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UNIFIED FACILITIES CRITERIA (UFC)

ARCTIC AND SUBARCTIC ENGINEERING

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ARCTIC AND SUBARCTIC ENGINEERING

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

NAVAL FACILITIES ENGINEERING COMMAND

AIR FORCE CIVIL ENGINEER CENTER

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

Change No.	Date	Location

This UFC supersedes UFC 3-130-01, 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 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 http://www.wbdg.org/dod.

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

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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.

This 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.

Cold regions engineering involves design and construction in locations that experience extreme, low-temperature conditions with freezing and thawing periods. In the design, construction, and maintenance of facilities such as buildings, roads, utilities, embankments, and other improvements in the Arctic and Subarctic regions, many problems are encountered that do not exist, or are not present to the same degree, in temperate regions. These problems have several causes:

- The presence of permafrost, with its potential for thaw and subsequent thaw settlement.
- The special properties of frozen soil, frozen rock, and ice
- The effects of frost action, specifically frost heave, in soil, rock, pavement, and other materials subject to intense annual freeze–thaw cycles.
- Drainage, water supply, and sewer disposal problems specific to those regions.
- The effects of solutes and the influence of salinity on frozen-soil properties
- The effects of changing climate, which present new challenges and environmental constraints.
- Other factors, such as the shortness of the above-freezing summer season, as well as the limited amount of daylight in fall and winter; environmental aspects; and difficult conditions for transportation, access, material and equipment supplies, and communications.

1-3 REISSUES AND CANCELS.

This document supersedes and cancels inactivated UFC 3-130-01, 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 pavements, which is incorporated into the UFC 3-250 and 3-260 series as discussed in paragraph 1-6.3. In addition to this volume, there are four other series volumes:

- 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 3-130-03, *Arctic and Subarctic Foundations for Freezing and Thawing Conditions*. UFC 3-130-03 includes horizontal and vertical foundations, considerations affecting foundation design, and construction and monitoring of facilities in the Arctic and Subarctic areas.
- 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.

UFC 3-130-01 serves as an introduction to the Arctic and Subarctic UFC series. It includes background information, data, and engineering considerations pertaining to the various elements of Arctic and Subarctic facility planning and design presented elsewhere in the series. Chapter 2 defines Arctic and Subarctic regions. Appendix B defines terms unique to cold regions and cold regions engineering. This volume also introduces risk assessment and resilience in terms of cold regions engineering. These are emerging topics in Arctic and Subarctic infrastructure, whose development is critical to planning sustainable projects. UFC 3-130-01 is not all inclusive. Other resources are cited to provide additional sources of information. The revision of the Arctic and Subarctic UFC series provides state-of-the-practice criteria and guidance for engineers, architects, and planners when planning, designing, and constructing DoD infrastructure in cold regions.[1]

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.

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[1] *New Construction Criteria for a Changing Arctic and Subarctic: The UFC 3-130 Series Revision Process,* Bjella et al.

1-6 GENERAL BUILDING REQUIREMENTS.

This UFC is an integrated part of the Arctic and Subarctic UFC 3-130 series. Use the other documents of this series in conjunction with this UFC to address construction aspects unique to cold regions. See Chapter 2 for the definitions of Arctic and Subarctic.

Often, conventional construction practices are acceptable in Arctic and Subarctic regions with appropriate modification to account for extreme cold temperatures, frost heaving soils, and permafrost areas. 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 Structural.

Use UFC 3-301-01 for the design and analysis of DoD buildings and other DoD structures. Also, use UFC 3-301-02 for Risk Category V structures.

1-6.2 Geotechnical.

It is essential for engineers to consider the effects of extreme low temperatures, freeze and thaw conditions, variable soil conditions, snow and ice, and drainage on soil properties such as bearing capacity and other geotechnical engineering requirements. Geotechnical investigations must be tailored to the individual projects and sites.

1-6.3 Pavements.

Comply with the UFC 3-250 and UFC 3-260 series. These series provide technical requirements and guidance for roads, pavements, and airfield design, construction, and maintenance. Note that pavements in the Arctic and Subarctic present unique challenges. Unlike the temperate pavements, it is essential for engineers to consider the effects of extreme low temperatures, freeze and thaw conditions, bearing capacity, material behavior, snow and ice, variable soil conditions and material properties, and drainage or the effects of groundwater in the pavement structure. Several cold regions textbooks include detailed information on pavements topics:

- *Cold Regions Pavement Engineering*, by Doré and Zubeck;
- *Introduction to Cold Regions Engineering*, by Freitag and McFadden;
- Permafrost Engineering Design and Construction, by Johnston; and
- *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers*, by McFadden and Bennett.

