors for many surfaces can be found in both *Frozen Ground Engineering,* by Andersland and Ladanyi, and *Heat Transfer in Cold Climates,* by Lunardini. Published n-factors can vary by location and orientation, and it is important to consider a range of values during model calibration.

6-4.2.2 Surface Energy Balance Approach.

The surface energy balance approach for establishing surface temperatures considers surface energy inputs and outputs at the ground surface over a given interval of time. The approach can more accurately reflect actual site conditions, but it also requires a higher level of site data than does using n-factors. An example of this approach applied to an elevated building is presented in “Thermal Design Considerations for Raised Structures on Permafrost,” by Oswell and Nixon. Required inputs can include air temperature, wind speed, snow depth and its thermal conductivity, longwave and shortwave radiation, surface albedo, vegetation height, and evaporation data, if appropriate.

6-5 MATERIAL PROPERTIES.

Values for the material properties should be derived from a detailed site investigation and testing. Some material properties commonly required for thermal analyses are listed in Table 6-1 and discussed in Chapter 5. Values used in early analyses may be refined based on the results of the model calibration step or analysis.

Table 6-1 Common Material Properties Used in Thermal Analyses

Material Property	Typical Source
Unit weight	Derived from site investigation following ASTM D7263
Moisture content	Derived from site investigation following ASTM D2216, *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*
Heat capacity (frozen/unfrozen)	Typically estimated from empirical relationships discussed in *Frozen Ground Engineering,* by Andersland and Ladanyi
Thermal conductivity (frozen/unfrozen)	Derived from site investigation following ASTM D5334, *Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Needle Probe Procedure*, or estimated using empirical relationships (see paragraph 5-2.2)
Unfrozen water content	Estimated from the empirical relationship proposed, by Tice, Anderson, and Banin, found in *Frozen Ground Engineering,* by Andersland and Ladanyi

6-6 MODEL CALIBRATION—GROUND TEMPERATURE.

During the exploration phase, it is typical to install temperature-measuring strings (such as thermistors or digital temperature sensors) in the boreholes created to log the soil profiles and retrieve soil samples for laboratory analysis. If this drilling and installation is done a year or two before construction, then the temperature profiles retrieved from these strings (whiplash curves) can be used to calibrate the thermal model. Probing for permafrost in early fall provides the depth of the active layer for a permafrost site and can be used to check the accuracy of the model for the area of undisturbed ground.

Thermal models must be developed using historical data and the results compared to the measured ground temperatures. This calibration is a critical step in the thermal modeling process. The input boundary conditions must be reevaluated if the model does not match measured temperature data.

6-7 THERMAL ANALYSIS.

After completing the model calibration, the thermal model can be used to make future predictions. Thermal modeling is an effective tool for understanding the relative difference of conditions. Consider the uncertainty in climate projections when developing thermal models and evaluating the resulting predictions. It can be impractical to run all the climate scenarios, so it is important to look at the range of the results. For example, a normal distribution of climate scenarios can be developed by comparing mean annual air temperature or freezing–thawing indices from each projection. This can be used to provide a range of the anticipated results. It is important to scrutinize results for realism, especially when modeling in warm permafrost zones (where there may be discontinuous permafrost).

CHAPTER 7 FOUNDATION DESIGN APPROACH

7-1 INTRODUCTION.

This chapter presents an overview of the foundation selection and design process for vertical and horizontal structures. Further discussion related to the design of shallow foundations is presented in Chapter 8 and discussion related to pile (deep) foundations is presented in Chapter 9. Examples of various types of foundations that have been used in Arctic and Subarctic areas are in Appendix A.

Selecting the general foundation concept is one of the first steps in the design process, following consideration of the general planning and design requirements and initial site investigation (discussed in Chapter 2 and outlined in Figure 2-1). Subsequent analysis and additional characterization may be required before a final design is selected. Although specific design issues may vary over the life of the facility, the concepts discussed are generally applicable to both new and rehabilitated foundation systems. Prior to finalizing the design, the designer must reconsider the estimated cost and how the design meets the functional requirements of the facility. Additional optimization may be required. For example, a pile design may have been developed for an unusual pile size that is either expensive or difficult to procure within the schedule limitations. Review and optimization could provide an alternate design using a different size or more readily available materials.

7-2 UNIQUE LOAD CONDITIONS AND LOCAL REQUIREMENTS.

Structures in areas characterized by frozen and thawing ground conditions are subject to geotechnical load conditions that are not common in temperate areas. Conditions unique to frozen ground are:

- Frost action
- Downdrag and settlement due to permafrost degradation and thaw subsidence
- Seasonal changes in near-surface materials
- Ice wedges and other massive ice formations

Different approaches to addressing foundation load conditions may be applied, and, in some instances, local practice or code requirements will dictate when a particular approach is required. Therefore, it may be necessary to check the design using different methods to ensure it is adequate. Each of the load conditions highlighted in the preceding list is briefly discussed in the following paragraphs.

7-2.1 Frost Action.

Frost action refers to both the process of (a) water freezing in soil, leading to a total volume increase or the build-up of expansive forces, and (b) subsequent thawing and related compression and reduction in soil strength. Very high loads are applied when ice forms at the freezing front, with varying effects on structures (see paragraphs 7-5 and 7-6).

7-2.2 Permafrost Degradation, Thaw Subsidence, and Downdrag.

7-2.2.1 Ground Thaw.

The thawing of frozen ground is another type of impact on foundation stability. The thawing of soil that has excess amounts of ground ice is of particular concern because it will cause settlement of shallow foundations and downdrag on deep foundations; therefore, it must be considered in the design. Permafrost degradation may be caused by multiple factors (see paragraphs 2-3.2 and 6-3.2), including construction activities that result in modification of the site thermal regime, normal facility operations, and naturally occurring climate change. Heat loss through the floor of a structure is an example of a cause of permafrost degradation that can affect the foundation to the extent that the structure is no longer sound and requires partial or full reconstruction. In other cases, where ground temperature in the permafrost is near freezing (for example, warmer than about 30°F [approximately −1°C]) or where saline conditions are found, site grading and development alone may raise ground temperatures enough to cause permafrost degradation.

7-2.2.2 Estimating Thaw Subsidence.

Estimate potential thaw subsidence using data from literature such as “Estimating Thaw-Strain Settlement of Frozen Fill,” by Crowther, “Permafrost Thaw and Ground Settlement Considering Long-Term Climate Impact in Northern Alaska,” by Yang et al., and “Frost Heave and Thaw Settlement Estimation of a Frozen Ground,” by Sinnathamby et al., preferably with correlation to site-specific index properties and laboratory testing, such as the thaw strain and thaw consolidation testing discussed in Chapter 5. If practical, field testing is an excellent method for estimating thaw consolidation and developing site-specific correlations for earthen structures. The test sections and monitoring incorporated into the design of the Inuvik Tuktoyaktuk Highway in the Northwest Territories, Canada, are examples of field testing and are discussed in “Monitored Thermal Performance of Varying Embankment Thickness on Permafrost Foundations,” by De Guzman et al.

7-2.3 Seasonal Changes in Near-Surface Materials.

Foundation designs must be evaluated for both winter and summer load and soil strength conditions. Freezing air temperatures cause a seasonally frozen and thawed zone (an active layer) to form near the ground surface. These changes may result in frost heave or loss of soil strength. In addition, as soil freezes and thaws, material properties, such as elastic modulus and its ability to resist loads, also change. For example, piles resisting lateral loads from seismic events or wind forces will have different soil structure responses in summer and winter.[1] Moreover, thermal expansion

[1] “Analysis of Laterally Loaded Piles in Frozen Soils,” Yang et al.

and contraction of bracing induces opposing strain loads in summer and winter that need to be considered in structural design.

7-2.4 Ice Wedges and Other Ground Ice Formations.

Massive ice formations, such as ice wedges, are common and generally ubiquitous on permanently frozen terrain. For examples of the types of ground ice found in northern Alaska and along the Beaufort Sea coast, see "Permafrost of Northern Alaska" and "Ground Ice in the Upper Permafrost of the Beaufort Sea Coast of Alaska," both by Kanevskiy et al. The presence of these massive ground ice features must be addressed in design documents. For example, pile design criteria commonly allow for some amount of massive ice, with provisions for increasing the depth of piles if more ice is encountered than was already accounted for. Footings or slab foundations underlain by massive ice formations must be designed to prevent thawing the underlying soil and may require the use of insulation[2] and ground cooling (see paragraphs 8-5.5.2 through 8-5.5.4). In cases where the ice formation is extensive, such as due to buried glacial ice or ice wedges, relocating facilities may be required[3] or the ice may need to be removed as part of a ground improvement program.

7-3 FOUNDATION DESIGN APPROACH.

Design, construction, and maintenance of foundations on permafrost and freezing or thawing ground conditions must satisfy certain material, environmental, and logistical challenges, as discussed in Chapter 2 and outlined here:

- Special properties and behaviors of soils, rocks, and building materials at low temperatures and under cyclic freeze–thaw action
- Permafrost that is subject to thawing and subsidence during and after construction
- Seasonal freezing and thawing of ground associated with frost heave, thaw settlement, and other effects
- Difficulty of excavating and handling frozen ground
- Limited availability of natural construction materials and support facilities
- Adverse conditions of temperature, wind, precipitation, distance, accessibility, working seasons, and cost

For general design approaches for permafrost areas, see *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz, and *Frozen Ground Engineering,* by Andersland and Ladanyi. Both are based on the thaw stability of the site and include examples of different foundation types for facilities of varying design life. These general approaches for permafrost areas are outlined in

[2] "Design, Construction and Operation of an Insulated Ice Drilling Pad, North Slope, Alaska," Hazen et al.
[3] "Structure and Properties of Ice-rich Permafrost Near Anchorage, Alaska," Kanevskiy et al.; "ARRC Rail Alignment Improvements Birchwood, Alaska Railroad Design—Construction in Marginally Frozen Relic Ice and Soil," Krzewinski et al.

Figure 7-1 and discussed in paragraphs 7-4.1 through 7-4.4. In areas with deep seasonal frost that affects foundations, designing a stable foundation still requires considering how the foundation soil changes and affects foundations as ground temperatures and properties of the soil change seasonally.

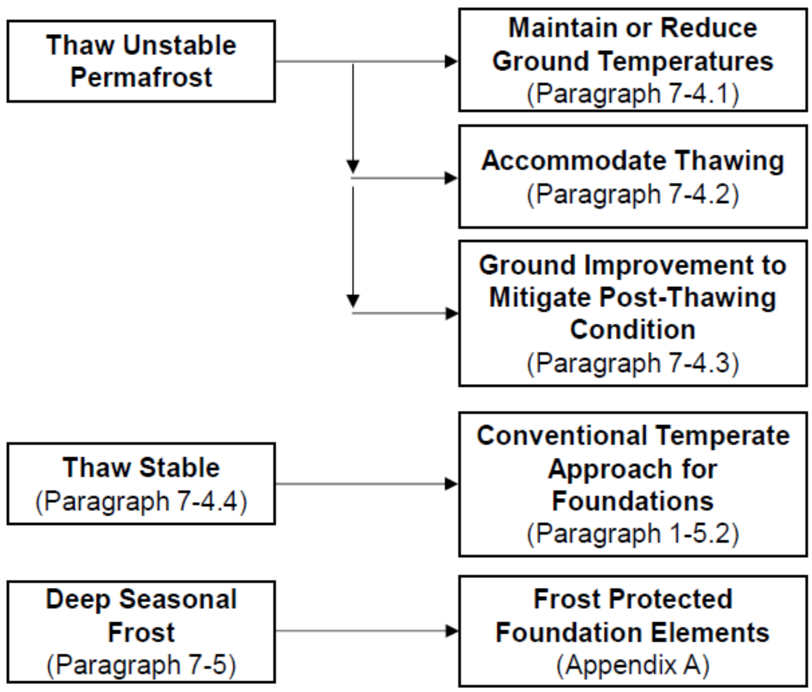
7-3.1 Maintain or Reduce Permafrost Ground Temperature.

The existing thermal regime must be maintained when foundations are resting on or within thaw-unstable permafrost because of the excess settlement and loss of bearing that occurs when ice-rich soil thaws. This approach is used in regions of both continuous and discontinuous permafrost and is typically accomplished for permanent structures by elevating the structure to decouple it from the underlying soil or by using a combination of insulation and cooling to control heat flow from the structure into the ground. Strategies to maintain ground temperatures in areas of deep seasonal frost may include insulation of the foundation perimeter (as for shallow frost-protected foundations), modification of site conditions, or, in the case of structures with internal temperatures that are below freezing (such as liquified natural gas tanks or refrigerated warehouses), a combination of insulation and heat loops can be designed to keep foundation soils thawed. Different approaches to meeting these objectives are described in paragraph 7-5.

7-3.2 Accommodate Thawing (Accept Thermal Regime Changes).

Foundations can be designed to accommodate changes in ground conditions when permafrost thaws. These conditions occur when facility development results in degradation of permafrost or when permafrost degradation is expected to occur naturally due to environmental changes. Common examples of site activities that can induce changes in the underlying permafrost include placement of granular soil over undisturbed permafrost to create an at-grade work pad for construction staging (which allows heat flow into the underlying soil) and activities that modify drainage or disturb surficial organic soil and vegetation. Even if a granular pad is thick enough to insulate the underlying permafrost from thawing, settlement may be induced along the perimeter of the fill area due to changes in surface drainage and a decrease in pad thickness in those areas. An example of this design approach is described in “Marginal Permafrost, a Foundation Material in Transition,” by Musial and Wyman, for pile foundations installed for a transmission line in Alaska. In the case of horizontal structures, allowing for thawing must include annual costs for releveling the embankment surface and patching the surface pavement. Most often, this annual maintenance is more cost-effective than constructing an embankment that is resistant to thawing.

Figure 7-1 General Design Approaches



Source: Adapted from *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz, and *Frozen Ground Engineering,* by Andersland and Ladanyi.

Foundations that allow some thawing of thaw-unstable permafrost are generally applicable for temporary facilities, facilities in support of military operations with a design life of five years or less, lighter structures, and horizontal structures (such as roadways and airfields), or when the thaw-unstable permafrost is underlain by relatively dense, thaw-stable materials. For lighter structures, this approach can involve limiting the heat input into the soil by thermally decoupling the structure from the permafrost using a raised foundation. This reduces settlement of the structure during its design life while also allowing access for releveling if required. This method is used for single-family housing and can be an effective foundation when costs are a limiting factor. Provisions for releveling are typically incorporated into the design.[4]

7-3.3 Ground Improvement to Mitigate Post-thawing Conditions.

Foundation soils may need to be modified or improved in all types of permafrost terrain, depending on expected conditions after a project is built. This approach entails either thawing and consolidating the frozen soil or over-excavating the soil and replacing it with soil that is not susceptible to frost. Thawing is accomplished using electrodes, heating mats, or steam, and the amount of energy applied depends on the ice content and the heat of fusion of the soil. The drainage characteristics of the thawed soils must be considered to allow the excess water to drain or be pumped and to improve stability by compacting the thawed soils to an appropriate density. The thaw-unstable soils must

[4] "Adjustable Foundation Design Development in Arctic Engineering," Borjesson and Clarke.

be relatively thin and NFS material readily available to make excavation and replacement a viable option. Once the ground conditions have been improved, conventional temperate foundation options are available for design and construction.

Soils that have been thawed may be in a weak or loose condition unless further modification or replacement is performed. If the thawed soils within an excavation are not drained and adequately compacted before winter weather sets in, they can refreeze and heave upon refreezing. If the refrozen soil subsequently thaws after placement of fill or completion of foundations, thaw-induced settlement may occur.

7-3.4 Thaw-Stable Permafrost.

When thaw-stable conditions are present at a site, such as sites underlain by ice-poor granular soil, foundations can be designed using the conventional foundation engineering practice outlined in the documents referenced in paragraph 1-5.2.

7-4 PROTECTION FROM FROST ACTION.

Protecting the foundation from seasonal frost action must be a consideration for each foundation design alternative. Frost action involves the harmful process of frost heave resulting from the formation of segregated ice lenses at the freezing front in soil during the freezing period, followed by thaw weakening or the loss of bearing strength when the seasonally frozen soil thaws. Heave forces may occur due to the formation of these ice lenses below the foundation or when frozen soil bonds to the foundation through adfreeze and lifts it as the surrounding soil freezes. Methods to protect a foundation from frost action involve using NFS foundation materials within the depth of frost, providing adequate drainage away from the foundation, maintaining a thawed condition around the foundation, resisting the potential frost heave forces, or isolating the foundation so it is not affected by the frost heave forces.

Design frost depths are developed using the thermal analysis methods described in Chapter 6. Results are heavily influenced by assumed climatic conditions (air freezing index), ground surface conditions (n-factors), and soil thermal properties. References for freeze and thaw depth determination are noted in Chapter 6 and more general discussion is included in several references, such as *Frozen Ground Engineering,* by Andersland and Ladanyi.

For frost heave to occur, the soil must be frost susceptible, a source of water must be available, and freezing temperatures must take place. If one or more of these conditions is prevented or eliminated, frost heave will not occur. See paragraph 5-2.1.1.2 for additional information.

7-4.1 Frost Susceptibility.

Frost susceptibility must be considered when designing foundations in Arctic and Subarctic areas. The frost susceptibility of a soil is generally defined by the content of material finer than the 0.02 mm size, as summarized in Table 5-2 and outlined in UFC 3-220-10. However, frost susceptibility is also related to the plasticity of fine-grained soil and the permeability of the foundation materials. Coarse-grained soil (such as sand and gravel) with trace to no fines is generally considered to have low frost susceptibility, whereas a silty or clayey soil is typically highly susceptible to frost. Generally, NFS material is specified, but in some instances where material sources are limited or facilities have a design life of less than five years, material with a low frost susceptibility may be appropriate and may satisfy design criteria. Additional testing may be required to justify the use of low-frost-susceptible material.

The percent passing the No. 200 sieve size is sometimes used to assess frost susceptibility, but this approach is typically used in areas where local experience and knowledge of material quality and performance is understood. Basing acceptance of materials during construction on the No. 200 result also will be beneficial during construction because the test can be more quickly performed than the hydrometer test needed to determine the 0.02 mm particle size.

7-4.2 Drainage.

Drainage is a very important consideration when trying to protect foundations against frost heave. Providing positive drainage away from the structure and the foundation subgrade through surface grading and buried drainage pipes limits the potential for ice lenses to form in the foundation materials. See Chapter 11 for requirements and paragraph 5-2.1.1.2 for information regarding the importance of groundwater on frost action.

The percent passing the No. 200 sieve size is sometimes used to assess frost susceptibility, but this approach is typically used in areas where local experience and knowledge of material quality and performance is understood. Basing acceptance of materials during construction on the No. 200 result also will be beneficial during construction because the test can be more quickly performed than the hydrometer test needed to determine the 0.02 mm particle size.

7-4.3 Maintain Thawed Conditions.

Maintaining the thawed condition around a foundation is usually accomplished for slab-on-grade buildings by insulating the perimeter as is done for frost-protected shallow foundations (see SEI/ASCE 32). The methods described by SEI/ASCE 32 are not directly applicable when the freezing-degree days exceed 4,500°F-days. However, the approach can be modified for colder temperatures like those found around Fairbanks, Alaska, as outlined in *Frost Protected Shallow Foundations (FPSF) for Interior Alaska Freezing Indices Between 4,000 and 8,000 Degree-Fahrenheit-Days: A Research Report,* by Perreault. At minimum, foundation insulation must consist of vertical insulation on the outside of footings. It is preferable to include insulation boards placed horizontally outside of the building perimeter, but this may be modified by local practice. The width and thickness of the insulation used depends on climatic conditions at the site. In addition to preventing freezing of soil beneath the foundations, the insulation helps with building energy efficiency.

Using floor insulation to improve the energy efficiency of a building is becoming more common. This is an important consideration when designing perimeter insulation because the reduction in heat loss through the floor increases the requirements for foundation insulation.

7-4.4 Resist Frost Heave Forces.

Frost heave can affect both deep and shallow foundations. Deep foundations are designed to provide sufficient embedment to resist the uplift loads applied to the perimeter of the foundation. Shallow foundations can be anchored or can incorporate structural elements such as lateral extensions to increase uplift resistance. Where practical, shallow foundations should extend to below the depth of frost to eliminate potential basal heave. Frost heave forces also may be resisted by increasing the weight of the structure, which is usually not cost effective.

Frost heave forces can be significant but varies with material type, as discussed in paragraph 9-7 and in other sources ("Russia and North American Approaches of Pile Design in Relation to Frost Action," by Nidowicz and Shur; *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz).

7-4.5 Isolate from Frost Heave Forces.

Isolating foundations from frost heave forces is accomplished in various ways, depending on if the foundation is deep or shallow. Insulation, which can include polystyrene, wood chips, or added soil fill, can be used to control freezing around the foundation. For piles, the portion of the pile in the active layer subject to uplift can be covered with a low-friction material to limit or prevent soil and ice from bonding to the pile. Materials used for this include soil-oil-wax mixtures, plastic, coal tar, Teflon, multiple layers of polyethylene sheeting, or similar nonadhering surface materials. For shallow foundations, it is common practice to place the footing below the depth of the active layer or to replace frost-susceptible soil in the subgrade with NFS material that extends below the anticipated depth of frost.

Compressible inclusions are another type of structural element that can be included in the foundation design to control frost heave on the base of footings or structural slabs.[5] This type of frost heave control involves limiting water movement in the soil and reducing the effect of ice expansion, versus the use of NFS materials. It can include low-strength expanded polystyrene (EPS) or extruded polystyrene (XPS) boards and blocks, rubber or plastic materials, or other collapsible materials analogous to those used to control foundation loads in areas with expansive soil. The success or failure of the approach depends on specific site conditions and good quality assurance and quality control during construction; hence, design should proceed carefully and include an evaluation of the elastic characteristics of each type of material used and its compatibility with applied loads, design life, and site conditions.

[5] "Foundation Design for Frost Heave," Widianto et al.; "The Compressible Inclusion Function of EPS Geofoam," Horvath.

7-5 DYNAMIC RESPONSE TO LOADING.

Dynamic loading is typically a result of seismic ground shaking or rotating machinery. The foundation response to each is different.

7-5.1 Seismic Ground Shaking.

Frozen ground is very stiff compared to unfrozen ground. For planning purposes, continuous permafrost regions that have a thin (on the order of a few feet) active layer can initially be characterized as Site Class B (as defined in the IBC) pending direct measurement of shear wave velocities and further site investigation. In regions of discontinuous permafrost, site classes will vary depending on the depth to permafrost, thickness of the permafrost, and designed long-term condition of the facility. Other aspects of seismicity to consider are seasonal changes in near-surface soils from frozen to unfrozen and how the depth of permafrost over time may increase due to site development and changes in climate. Deep seasonal frost affects site responses[6] and must be considered during design.