These texts include design methodologies, material selection, approaches for proper calculations of structural design, strategies for constructing new roads, recommendations for rehabilitating old or damaged surfaces, maintenance techniques, as well as case studies of problems and respective solutions.

1-7 CYBERSECURITY.

All facility-related control systems (including systems separate from a utility monitoring and control system) must be planned, designed, acquired, executed, and maintained in accordance with UFC 4-010-06, and as required by individual Service Implementation Policy.

1-8 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.

1-9 MODULAR OR NONPERMANENT FACILITIES.

Use UFC 1-201-01 for the minimum requirements for life safety and habitability-related design of nonpermanent facilities for use by DoD in support of military operations. This includes portable structures intended for use up to 3 months, 24 months, 60 months (5 years), and semipermanent facilities that can be extended to 25 years. Portable structures require specific foundation considerations for placement on the frozen ground (see UFC 3-130-03). Additionally, the effects of extreme low temperatures in the Arctic and Subarctic environment, including freeze and thaw conditions, snow drifting or snow and ice effects, and material behavior of the structures, must be determined.

1-10 PERSONNEL REQUIREMENTS.

Engineering decisions for the planning, design, construction, and maintenance of infrastructure in Arctic and Subarctic regions are based not only on applicable federal, state, and local codes but also on the expertise of engineers or practitioners with experience dealing with the unique conditions and the extreme weather of these regions. The intent of this UFC, and the Arctic and Subarctic UFC series, is to provide requirements and guidance to prevent significant missteps in the planning, design, and construction of cold regions infrastructure. Consultation with experienced engineers at the Command, District, and Installation level is required to ensure technologies and practices that are unsuitable for this environment, or a specific location, are not proposed. This UFC provides indicators of potential problem areas that may require unique engineering solutions outside the realm of those seen in temperate or standard construction practice.

The Engineer of Record or Designer of Record (DoR) must be a registered design professional, defined as an individual licensed to practice engineering in the project area; knowledgeable in the design and construction of infrastructure in Arctic and Subarctic areas; and experienced with the permafrost, frozen ground, and other geotechnical and climate conditions found in these regions. Some jurisdictions require licensure in the location of the project to obtain permits and approvals.

1-11 PLANNING.

Follow the site planning requirements as described in UFC 3-201-01. This includes environmental requirements, land-use restrictions, building setbacks, flood hazard areas, utility connections, utility offsets, vehicle circulation, buffers from natural and manmade features, and other similar requirements. Use UFC 3-201-01 prior to starting design to determine specific project requirements (such as demolition, site development, water distribution, and wastewater collection). Familiarization with the UFC 3-130 series at the planning stage is advisable to anticipate and prepare for issues of concern for structure and infrastructure development in Arctic and Subarctic areas.

1-12 APPLICABLE POLICIES AND PROGRAMS.

Comply with UFC- 3-201-01 for National Environmental Policy Act (NEPA) actions. NEPA is not unique to climate regions.

Arctic and Subarctic military facilities can either benefit or adversely impact the environment, affecting the air, water, land, local ecology, and socioeconomic environment. Despite low population density and minimal development, the fragile nature of the ecology of the Arctic and Subarctic has attracted the attention of environmental groups. Actions that may meet the criteria for a Categorical Exclusion (CX or CATEX) at other locations may not apply in the Arctic and Subarctic. Areas of particular concern in the Arctic and Subarctic include, but are not limited to, threatened and endangered species and habitat; wetlands; migratory birds; and historic, archaeological, and cultural resources for both Indigenous peoples and early settlers.

1-13 APPROVALS AND PERMITS.

During the planning, design, and construction of the project, the DoR will be responsible for obtaining all necessary permits and approvals and for complying with all applicable laws, codes, and regulations, or overseas equivalent. Regulatory authorities may be at the federal (to include Occupational Safety and Health Administration [OSHA]), state, or local level. In the United States and its territories and possessions, the government will review permits for acceptability. In locations outside the United States and its territories and possessions with Host Nation agreements, follow permit approval procedure as directed in the project scope and by the Government Project Manager. In locations outside the United States and its territories and possessions without Host Nation agreements, the government will review and approve plans for compliance. Consult with the Government Project Manager to determine the appropriate signatories for permit applications.