7-5.2 Liquefaction and Seismically Induced Settlement.

Frozen ground is not considered to be liquefiable, but liquefaction and seismically induced settlement become design considerations when permafrost is expected to thaw over the life of a facility or if the site was previously frozen in recent times. Recently thawed soils may be in a normally consolidated state or, more likely, an unconsolidated condition. Analyses must be conducted considering both the immediate and long-term thermal state of the foundation soils and the presence of layers of frozen and unfrozen material that may develop over time.

The site response of facilities is influenced by the presence of permafrost. Of particular concern is the change in response as subsurface conditions change from frozen to thawed, either seasonally or due to construction or climate change. For example, relatively deep thawing was predicted due to construction and facility operations at a site with warm permafrost on Eielson Air Force Base near Fairbanks, Alaska. This change in site conditions would have caused an increased risk of liquefaction due to regional seismicity; therefore, a mitigation program (consisting of thawing and ground improvement) was conducted to reduce the potential impacts from both thawing permafrost settlement and potential liquefaction-induced damages that may have occurred because of an earthquake after the ground thawed. Other common options to improve ground conditions and reduce liquefaction potential and seismically induced settlement are deep dynamic compaction and vibrocompaction.

7-5.3 Cyclic Machine Loading.

Rotating machinery, such as turbines, compressors, and generators, may induce cyclic loads that are sustained or continuous over the project life. Cyclic loads due to rotating machinery are different from those imposed by earthquakes and other transient state

[6] "Frozen and Unfrozen Shear Wave Velocity Seismic Site Classification of Fairbanks, Alaska," Cox et al.; "Effects of Seasonally Frozen Soil on the Seismic Behavior of Bridges," Xiong and Yang.

design forces, which typically have varying frequency, amplitude, and duration. Usually, the cyclic loads have well-defined operational amplitude and frequency domains that can be dampened structurally so that loads imposed on foundations are minimized. If the thermal state of foundation soils is expected to change over the life of a structure, additional analysis will be required to check the foundation's response to differing thermal states. Engineering judgment is required to determine the most suitable means and measures for addressing the effect of cyclical loads on pile foundations. Paragraph 9-11 presents further discussion regarding the effect of cyclical loads on adfreeze piles.

7-6 INSULATION AND CONTROL OF HEAT FLOW.

Structures are often elevated above the ground surface to decouple heat flow from the building into the ground in areas underlain by permafrost. Insulation is also commonly incorporated into the design of foundations to control heat flow and is an integral part of both structural foundation systems discussed in Chapter 9 and within fills used for horizontal structures (see Chapter 10).

For vertical and horizontal structures, insulation in foundations is typically either EPS or XPS. Cellular glass and other materials, such as urethane foam, are also used in specific applications. The insulation must have strength and strain characteristics compatible with applied dead and live loads and environmental conditions. Consider cellular glass products when heavy loads like those beneath liquefied natural gas tanks, aircraft ramps and tarmacs, or rotating radars are present; when little or no compression under load is a design requirement; when high fire resistance is needed; or when resistance to petroleum and solvents is a design requirement.

7-6.1 Insulation for Structural Foundations.

In general, XPS and EPS insulation beneath structural foundations should have a minimum compressive strength of 60 psi (414 kPa) measured at 5% strain. In addition, geomembranes must be placed over insulation installed beneath foundations to protect the insulation from degradation due to spills of hydrocarbons or other solvents that will degrade the material.

Polystyrene insulation is degraded by petroleum products and solvents, and it should be protected by a membrane liner when used in a foundation application, such as a flat loop thermosyphon (see paragraph 8-5.5), or in other situations where degradation by exposure to petroleum products and hydrocarbons will adversely affect its intended function.

7-6.2 Insulation for Horizontal Structures.

For horizontal structures, consider XPS or EPS insulation with a minimum compressive strength of 40 psi (276 kPa) measured at 5% strain. The most severe loading conditions in horizontal structures may occur during construction. It is imperative that the insulation material characteristics be matched to applicable design and performance criteria, and it must be recognized that constructability considerations may control the selection of materials in horizontal structures.

7-7 FACTOR OF SAFETY.

7-7.1 Working Stress Design.

Much of the design practice for foundations in frozen and freezing ground conditions was developed based on working stress design principles and use of a single global factor of safety (FS). The appropriate global FS for a given working stress design analysis may vary, depending on factors such as the criticality of a structure, uncertainty of conditions, or uncertainty in potential climate impacts. FS values for DoD projects are provided in UFC 3-220-01 and additional discussion is presented in Chapter 8 and Chapter 9 of this UFC.

7-7.2 Limit State Design.

Geotechnical engineering practice in temperate conditions increasingly is applying limit state design, including consideration of serviceability limit state and ultimate limit state principles or using limit state design based on load resistance factor design, but these are not widely applied in frozen ground situations. These general concepts and an approach to bridging the gap in working stress design and limit state design concepts in unfrozen conditions is presented in the *Canadian Foundation Engineering Manual* by the Canadian Geotechnical Society and in “Eighteenth Canadian Geotechnical Colloquium: Limit States Design for Foundations,” Parts I (“An Overview of the Foundation Design Process and Limit States Design for Foundations”) and II (“Development for the National Building Code of Canada”), both by Becker.

Consideration of limit states is an implicit part of codes. There are many national and local codes and standards that may need to be considered during design that may or may not have specific code requirements for foundation design in Arctic and Subarctic regions, especially when permafrost is present. Some of these national and local codes can be found as follows:

- In the U.S., consult the American Petroleum Institute, IBC, and Uniform Building Code.
- In Canada, consult the National Research Council Canada, National Standard of Canada, and Canadian Standards Association.
- In Europe, consult the Eurocode.

In the absence of specific requirements, it will be necessary to consider site conditions and recommendations found in the professional literature, including this and other UFCs in the series, texts such as *Frozen Ground Engineering,* by Andersland and Ladanyi, and supplemental resources like those listed in Appendix C.

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CHAPTER 8 SHALLOW FOUNDATION DESIGN

8-1 INTRODUCTION.

Shallow foundations may be used in areas of freezing and thawing soil, including those underlain by permafrost, provided that both the thermal impacts of structures and the overall behavior of foundation materials discussed in previous chapters are considered. Shallow foundations may be placed on granular pads and may incorporate insulation or, where the granular pad is underlain by permafrost, systems to maintain or cool the foundation soils. The timing of construction is an important consideration in permafrost areas to avoid thawing foundation soils that will support shallow foundations.

Design of the foundation system generally involves conventional bearing capacity and settlement calculations, whereas design of the granular pad subsystem involves thermal analyses like those discussed in Chapter 6. Calculating settlement involves conventional techniques for consolidation potential if permafrost will be allowed to thaw and evaluation of creep of frozen soil. Establishing these design criteria requires good site data, including information about ice content and its extent, ground temperature, and subsurface stratigraphy and material type. Consideration also must be given to the duration and magnitude of applied loads. For example, even relatively low ground pressures applied for the duration of the project life may result in significant creep in ice-rich soil, while relatively high ground pressures may be carried with little deformation if the load is only applied for a short period of time. Refer to Appendix A for representative examples of foundation configurations.

8-2 SHALLOW FOUNDATIONS ON THAW-STABLE PERMAFROST.

Shallow foundations on thaw-stable permafrost, such as coarse granular soil and rock without excess ice, should be designed according to conventional temperate zone methods that consider bearing capacity and settlement. For coarse granular soil, the friction angle may be estimated from information, such as drilling action or blow counts, collected during the geotechnical investigation. Similar to the way these data are affected when sampling coarse gravel and cobbles, blow count data from methods such as split spoon sampling (ASTM D1586, *Standard Test Method for Standard Penetration Test and Split-Barrel Sampling of Soils*) may be exaggerated in frozen ground. Thus, blow count data in frozen ground must be considered a relative measure of consistency between sample locations at the time of the investigation and should not be used with standard correlations between blow count and material property used in temperate conditions.

One case where correlations between field parameters and material properties may be useful is for estimating soil strength in ice-poor material. Soil strength may be conservatively estimated by assuming a saturated unfrozen soil at the same frozen dry density as in situ material and using correlations such as those found in UFC 3-220-10.

8-3 SHALLOW FOOTING WITH GROUND IMPROVEMENT.

Shallow footings and ground improvement are often used by USACE, Alaska District, in areas of discontinuous permafrost. Most commonly, pockets of discontinuous permafrost are thawed. The thawed soil may require densification to reduce settlement potential and potential for liquefaction (see paragraph 12-3.5). Foundations are designed to provide frost action protection that is appropriate for the area.

Permafrost may be prethawed beneath heated buildings using techniques such as electric probe thawing, cold or warm water injection thawing, steam thawing, or heating mats. However, if the near-surface permafrost to be thawed is thaw-unstable and ice-rich, it must have thaw-stable and ice-poor permafrost underneath to provide stability. If there is sufficient time in a project schedule, clearing a site of vegetation can be a cost-effective method for thawing ground, especially in areas of discontinuous permafrost; however, years may be required to accomplish this, depending on the depth of thaw desired and other local conditions. After the permafrost has been thawed, conventional temperate zone ground improvement techniques, such as preconsolidation of deep dynamic compaction, may be needed to further stabilize the site. Design shallow spread footings according to conventional temperate zone methods that consider bearing capacity, settlement, and seasonal frost. Additional ground truthing activities, such as soil borings, cone penetration tests, or compaction testing, are generally required to verify that conditions meet the design expectations after the area has been thawed and consolidated.

8-4 SHALLOW FOOTINGS ON GROUND SURFACE.

Shallow foundations bearing on the ground surface or at shallow depth can be used when they are supported on NFS fill and when no excessive long-term settlement is anticipated due to changes in the thermal regime of the foundation soil. Surface footings can also be used to accommodate anticipated settlement or heave.

Buildings supported on surface footings often incorporate a rigid base or space frame structure to maintain the building’s integrity in the event of differential movement and to span footings that may lose support until the system can be re-leveled. Space frames are rigid structural systems that are laterally connected to the vertical supporting elements. These systems can be releveled while the structural system serves to maintain the integrity of the superstructure by limiting differential movement between the structural elements, such as doors and framing, while also limiting horizontal displacement of the supporting elements during vertical displacement and dynamic (such as seismic) loading. Typically, these systems are built on a granular pad, but they can also be placed on natural ground that has suitable bearing capacity. The benefits for lighter structures are ease and rapid construction with provision for releveling as needed.

8-5 SHALLOW FOOTINGS ON IN SITU PERMAFROST.

This foundation method involves installing footings below the maximum anticipated depth of permafrost thaw over the life of the foundation (See *Permafrost Engineering*

Design and Construction, by Johnston). Typically, the footings are set on a bed of NFS granular fill or within an embankment, as shown in the typical sections in Appendix A. This foundation method is applicable for temporary facilities, facilities in support of military operations with a design life of five years or less, lighter structures, horizontal structures (such as roadways and airfields), and for cold permafrost soils that have minimal potential for thaw strain or long-term degradation of the thermal regime. Thermal analysis or site monitoring is used to estimate the active layer depth in the backfilled pits, which will likely be deeper than baseline conditions due to the backfill material and disturbance of the ground surface. Insulation placed near the ground surface may often further reduce the active layer depth and may be combined with other methods of ground cooling to maintain ground temperatures.

Elevate heated structures to provide ventilation to minimize heat transfer from the structure into the ground. A rigid framework and an adjustable leveling system may also be considered for lightweight structures to mitigate potential differential settlements.

8-5.1 Foundation Design Process.

The foundation design for shallow footings on in situ permafrost requires checking the bearing capacity, displacement under load, and settlement that may occur due to creep. Thermal analysis is required to estimate long-term changes in ground temperature and the potential for thawing due to construction and must recognize potential climate impacts during the design life. Depending on the structure, frost-protected shallow foundations like those described in paragraph 7-5.3 may be appropriate, provided thermal effects and differences in heated and unheated structures are considered. The general procedure for designing shallow foundations in permafrost is outlined here:

1. Select footing depth based on the expected deepest thaw and required lateral support.
2. Estimate the warmest ground temperature, including temperatures beneath the structure, using appropriate material properties.
3. Select footing based on bearing capacity theory and the desired FS.
4. Modify footing size as appropriate.
5. Check settlement during design life.

8-5.2 Bearing Capacity.

The ultimate bearing capacity, q_u, follows the general form taken from conventional bearing capacity theory and includes conventional terms (N values) for cohesion, surcharge, and self-weight and factors (F) for shape, depth, load inclination, base, and ground inclination. Refer to *Frozen Ground Engineering,* by Andersland and Ladanyi, section 7.2, for the equation, definition of terms, and details on application. Analyses to estimate ultimate bearing capacity must be performed in terms of total stress. The effects of ground temperature, time of loading, and ice content of the soil must be considered when estimating values of cohesion and friction angle. In addition, the friction angle used to estimate N values should correspond to an unconsolidatedundrained value for a given frozen soil density. (See pages 171–179 in *Frozen Ground Engineering,* by Andersland and Ladanyi, for details on application.) In general, for short-term loads and cold ground temperatures, the bearing capacity of frozen soil can be relatively high. As time and load increases, creep and changes in ground temperature become a consideration. Refer to paragraph 7-8 for a discussion of FS.

Strength testing under temperature-controlled conditions must be considered if relying on the long-term bearing capacity of ice-rich material. Strength testing also must be used to verify long-term creep behavior (see paragraph 8-5.3.1).

8-5.3 Settlement.

Footing size is generally controlled by considering settlement rather than by the bearing capacity of frozen ground. Both short-term and long-term settlement occurs when loads are applied to frozen soil. Five types of deformation occur when loading frozen ground:

- Instantaneous-elastic (soil may rebound partially)
- Instantaneous-plastic (irreversible, bearing failure)
- Viscoelastic (reversible)
- Consolidation (irreversible)
- Creep or viscoplastic (irreversible)[1]

Of the five types of deformation in frozen soil, instantaneous-plastic, consolidation, and creep are the most significant. Creep and consolidation of frozen soil require special attention. Instantaneous-plastic deformation is determined using conventional soil mechanics and accounting for the temperature dependency of short-term cohesion in frozen soil. Creep and consolidation of frozen soil are time dependent and are discussed in paragraphs 8-5.3.1 and 8-5.3.2.

8-5.3.1 Creep Settlement of Footings.

Creep settlement of footings can be substantial at low stresses if the soil has a high ice content, temperatures warmer than 23°F (−5°C), or both. Low ice content soils with low stress conditions will have lower rates of creep; however, creep must still be considered in design. Additional discussion of creep and guidelines for pile foundations are presented in paragraph 9-5.3.4.

Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost, by Linell and Lobacz, outlines methods for estimating the creep of footings. However, cavity expansion theory has also been shown to give good results for ice-rich homogeneous frozen soil[2] and other soil types. Creep parameters may be estimated from published data, provided the materials and site conditions associated with the published data are appropriate for use in the analysis. Alternatively, creep rates can be

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[1] *Frozen Ground Engineering*, Andersland and Ladanyi; *Rheological Properties and Bearing Capacity of Frozen Soils,* Vailov.
[2] "Creep of a Strip Footing on Ice-rich Permafrost," Sayles.

measured for specific soil types, ground temperatures, and loading rates in the laboratory (see paragraph 5-2.4).

8-5.3.2 Consolidation.

The consolidation behavior of frozen soil is poorly understood. Initial evaluations must consider consolidation to be a design consideration when ground temperatures are warmer than between 31.5°F (−0.3°C) in silty sand and 29°F (−1.7°C) in clay. When ground temperatures are colder than the threshold values, consolidation is expected to be very slow and thus not a design consideration.[3]

Upon thawing, total potential thaw settlement under a footing can be approximated based on the total volume of ground ice within a unit of soil within approximately 6.5 ft (2 m) of the footing. Using this approximation for deeper depths overestimates potential thaw settlement at deeper depths due to bridging of underconsolidated soils. Consolidation will also occur once the soil is thawed and can be estimated using soil mechanics principles for unfrozen soil. Perform laboratory testing to determine total thaw strain. Consolidation after thawing must be considered for some soil types, but it requires specialized testing, as noted in Chapter 5 and discussed in UFC 3-130-02.

8-5.4 Frost Heave Forces.

Shallow foundations may be subjected to frost heave forces along the base of footings. This can result from the refreezing of seasonally thawed soil or the refreezing of sites where the thermal regime was disturbed during construction. Analysis methods for estimating frost heave forces are outlined in *Frozen Ground Engineering,* by Andersland and Ladanyi. Alternatively, frost heave tests can be conducted to measure uplift forces in the laboratory or in the field.

8-5.5 Shallow Foundation Configurations on Permafrost.

Shallow foundations may be configured in various ways in permafrost areas, depending on site conditions and specific design requirements. Common practice is to elevate a heated structure when practical to provide ventilation and minimize heat transfer to limit thawing beneath the building. However, this is not always a practical solution, and other options, like those discussed in the following paragraphs, may need to be considered. See Figures A-6 through A-14 for example foundation configurations. Additional examples can be found in the following:

- *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost*, by Linell and Lobacz
- *Permafrost Engineering Design and Construction*, by Johnston
- *Cold Region Structural Engineering*, by Eranti and Lee

[3] *Handbook for the Design of Bases and Foundations of Buildings and Other Structures on Permafrost*, Vyalov and Porkhaev.

- *Construction in Cold Regions, A Guide for Planners, Engineers, Contractors, and Managers*, by McFadden and Bennett
- *Frozen Ground Engineering*, by Andersland and Ladanyi
- *Review of Thermosyphon Applications*, by Wagner

8-5.5.1 Shallow Footings on or Below Granular Pads.

8-5.5.1.1 Granular Pads.

Footings may be placed on or within granular pads or embedded beneath the pad. The footing depth depends on the depth of thawing anticipated over the life of the foundation. Granular pads provide insulation that protects the underlying permafrost from thawing and a working surface around the structure. Preferably, the fill will be thick enough that the active layer remains within the pad and above frozen soils that could potentially thaw and cause settlement. Penetrations of building foundations for drains or other utilities can be a source of unanticipated thawing and settlement due to leakage of fluids or other heat sources. Extra attention should be given to the details of penetrations and quality control around them during construction.

Thermal analysis is required to estimate the granular pad thickness needed to prevent thawing to the level of footing foundations. If the active layer extends below the footing elevation into underlying thaw-unstable soils during the design life, excess settlement of footings may result, and frost heave may occur when refreezing the following winter. Settlement due to creep also must be considered. Bearing capacity and settlement are calculated according to the methods described in paragraphs 8-5.2 and 8-5.3.

8-5.5.1.2 Post and Pad Foundations.

Post and pad foundations are another type of foundation that is often used for temporary facilities, facilities in support of military operations with a design life of five years or less, lighter structures, and horizontal structures (such as roadways and airfields). The footing in this case may be supported on a granular pad or below the depth of anticipated thawing. This type of foundation is illustrated in Figures A-7 through A-9. The support, or post, rising from the footing is often adjustable to accommodate potential settlement, especially when the footings are shallow and might be within the depth of potential thawing or subject to long-term creep settlement.

8-5.5.2 Shallow Footings on Insulated Granular Pad.

This foundation method is designed using techniques like those for a shallow foundation on a granular pad, except insulation is used to decrease the required pad thickness or enhance thermal isolation of the footing. Insulation is often placed near the bottom of granular fill, based on consideration of constructability and to minimize potential damage during construction. The location and extent of insulation beyond the edge of a structure needs to be checked to avoid thawing under the edges. It is good practice to include some depth of granular soil beneath the insulation to accommodate the potential for thaw penetration into the underlying soils. The amount of granular soil beneath the insulation and the location within the granular pad will depend on variation in the natural ground surface, design requirements, climate, and local experience.

Insulation alone will not generally be sufficient to prevent the thawing of frozen ground below continuously heated structures unless the insulation layer is very thick, which is typically not economical. Thermal analysis must be conducted to show that the underlying permafrost will not be degraded during the life of continuously heated structures. For temporary construction, insulated rig mats have been used to preserve underlying pads of snow and ice and allow operations over multiple seasons.[4] Ground thermal analyses must be conducted to support the design of these types of temporary facilities, facilities in support of military operations with a design life of five years or less, lighter structures, and horizontal structures (such as roadways and airfields), which may also be applied to gravel pads.

8-5.5.3 Shallow Footings on Ventilated Granular Pad.

Ventilated granular pads are cooled by natural or forced ventilation through ducts that have commonly been metal pipes but could be other materials, provided they can sustain the applied loads and provide the desired ventilation performance. An example of this type of system is shown in Figure A-10.

The ventilation ducts within the pad are opened during the freezing season and closed in the spring when air temperatures approach 32°F (0°C). As discussed in “Active Freezing Techniques,” by Mageau and Nixon, in warm permafrost regions, natural ventilation may be feasible for a small building in the range of 33 ft (10 m) in the lateral dimension (width), and has been shown to be effective in cold permafrost regions to widths of 100 to 150 ft (30 to 45 m). However, Mageau and Nixon indicate that forced-air systems are likely needed to achieve the required airflow for larger structures. In general, use has decreased due to both operational challenges and as flat loop thermosyphon systems have improved. The performance of air-ducted foundations over a 50-year period was reviewed in “Air-Ducted Hangar Foundations at Thule, Greenland,” by Bjella, who noted that drainage effects of the design must also be considered.

8-5.5.3.1 Ventilated Pad Design Method.

An overview of active freezing design methods using air ducts and other methods is presented in “Active Freezing Techniques,” by Mageau and Nixon. They note that for larger structures, an airflow rate of 0.32 ft^3/s (0.009 m^3/s) would be required for each 10 ft^2 (1 m^2) of heated floor area for a 70°F (21°C) structure having up to 10 in. (254 mm) of insulation. They also provide insulation and gravel pad thickness requirements for different ground surface temperatures. Forced air ducts are normally 1 ft to 2.5 ft (0.3 to 0.8 m) in diameter, with center-to-center spacing of three to four diameters, which are then sometimes connected to buried or aboveground manifolds in groups of four to six.

[4] “Design, Construction and Operation of an Insulated Ice Drilling Pad, North Slope, Alaska,” Hazen et al.

8-5.5.3.2 General Design Considerations.

Pad design considerations include winter prevailing wind direction and snow drifting, airflow rate, duct spacing, duct length, thermal properties of the pad and duct system, and pad thickness. Due to the uncertain nature of wind velocities that will occur in the ducts, base designs on natural convection circulation induced using dissimilar height duct plenums. This intake and outlet stack differential is designed to provide minimum design airflow at zero wind conditions. Increased airflow due to changes in wind velocity is assumed to be greater than the natural convection circulation and enhance cooling. Designing natural ventilation systems requires extensive data on year-round average air velocities in ducts, high safety factors, or a high tolerance to insufficient heat removal and resulting settlements. Forced ventilation systems using fans require maintenance but allow for design using predetermined air velocities. Use differential temperature controllers to control fan and damper operation, and establish ground temperature monitoring within the granular pad. Changes in drainage must also be considered and provided for in the design to ensure the ducts do not become flooded or blocked by icing.

8-5.5.3.3 Maintenance Considerations.

Ventilated pads have a history of failure when maintenance and monitoring is not performed. The ducts tend to fill with snow and other wind-blown debris, effectively eliminating the airflow needed to cool the soil. In addition, warm air circulation can increase the thaw rate of the underlying permafrost if duct dampers are left open or are opened by wind during the summer.

Cooling effects can be enhanced by placing insulation on the ground surface beneath and around structures in the summer to limit heat gain and by removing this insulation in winter to enhance cooling. For raised structures with passive refrigeration, care needs to be taken to prevent snow accumulation and storage of materials in the raised space. Planning for long-term seasonal maintenance of these systems is critical to their successful application, as is understanding snow drifting and wind direction. Snow fences may be required to mitigate snow drifting, but there are also long-term issues to consider with degradation of permafrost where snow accumulates due to snow fences.

8-5.5.4 Shallow Foundations on Refrigerated Granular Pad.

8-5.5.4.1 Refrigerated Granular Pads.

Refrigerated granular pads are composed of an insulated granular pad that is cooled by a refrigeration system (for example, piping) placed within the pad, as shown schematically in Figure A-12. These foundation systems are usually used for slab foundations on permafrost with excess ice that is susceptible to unacceptable displacements if thawed. These systems are used in bulk fuel storage tanks, heated warehouses, industrial process facilities, and high-floor-load facilities such as hangars and vehicle maintenance facilities. Refrigeration systems may be passive (meaning they do not require external energy sources) or active (meaning they require external power to operate).

8-5.5.4.1.1 Passive Refrigeration.

Refrigeration of granular pads is commonly accomplished using passive two-phase thermosyphons configured with flat loop evaporators within the fill beneath a building. This and other applications of thermosyphons for refrigeration are described in *Review of Thermosyphon Applications*, by Wagner; "Thermosyphon Applications in Cold Climates," by Zarling; and "Some Considerations Regarding the Design of Two-Phase Liquid/Vapor Convection Type Passive Refrigeration Systems" and "Recent Developments in Thermosyphon Technology," both by Yarmak and Long. Passive thermosyphons use natural convection and have no external power requirements. Include accommodation for ground temperature measurement beneath the structure in the design, and allowance must be made for periodic monitoring and maintenance as part of integrity management and life-cycle planning.

8-5.5.4.1.2 Active Refrigeration.

Active refrigeration systems or refrigeration systems that rely on a mechanical method to remove heat include chilled-liquid systems, forced-air convection systems, and direct-expansion systems. Their advantage is year-round cooling. Mechanical cooling can be added to a two-phase thermosyphon to create a hybrid thermosyphon,[5] or mechanical cooling can be used alone to achieve rapid cooling using a cold fluid such as brine. Active systems require active management of operation, ongoing maintenance, and a source of power. Long-term operations and maintenance costs must be considered when planning the use of mechanical systems of refrigeration.

8-5.5.4.2 Design.

Design of a slab-on-grade structure with two-phase passive thermosyphons is described in "Passive Techniques for Ground Temperature Control," by Long and Zarling, but thermal analyses can readily be accomplished using commercial 2D analysis software such as TEMP/W. Thermosyphon technology continues to improve the performance of horizontal thermosyphons (flat-loop systems), which allows for thinner pad construction, more space between aboveground finned condenser sections, and reduced costs. Design methodology requires that the NFS pad placed below the building floor and insulation containing the thermosyphon evaporators does not thaw to its base prior to the onset of the next winter's freezing season because thermosyphon systems only work when air temperatures are colder than ground temperatures. Important design variables include air temperature, wind speed and direction, building temperature (boundary condition), and details regarding embankments used to support the facility, such as insulation type and thickness, thickness of NFS fill, soil thermal properties, and thermosyphon conductance and spacing.

8-5.5.5 Complex Foundation Configurations.

Complex foundation configurations may be required for some facilities involving different types of foundations for the same structure. This type of combined and complex

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[5] *Demonstration of an Artificial Frozen Barrier*, by Wagner and Yarmak.

foundation requires thorough site investigation and analysis such that bearing capacity and settlement remains uniform and acceptable across the entire structure.

8-5.5.6 Structure Location on Granular Pad Overlying Permafrost.

When siting buildings on granular pads, it is important to locate footings back from the edge of the pad so they will not be affected by thawing during the life of the structure. The depth of thaw tends to be deeper at the edge of pads, which can result in more cracking and settlement in these areas. The deeper thaw is a function of snow drifting, solar radiation, and water ponding near the toe of the slope that frequently develop when gravel pads are placed on permafrost.

General practice has been to increase the setback from the edge of granular pads built on permafrost as climate has changed. In the absence of other data or site-specific ground thermal modeling, structures should be set back from the crest of embankment slopes a minimum of 12 to 16 ft (4 to 5 m) or 1.5 times the pad thickness, whichever is greater. Using insulation or construction techniques such as air convection embankments (ACE) and changes in the design life may warrant reducing the setback requirement. For example, embankments for facilities that will be operational for short periods, such as a year or two, will be less sensitive to the effects of thawing at the edges of pads than those in place for longer periods of time.

CHAPTER 9 PILE FOUNDATION DESIGN

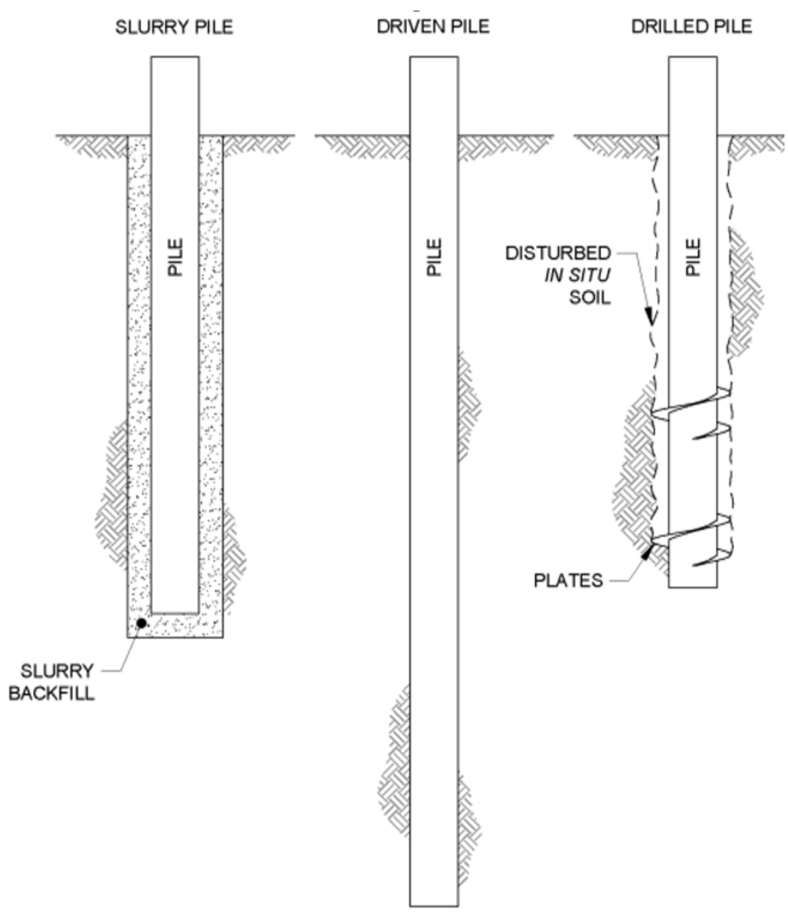
9-1 INTRODUCTION.

Piles are a common type of deep foundation used in Arctic areas of North America. The installation of pile foundations causes changes to the ground and requires varying design methods for different types of deep foundations. Piles are readily available, adaptable to a variety of conditions, and have a long history of successful installation. For general design principles for piles in permafrost and a discussion of frozen soil properties, see Chapter 8 of *Pile Foundations in Engineering Practice,* by Prakash and Sharma. Photographs of pile installations are included in Figures A-15 through A-19.

9-2 GENERAL PILE TYPES.

Pile types may be broadly classified by installation method. Several different types of piles commonly used in North America are shown conceptually in Figure 9-1. Pile material and structural sections will vary, and their selection must consider local practice and availability.

Figure 9-1 Typical Pile Types for Permafrost Areas



9-2.1 Slurry Piles.

Slurry piles are installed by drilling an oversized hole and setting either an open or closed end pile into place. The annular space between the pile and borehole wall is backfilled with slurry, as described in paragraph 9-2.1.5, that freezes after a few days to weeks. The hole diameter should be a minimum of 2 in. (50 mm) larger than the outside diameter of the pile, but providing a 3 to 4 in. (76 to 100 mm) annular space with a larger diameter hole is not uncommon and may facilitate densification. The oversized hole allows for very accurate positioning of the pile but may also require specialized drilling equipment like that shown in Figure A-16. Slurry is densified by vibrating the pile or using concrete vibrators. For piles longer than 30 to 40 ft (9 to 12 m), the entire pile should be vibrated, and more care must be given to specification and control of the gradation of the slurry.

9-2.1.1 Slurry Adfreeze.

Slurry piles gain support from the bond between the pile and frozen slurry, which is termed adfreeze strength and is discussed further in paragraph 9-5. The adfreeze strength can be greatly reduced by the presence of pockets of saline groundwater or the inflow of surface water from the active layer in summer. Saline groundwater may be encountered during drilling and will reduce the adfreeze capacity and potentially lead to increased creep if allowed to mix with the slurry. Tip resistance is commonly not included in North American practice because the vertical displacement that occurs due to adfreeze bond creep is usually less than the vertical displacement required to engage the tip resistance.

Pile capacity is controlled by the adfreeze bond between the slurry and pile. The pile–slurry bond can be increased by roughening the pile surface or incorporating measures such as shear studs or other deformations on the pile. The strength gained through roughening the pile surface may increase pile capacity on the order of three to seven times, based on testing of deformed bars and relatively small-diameter piles.[1] Adding helical shear plates greatly increases capacity and reduces creep deformation by shifting the location of the shear plane into the slurry. An example of a helically wrapped pile is shown in Figure A-17.

9-2.1.2 Ground Temperature Sensitivity.

Ground temperature is one of the most important criteria for the design of piles, influencing both strength and creep behavior. The sensitivity of pile capacity to ground temperature is especially important in warm permafrost, which is permafrost with ground temperatures warmer than about 30°F (−1°C). For example, a pile in permafrost at 30°F (−1°C) will have twice the sustained adfreeze capacity as a pile at 31°F (−0.56°C) and four times the capacity of a pile at 31.5°F (−0.28°C). Hence, refrigeration systems are commonly employed in combination with ground insulation to maintain or reduce the ground temperature and are frequently part of foundations for critical structures.

[1] “Thread Bar Pile for Permafrost,” Holubec.

9-2.1.3 Helical Shear Piles.

A helical shear pile is a specialized type of pipe pile that has a narrow (typically 2- to 4-in. wide [50 to 100 mm]) helical wrap (flight) around the circumference of the pile. The helix can be installed on pipe piles to increase capacity and reduce creep. Helix shear piles are especially effective at improving load resistance in areas with warm or saline permafrost because the helix moves the critical shear plane away from the surface of the pile into the slurry or slurry–permafrost boundary. A typical use is to provide added resistance to frost heave or uplift so that pile length can be minimized.

9-2.1.4 Slurry Shear Piles.

Shear piles are like helical shear piles, but instead of a continuous helical wrap, individual rings are welded onto the pile. Their use is not common in the U.S. (in 2024) but may have application, depending on local resources.

9-2.1.5 Slurry Mixtures.

Slurry mixtures typically consist of water and either sand, silt, or a mixture of the two, but they may include cement additives for some conditions (see paragraph 9-2.1.6). Sand–water mixtures result in an adfreeze capacity that is about 50% greater than silt slurry. Also, the sand–water mixture will have a lower moisture content than when mixed with silt, so the latent heat of fusion is less and, consequently, the freezeback time is faster. To develop dense backfill, the slurry must be fully thawed when placed, but the slurry temperature must also be kept near freezing to reduce freezeback times. Mixing water with frozen sand generally results in a slurry with high ice content, which should be avoided. If the piles do not include a refrigeration system, the time for freezeback of the slurry can be slow if the ground temperatures are warm or saline conditions are present. In this case, the slurry around open pipe piles can be frozen quickly by blowing cold winter air through a duct to the bottom of the pile, allowing it to return up the annulus. Mechanical refrigeration has also been incorporated within piles to enhance freezeback.

A typical sand–water slurry specification has 93% to 100% passing the U.S. No. 4 sieve size and 0% to 17% passing the U.S. No. 200 sieve size, mixed to a 6-in. (150 mm) slump that is mixed with clean water so the temperature is no warmer than 40°F (4.4°C).[2]Slurry specifications will vary, depending on local practice and the availability of material. Frozen material should not be included in slurry mixtures. Proper mixing of slurry materials is critical, especially if cuttings are used, and the ability to do so may dictate the slurry materials used.

9-2.1.6 Cement Slurry Piles.

9-2.1.6.1 Standard Cement Slurry Piles.

Cement slurry consists of a mixture of cement, sand, and water in the annular space between the pile and permafrost. Depending on the grout mix design and water-to-

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[2] *Permafrost Engineering Design and Construction*, Johnston; *Frozen Ground Engineering*, Phukan.

cement ratio, cement slurry can provide very high bond strength between the pile and slurry, especially in saline soil conditions. If very high bond strength is developed, the capacity of the pile will be controlled by shearing at the permafrost–slurry interface instead of at the pile–slurry interface.

Attention must be given to the grout mix design to ensure the grout sets before freezing and does not shrink or crack. Cement must be formulated for use in cold temperatures, but with proper mix design, cement slurry can be used effectively at ground temperatures as cold as 14°F (−10°C). Load testing to confirm the permafrost–adfreeze slurry bond strength is required when relying on the cement content of the slurry to increase capacity if conditions vary from previous installations. For further description of the use of cement slurry for piles, see “Laboratory and Field Performance of High Alumina Cement-Based Grout for Piling in Permafrost,” by Biggar et al., and paragraph 9-5.3.3.

9-2.1.6.2 Grouted Micropiles.

Grouted micropiles are a special type of cement slurry pile. Micropiles use a small-diameter (typically <4 in. [100 mm]) steel bar, such as those manufactured by Dywidag or Williams, that is installed in a grout-filled hole. They are best suited to use as anchors when they can be installed in bedrock or thaw-stable ground, although micropiles can also be used to carry vertical and horizontal loads in other types of material when used in conjunction with surface casings. The capacity of micropiles is very sensitive to installation methods and ground conditions. Testing has shown that they may not develop significant capacity when bonded in ice-rich permafrost;[3] therefore, they should be used cautiously in this type of material, in combination with a load test program during design and a proof testing program during construction to verify that capacities are being achieved.

9-2.2 Driven Piles.

Piles can be driven in frozen ground using a conventional impact hammer or vibratory hammers, often in combination with thermal modification. However, soil type and ground temperature must be considered because these factors affect drivability. Pile installation methods depend on the soil type, subsurface temperatures, and pile type. Local experience and equipment availability are often important factors affecting how successfully piles are installed, especially in remote areas. The presence of ice lenses or cobbles frozen in the soil matrix may inhibit pile driving or result in stress concentrations associated with damaged piles. For general background on pile installation in frozen ground, see *Frozen Ground Engineering,* by Andersland and Ladanyi; *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz; and *Driven Piles in Permafrost, State of the Art*, by Nottingham and Christopherson. Driving steel H-sections and open-end-pipe piles into frozen ground can be accomplished using a wide range of impact-driving equipment, including vibratory hammers[4] and hydraulic rock-breaker-type hammers. Reinforced pile

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[3] “Field Tests of Grouted Rod Anchors in Permafrost,” Johnston and Ladanyi.
[4] “The Adfreeze Strength Characteristics of Vibratory Driven Piles,” Mayrberger et al.

tips must be included with the design to reduce the potential for damaging piles during installation.

9-2.2.1 Predrilling or Thermal Modification (Prethawing).

Direct driving may not be possible, depending on several factors, including ground temperature, soil type, and the presence of saline soil. In general, piles are easier to advance when ground temperatures are warmer and in finer-grained soils. In colder ground with significant gravel content, pile driving may require predrilling and, in some cases, thermally modifying (prethawing) a small volume of soil around the predrilled hole. Prethawing can be accomplished by adding warm water to the predrilled hole or inserting a steam probe. The temperature of the water and amount of time for prethawing must be monitored, especially if steam thawing is used, to control the volume of soil thawed.

The ratio of the predrilled hole size to the pile diameter may vary, but it is typically on the order of 80% to 90% unless the soil is thermally modified. For criteria on minimum hole diameter for thermal modification, see “Pile Construction Practices in Arctic Regions State-of-the-Art,” by Nottingham et al. A predrilled hole that is not prethawed can promote stress concentrations at the pile tip during installation, which can lead to localized buckling. Local practice and equipment must be considered when developing specifications, or installation of test piles must be planned for during design to verify means and methods. Refer to “Pile Construction Practices in Arctic Regions State-of-the-Art” for further discussion of this approach to facilitate pile installation.

9-2.2.2 Pile Testing.

When driving piles in unfrozen ground, it is standard practice to perform high strain dynamic load testing using a pile driving analyzer to estimate capacity and monitor pile performance during driving. Testing driven piles with a pile driving analyzer in frozen ground may provide some information regarding pile stresses, but the data are not a reliable indicator of final capacity in permafrost areas due to the way in which load capacity in permafrost is developed. Measuring penetration resistance under an impact hammer or penetration rate under a vibratory hammer provides qualitative data but should not be used as a basis for determining the axial capacity. Use conventional static pile load tests performed according to ASTM procedures instead of impact testing for piles installed in permafrost. Special consideration is needed for long-term testing to measure creep rate because of the time required to hold loads and the potential for seasonal changes in ground temperature to affect results.

9-2.3 Helical (Drilled) Piles.

Helical (drilled) piles are used in permafrost areas of Alaska and Canada, but, depending on ground conditions, predrilling may be required to facilitate installation. For example, installations in coarse-grained materials such as those around Deadhorse, Alaska, may require both predrilling and thermal modification. Helical piles have one or more spiral plates welded at specific locations along the shaft. The shaft width typically varies from 1.5 to 36 in. (40 to 910 mm) in diameter, with helices that can vary from 6 to

48 in. (150 to 1220 mm) in diameter. The diameter of the top shaft section may be increased to provide greater lateral capacity to allow for retrofitting or because of anticipated thaw degradation and reduction of soil strength.

Helical piles are installed by drilling each pile into the ground using hydraulic drill equipment. The rate of advancement must be carefully matched to the rotation so soil disturbance is minimized, and the pile is essentially drilled into the soil. Their use is limited by the torque capabilities of the equipment, but they have been used in areas with degrading permafrost or high salinity soil conditions. Perform load testing to validate the design, but production installation is commonly monitored based on applied torque.

Helical (drilled) piles are commonly used for projects that require higher pull-out capacity (anchors) or where frost jacking forces control the design loads. Other benefits include rapid installation, little installation noise or vibration, no casing or dewatering requirement, lightweight installation equipment, the ability to be loaded immediately after installation, and their ability to be removed and reused (temporary facilities or facilities in support of military operations with a design life of five years or less).

9-2.4 Structural Materials.

Pile materials should be selected based on local practice, availability, and structural requirements, but steel, concrete, and timber piles have historically been widely used. In northern Alaska, steel pipe and H-piles are the most common types used in permafrost (in 2024); this is due to their drivability, high vertical and lateral load capacity, and ease of modification through welding. Pile design must consider corrosion potential, which will vary with location, and may include consideration of saline pore water (for example, in Utqiagvik, Alaska) and external environmental conditions such as salt spray or flooding salt water. Concrete piles are rarely used in the Arctic areas of North America but are more common in other parts of the world, where they are installed in permafrost using predrilling and slurry backfill methods. Concrete piles are typically precast and pretensioned to resist tensile loads due to frost heave forces. Timber piles may also be used, provided they have sufficient capacity and are protected from decay and deterioration in the active layer.[5]

9-3 PILE SYSTEMS WITH ADDITIONAL GROUND COOLING.

Ground cooling systems may be used with each general pile type, in combination with insulation, to enhance or maintain the capacity of piles by controlling ground temperature.[6] Cooling systems in common use in North America include passive thermosyphons installed within or adjacent to adfreeze piles, piles built as passive thermosyphons, and active ground freezing systems used to stabilize excavations. Air or liquid cooling can also be used to enhance freezeback or maintain ground

[5] *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost*, Linell and Lobacz.
[6] *Review of Thermosyphon Applications*, Wagner.

temperature, but these methods are less common for permanent installations in North America at this time (2024) given the availability of thermosyphon systems.

The purpose of incorporating cooling with pile systems is to reduce ground temperature so the piles can be designed for higher adfreeze and reduced creep, or to maintain ground temperature over the life of the structure. Additional cooling is generally required when ground temperatures are warmer than 30°F (−1°C), as they often are in western Alaska, or because ground temperatures are expected to warm over the life of the facility. They may be integral to the pile or installed adjacent to the foundation or structure.

9-4 END-BEARING PILES.

End-bearing piles are best suited to conditions where stable, dense sand, gravel, or bedrock is present. Conventional design procedures for temperate conditions can be applied to estimate capacity.

End-bearing capacity of deeper piles (such as slurry piles) is typically ignored in permafrost unless the tip is seated on undisturbed, ice-poor, dense sand, gravel, or bedrock materials that will not creep more than design tolerances over the life of the foundation. Studies of pile performance in ice-rich permafrost have shown that the end-bearing resistance of the pile on undisturbed frozen soil or ice is low until the pile has settled about 30% of the base diameter, assuming constant ground temperature. Given common design settlement rates of about 1 mm/year, the end-bearing resistance mobilized over the life of the foundation will generally be very low and is neglected in practice.