1-14 SAFETY CONSIDERATIONS.

1-14.1 Facility Safety.

Use UFC 1-200-01, paragraph 1-6.3.4, for facility-safety-related requirements. All DoD facilities must comply with Department of Defense Instruction DoDI 6055.01 and applicable OSHA safety and health standards.

1-14.2 Safety for Geotechnical Investigations.

Comply with UFC 3-220-01, paragraph 2-4.2.

1-14.3 General Safety for Cold Regions Operations.

Awareness of safety aspects relevant to field activities is especially important in the Arctic and Subarctic. Consider safety awareness and planning when conducting site reconnaissance or field assessment for site planning and construction, including but not limited to

- cold weather hazards such as freezing injuries, dehydration, hypothermia, frostbite;
- encountering wildlife;
- visibility;
- slip and fall hazards on snow and ice surfaces and uneven terrain;
- limited daylight during the winter months; and
- site-specific safety and health plan considering support contingencies at remote locations.

1-15 BEST PRACTICES.

Appendix A identifies background information; lessons learned; and proven best practices, methodology and approaches pertinent to engineering planning, design, and construction in Arctic and Subarctic locations. 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. For Best Practices guidelines not discussed in the UFCs, the DoR must submit to the Government Project Manager a list of the guidelines or requirements being used for the project with documentation sufficient for review and approval prior to completing design.

1-16 GLOSSARY.

Appendix B contains acronyms, abbreviations, and a list of terms used in this document and are specific to cold regions engineering, design, and construction.

1-17 SUPPLEMENTAL RESOURCES.

Appendix C provides supplemental resources on subjects related to Arctic and Subarctic engineering, design, and construction. These resources are valuable tools to the engineer for additional information on topics pertinent to and affiliated with cold regions engineering. It also identifies additional background information and resources for accomplishing building design and construction in Arctic and Subarctic regions.

1-18 REFERENCES.

Appendix D contains a list of references used in this document. The publication date of the code or standard is not included in this document. Unless otherwise specified, the most recent edition of the referenced publication applies.

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CHAPTER 2 ARCTIC AND SUBARCTIC ENVIRONMENT AND CLIMATE

2-1 INTRODUCTION.

This chapter provides background information on the environment, site characteristics, and climate conditions unique to Arctic and Subarctic regions for engineering, design, construction, and maintenance of facilities and other infrastructure. The topics include permafrost and ground ice, permafrost structure and stability, geomorphic features, permafrost structure, climatic conditions (such as air-temperature distribution, design freezing index, ground temperature, snow, wind, and visibility), climate change, vegetation, wildfires, seismic condition, and freeze and thaw of soils.

For the purposes of the UFC 3-130 series, the Arctic is characterized by mean annual temperature ranges between below 32°F (0°C) for the coldest month and below 50°F (10°C) for the warmest month of the year (see Appendix B, paragraph B-3.2).[1] Generally, Arctic conditions are found north of the Arctic Circle (approximate latitude of 66°33' N). The Arctic Circle marks the latitude above which the sun does not set on the summer solstice and does not rise on the winter solstice. The Subarctic is characterized by mean annual temperature ranges between below 32°F (0°C) for the coldest month and above 50°F (10°C) for the warmest month (see Appendix B, paragraph B-3.2). Subarctic conditions are generally south of the Arctic and north of temperate forests, between latitudes 50° N and 70° N. Other cold regions, with similar temperature and ground conditions, exist in the Aleutian Islands and at high altitudes in mountainous areas of the globe and therefore warrant cold regions engineering considerations. Additional discussion of Arctic and Subarctic conditions as they pertain to each specific topic are found in the other documents of the UFC 3-130 series.

2-2 PERMAFROST AND GROUND-ICE DISTRIBUTION.