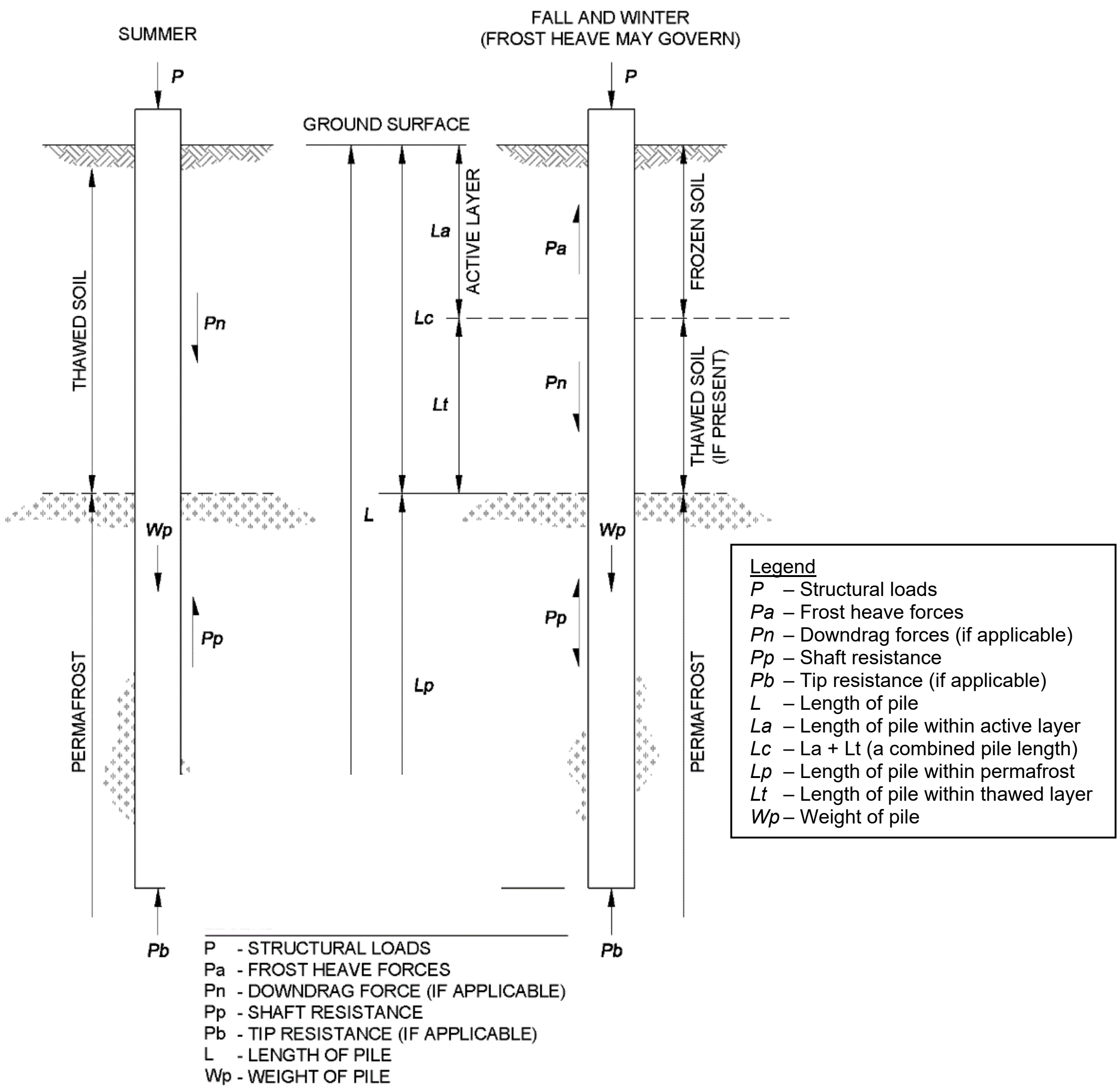
9-5 ADFREEZE PILES.

Piles installed in permafrost can provide long-term support for heavy loads if the design considers the mechanics and changeable nature of permafrost. The pile capacity, in compression or tension, will be significantly influenced by site conditions, such as ice content, thermal condition, and soil salinity, and by the nature and duration of the load application, pile type, and installation method. Therefore, a thorough understanding of both the thermal regime throughout the intended structure’s service life and the soil properties is needed to determine the optimal pile design and allowable pile capacity. Considerations in the design of adfreeze piles are presented in the following paragraphs.

9-5.1 Pile Capacity—Seasonal Change in Resistance.

The capacity of piles in permafrost will vary from winter to summer due to changes in the ground temperature and corresponding changes in the mechanical properties of the permafrost (see Figure 9-2). In the later part of the summer season, the active layer will become fully thawed (see Figure 2-5). As winter cooling begins, the active layer begins to refreeze, with attendant development of seasonal frost heave forces along that portion of the pile within the active layer. However, adfreeze shear strength (shaft resistance) will increase as the permafrost temperatures oscillate toward the cold side of the trumpet curve.

Figure 9-2 Seasonal Load and Resistance



9-5.2 General Relationships.

The geotechnical pile capacity is determined by integrating the shaft and tip resistance over the respective pile areas and including an appropriate FS for both adfreeze and creep-controlled conditions, as indicated in Equation 9-1. The effect of potential downdrag must also be considered and is discussed further in paragraph 9-9. The general relationship for pile capacity expressed in Equation 9-1 is applicable to both adfreeze and creep-controlled conditions, provided appropriate values are used for each of the parameters.

Equation 9-1. General Form of Equation for Vertical Pile Capacity

$$Q_a = \frac{1}{FS}(Q_s + Q_p)$$

Where:
Q_a = allowable pile capacity for a given load condition
Q_s = adfreeze capacity based on allowable adfreeze strength for given ground temperature and design creep rate
Q_p = pile capacity mobilized at the tip when ground conditions are appropriate (Tip capacity may be ignored for ice-rich conditions because the strain needed to mobilize the tip resistance typically exceeds allowable strain along the shaft.)
FS = factor of safety, which will vary with load case (Refer to paragraph 7-8 and UFC 3-220-01 for additional requirements.)

9-5.3 Adfreeze (Shaft Resistance).

The term adfreeze refers to the tangential shear strength developed along the interface of a pile and the surrounding in situ soil or engineered slurry. Adfreeze strength is a function of ground temperature, salinity, soil-slurry type, moisture content (including ice content), pile material and roughness, and installation method (typically either a slurry or driven pile). The pile shaft condition and presence of adfreeze reduction agents, such as paints, oil, and mill slag, can also affect the adfreeze strength. The ultimate resistance to compression or tension loads on the pile can be estimated by summing the unit resistance over the surface area of the pile that is exposed to soil or slurry within the permafrost.

9-5.3.1 Common Values of Adfreeze.

Commonly applied values of adfreeze strength are presented in the following references.

9-5.3.1.1 Linell and Lobacz.

In *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* Linell and Lobacz developed recommended adfreeze strengths based on an analysis of specific dimensioned steel and timber test piles embedded approximately 10 ft (3 m) in permafrost at ground temperatures between 32°F and −27°F (0°C and −33°C) with gradual incremental loading. Their recommendations are in terms of average sustainable adfreeze for both in-place soil and engineered silt or granular slurry. The creep displacement associated with the sustainable adfreeze strength is implied to be less than 1 in. (25 mm) over a 20-year service life. They also note that hard, sound freshwater ice shows a lower rate of creep deformation (and higher adfreeze strength) than frozen slurry at some temperatures.

9-5.3.1.2 Weaver and Morgenstern.

"Pile Design in Permafrost," by Weaver and Morgenstern, presents recommendations for the adfreeze strength of ice and soil at ground temperatures between 30°F and 23°F (−1°F and −5°C) in terms of the long-term cohesive strength of the frozen soil and an empirical roughness coefficient given by the factor, *m*, as shown in Equation 9-2.

Equation 9-2. Long-Term Shear Strength

$$\tau_{lt} = mc_{lt}$$

Where:
τ_{lt} = long-term shear strength
m = an empirical roughness parameter
c_{lt} = long-term cohesive strength of the soil

Suggested values for *m* in Equation 9-2 from "Pile Design in Permafrost," by Weaver and Morgenstern, were 0.6 for steel piles, 0.7 for concrete piles, and 1.0 for corrugated steel pipe piles. Equation 9-2 is based on a review and analysis of published pile test data, with the caution that piles supported in permafrost at temperatures warmer than 30°F (−1°C) may require special precautions, such as the addition of (artificial) cooling, to develop axial capacity.

9-5.3.1.3 Continued Research.

Research continues on the capacity of piles in frozen ground, and specific research may develop alternate values for the empirical roughness parameter or the form of Equation 9-2. For example, research on the adfreeze strength of a steel pile installed in Leda clay under varying ground temperature and normal stress indicated that a higher roughness coefficient, *m*, may be appropriate for the testing conditions and that the strength equation should include an additional frictional factor.[7] These results demonstrate the evolving nature of frozen ground engineering and the value of test programs for assessing design variables.

9-5.3.2 Roughness.

Adfreeze values in the literature generally do not consider differences in pile roughness, other than the roughness inherent in different pile materials (such as steel, concrete, timber). For steel piles, surface conditions have been shown to have a significant effect on pile capacity. In "Effect of Backfill Properties and Surface Treatment on the Capacity of Adfreeze Pipe Piles," by Sego and Smith, sandblasting a steel pile was shown to double the adfreeze strength at the pile–slurry interface, relative to untreated mill-finished steel pipe piles.

[7] "Interface Shear Strength Characteristics of Steel Piles in Frozen Clay Under Varying Exposure Temperature," Aldaeef and Rayhani.

9-5.3.3 Cement Slurry (Shaft Resistance).

Cement grout is a type of slurry that is considered separately from the conventional sand–water slurry discussed in paragraph 9-2.1.5 because of the considerable strength gain that can be achieved. In “Laboratory and Field Performance of High Alumina Cement-Based Grout for Piling in Permafrost,” Biggar et al. show that using cement grout doubled the pile load carrying capacity for a given displacement rate when the native soil had salinity up to 30 ppt, which is not an uncommon value (see paragraph 2-4.1.7). Although grout backfill will likely be more expensive than sand–water slurry, it may be preferable because of a lack of suitable material or because of the salinity in the soil.

The use of cement grout will likely move the critical shear plane from the pile–slurry interface to the interface between the soil and slurry for properly prepared steel pile surfaces. By shifting the critical shearing surface, the overall pile capacity increases because the surface area where shearing occurs is increased. However, in ice-bonded permafrost, the grout–in situ soil interface adfreeze bond should be reduced from the steel pile–grout interface adfreeze strength due to the material property differences between the steel and in situ soils. The reduction factors depend on the in situ soil material at the ground interface, with well-graded, clean sands and gravels having greater strength then high-plasticity clays for similar environmental conditions.

9-5.3.4 Creep Settlement.

Piles in permafrost will creep when installed in both ice-rich and ice-poor conditions, but consideration of creep becomes especially important when soils are ice-rich or have a high saline content because of the higher creep potential associated with these materials. In ice-poor soil or bedrock, piles can be designed for end bearing, provided frost jacking and uplift forces do not control the design.

Although creep is a highly complex phenomenon (see paragraph 5-3.2), in practice, creep effects are limited by controlling stress levels along the pile or by decreasing the ground temperature, which reduces the creep rate. Because creep is time and temperature dependent, it becomes important to establish the service life and the acceptable total and differential settlement tolerances of structures because these will dictate allowable stress levels over time. A common design standard is to design structure foundations for a creep rate of 1 in. in 100 years.

9-5.3.4.1 Creep Criteria.

If there is no slip between the pile and the soil, the pile settlement is equal to the cumulative shear deformation of frozen soil in contact with the pile. Equation 9-3, based on Equation 7.3-15 in *Frozen Ground Engineering,* by Andersland and Ladanyi, expresses the settlement (S) from primary creep using the International System of Units, as shown here:

Equation 9-3. Creep Criteria

$$s = \frac{3^{(n+1)/2}}{n-1} * a * \left(\frac{\dot{\varepsilon}_c}{b}\right)^b * \left(\frac{\tau_a}{\sigma_{c\theta}}\right)^n * t^b$$

Where:
a = pile radius (m)
τ_a = average shear stress along the pile–soil interface (MPa)
$\dot{\varepsilon}_c$ = creep strain rate (m/t)
t = time (hours)
$\sigma_{c\theta}$ = reference stress = $\sigma_{c0} * (1 + \theta/\theta_c)^w$ (Mpa)
σ_{c0}, n, b, w = experimentally determined values based on soil type
θ = soil temperature, −T(°C) or absolute value
θ_c = reference temperature, arbitrarily 1°C

Representative creep parameters that may be used in Equation 9-3 were compiled in *Frozen Ground Engineering*, by Andersland and Ladanyi, from a variety of source documents. Considerable judgement is required when using creep parameters, and designers must be familiar with the source documents and properties of the materials tested to confirm they are representative of the material being analyzed. Use field or laboratory testing like that described in *Creep of Frozen Soils*, by Sayles, to confirm the applicability of the values chosen for the design when warranted by project complexity.

Because creep of ice and ice-rich materials is poorly defined at temperatures warmer than 30°F (−1°C), piles in warm ice-rich permafrost must be refrigerated (see paragraph 9-6). Lowering ground temperature reduces the creep rate. However, it might take multiple winters to cool the soil to less than 30°F (−1°C) when using thermosyphons in warm permafrost areas. In addition, horizontal insulation may be required to assure stable ground temperatures are maintained.

9-5.3.4.2 Soil Salinity Effects.

Soil salinity in permafrost is an important parameter that must be characterized during site investigation and laboratory testing (see paragraph 5-3.1). The effect of salinity on creep was investigated in “Design of Vertical and Laterally Loaded Piles in Saline Permafrost,” by Nixon and Neukirchner, and in “Time-Dependent Displacement Behaviour of Model Adfreeze and Grouted Piles in Saline Frozen Soils,” by Biggar and Sego, who provide a design approach for saline soils. They show that soil salinity may increase the creep displacement of vertically and horizontally loaded piles by as much as 10 to 100 times that of nonsaline frozen soil.

9-5.3.4.3 Ground Temperature Effects.

Creep rate increases with increasing ground temperature. The creep of ice and ice-rich materials is poorly defined at temperatures warmer than 30°F (−1°C); therefore, piles in warm, ice-rich permafrost should be refrigerated, either passively or through mechanical means, to maintain or reduce the creep rate. In addition, horizontal insulation may be required to ensure stable ground temperatures are maintained. If ice-poor soils or bedrock are present in areas with warm, saline permafrost, piles should be designed as end bearing in these materials.

9-5.3.5 Allowable Adfreeze Shear Stress.

Creep is considered in the design of adfreeze piles by determining an allowable adfreeze shear stress. The allowable shear stress depends on several factors, including time of loading, ground temperature, and allowable displacement over the design life. Estimated values of adfreeze shear stress are established based on an understanding of site conditions, published data from the literature, and site-specific testing. Design values are selected from the developed relationships by either reducing the allowable shear stress for a given time of loading by a factor or selecting an allowable value for an increased time of loading.

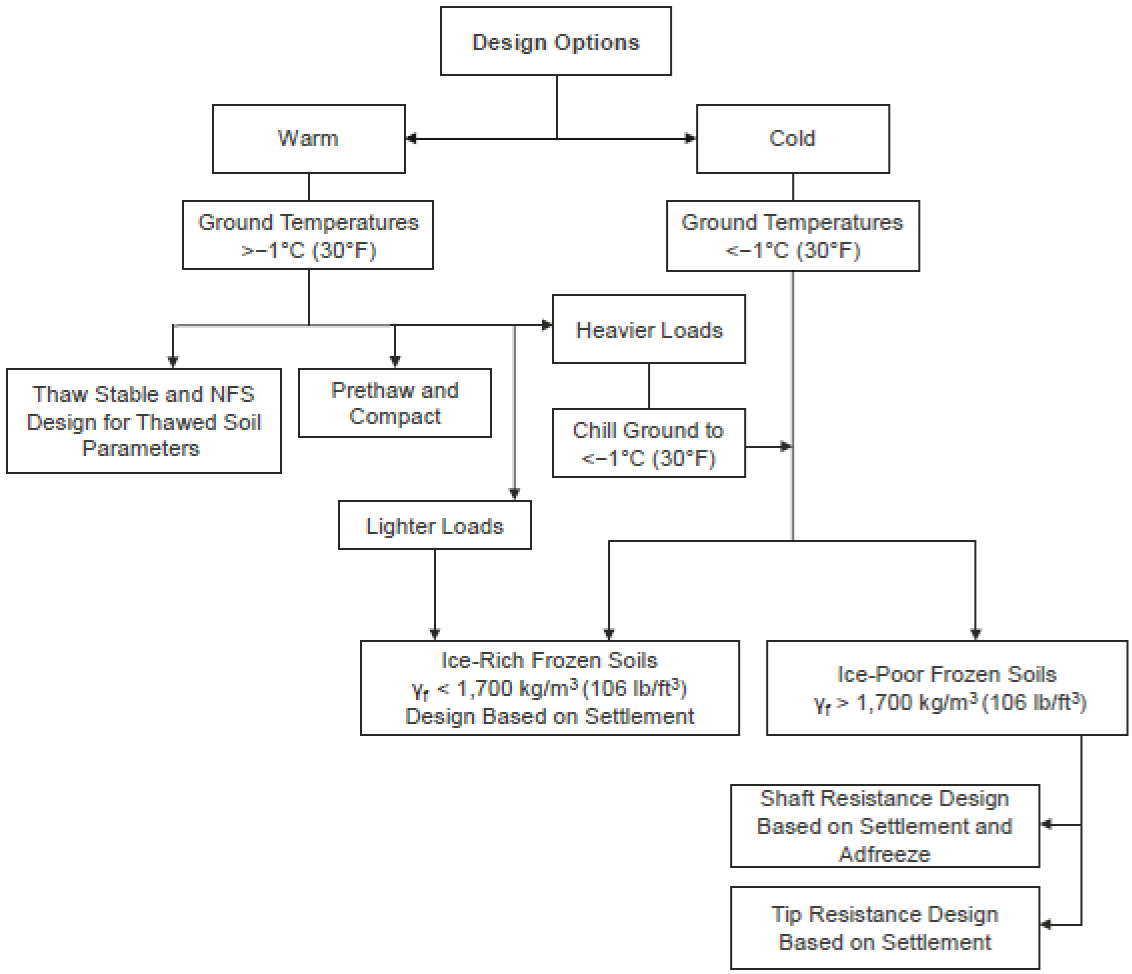
9-6 ADFREEZE PILE DESIGN PROCESS.

General design procedures for adfreeze piles, including charts for estimating adfreeze bond strengths and creep parameters, are presented in *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz; “Pile Design in Permafrost,” by Weaver and Morgenstern; *Pile Foundations in Engineering Practice,* by Prakash and Sharma, and *Frozen Ground Engineering,* by Andersland and Ladanyi. Recent updates to engineering practice must also be considered and include issues such as the following:

- The projected warmest or average permafrost temperature of the site for design and how this will be established. Ground thermal modeling may be required to predict changes in ground temperature.
- The tangential adfreeze bond strength along the pile length in permafrost as a function of temperature in ice-poor permafrost.
- The allowable shear strength associated with the design pile displacement for piles in ice-rich or saline permafrost.
- The embedment depth in permafrost to support the structural loads and resist downdrag and upward frost heave forces.
- The pile material, size, shape, and method of installation.
- Complete freezeback to the design temperature before loading, which is typically monitored using thermistor strings.

One approach to the design of piles in permafrost proposed in “Pile Design in Permafrost,” by Weaver and Morgenstern, is based on maximum ground temperature and the performance of piles, depending on their installation in ice-rich or ice-poor permafrost (see Figure 9-3). However, Figure 9-3 should be applied cautiously at sites where the permafrost is warmer than 30°F (−1°C) and creep effects or potential site changes over time may control the design.

Figure 9-3 Adfreeze Pile Design Process in Permafrost



9-7 TANGENTIAL ADFREEZE (FROST HEAVE).

The magnitude of frost heave forces is related to many factors, including soil and ground ice type and heterogeneity, variation of soil temperature with time and depth, rate of freezing, availability of water, foundation surface type, overburden pressure, pile load, and pile type. The following variables are especially significant when determining the minimum pile length necessary to resist frost heave:

- Pile loads and duration of loading
- Active layer thickness
- Tangential adfreeze bond strength in the active layer
- Pile shaft resistance below the active layer
- Serviceability limit state or failure criteria (pile vertical or lateral displacement at which maintenance must be done)

Design values of tangential adfreeze used in North American practice commonly are on the order of 30 psi (~200 kPa) to 60 psi (~400 kPa), depending on the standards being used (Table 9-1). However, 40 psi (275 kPa) is a very commonly applied value in North America for silty, frost-susceptible soil in the absence of other data.

Table 9-1 Published Values of Tangential Adfreeze in Absence of Other Data or Specification

Soil Type	Tangential Adfreeze
Silty frost-susceptible soil (commonly applied in North America)	40 psi (275 kPa)
Organic soil	10 psi (70 kPa)
Silty granular soil	20 psi (140 kPa)

Source: Adapted from “Foundations in Cold Regions,” by Phukan.

9-7.1 Minimum Pile Embedment and Frost Heave.

The minimum embedment needed to resist frost heave must be considered in every design. Pile heave due to frost action cannot occur unless the uplift force, *Pa*, exceeds the resistance provided by the length of pile embedded below the active layer, *Pp*, and the applied load on the pile (pile weight plus normally applied dead and live loads), as illustrated in Figure 9-2. The uplift force depends on the active layer thickness, the adfreeze bond strength in the active layer, the supply of water to the freezing plane, and the ability of the material to transmit water to the freeze plane. The pile uplift resistance depends on the embedded length of the pile below the active layer and the integration of shaft resistance along that length.

9-7.2 Engineering Measures to Mitigate Frost Heave.

Three conditions are required for frost heave and the development of the resulting tangential heave load:

- Freezing temperatures that change water in unfrozen soil to ice when the soil freezes
- Availability of water that moves to the freezing front due to capillary forces
- Frost-susceptible soils that can wick the available water to the freezing front

If one of these necessary conditions are eliminated, frost heave should not occur. Examples of engineering measures used to control and mitigate frost effects are discussed in paragraph 7-2.1 and paragraph A-8.

9-8 LATERAL LOADS.

Piles embedded in permafrost to sufficient depth to resist uplift forces and structural loading generally have high resistance to lateral loads during short-term loading, such as due to wind. If these same piles are subjected to sustained lateral loads, the capacity must be reduced due to creep that will occur. For methods for estimating the p-y (load-deformation) response of laterally loaded piles in permafrost for various load durations, see “Analysis of Laterally Loaded Piles Embedded in Layered Frozen Soil” and “Lateral Pile Analysis Frozen Strength Criteria,” both by Crowther, and “Analysis of Laterally Loaded Piles in Frozen Soils,” by Yang et al. *Frozen Ground Engineering,* by Andersland and Ladanyi, reports that long-term lateral loads on piles installed in ice-rich frozen ground, whether slurry or drilled, can rotate about the length of the pile over time, virtually eliminating the depth of fixity.

9-9 DOWNDRAG.

Downdrag will develop on a pile installed in frozen ground for several reasons, including thawing and settlement of ice-rich permafrost along the length of the pile and seasonal heave and thaw of frost-susceptible soil at the ground surface. In areas of significant seismic risk, liquefaction of soils that have thawed is another significant cause of downdrag that requires mitigation through ground improvement. As noted in paragraph 9-5.2, downdrag effects should be considered during design, and, if they are found to be a significant design issue, measures to mitigate the downdrag must be incorporated into the design. These mitigation measures include isolation of the pile from shallow frost heave and settlement effects, use of insulation or cooling to prevent a decrease in the depth of permafrost or thawing of ice-rich material along the length of the pile, changes in the pile geometry to provide greater resistance to anticipated load conditions, and ground improvement after thawing.

9-10 TENSION LOADS.

Design pile resistance to applied uplift or tension loads using appropriate adfreeze values for the design conditions and appropriate reduction for uplift, like that applied in the design of foundations in temperate regions using standards discussed in paragraph 1-5.2.

9-11 CYCLIC LOADS.

9-11.1 Machine Loads.

The behavior of adfreeze piles subjected to cyclical loads from machine loads such as from generators and other vibrating equipment is a special case (see paragraph 7-6.3) that requires careful analysis because the effects of these loads on adfreeze are not well defined. Model testing and monitoring indicate that cyclic loads increase the displacement rate of adfreeze piles relative to static-only axial loads for similar engineering and geologic conditions.[8] The magnitude of the increase is related to the

[8] “Displacement of Piles Under Dynamic Loads in Frozen Soils,” Parameswaran; *Vibration Amplitudes in the Inuvik Powerhouse*, Pernica et al.; “Dynamic Load Effect on Settlement of Model Piles in Frozen Sand,” Stelzer and Andersland; “Adfreeze Strength of Model Piles in Frozen Soil Under Dynamic Loads,” Zhang et al.; “The Settlement of Model Piles in Frozen Soil Under Dynamic Loading,” Zhang et al.

amplitude of the load, pile roughness, foundation rigidity, and other factors influencing creep in permafrost.

9-11.2 Sustained Axial Loads.

Adfreeze piles subjected to sustained axial cyclic loads require careful evaluation during the site assessment and engineering design phases. Site evaluation is particularly important if pore water salinity is present along or near pile embedment depths in the planned development area. Depending on geotechnical conditions and structural loadings, a comprehensive site and project analysis may be required for adfreeze pile design, including pile load testing. General adfreeze pile design recommendations are described below.

9-11.2.1 Structural Methods.

Structural methods to eliminate or reduce the cyclic loads to the adfreeze piles must be evaluated early in the design process and are the preferred approach to mitigating the effects of dynamic loads on adfreeze piles. Structural methods may include base isolation and dampening for machine-induced cyclic loads. If structural methods will not eliminate cyclical loading on adfreeze piles, engineering methods to permanently decrease the ground temperatures around cyclically loaded piles must be implemented because this will reduce the creep rate. Ground cooling is particularly important for sites with warm permafrost or elevated pore water salinity. Engineering methods may include the use of rigid insulation within pad fill, passive subgrade cooling, and active refrigeration.

9-11.2.2 Slurry.

For slurry adfreeze piles, dense slurry consisting of saturated, well-graded sand and gravel is recommended. Potable water is recommended for the slurry to reduce weakening by salt or other contaminants. Grout can be used in lieu of slurry in specific applications, although it should be designed for the expected ground temperatures and tremie placed.

9-11.2.3 Pile Surface Texture.

Steel and concrete adfreeze pile surfaces planned for slurry backfill should either be roughened by sand blasting to remove coatings, corrosion, and expose bare metal or lugs, helix wraps, or other structural protrusions that extend into the slurry or grout backfill should be installed around the piles. Structural protrusions should also be considered for timber adfreeze piles.

9-11.3 Creep.

Testing results showed that small cyclical loads will accelerate the creep of adfreeze piles in frozen sand by a factor of about 2 for alternating stresses of as little as 3% to

5% of the static stress.[9] Therefore, a 50% reduction from the allowable static adfreeze strength is sometimes considered as an initial estimate for design. For critical facilities, pile load tests should be conducted to determine or confirm a site-specific creep rate due to applied dynamic loads.

9-12 ADDITIONAL CONSIDERATIONS.

9-12.1 Pile Load Testing.

Pile load tests are used to verify design assumptions and optimize pile design. The results may provide insights on site conditions and foundation responses that cannot be captured by field investigation and laboratory testing alone. Pile load tests should be conducted on up to approximately 10% of the piles installed, but the actual number tested will depend on the scale of the project, uncertainty of soil conditions, confidence in the soil property characterization, and confidence in the installation method. Procedures for load tests are found in ASTM D5780, *Standard Test Methods for Individual Piles in Permafrost Under Static Axial Compressive Load*.

In selecting the number of piles to be tested, the uncertainty of soil conditions and confidence in the soil properties and thermal regime should be considered. For example, when the length of helical piles installed within the active layer is designed to carry a portion of the load, soil and moisture content variation across the site may have a higher potential to affect pile capacity. In comparison to slurry piles, which can be closely monitored and controlled, approximately 10% of helical piles should be tested, while fewer slurry piles can be tested. Design of pile load tests conducted in freezing air temperatures, or under long-term sustained loads, requires specific measures, such as providing shelter for test equipment or load cells that are susceptible to freezing. Significant time and effort are required when conducting long-term load tests in the Arctic and Subarctic. Examples of longer-term load tests in permafrost conditions are presented in “The Adfreeze Strength Characteristics of Vibratory Driven Piles,” by Mayrberger et al., and in general references such as *Frozen Ground Engineering,* by Andersland and Ladanyi.

9-12.2 Utility Connections to Buildings.

Incorporate flexible utility connections into the design to accommodate potential differential movements between the building and surrounding ground surfaces that occur due to seasonal frost action. For example, properly designed pile-supported structures will have little long-term settlement, but the surrounding ground surface may continue to settle because of thermal changes caused by site development or longer-term environmental changes at the site. If only vertical displacement is anticipated, the utility connections can be made with slip interfaces to facilitate movement between the structure and the underlying soils. See UFC 3-130-05 for further discussion.

[9] “Displacement of Piles Under Dynamic Loads in Frozen Soils,” Parameswaran; *Effect of Dynamic Loads on Piles in Frozen Soils*, Parameswaran.

9-12.3 Monitor Drilling for Slurry Piles and Predrilled Holes.

Design criteria commonly assume a certain amount of massive ice will be present along the length of the pile, which needs to be confirmed through logging cuttings produced during installation to confirm that conditions are as expected or that specific geologic units, such as a bearing layer, have been encountered. Therefore, drilling operations must be monitored and logged by personnel who are experienced with logging frozen soil and familiar with the anticipated subsurface conditions assumed in the design. If necessary, additional confirmation of subsurface materials can be accomplished using a downhole camera or lights to illuminate the borehole sidewalls and allow direct observation of conditions. When the amount of massive ice exceeds the design criteria, it is common to extend the pile an additional foot per foot of excess massive ice. Changes in pile length may require field splicing, which will affect the production of pile installation and schedule, especially if sufficient material is not on hand, which is often the case if the site is in a remote location.

A percentage of slurry piles should include installation of small-diameter casings to allow for installation of thermistor strings, which will in turn allow for measurement of ground temperatures to confirm that slurry has frozen back. The actual number of thermistors installed will depend on the number and configuration of the slurry piles.

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CHAPTER 10 HORIZONTAL STRUCTURE DESIGN

10-1 SITE INVESTIGATION CONSIDERATIONS FOR HORIZONTAL STRUCTURES.

In general, the site investigations for horizontal structures (such as road and airfield embankments, pipelines, and other long linear infrastructure) must follow the criteria referenced in UFC 3-130-02, UFC 3-220-01, UFC 3-250-01, *Pavement Design for Roads and Parking Areas*, EM 1110-1-1804, and Chapter 7 of this UFC. Other general discussion is found in technical literature, such as the following:

- *Roads and Airfields Constructed on Permafrost, A Synthesis of Practice*, by Connor et al.
- *Thaw Stabilization of Roadway Embankments Constructed Over Permafrost Areas*, by Zarling and Braley
- *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions*, by the Transportation Association of Canada

Foundations for horizontal structures will cross or span varying terrain or permafrost conditions and must consider not only the stability within the specific terrain unit and the transitions between terrain units, but also water features and mitigation of thermal erosion due to water. Foundations for horizontal structures may affect the subsurface conditions over time, and those effects need to be considered for the design life of the structure. The site investigation results will allow for evaluating and selecting appropriate foundation types for the project alignment and structure.

10-2 SELECTION OF FOUNDATION TYPE.

Foundation selection depends on the conditions of the existing terrain. In areas of seasonal frost, embankments and other horizontal structures should be constructed when the ground is thawed, using methods described in UFC 3-250-01, where several methods to protect the embankment section from seasonal frost effects are described in detail.

There are several different foundation options for permafrost regions. These options generally require active methods that provide thermal protection of the underlying soil, achieved either through thickened embankment fill or a combination of insulation such as rigid XPS or EPS insulation and embankment fill. Other methods may also be utilized, including air-convective embankments, air-convective shoulder treatments, or passively cooled embankments using open ducting or thermosyphons. In some cases, if the underlying permafrost is relatively thaw-stable, passive methods (such as allowing the permafrost to thaw) may be used. Additional details and considerations can be found in documents such as the following:

- *Embankment Design and Construction in Cold Regions*, by Johnson
- *Cold Regions Utilities Monograph*, by Smith

- *Frozen Ground Engineering*, by Andersland and Ladanyi

10-3 CONTROL OF HEAT TRANSFER AND DEGRADATION OF PERMAFROST.

Heat transfer from horizontal structures can be costly to control, and total prevention of the thawing of the underlying embankment and natural soil is often impractical. A cost analysis may dictate allowing for thaw with intervals of maintenance or patching prior to developing excessive differential settlement. Allowing for thawing must include annual costs for releveling the embankment surface or patching the surface pavement. Most often, this annual maintenance is more cost-effective than constructing an embankment that is resistant to thawing.

When insulation is used, material properties must be appropriate to provide sufficient strength and performance over time. For example, EPS, commonly used as lightweight fill, requires a more robust structural section above it to withstand repetitive loads than higher density materials with better strength in combination with low strain would require. Both EPS and XPS may be appropriate for a given application, but material properties must be carefully considered to attain proper performance. Insulation must also have a shear strength sufficient to resist applied loads and loads anticipated during construction, which may be higher than the structural loads.

10-3.1 Site Selection.

Terrain unit analysis and site investigations that characterize changes in near-surface conditions are critical to selecting the best route or alignment for horizontal structures, especially in permafrost environments where thaw-unstable terrain may be avoided by careful site selection. Passive methods may be utilized in terrain units classified as thaw stable. In areas that are thaw unstable (such as ice-rich polygonal ground), active methods may be employed; however, these are costly in long structures such as roadways. Route or alignment selection must consider the potential effects of thaw-unstable terrain and related geohazards on the project. A combination of desktop, remote sensing, and field methods can be effectively employed to characterize sites and monitor their performance over time.

10-3.2 Removal—Excavate and Replace.

This method is typically used where thaw-unstable permafrost conditions exist. A variety of excavation methods are available for frozen ground, depending on soil type, moisture (ice) content, and planned excavation depth. Typical frozen ground excavation equipment consists of single-tooth rippers, cutters, hydraulic impact breakers, and conventional bucket excavators with frost teeth. Drilling and blasting may be cost effective if large volumes of material must be moved. For options and additional details, see Chapter 9 of *Frozen Ground Engineering,* by Andersland and Ladanyi.

10-3.3 Stability of Slopes during Thaw.

The thermal effects and subsequent stability of embankment side slopes can be substantial. Embankments over frozen ground typically must be designed to be wider and to have flatter side slopes than those in temperate climates. Embankments wider than those used in temperate areas, along with flattened side slopes, can be used to provide sacrificial slopes that can deform while having little significant effect on the working embankment.[1] A recent study, "Thermal Stabilization of Embankments Built on Thaw-Sensitive Permafrost," by Kong and Doré, used very shallow shoulder slopes, most prominently on the downwind side of the embankment, that allowed for wind scouring of the snow and prevented snow piling and drifting in the ditch areas, preventing warming due to increased winter insulation from snow. Thermal analysis and a review of studies such as *Embankment Design and Construction in Cold Regions,* by Johnson, and Chapters 9 and 11 of *Frozen Ground Engineering,* by Andersland and Ladanyi, provide additional information.

10-4 PAVEMENT STRUCTURES.

Horizontal structures, or embankments, are designed to support concrete and asphalt airfields, roads, parking areas, and other linear structures (including unsurfaced, or gravel, roads). Embankment and pavement design must follow UFC 3-260-02, *Pavement Design for Airfields*, for airfields and UFC 3-250-01 for roads and parking areas. Additional considerations for embankment and pavement structures in cold regions can be found in *Cold Regions Pavement Engineering,* by Doré and Zubeck.

Construction of embankments often changes the natural thermal regime of the ground, creating the potential for thaw settlement, frost heave, and consolidation. Thaw settlement often occurs at ice-rich locations, such as those with wedge ice. The subsequent free water produced during thawing will then freeze the following winter season, creating frost heave. Frost heave can occur just as readily at nonthaw-settled locations in cases where there are frost-susceptible soils, water, and freezing temperatures, which can create ice lenses within the embankment. The formation of these ice lenses can result in differential surface movement during freezing and significant loss of strength during thaw. Embankments constructed of NFS material perform well but can still undergo destructive deformation and settlement if constructed over thaw-unstable subgrades.

10-5 DRAINAGE STRUCTURES.

Effective drainage is critical for the long-term performance of horizontal structures. Improper design or construction, in combination with thermal degradation, can affect the stability and functionality of these structures. Retention and storage requirements may be different than those in temperate areas due to impermeable freezing ground. Appurtenances must also be sized to accommodate changes in precipitation due to climate and vegetation changes during the life of the structure. Drainage structures, including culverts, are addressed in Chapter 11.

Horizontal structures have the potential to affect surface water and groundwater flow across a site, such as by altering runoff patterns or blocking drainages. These changes,

[1] *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions,* Transportation Association of Canada.

including cross-embankment flow, may alter the permafrost depth, inducing catastrophic thawing of thaw-unstable materials in the drainage pathway. Careful consideration of both the number of drainage structures and their potential to affect the thermal conditions at a site (such as ponding water, ditches, and culverts) must be considered. It is critical that embankments that become impoundments during periods of high runoff are sufficiently impervious and incorporate measures to prevent seepage pathways from developing along culverts that may penetrate the embankment.

CHAPTER 11 DRAINAGE AND DRAINAGE STRUCTURES

11-1 INTRODUCTION.

General guidelines for drainage and groundwater are covered in UFC 3-130-01. Surface water and groundwater can have very detrimental effects in permafrost areas and require special consideration for every project. Proper drainage is necessary to maintain the thermal stability of the structure and reduce the need for future maintenance. When possible, avoid construction of foundations in areas where natural groundwater and surface water flow exists. In most cases, this is impossible; therefore, additional drainage pathways are required to ensure water is conveyed through the embankment in a nondestructive manner. Permafrost features, such as ice wedges or other types of massive ground ice, are especially sensitive to thawing, and these areas should be avoided when possible.

11-2 VERTICAL STRUCTURES.

Positive drainage must be developed to drain water away from the foundations of vertical structures to prevent ponding and degradation of frozen ground conditions. When embankments or pads are used over permafrost terrain, the physical limits of the pads must include room for setbacks and insulation that may be required. This allows for sacrificial slope edges that can fail due to permafrost degradation related to the effects of ditching, ponding water, and thawing related to seasonal snow drifting, without damaging the embankment.

11-3 HORIZONTAL STRUCTURES.

Several surface water and groundwater mechanisms can negatively affect horizontal structures by enhancing permafrost degradation and erosion along ditches and drainage along the toe of embankments, forming aufeis when natural drainage is blocked, building up ice, and causing cross-drainage thawing of permafrost below the structure. Adverse drainage effects can be avoided by rerouting the alignment around or away from natural drainage features or can be mitigated by drainage improvements. Drainage improvements can be challenging, and it is difficult to ensure flow moves through the designed structures. Examples of aufeis mitigation can be found in “Aufeis Formation and Remediation,” by Zufelt and Daly, and “Aufeis Formation and Prevention,” by Slaughter.

The highway between Inuvik and Tuktoyaktuk in Northwest Territories, Canada, is an all-weather road that traverses varied permafrost terrain and opened in 2017. The highway construction incorporated innovative test sections with minimal fill thickness in select areas that are being monitored to support research into the performance and are focused on (1) assessing performance of the highway, (2) providing advance alerts to potential problems, and (3) building expertise for future application. Recent updates on insights gained from the Inuvik Tuktoyaktuk Highway should be considered for relevance to planned project activities.

11-3.1 Surface Water Control—Culverts.

Culverts are generally required to ensure control of water movement across horizontal structures. Culverts have a history of poor performance in cold regions due to the thawing of frozen materials adjacent to and under the drainage structure, ice buildup due to impeded flow, inadequate installation, and thermal effects on the underlying soil. In addition, buried piping and culverts frequently heave or settle, due to the previously mentioned errant flows, creating irregularities in the surface that may require long-term maintenance. Carefully consider the frequency of placement and the sizing of these structures. Often, the number of drainage structures specified during design is inadequate to ensure no cross-embankment flow occurs. In general, overdesign culverts with respect to the number of cross-embankment appurtenances, strategically placed for effective water conveyance, oversized to accommodate seasonal icing, and properly constructed. Inlets and outlets may heave or become filled with ice; this may warrant installation of heat trace or steam pipes to keep culverts from being blocked by ice in winter. Inclinations on both the shoulder slope and the cut slope, as well as the drainage ditch inclinations, will change as permafrost degrades under the side slopes and ditches. This creates areas where water ponds and fails to reach drainage structures. Also, thawing at the location of a drainage structure will increase the height required for the water to pond before running through the drainage structure, resulting in stranded culverts many feet above the elevation of the ditch line.

Consider phasing culvert installation during construction. Installing culverts during embankment construction often leads to better long-term performance than installing culverts after embankment construction. Careful consideration of location is required. When possible, systematically place culverts at specific locations that are identified as drainage pathways during spring thaw, thereby avoiding ponding related to the embankment construction. It is common practice to install culverts at two elevations at critical water crossings. This ensures water can flow in the spring when the lower culvert is iced up and covered in snow and also provides a second flow path in the event of a storm surge. Compaction must be controlled to ensure the long-term performance of the culvert and the embankment. Additional information can be found in *Cold Regions Hydrology and Hydraulics: An American Society of Civil Engineers Monograph,* by Ryan and Crissman, and *Frozen Ground Engineering,* by Andersland and Ladanyi.

11-3.2 Surface Water Control—Storage.

The design of surface water storage used for stormwater or snowmelt management systems must be carefully considered. In regions with seasonally frozen ground, these considerations must include the effects of early winter shallow freezing on drainage pathways versus the deep frost late into the spring, when snowmelt runoff storage must be accommodated. In permafrost regions, the impoundment of surface water often causes thermal alterations to the underlying permafrost, with unintended consequences such as thermal erosion and talik development or subsidence.

11-3.3 Subsurface Water Control.

Subsurface groundwater is generally present both above and below permafrost. The subpermafrost groundwater can have enough hydrostatic pressure to cause artesian flow when wells are constructed through the frozen mantle and the hydraulic potential is much greater in elevation. These types of artesian conditions can also be found in regions with high-salinity soils, where zones of hyper-saline permafrost may have high hydrostatic pressure and behave in a thawed manner. Wells with unintended artesian conditions will cause thawing of the immediately surrounding permafrost, which can affect the stability of the well and adjacent structures. Ground freezing has been used to reverse the thermal erosion and reduce adverse effects.

A gravel pit in the Fairbanks area, adjacent to a local hillside, was advanced in permafrost terrain. The thickness of the frozen zone of gravel was approximately 100 ft (30 m). A groundwater well was installed in the pit to measure water depth. Due to the artesian conditions, unintended flow through the installed well occurred, and the gravel pit quickly filled with water and had to be abandoned until the well could be refrozen in place using active freezing methods. Once the well was refrozen, the pit was dewatered, and gravel mining commenced.

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CHAPTER 12 CONSTRUCTION CONSIDERATIONS

12-1 INTRODUCTION.

Construction in the Arctic and Subarctic often occurs at self-contained work sites that are remote and have long supply chains and limited logistical support. The challenges of working at remote sites are compounded by weather extremes that affect equipment and the productivity of personnel, as well as potentially limiting sea-ice access during sealift operations. The cold regions environment is also sensitive to construction impacts that can greatly modify site conditions, as well as permitting issues and other limitations on operations discussed in Chapter 2. This chapter discusses general considerations relative to construction planning and logistics, site development and ground improvement, and other development activities. Additional discussion regarding construction issues in the Arctic and Subarctic can be found in many sources, such as the following:

- *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost*, by Linell and Lobacz
- *Permafrost Engineering Design and Construction*, by Johnston
- *Cold Region Structural Engineering*, by Eranti and Lee
- *Embankment Design and Construction in Cold Regions*, by Johnson
- *Thermal Analysis, Construction, and Monitoring Methods for Frozen Ground*, by Esch
- *Construction in Cold Regions, A Guide for Planners, Engineers, Contractors, and Managers*, by McFadden and Bennett

12-2 PLANNING AND LOGISTICS.

Prior planning and consideration of supply chain and logistical limitations are critical for successful implementation of work in the Arctic and Subarctic. Often, years of preparation and preliminary site work are needed prior to development of a new facility at a remote site. For example, it may be necessary to first establish temporary facilities or facilities in support of military operations using soft-sided structures (such as tents) for fuel, power, water, sanitation, and communications to facilitate primary site development and permanent structure construction. Depending on mission and schedule requirements, site development must include planning for work during winter conditions. Airport and dock construction may also be part of the site development work, requiring careful planning for material logistics and delivery schedules. For terrestrial logistics, seasonal ice roads may be needed to allow overland access (see UFC 3-130-01), and these activities generally will require completion of multiple environmental studies to secure permits, access (see UFC 3-130-01), and withdrawal of water from lakes or rivers.

12-3 SITE DEVELOPMENT.

Site development typically will include construction of a work pad that is graded to provide a level working surface. The extent of grading and fill placement at a facility depends on the number and size of embankments needed to support the full build-out of vertical and horizontal structures and the intended life of the site. For example, temporary facilities or facilities in support of military operations with a design life of five years or less may perform adequately with less fill than is required to support pavements and activities that are expected to occur over decades. To facilitate rapid construction, special considerations are required when constructing an embankment in the Arctic, particularly when construction occurs during winter months (see UFC 3-130-01). Challenges include compacting and engineering testing of the granular fill placed during freezing weather.[1] Also, the potential for thaw settlement is high if portions of the winter-constructed embankment thaw in summer and require recompaction of structural material to achieve proper stiffness.[2]

12-3.1 Protection of Natural Ground Surface.

Minimize disturbance of natural tundra overlying frozen ground because this will increase thaw degradation and potentially affect the functionality and stability of facilities.

12-3.2 Construction Constraints.

The use of granular pad foundation subsystems will be limited by the subgrade conditions. In areas where seasonal subgrade thawing will result in difficult construction, granular pad foundation subsystems are typically constructed in the winter to mitigate summer construction problems. These summer construction problems may include instability of the thawed surface soils and thawing of permafrost in excavations or where surface organics are disturbed. Water entering excavations through the active layer may also complicate summer construction. However, construction of granular pads in the winter presents its own set of problems that must be considered. The soil in granular pads constructed in the winter tends to bind together, making compaction difficult and resulting in fill that is looser than desired. Measures such as using thawed aggregate or reworking materials in the summer may be required depending on design criteria, which may affect construction schedules or design selection. Similarly, providing good drainage at the edges of pads is an important consideration (see Chapter 11).

Use select granular materials for best results, which may be a limitation in some areas where high-quality fill is not available. The granular materials must be relatively dry and free of frozen clods to allow proper placement and compaction during freezing conditions. Granular materials must also have low frost susceptibility.

[1] "Construction—Wintertime Compaction and LNG Facilities in Fairbanks, Alaska," Prusak et al.
[2] "Estimating Thaw-Strain Settlement of Frozen Fill," Crowther; "Cold Regions Earthwork," Tart.

12-3.3 Compaction During Periods of Freezing Air Temperatures.

Proper placement and compaction of structural fill can be conducted in temperatures below freezing. Careful planning and selection of the embankment material is required. Fill can be placed to an appropriate density in freezing weather with little to no detrimental effects upon thawing. This is especially important at sites where there is a limited window of time, either when air temperatures are above freezing (such as in Antarctica and Greenland) or due to other schedule constraints. The limiting temperature will depend on the material properties and method used to keep fill material in a thawed or near-frozen state. However, in “Construction—Wintertime Compaction and LNG Facilities in Fairbanks, Alaska,” Prusak et al. showed the limiting air temperature to be approximately 15°F (−10°C). At air temperatures below that value, it became difficult to achieve the desired fill density.

Around-the-clock construction monitoring (engineering controls) is especially important for placement of compacted fill in freezing conditions to ensure the site is free of snow and prepared in accordance with the specifications before placing additional lifts. Around-the-clock inspection also allows for the density of the lift to be measured immediately after placement, but prior to freeze.

An alternate method for establishing compaction criteria is to use a test fill that is built to establish compaction criteria and verify that desired compaction is being achieved using the available equipment at a site. It is important to establish correlations between in-place density and number of passes from specific compaction equipment supplemented by laboratory testing. Test fills are most applicable when the materials used do not exhibit a normal moisture density relationship, which may be the case for coarse crushed rock. A testing plan is required to establish the geometry of the test fill, testing and measurement methods, and acceptance criteria. The testing plan should include laboratory testing to develop compaction curves and establishing moisture–density relationships on the test fill material as a reality check on the field-generated data, whenever possible.

12-3.3.1 Winter Fill Placement.

12-3.3.1.1 General Use.

Winter construction and placement of frozen fill for roads and work pads may be required due to rapid construction schedules, improved mobility during the winter, and the need to meet permit restrictions aimed at minimizing environmental impacts and disturbance of the tundra. Placement of fill in freezing weather requires careful planning and control to ensure performance is as intended. Roads are often constructed according to standards that differ from those applied to embankments supporting building foundations. For example, fill that is supporting structures may need to be kept in a thawed condition so the fill can be compacted before it freezes. Frozen fill may be suitable for roads so long as provision is made in the schedule to recompact the fill as it thaws in the summer.

12-3.3.1.2 North Slope.

Winter construction and placement of frozen fill for roads and pads is a common practice on Alaska’s North Slope. Winter construction offers improved mobility and the ability to meet permit limitations on operations aimed at minimizing environmental impacts and tundra disturbance. This process generally requires a two-season operation. Sand and gravel used for roads and pads are mined in the winter and placed frozen, typically with 10% to 20% overbuild to allow for the thawing and settlement that occurs in the summer, when the material is reworked and compacted. Winter-placed gravel must be reworked to thaw and drain excess moisture before being compacted. Other factors to consider include breaking frozen clods of soil and preparation of the site to remove surficial snow and ice that may thaw and result in an unstable fill upon thawing.

12-3.3.1.3 Permanent Structures.

A different approach is applied for pads supporting permanent structures, such as those discussed by Prusak et al. in “Construction—Wintertime Compaction and LNG Facilities in Fairbanks, Alaska.” In this instance, fill materials were pre-thawed and placement was closely monitored to ensure compaction could be achieved before the material began to freeze. Compaction was successful to temperatures of 20°F (−6.7°C).

12-3.3.2 Seasonal Considerations for Incorporating Insulation.

When insulation is incorporated into embankment design, the schedule for construction must be considered. If fill material is placed late in the season, the insulation has the effect of limiting winter cooling. In general, it is preferable to place insulation early in the construction season to help maintain the colder ground temperatures while site work is completed. If schedule constraints dictate that insulation must be placed in late summer or fall, when ground temperatures are at their warmest, it is prudent to review design assumptions and implement mitigations, such as adding extra cooling capacity to foundations where thermosyphons are being installed.

12-3.4 Site Improvement Methods.

Site improvement methods such as those described in the paragraphs that follow may be required if there is long-term potential for thawing at permafrost sites that can lead to a reduction of bearing capacity and an increase in liquefaction potential. The extent of ground improvement will depend on site history, design life, and anticipated changes in ground conditions over the life of the facility. These activities may add one or more years to project schedules, especially when there are seasonal access constraints, which are often associated with remote sites.

12-3.4.1 Ground Thawing.

12-3.4.1.1 General.

Ground thawing is used when post-construction conditions are expected to degrade over time due to high ice content, such as when permafrost areas thaw over the life of a facility. Ground thawing is often used in conjunction with other ground improvement techniques, such as deep dynamic compaction or vibrocompaction, because thawed ground will likely be loose and saturated. Application of another ground improvement technique is especially important in seismic areas to reduce the liquefaction potential of thawed areas.

12-3.4.1.2 Forced Ground Thawing.

Several methods are used to force ground thawing, including thaw points driven into the ground, thaw pipes placed in drilled holes, or heating mats placed on the ground surface. Construction planning must include consideration of dewatering that may be needed when the ground is thawed, as well as the potential for encountering site contamination. Clearing vegetation is also an effective method for thawing permafrost, but it may require several years before the site is thawed to sufficient depth for construction. This approach is limited to the Subarctic, where the air and permafrost temperatures are relatively warm.

12-3.4.1.3 Heating Probes.

Two F-35A aircraft hangar-facility projects designed and constructed by USACE at Eielson Air Force Base, Alaska, required initial ground thawing to mitigate potential differential settlement from discontinuous permafrost underlying the project sites. Ground thawing was accomplished using electric heating probes (0.75 in. diameter [19 mm]), wired to a 220 volt single-phase generator and installed within a 1.25 in. (32 mm) casing drilled to a final depth of 25 ft (7.6 m). The heating probes were placed on a 10 ft (3 m) grid pattern across the treatment area, with one thermistor string installed for every 12 heating probes to monitor the progress of permafrost thawing. In this case, electric heating probes (700°F [371°C] heating elements) were used instead of steam points to facilitate faster thawing and to avoid the introduction of water into the subgrade, which would complicate further site development. Well points were installed to extract thaw water and facilitate the circulation of heated water and thawing effect within the permafrost. The projects are in an area of high seismicity, with underlying soil strata that include thawed permafrost subject to seismic-induced liquefaction settlement. Accordingly, the sites were further improved by means of deep dynamic compaction (DDC).

12-3.4.2 Excavation and Replacement.

Excavation and replacement of thaw-susceptible soil ensures compaction and the long-term performance of the site. The availability of appropriate materials and suitable construction equipment will affect the economics and dictate the feasibility of this ground improvement method. Excavate in the spring when the ground is still frozen; however, depending on ground conditions, excavations may be difficult to perform or may require blasting. If excavations extend into summer, they must be dewatered so water does not pond in the excavation prior to backfilling. Well-trained quality assurance is needed to ensure excavation has reached the ice-poor to ice-free limits.

12-3.4.3 Thermosyphons.

12-3.4.3.1 Passive Cooling.

Passively cooled thermosyphons are used to maintain or reduce ground temperatures without the need for mechanical refrigeration systems.[3] Installations must be designed to provide adequate cooling capacity for site conditions, including understanding ground temperature and wind speeds at the site. Additional considerations are discussed in paragraph 8-5.5.4 and examples of thermosyphon installations are shown in paragraph A-10. Performance is related mainly to wind speed and finned condenser area, and it is important to place passively cooled thermosyphons to maximize their effectiveness and to group them in areas around a structure to avoid damage to the thermosyphons from snow removal or other maintenance activities. Include periodic monitoring and maintenance as part of integrity management and life-cycle planning.

Control of seepage and use of NFS materials is especially important when passive refrigeration, such as that discussed in paragraph 8-5.5.4, is installed as part of the foundation design to limit the potential for heave of the foundation elements as the ground refreezes. Ponded water should not be allowed to accumulate in excavations needed to install flat loop thermosyphon systems because this may result in excessive heaving beneath foundations.

12-3.4.3.2 Hybrid Systems.

There are also hybrid systems that incorporate an attachment that allows for use of a vapor compression refrigeration system to cool the condenser enough to activate the thermosyphon during every season. Further details can be obtained from the only licensed manufacturers in North America (in 2024): Arctic Foundations or Arctic Foundations Canada.

12-3.4.4 Active (Mechanical) Ground Freezing.

Active or mechanical ground freezing may be an option for some sites. This method is adaptable to many situations, provides relatively strong soil structures within a matter of months, and is easily reversible by applying heat. However, these systems have high energy requirements because they use circulating coolants that must be maintained at temperatures between −20°F (−29°C) and about −75°F (−59°C). For design and construction considerations, see Chapter 6 of *Frozen Ground Engineering,* by Andersland and Ladanyi. A case study, “Construction Ground Freezing—A Look at Modeled versus Measured Performance,” by Daggett et al., compares modeled to measured performance of mechanical ground freezing.

Another relatively simple approach to construction ground freezing involves blowing cold air into open pipe piles or along the face of excavations. This approach has been effective for enhancing freezeback around piles and temporarily cutting off the seepage of saline groundwater into open excavations during construction of utilidors in Utqiagvik.

[3] *Review of Thermosyphon Applications,* Wagner.

12-3.5 Methods of Site Improvement After Thawing.

Frozen ground that has been thawed will require site improvement using the same techniques as applied in temperate areas. These methods could include vibrocompaction, deep dynamic compaction (see paragraph 12-3.4.1) or other methods, such as wick drains or stone columns, to enhance consolidation. In seismically active areas such as Alaska, ground improvement may be required to provide stable foundation conditions for both permanent dead loads and earthquake-induced loads, to improve bearing capacity, to mitigate excess settlement that may occur, and to reduce the liquefaction potential. These ground improvement techniques are often proprietary to specialty contractors and may require an extra level of design analysis and specification development. Post improvement testing is required to demonstrate that the desired level of ground improvement has been achieved.

Two F-35A aircraft hangar-facility projects designed and constructed by USACE at Eielson Air Force Base, Alaska, required ground improvement by DDC after initial thawing of underlying discontinuous permafrost. DDC was performed to mitigate potential seismic-induced liquefaction settlement of the subgrade soils. The complete sequence of ground improvement consisted of (1) over-excavating near-surface soils subject to seasonal freeze and thaw; (2) thawing permafrost using electric heating probes; (3) preparing a stable excavation surface with several feet of classified fill; (4) performing DDC across the treatment area, extending 25 ft (7.6 m) beyond structural limits; and (5) after DDC, proof rolling the area with a large vibratory roller, with the addition of classified fill compacted in 12 in. (305 mm) lifts to 95% density per ASTM D1557, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))*. DDC was accomplished using a 16 ton (14.5 metric ton) tamper dropped from a height of 50 ft (15 m), producing 4 ft (1.2 m) craters on a 10 ft (3 m) grid pattern. Each DDC point was subject to four to eight drops, with some areas needing a second pass to achieve the required degree of improvement. Ground improvement was verified by performing pre-DDC and post-DDC geotechnical borings, measuring the level of soil densification through the increase in standard penetration blow counts (modified ASTM D1586 using the large diameter split spoon sampler). The required level of ground improvement was achieved to the maximum target depth of 40 ft (12 m). Alternative ground improvement methods (such as vibrocompaction and permeation grouts) and deep foundations (driven piles) were considered during the design phase. DDC combined with ground thawing was selected as the best approach, with respect to cost, local experience, and suitability, for the specific ground conditions.

12-4 CONCRETE AND GROUT UNDER FREEZING CONDITIONS.

Concrete or grout can be used for anchors and foundation elements. However, poured concrete requires careful mix design so the concrete has sufficient time to cure before freezing and because the concrete may include admixtures. The foundation may need to be protected from cold air temperatures or placed inside a tented structure during curing. For footings in remote locations, prefabricated footings that can be placed on a vessel for transport are often used instead of poured footings.

For further information on mix design and placement of concrete under freezing conditions, see the following publications:

- ACI 306R
- *Creep Behavior of Shallow Anchors in Ice-Rich Silt,* by Zhang et al.
- "Development of Innovative Antifreeze Grout Mortar for Anchor Applications in Cold Regions," by Lin et al.
- *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz
- *Cold Region Structural Engineering,* by Eranti and Lee
- *Construction in Cold Regions, A Guide for Planners, Engineers, Contractors, and Managers,* by McFadden and Bennett

Refer to UFC 3-130-01 for requirements on placing concrete.

CHAPTER 13 PERFORMANCE MONITORING AND MAINTENANCE

13-1 GENERAL.

Well-designed and -implemented performance monitoring programs are used to inform decisions about maintenance activities that are necessary for preserving the original capital investment and performance of structures. Monitoring includes measuring ground temperatures in permafrost areas, measuring deformation for critical foundation components, and visual inspection, and is linked to baseline measurements, established performance criteria, and clear data recording standards.

Management of geotechnical monitoring data is an evolving area or practice without specific guidance used to help optimize operations and maintenance. It has most commonly been applied to linear infrastructure and can be relatively simple (such as documenting end-of-construction conditions and periodic monitoring) or can involve more extensive data acquisition and monitoring linked to risk and cost–benefit analyses. Detailed guidance related to geotechnical asset management for transportation projects can be found in *Geotechnical Asset Management for Transportation Agencies*, by the National Cooperative Highway Research Program, or a library of online resources found on the Ohio Department of Transportation website (https://www.transportation.ohio.gov/working/engineering/geotechnical/asset-management/asset-management#page=1).

13-1.1 Ground Temperature.

Ground temperature is one of the most important and commonly measured parameters for assessing the capacity and performance of foundation systems where frozen ground is present. A ground temperature monitoring system, consisting of temperature sensors installed at various locations and depths, provides early warning to managers and engineers about changing conditions that risk foundation damage.[1] Ground temperature in North America is typically measured using thermistor strings or digital temperature cables with known calibrations of output to temperature. Other methods of measuring ground temperature, such as thermocouples, may also be appropriate; consult with the geotechnical engineer of record for additional guidance. Ground temperature monitoring systems can be coupled with data loggers and installed at many locations. For remote installations, solar-powered systems with satellite uplinks may be used to provide real-time monitoring and analysis of data. Other techniques for measuring ground temperature are discussed in Chapter 3 of *Thermal Analysis, Construction, and Monitoring Methods for Frozen Ground,* by Esch.

Ground temperature measurement is especially important for flat loop thermosyphon systems or active refrigeration systems, like those used in mainline refrigeration units along the Trans-Alaska Pipeline System. Because these systems are difficult or impossible to access, instrumentation must be installed at the time of construction and

[1] *Improving Design Methodologies and Assessment Tools for Building on Permafrost in a Warming Climate,* Bjella et al.

include redundant sensors. Regularly calibrate sensors because the data from many of the sensors on the market today will drift over time.

13-1.2 Settlement, Tilt, and Lateral Movement.

Settlement, tilt, and lateral movement of structural foundation elements are common measures of foundation performance. Settlement and tilt are determined by conventional optical survey measurements, although there are tilt meters and crack monitoring gauges that allow continuous measurement of these parameters. Gauges are used in temperate climates and are deployable for cold climate applications, provided they are also winterized.

Settlement can also be monitored using drone-based or ground-based lidar surveys and high-resolution remote sensing data, such as interferometric synthetic aperture radar, for large or remote sites. However, the accuracy of these surveys, especially those involving remote sensing, must be checked. Survey control may be needed to improve accuracy, and survey monuments will need to be designed to resist frost movement. Features included in these types of monuments are illustrated in Figure 5.1 of *Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost,* by Linell and Lobacz. They require a casing around the survey marker that is filled with a media such as silicone oil or a wax-oil mixture. The marker must be anchored into permafrost deeper than the estimated depth of thawing anticipated over the life of the marker.

13-1.3 Groundwater.

Groundwater can be a significant factor in the stability of embankments or foundation systems. Conventional systems (such as open standpipes or pressure transducers) provide simple and effective measurements in areas of seasonal frost or below the base of permafrost. However, both systems will freeze, and pressure transducers are not well suited to long-term measurements in freezing conditions unless the system is winterized. Geophysical surveys like those discussed in UFC 3-130-02 are also commonly used to identify thawed areas and unfrozen zones within permafrost.

13-1.4 Visual Inspection.

Specific observations and the frequency of inspections will vary depending on the structure, but examples include noting the condition of thermosyphons, blocked airflow below elevated structures, fluids leaking from elevated structures, and out-of-level doors, windows, and floors. Other features worthy of notice during a visual inspection include cracks developing within structures and pavements; changes in grade, areas of subsidence, and tension cracks in the ground external to structures; differential movement and disturbance of utilities entering buildings; and evidence of site modifications that may pose future facility instability issues, such as removal of vegetation, which will increase the risk of thaw degradation.

13-2 MAINTENANCE OPERATIONS.

Well-planned and -implemented monitoring programs provide indications of developing stability problems before they affect the structure. Catastrophic acute foundation failures are rare, but chronic problems can occur in the Arctic and Subarctic due to inappropriate engineering or unforeseen site conditions in design and construction. Chronic problems related to thawing permafrost may not become apparent until well after construction, but ground temperature monitoring like that discussed in paragraph 13-1.1 can help prevent disastrous outcomes. Examples of this monitoring include identifying areas where ground temperatures are higher than desired due to heat inputs from the structure, identifying areas of the site with high local ground-ice contents, measuring lateral translation, and measuring settlement (either locally or area-wide) to make sure it is not excessive.

13-2.1 Operational Impacts to Consider.

Normal day-to-day facility activities can affect the thermal regime and the support capacity of foundations. Plowing snow away from structures maintains colder permafrost temperatures, avoids thawing of ground ice, and prevents the resulting localized thaw settlement and structure damage. If snow drifts are not cleared or if plowed snow is stockpiled, the insulating effect will change the local thermal regime and can warm up the underlying permafrost soils and, over time, trigger permafrost degradation that can affect the structure performance. Similarly, blowing snow into ditches adds insulation in these areas and contributes to ponding near the toe of embankments. Preparing an operations manual will provide guidance to the maintenance team over the long term, thus improving the performance of foundations.

13-2.2 Mitigation Measures.

Develop appropriate mitigation measures to address observed movement or foundation distress based on an understanding of the cold regions design principles and criteria provided in previous paragraphs. Examples of mitigation measures include the following:

- Adding additional ground cooling capacity to a facility.
- Redirecting drainage to eliminate the added heat loss and associated permafrost degradation caused by flowing water.
- Incorporating adjustable foundation elements.
- Changing the surface energy balance by managing vegetation.

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APPENDIX A BEST PRACTICES

A-1 INTRODUCTION.

The Best Practices Appendix is considered to be guidance and not requirements. Its main purpose is to communicate proven facility solutions, systems, and lessons learned but may not be the only solution to meet the requirement. It identifies additional background information and practices for accomplishing the design of foundations for freezing and thawing conditions. The DoR is expected to review and interpret this guidance and apply the information according to the needs of the project. If a Best Practices document has guidelines or requirements that are not discussed in the Unified Facilities Guide Specifications (UFGS) or UFC, the DoR must submit a list of the guidelines or requirements being used for the project, with sufficient documentation, to the Government Project Manager for review and approval prior to incorporation within the design.

A-2 CANADIAN EXPERIENCE.

Various guides and national standards have been developed for use in Canada, including some by the government of the Northwest Territories. These guides and standards contain performance guidelines, design data, preferred materials and methods, and logistical considerations developed from decades of experience with the design and construction of foundations in the Canadian north. Over time, certain products and approaches to constructing foundations have proven successful and have been adopted by design consultants and builders working in the Canadian north. These guidelines and standards should be reviewed as they document both failures and successes in foundation construction and durability in cold regions. Publications relevant to foundations in cold regions include the following:

- *National Standard of Canada CAN/BNQ 2501-500/2017: Geotechnical Site Investigations for Building Foundations in Permafrost Zones*, by the Bureau de Normalisation du Quebec
- Chapter 13 of the *Canadian Foundation Engineering Manual*, by the Canadian Geotechnical Society, for an alternative approach for estimating frost heave potential is to measure the segregation potential of the soil

A-3 OTHER CODES AND STANDARDS.

The effects of these various codes and standards will vary, as will the way specific requirements may need to be handled on a project. Extensive literature is published by sources in the U.S. (such as the American Petroleum Institute, International Code Council, International Conference of Building Officials) and by the National Research Council Canada and the European Union, but there is no prescriptive code requirement for foundation design in permafrost regions. Russia, however, has developed an extensive body of regulatory documents, which include a series of national building codes, standards, territorial building codes, and guiding regulations with specific design criteria for permafrost areas. Resident professionals who are familiar with the specific requirements in the project area are a valuable resource to consult during project planning to confirm local practice and avoid delays in project design approval and construction.

A-4 PLANNING AND DESIGN CONSIDERATIONS.

Military installations in cold regions may be self-contained or connected to existing public or industrial infrastructure. Where public or private infrastructure exists, specific standards and practices for construction may need to be followed. Other installations own, operate, and maintain their own facilities. For those installations, direction from the installation staff, often in the form of installation facilities standards (IFS), should be solicited and followed. New installations may benefit from the guidance used at existing military installations or local municipalities. Revegetation after construction should follow applicable IFS guidance and local requirements. IFSs are available on the WBDG at https://www.wbdg.org/airforce/ifs.

Modular construction, where an entire facility or a major component of a facility is preassembled and shipped via barge or sled to the point of use, has been used at oil field developments on the northern coast of Alaska. It is advantageous in these locations because the construction season is short and labor costs are relatively high. Barges can usually begin to arrive in Utqiagvik, Alaska, and the eastern Arctic around the first of September. This means the nonmodular construction materials must be shipped a year in advance and stockpiled for the next construction season. Facilities may also be built on-site using basic structural materials, or significant components (such as mechanical assemblies) may be preassembled at the point of manufacture. The approach adopted depends on logistical limitations specific to each site, and the use of modular construction needs to be discussed with the design team on a case-by-case basis. Prefabrication of foundation assemblies has been shown to be cost-effective in remote locations and locations with a high cost of labor.

A-5 CLIMATE CHANGE CONSIDERATIONS.

A-5.1 Intergovernmental Panel on Climate Change.

The IPCC provides a common source of information relating to emission scenarios, provides third-party reviews of models, and recommends approaches to documenting future climate projections. Periodically, the IPCC issues assessment reports summarizing the current state of climate science. The most current complete synthesis of information regarding climate change must be used in climate analyses. The IPCC does not run the models but acts as a clearinghouse for the distribution and sharing of the model forecasts.

In the IPCC Fifth Assessment Report (AR5), which consists of Working Group Reports and a Synthesis Report, potential scenarios for future climate are designated as RCPs, while in the IPCC Sixth Assessment Report (AR6), SSPs are used. Both sets of scenarios include a suffix that specifies the radiative forcing projected to occur by 2100. For example, SSP2-4.5 denotes a pathway that is characterized by climate change mitigation and adaptation options of SSP2, which would result in 4.5 watts per square meter of radiative forcing by 2100 (like RCP4.5). Compared to AR5, a wider range of scenarios are provided in AR6, covering an updated set of pathways by which future climate may unfold. The RCP and SSP scenarios for similar radiative forcing values provide comparable trajectories of future climate. For example, both SSP1-2.6 and RCP2.6 are characterized by sustainable development proceeding at a reasonably high pace. Similarly, both SSP5-8.5 and RCP8.5, which are commonly considered for work in Arctic areas, are characterized by high greenhouse gas emissions.

A-5.1.1 IPCC Fifth Assessment Report (AR5).

Documents from the AR5:

- *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker et al.
- *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Field et al.
- *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Barros et al.
- *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer et al.
- *Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Pachauri et al

A-5.1.2 IPCC Sixth Assessment Report (AR6),

Documents from the AR6:

- *Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte et al.
- *Climate Change 2022: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner et al
- *Climate Change 2022: Mitigation of Climate Change, Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla et al

A-5.2 Downscaling Climate Data and Sources.

A-5.2.1 Scenarios Network for Alaska + Arctic Planning (SNAP).

Downscaled climate data for the Arctic and Subarctic is available through the SNAP project at University of Alaska Fairbanks. The SNAP website (https://uaf-snap.org/climate-tools/) includes a collection of tools that use downscaled climate data to estimate projected changes in a variety of different climate variables and scenarios, such as those noted in paragraph A-5.1. The tools that follow can be found at the SNAP website:

- Community Climate Charts
- Precipitation Projections for Alaska Infrastructure
- Community Wind Data
- Arctic Environmental and Engineering Data + Design Support System (Arctic-EDS)

A-5.2.2 Climate Data Portals.

Climate data portals can provide climate projections that are readily accessible and provide regional or global coverage. Examples include the following:

- IPCC Interactive Atlas (https://interactive-atlas.ipcc.ch/)
- World Bank Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/)

These portals provide information for both AR5 and AR6. However, they may not provide enough information for design applications, which require higher resolution climate data (see paragraph A-5.2.3). The projections available from these portals can be used to understand how downscaled climate projections compare to regional or global projections and how downscaled projections from AR5 compare to projections from AR6. Climate data portals are often updated much faster than daily downscaled data and provide good summaries of the most recent projections.

A-5.2.3 Daily Downscaled Climate Data.

Daily downscaled climate projections can be downloaded from SNAP and from a variety of other sources at a daily resolution. One example is NASA’s NEX-GDDP, which provides projections of total precipitation, wind speed, relative humidity, solar radiation, and mean, minimum, and maximum temperature for an ensemble of climate models and emissions scenarios.

A-6 CLIMATE AND CONTINUAL IMPROVEMENT.

USACE evaluated climate risk in the design process for shore protection at Utqiagvik, Alaska. First, a climate change dataset was developed to establish projected changes in air temperature over time using an ensemble of climate models and scenarios. Using this dataset, thermal analyses were conducted to assess the potential for an eroding permafrost slope to thaw, based on the planned construction and potential changes in future climate. This is an example of the first stage of the MAC process for assessing climate risks. Details of each stage of the MAC process are described below.

A-6.1 First Stage.

The initial stage of the MAC process involves the assessment of climate risks. For engineering foundation design, this includes establishing historical climate conditions and obtaining projections of future climate conditions for climate-related design parameters. Climate risk thresholds may then be established for when key climate parameters may affect the foundation designs. Depending on the projected changes, the uncertainty in these parameters, and the sensitivity of the foundation design, climate risks may be identified and ranked. These risks may depend on a given climate parameter meeting or exceeding a predefined value.

A-6.2 Second Stage.

In the second stage of the MAC process, adaptation options are developed to address the climate risks identified in the first stage. Adaptation pathways provide decision-making support on when to implement the adaptation options. For engineering foundation design, this may include adjusting the initial design to account for projected climate changes or developing provisional measures that can be phased into the project over time as climate risk thresholds are reached.

A-6.3 Third Stage.

The final stage of the MAC process involves monitoring and surveilling designs at climate risk thresholds established in the first stage. Given the level of uncertainty involved in future climate projections, this step acts to confirm the risks identified in the first stage and the adaptation options implemented in the second stage as new information becomes available. This information may include new on-site observations or updated climate projections. If climate risk thresholds are approached or met, the MAC process cycle may be repeated with this new information.

A-7 SLOPE GEOHAZARDS.

When selecting building sites or routes for linear infrastructure, it is important to remember that slopes in permafrost areas migrate downslope over time due to the force of gravity, depending on ground ice content, active layer moisture, and ground ice temperature. The slope movements constitute geohazards that must be considered when planning a project. Table A-1 lists some of the more common slope processes, the relative speed at which they occur, and related engineering issues. Figure A-1 through Figure A-5 show representative examples of some geohazards. Additional illustrations of permafrost features are found in the following:

- *Glossary of Permafrost and Related Ground-Ice Terms*, by Harris et al.
- *Permafrost, A Guide to Frozen Ground in Transition*, by Davis
- *The Periglacial Environment*, by French

- *Geocryology: Characteristics and Use of Frozen Ground and Permafrost Landforms*, by Harris et al

Table A-1 Slope Processes and Related Engineering Concerns

Speed of Process	Process	Description	Engineering Issues
Slow	Solifluction	• Geomorphic features produced by solifluction include uniform sheets of locally derived surficial materials and tongue-shaped lobes.[1] • Can occur on slopes as low as 3°.[2]	• Disturbing solifluction lobes, when or as they are thawed, can cause slides to occur. • Structures located on these lobes can move or be disturbed, including localized impact on piles.
	Creep	• Related primarily to the presence of ice within soil.	• Structures can move or be disturbed.
Intermediate to rapid	Frozen debris lobe	• Described in "Frozen Debris Lobe Morphology and Movement: An Overview of Eight Dynamic Features, Southern Brooks Range, Alaska" by Darrow et al.	• Structures can be displaced or disturbed. • Can result in severe structure damage, entire loss, or need to relocate.
	Thermo-erosion gullying	• See definition in paragraph B-3 • This process is occurring in the upland silts of interior Alaska.	• These features can cause sinkholes and instability, most commonly in horizontal structures.
Rapid	Active-layer detachment	• Common on colluvial slopes in areas of fine-grained, ice-rich deposits, where they occur as shallow slumps. • Occur more frequently during warm summers or following disturbance of the vegetation or ground surface by, for example, tundra or forest fires or engineering activity, when the depth of thaw is greater than normal.[3]	• Structures can move or be disturbed. • Detachment failures that expose massive ice or icy sediments can develop into retrogressive thaw slumps.
	Thaw slumping	• Geomorphic features produced by thaw slumping are retrogressive thaw slumps. These can be large features with an exposed face more than several meters high with a long crest length.	• Structures will likely move or be disturbed. • Can result in severe structure damage and entire loss.

1. *The Periglacial Environment*, French.
2. *Permafrost and Related Engineering Problems in Alaska*, Ferrians et al.
3. *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms*, van Everdingen.

Figure A-1 Solifluction Lobes (Alaska Range)

Photo courtesy of R.G. Tart Jr., Golder Associates.

Figure A-2 Frozen Debris Lobe

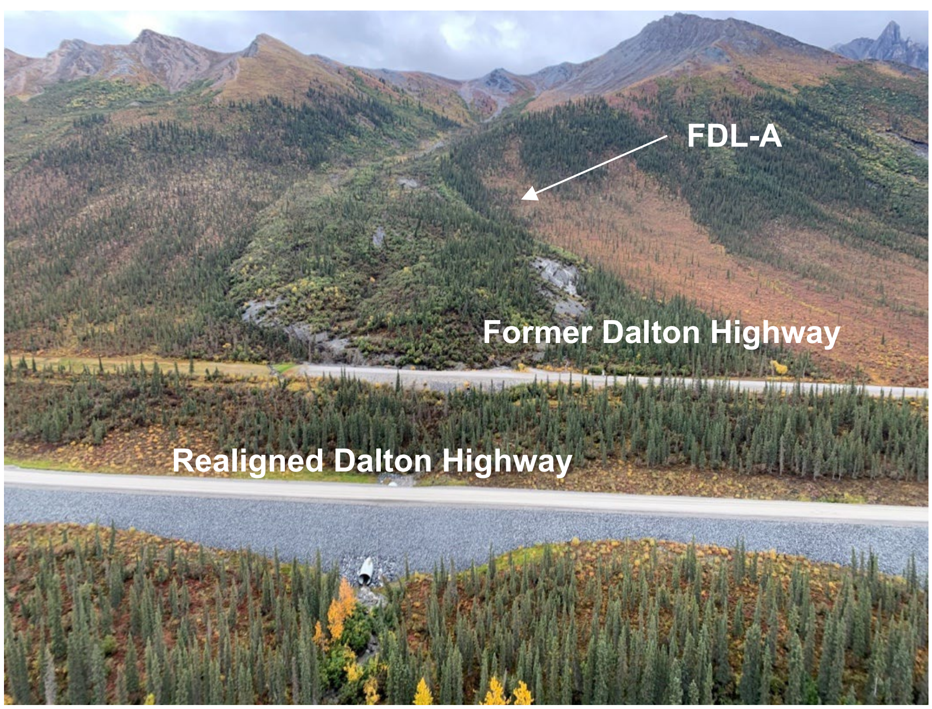


Photo courtesy of WSP USA.

Figure A-3 Connected Sinkholes Formed after Material Site Development (Dempster Highway, Canada)

Photo courtesy of WSP USA.

Figure A-4 Retrogressive Thaw Slump (Mackenzie River, Canada)

Photo courtesy of T. Krzewinski, WSP USA.

Figure A-5 Active Layer Detachment

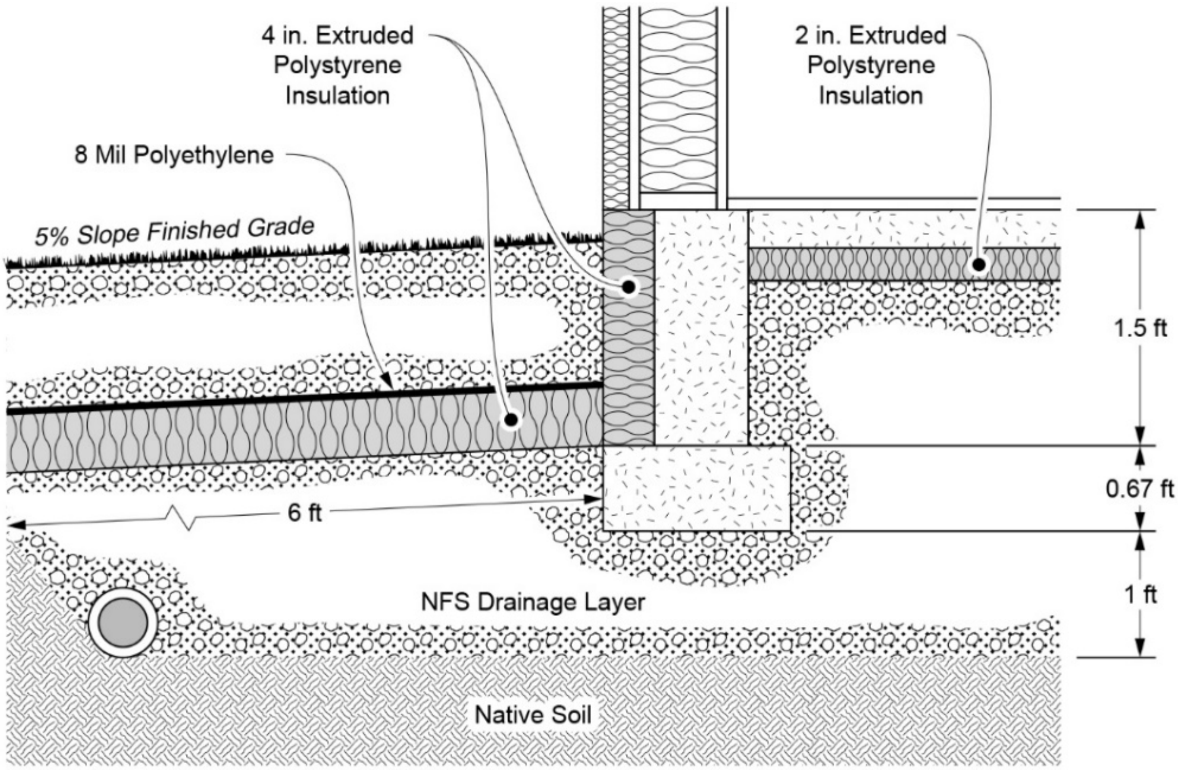
Photo courtesy of R.G. Tart Jr., Golder Associates.

A-8 FROST PROTECTION.

Frost effects on foundations are discussed in paragraphs 7-5 and 7-6. Frost effects include frost jacking due to frost heave in seasonally frozen ground, basal or upward thrust when soil beneath footings freezes and heaves, and lateral thrust on retaining walls due to freezing of the ground. General measures to mitigate frost effects on foundations include isolation of deep foundations within the freezing soil or deeper installation to provide sufficient uplift to resist frost heave forces, flanges to increase uplift resistance, use of NFS material to reduce capillary action and formation of ice within the freezing soil, and drainage to cut off water that may migrate to the freezing front and enhance formation of ice within the freezing soil. *Cold Region Structural Engineering,* by Eranti and Lee, provides further discussion.

Figure A-6 illustrates a frost-protected shallow foundation used in seasonal frost areas to mitigate formation of frost beneath footings though a combination of insulation and heat flow through the building foundation (see paragraph 7-5.3). The effects of floor insulation used to improve energy efficiency must be carefully considered if heat flow is being relied on to prevent frost formation and may require adjustment of design parameters.

Figure A-6 Example of Frost-Protected Shallow Foundation



Source: Reproduced from *Shallow Insulated Foundation at Galena, Alaska: A Case Study,* by Danyluk, Figure 4.

A-9 FOUNDATION OPTIONS.

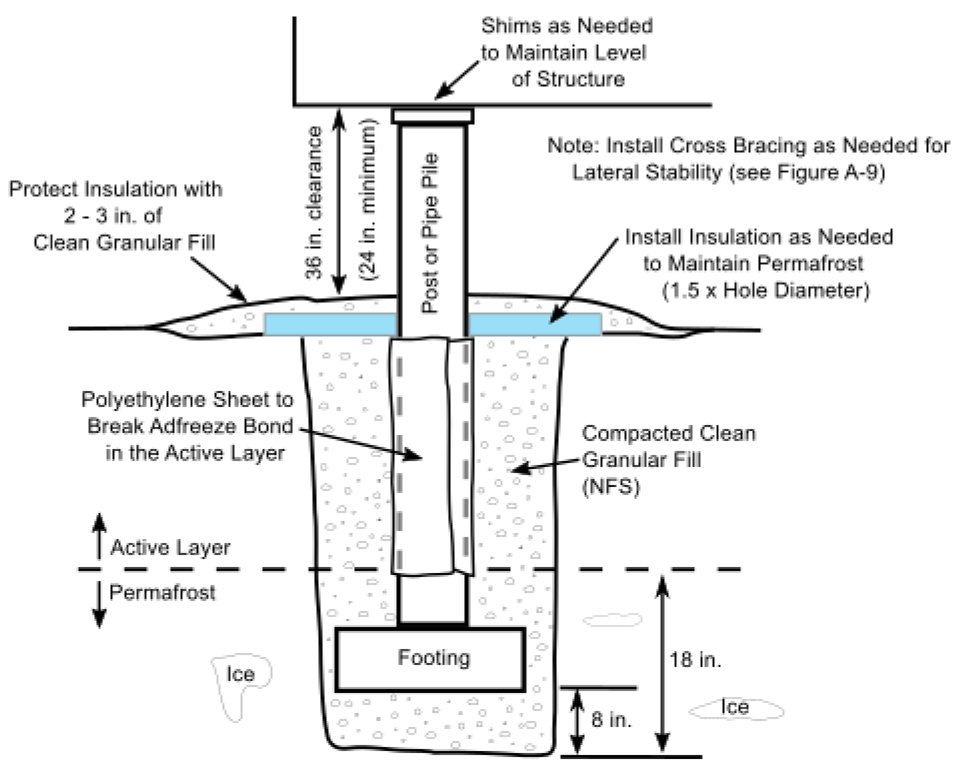
There are many options and design variations for shallow and deep foundations in Arctic and Subarctic areas, depending on site-specific conditions and facility requirements. Granular pads may be part of a building foundation subsystem or a foundation for horizontal structures. Pads should be constructed from NFS material, and they may incorporate passive or active cooling, insulation, ventilation, or some combination of these thermal techniques to mitigate heat flow from structures, maintain the existing thermal regime, and minimize frost heave potential. Table A-2 presents a partial list of foundation types, but options continue to evolve as new technologies are developed or environmental conditions dictate adaptations.

Table A-2 Partial List of Foundation Types

Shallow Foundation	Deep Foundation	Foundation Subsystem
• Spread footing • Post and pad • Raft foundation • Structural slab • Frost protected	• Slurry piles • Driven piles • Drilled (helical) piles • Adfreeze piles • Passively cooled piles (thermopile or thermosyphon) • End bearing piles • Shear piles • Micropiles • Vibe piles	• Granular pad • Insulated pad • Passively cooled (thermosyphon) pad • Ventilated pad (ducts, air cooled embankment) • Combination of the above

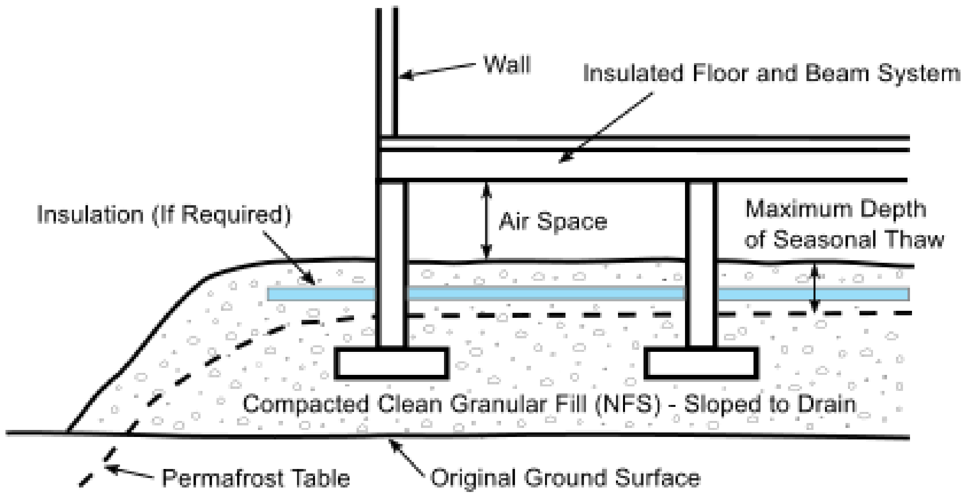
Examples of shallow foundations like those discussed in Chapter 8 are presented in Figure A-7 through Figure A-10 for conditions where permafrost is present. Figure A-8 and Figure A-9 also illustrate how the permafrost level can aggrade into thick foundations when climatic conditions are favorable.

Figure A-7 Example Footing in Shallow Permafrost



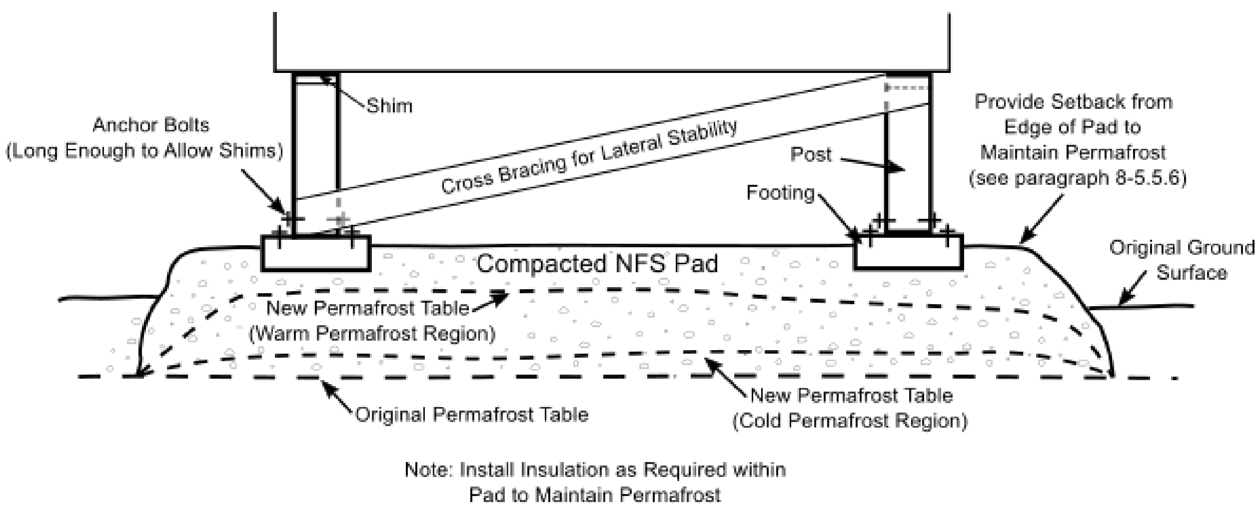
Source: *Design Manual for New Foundations on Permafrost,* Figure 3.9. Adapted with permission of the Cold Climate Research Center and the United States Permafrost Association.

Figure A-8 Example Footing in Insulated Pad Where Permafrost Level is Expected to Aggrade into the Pad



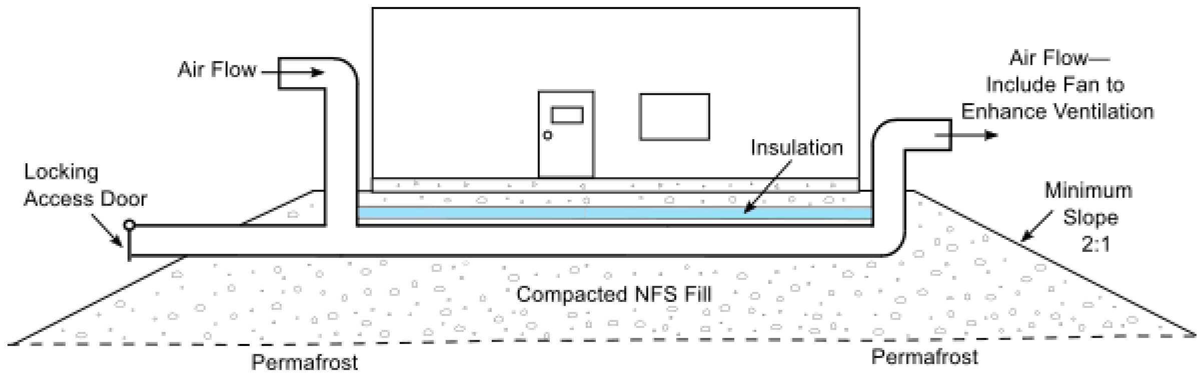
Source: *Permafrost Engineering Design and Construction,* by Johnston, Figure 7.16a. Adapted with the permission of John Wiley & Sons.

Figure A-9 Post and Pad Concept—Thick Fill



Source: *Design Manual for New Foundations on Permafrost,* Figure 3.12. Adapted with permission of the Cold Climate Research Center and the United States Permafrost Association.

Figure A-10 Example Air-Ducted Slab on Grade

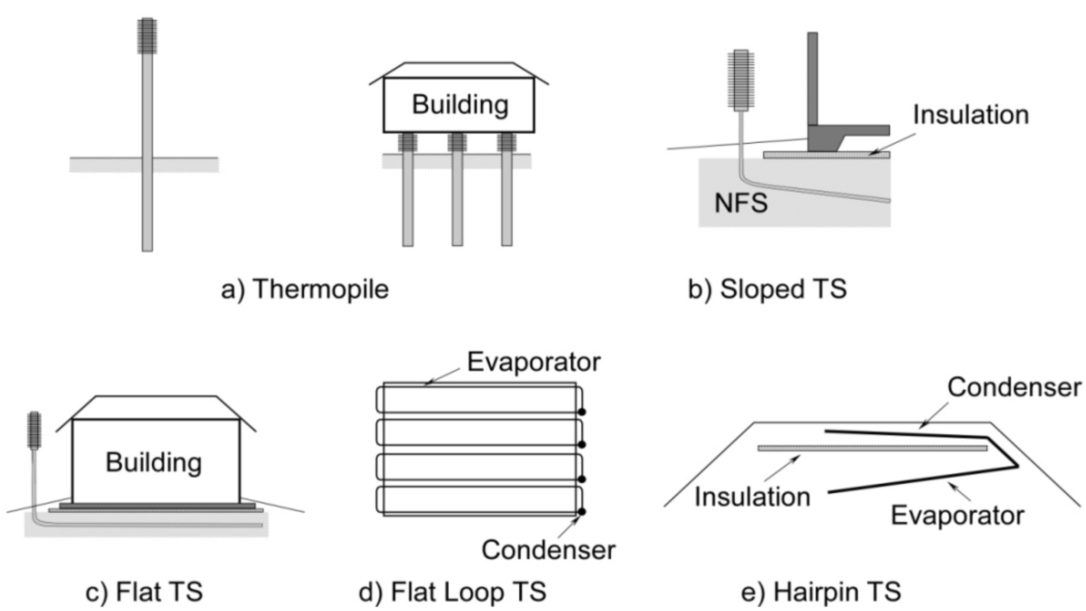


Source: Construction in Cold Regions, A Guide for Planners, Engineers, Contractors, and Managers, by McFadden and Bennett, Figure 4.5.7. Adapted with the permission of Wiley Books.

A-10 THERMOSYPHONS.

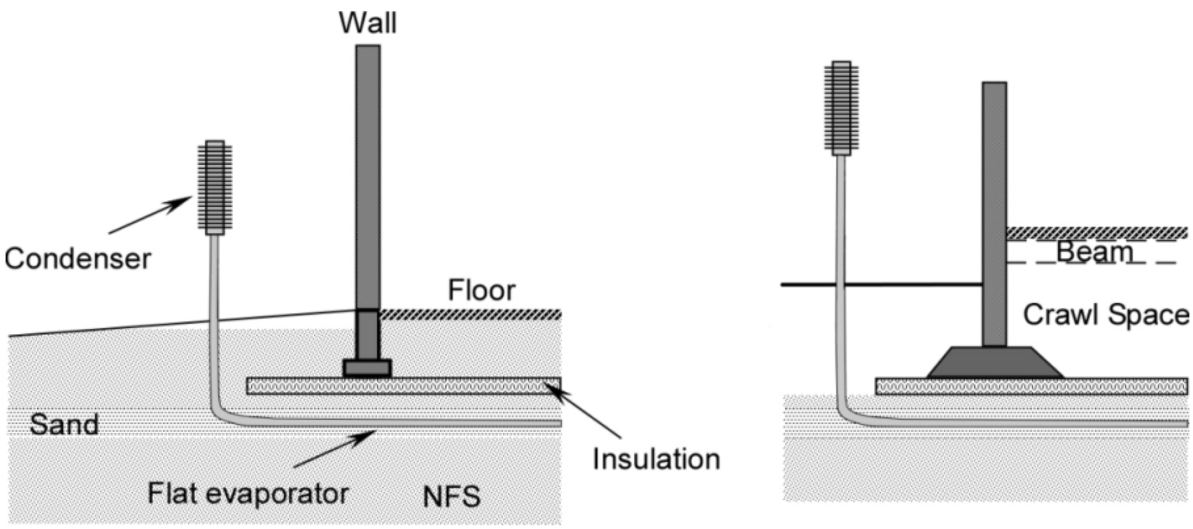
Thermosyphons like those discussed in paragraphs 8-5.5.4 and 9-3 are widely used to provide passive cooling of foundation systems in permafrost areas. They are used in both single pipe flat loop configurations, as discussed in *Review of Thermosyphon Applications,* by Wagner, and shown conceptually in Figure A-11 and Figure A-12. Vertical thermosyphons can be configured to fit within a pile or be installed adjacent to them, or a pile can be built as a thermosyphon. Hybrid thermosyphons are another configuration that uses a low-energy chiller below the condenser to activate the thermosyphon when the ambient air temperature is above freezing. Figure A-13 and Figure A-14 present representative thermosyphon applications.

Figure A-11 Typical Thermosyphon (TS) Applications



Source: Reproduced from *Review of Thermosyphon Applications,* by Wagner, Figure 5.

Figure A-12 Schematic of Shallow Foundation Using Thermosyphons to Refrigerate Granular Pad



Source: Reproduced from *Review of Thermosyphon Applications,* by Wagner, Figure 7.

Figure A-13 Flat Loop Thermosyphon Condensers Configured Adjacent to an Aircraft Hangar with Flat Loops Extending Beneath Building Footprint (Deadhorse, Alaska)

Photo Courtesy of WSP USA.

Figure A-14 Condensers (White) of Thermosyphons Configured within Foundation Piles (Goldstream Creek, Alaska)

Photo courtesy of WSP USA.

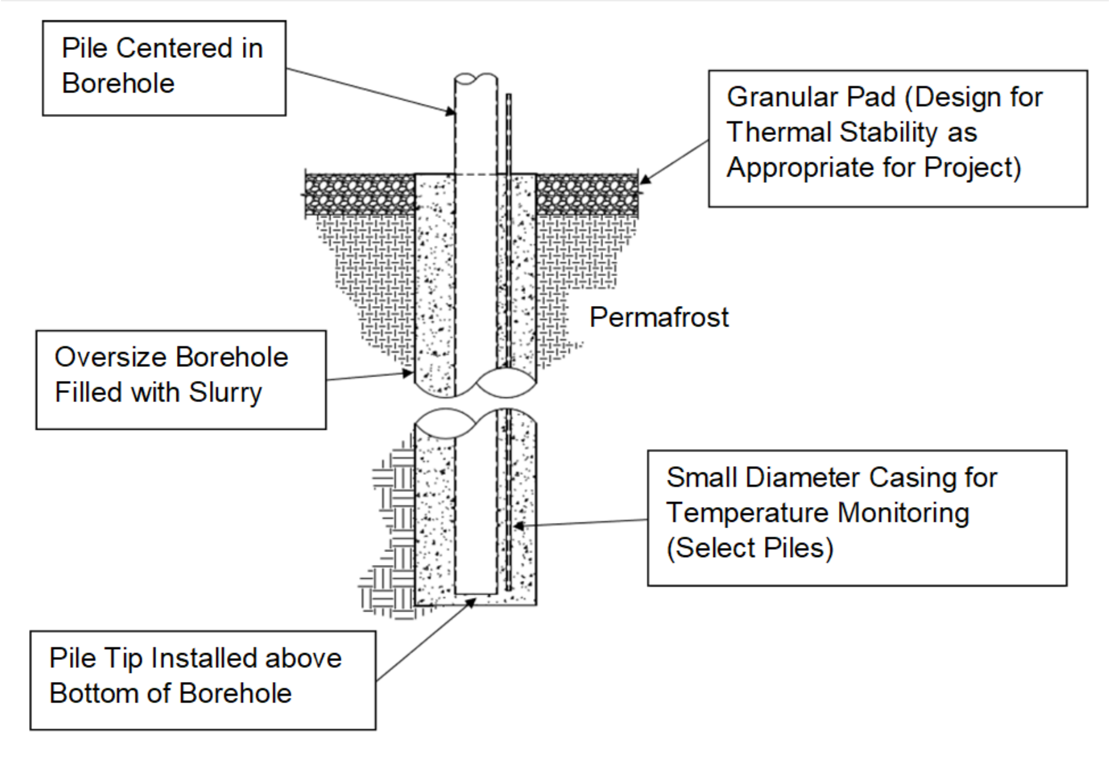
A-11 EXAMPLE PILE INSTALLATIONS.

As described in Chapter 9, piles can be configured in many ways, depending on specific foundation design criteria and structural support requirements. In North America (in 2024), steel piles are the most common type used for industrial applications, but timber piles were historically used extensively and may be encountered in existing facilities. Concrete piles are also used in permafrost areas, but to a lesser extent than steel piles. The designer should be familiar with local practices and the availability of pile materials.

A-11.1 Slurry Piles.

Figure A-15 illustrates a simple slurry pile installed in permafrost. This type of pile is generally supported by adfreeze between the pile and slurry, and the design for long-term compressive loads is typically controlled by the allowable creep rate defined in the foundation design criteria. Conventional adfreeze piles are installed with their tip above the bottom of the borehole as they typically do not include an end-bearing component. Additionally, adfreeze piles are often fixed-length with a prefabricated cap, so suspending them in the hole allows the cap to be precisely set. Many adfreeze piles are also installed open ended; and slurry at the base is preferable to icy cuttings. However, piles can bear on the bottom and be cut off to design elevation depending on details of the connection and other design requirements. For ice-poor conditions, other configurations may be appropriate, as indicated in Chapter 9.

Figure A-15 Example Slurry Pile



A-11.2 Pile Drilling.

Specialized drilling equipment like that shown in Figure A-16 may be required to advance oversize boreholes in permafrost.

Figure A-16 Example Drilling Oversize Borehole (North Slope, Alaska)

Photo courtesy of WSP USA.

A-11.3 Helical Piles.

The capacity and creep resistance of adfreeze piles may be increased by use of shear plates or a helical wrap like those shown in Figure A-17. Figure A-18 shows finished thermo-helix piles supporting a large, elevated structure. The thermo-helix piles are a thermopile with the addition of helical wrap. Helical piles like that shown in Figure A-19 may be an efficient option for some types of structures, especially when clearances are tight. The success of the installation depends on ground conditions and available equipment.

Figure A-17 Example Helical Shear Piles

Photo courtesy of Arctic Foundations.

Note: The coating at the top of the pile is to reduce solar radiation gain and provide corrosion protection in the active layer.

Figure A-18 Thermo-Helix Piles Supporting Elevated Structure (Kotzebue, Alaska)

Photo courtesy of Arctic Foundations.

Figure A-19 Example Helical Pile (Western Alaska)

Photo courtesy of WSP USA.

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APPENDIX B GLOSSARY

B-1 INTRODUCTION.

The following acronyms and terms are used in this document and are specific to cold regions foundation engineering, design, and construction. UFC 3-130-01 provides a more comprehensive list of acronyms and terms for general cold regions engineering.

B-2 ACRONYMS.

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BIA	Bilateral Infrastructure Agreements
BNQ	Bureau de Normalisation du Quebec
C	Celsius
DDC	Deep Dynamic Compaction
DoD	Department of Defense
DoR	Designer of Record
EM	Engineering Manual
EPS	Expanded Polystyrene
F	Fahrenheit
FGS	Final Governing Standards
FS	Factor of Safety
ft	Foot
ft^2	Square Foot
ft^3/s	Cubic Foot per Second

GCM	Global Climate Model
HNFA	Host Nation Funded Construction Agreements
IBC	*International Building Code*
in.	Inch
IPCC	Intergovernmental Panel on Climate Change
kg/m^3	Kilogram per Cubic Meter
km	Kilometer
kPa	Kilopascals
kph	Kilometer per Hour
lb/ft^3	Pound per Cubic Foot
m	Meter
m^2	Square Meter
m^3/s	Cubic Meter per Second
MAC	Mining Association of Canada
mi	Mile
mm	Millimeter
MPa	Megapascal
mph	Mile per Hour
NASA	National Aeronautics and Space Administration
NEX-GDDP	Earth Exchange Global Daily Downscaled Projections
NFS	Nonfrost-susceptible
OEBGD	*Overseas Environmental Baseline Guidance Document*
ppt	Part per Thousand
psi	Pound per Square Inch
RCP	Representative Concentration Pathway
SEI	Structural Engineering Institute

SNAP	Scenarios Network for Alaska + Arctic Planning
SOFA	Status of Forces Agreements
SSP	Shared socioeconomic pathway
UFC	Unified Facilities Criteria
USCS	Unified Soil Classification System
XPS	Extruded Polystyrene

B-3 DEFINITION OF TERMS.

Active layer detachment: A slope failure in which the thawed or thawing portion of the active layer detaches from the underlying frozen material.

Adfreeze: The process by which two objects adhere to each other via ice.

Aufeis: The type of ice that forms when water emerges from the ground under freezing conditions and is exposed to extremely cold air.

Basal heave: An upward normal force that acts on base, or bottom face, of shallow foundations or pile caps that bear within the frost depth.

Frozen debris lobe: Elongated, lobate permafrost features that mostly move through shear in zones near their bases.

Granular soil: Gravel, sand, or silt with little or no clay content.

Horizontal structures: Roads, airfields, and similar structures.

Longwave radiation: Electromagnetic thermal radiation emitted by Earth's surface, atmosphere, and clouds.

Multichannel analysis of surface waves: A seismic method that measures the shear-wave velocity distribution, which can be used to determine the depth to bedrock and shear strength or soil stability. This can be used in liquefaction studies, sinkhole mapping, fault mapping, and assessments of earthquake resilience.

Radiative forcing: The change in energy flux in the atmosphere caused by natural or anthropogenic factors of climate change as measured in watts per meter squared (W/m^2).

Sensible energy: The energy that causes a change in temperature of a substance without phase change. This is also the energy felt by humans as heat. It is the amount of energy needed to increase or decrease the temperature of a substance.

Shortwave radiation: Incoming ultraviolet, visible, and a limited portion of infrared energy from the sun.

Surface energy balance: Balance between all surface energy inputs and outputs at the surface over a given interval of time.

Talik: A perennially unfrozen zone below the active layer or within permafrost. Taliks may penetrate the permafrost (a “through talik”) or be a zone between the active layer and the top of the permafrost.

Thaw degradation: Change in thermal state from frozen to thawed, usually accompanied by volume change in excess moisture from thawed ice structures.

Thaw points: Pipes that allow steam to be used to enhance thawing of permafrost.

Thaw-stable material: Frozen soil or rock that undergoes minimal volume change or strength loss when it thaws, such as clean granular soil or quarry rock without interstitial ice.

Thaw strain: The amount that frozen ground compresses upon thawing.

Thaw-unstable material: Frozen soil or rock with total ice content greater than its water content under normal consolidation conditions.[1] Also referred to as *thaw-sensitive* or *ice-rich*.[2] Thaw-unstable material will lose significant strength and settle when it thaws. An example of this material is fine-grained soil with a significant volume of interstitial ice. Rock also may be thaw unstable when fractured and containing significant ice within the rock structure.

Thermo-erosion gullying: Thawing permafrost can result in ground-ice erosion and sediment displacement (thermo-erosion), which can lead to permafrost tunneling and development of gully networks. A combination of mechanical erosion and gravitational processes results in soil subsidence and channel inclusions, resulting in a mixing of soil horizons and continued erosion of adjacent soils. Thermo-erosion gullies enlarge both retrogressively upslope and through deepening and widening of the initial incision.

Thermopile: A structural pile built to function as a thermosyphon.

Thermosyphon: A passive refrigeration device charged with a two-phase working fluid, such as carbon dioxide (CO_2) (in liquid and gaseous states), that uses natural convection to passively exchange heat between the ground and environment without a mechanical pump.

Transient layer: An ice-rich zone that acts as a thermal buffer to protect the underlying permafrost due to its relatively higher ice content and the significant heat needed to thaw this layer.

Trumpet curve: The envelope of ground temperature bounding all whiplash curves. The shape and limits of the trumpet curve may shift right or left depending on ground

[1] *Frozen Ground Engineering*, Andersland and Ladanyi.
[2] *Glossary of Permafrost and Related Ground-Ice Terms*, Harris et al.

temperature and with time at a given site in response to changes in ground temperature.

Vertical structures: Buildings, towers, and similar structures.

Whiplash curve: Ground temperature at a given moment; in aggregate, these form the trumpet curve.

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APPENDIX C SUPPLEMENTAL RESOURCES

The following references are reliable sources for information related to foundations engineering and design. These sources provide direction for specific applications not addressed in this UFC or provide additional information to guide or aid the designer in the various phases of the design. This list is provided for the convenience of the designer and may not include references for all specific applications relevant to all projects. The designer is responsible for ensuring the design conforms to all criteria relevant to the project.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS

LRFDBDS-9, *LRFD Bridge Design Specifications*, 9th edition

AMERICAN SOCIETY OF CIVIL ENGINEERS

https://ascelibrary.org

Conferences Series (With Proceedings)

Congress on Technical Advancement

International Conference on Cold Regions Engineering

International Symposium on Cold Regions Development (ISCORD)

Regional Conference on Permafrost (with the U.S. Permafrost Association)

Monographs and Specialty Publications

Arctic Coastal Processes and Slope Protection Design, A.C.T. Chen and C.B. Liedersdorf, Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 1988

Cold Regions Construction, D.F. Jordan and G.N. McDonald (eds.), Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 1983

Design for Ice Forces, S.R. Caldwell and R.D. Crissman (eds.), Technical Council on Cold Regions Engineering, ASCE, Reston, VA, 1983

Foundations in Permafrost and Seasonal Frost, A.F. Wuori and F.H. Sayles (eds.), Technical Council on Cold Regions Engineering, ASCE, Reston, VA, 1985

Freezing and Thawing of Soil-Water Systems, D.M. Anderson and P.J. Williams (eds.), Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 1985

Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate, S.A. Shoop (ed.), ASCE, Reston, VA, 2020

Frozen in Time: Permafrost and Engineering Problems, S.W. Muller (edited by H.M. French and F.E. Nelson), Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 2008

Innovative Design and Construction for Foundations and Substructures Subject to Freezing and Frost, Geotechnical Special Publication No. 73, C.K. Tan (ed.), ASCE, Reston, VA, 1997

Permafrost Foundations: State of the Practice, Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 2007

Research on Transportation Facilities in Cold Regions: Proceedings of a Session, O.B. Andersland and F.H. Sayles (eds.), Technical Council on Cold Regions Engineering, ASCE, Reston, VA, 1986

Roads and Airfields in Cold Regions, T.S. Vinson. J.W. Rooney, and W.H Haas (eds.), Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 1996

Thermal Design Considerations in Frozen Ground Engineering, T.G. Krzewinski and R.G. Tart (eds.), Technical Council on Cold Regions Engineering Monograph, ASCE, Reston, VA, 1985

CANADIAN STANDARDS ASSOCIATION

https://www.csagroup.org/

CAN/CSA-S500-21, *Thermosyphon Foundations for Building in Permafrost Regions*, National Standard of Canada

CAN/CSA-S501-14, *Moderating the Effects of Permafrost Degradation on Existing Building Foundations*, National Standard of Canada

CAN/CSA-S503:20, *Community Drainage System Planning, Design, and Maintenance in Northern Communities*, National Standard of Canada

CSA PLUS 4011:19, *Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation*, National Standard of Canada

INTERNATIONAL TECHNICAL ASSOCIATIONS AND CONFERENCES

Arctic Council, https://arctic-council.org

Arctic Technology Conference (ATC), Offshore Technology Conference (OTC), 2011, https://www.otcnet.org/

Canadian Permafrost Association, https://canadianpermafrostassociation.ca/

International Permafrost Association, https://www.permafrost.org/

UNIFIED FACILITIES CRITERIA

https://www.wbdg.org/dod/ufc

UFC 3-260-01, *Airfield and Heliport Planning and Design*

UFC 4-010-01, *DoD Minimum Antiterrorism Standards for Buildings*

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