Permafrost boundaries further define the Arctic and Subarctic regions. Permafrost distribution is divided into classifications, including continuous permafrost, discontinuous permafrost, sporadic permafrost, and isolated patches. Permafrost extent provides general information on ground-ice content (Figures 2-1 and 2-2). See Appendix A, paragraph A-5, for additional information on permafrost extent and distribution under natural, undisturbed ground cover conditions in the area with a mean annual air temperature of 21°F to 30°F (−6.1°C to −1.1°C). Surface temperatures are potentially available from global observational networks or from observation stations. Actual ground-temperature measurement at the specific location provides more-accurate information of the site conditions. The existence of perennially below-freezing ground temperatures is a result of many factors other than air temperatures, including solar radiation, surface cover, snow cover, wind, soil type, soil moisture content, groundwater flow, and presence of stationary or moving surface water. Landscape changes due to

[1] The way the Arctic and its location are defined varies based on the topic of concern. Many of the common definitions are based on scientific, climatic, geologic, biologic, marine, and political considerations. Cold regions engineers define the Arctic and Subarctic regions in terms of permafrost boundaries, ice contents, ground temperatures, air temperature (freezing-degree days), snow and ice distribution, and other factors that influence design and construction.

land developments, forest fires, or stream meandering may alter permafrost conditions over many years.

Figure 2-1 Circum-Arctic Map of Permafrost and Ground-Ice Conditions

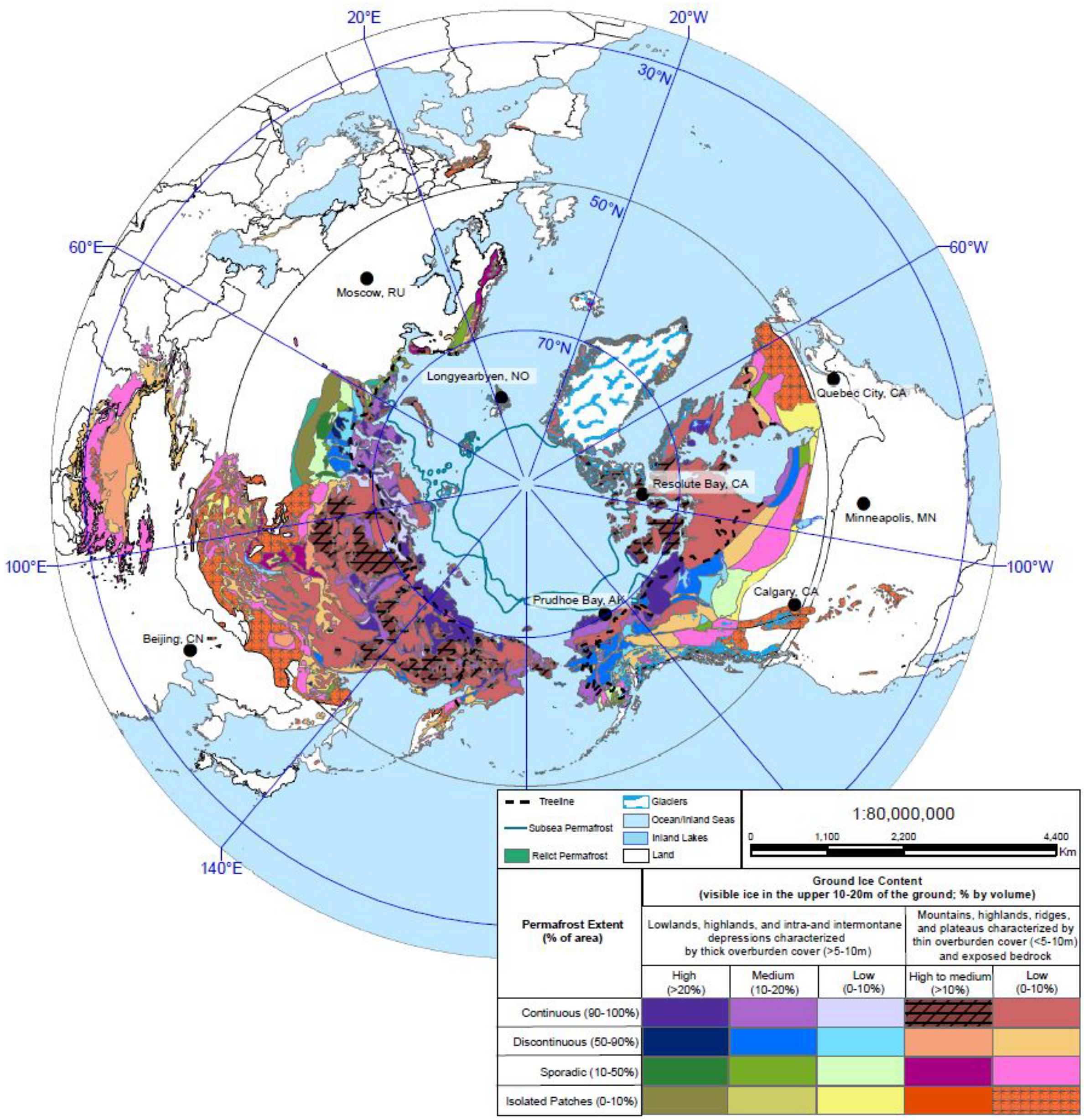
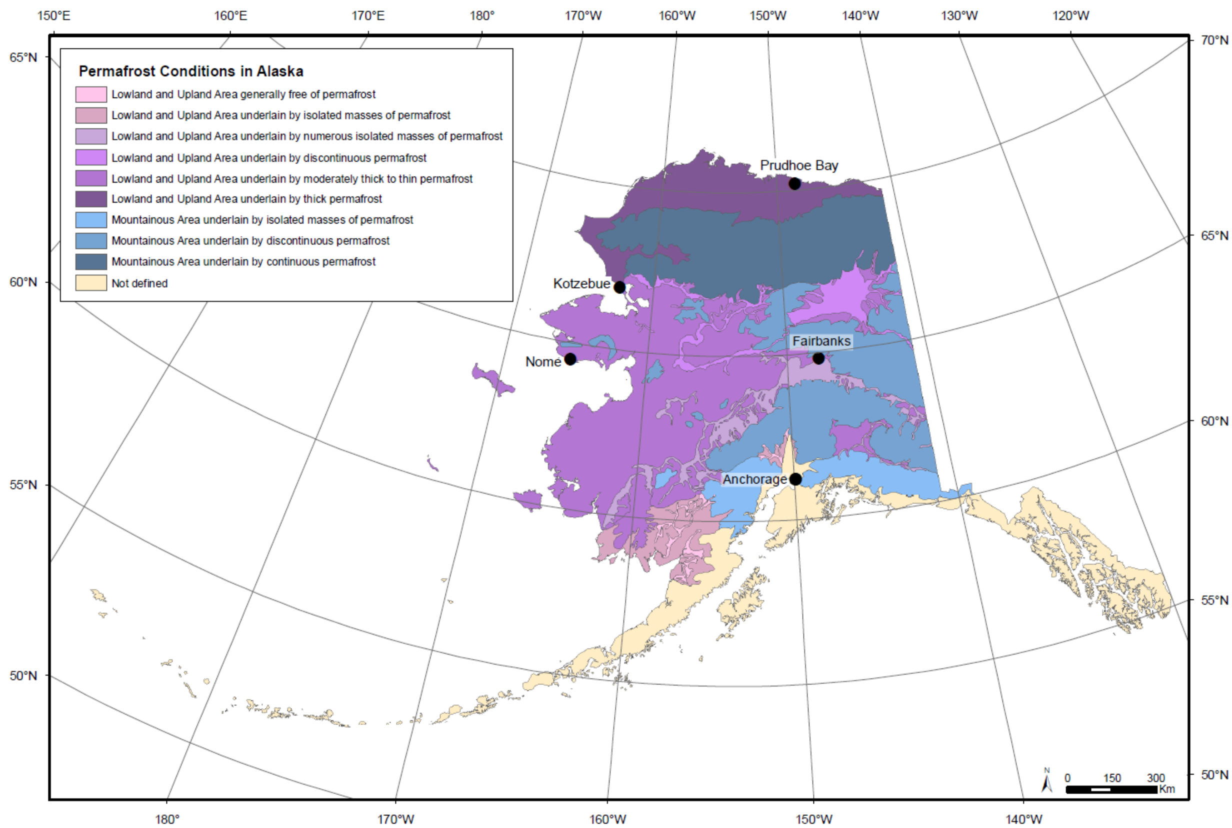


Figure 2-2 Permafrost Conditions in Alaska



2-3 GEOMORPHOLOGY AND SURFICIAL FEATURES.

Understanding the geomorphic features of the permafrost landforms is important in the design and construction of facilities in the cold regions. Thus, guidance for design and construction in Arctic and Subarctic environments requires thorough consideration of ground characteristics, climatic information, and local thermal conditions, as well as the physical, mechanical, and thermal properties of the permafrost and seasonally frozen ground. See Appendix A, paragraph A-5.1, for additional resources on this topic.

The cold regions landforms are unique geomorphic features produced from frost action, permafrost degradation, mass degenerative and other geologic processes, or cryogenic actions in the active layer and in permanently frozen ground. These features include solifluction markings, pingos, thermokarst depressions, and patterned ground. They can serve as important indicators of ground conditions, such as the likelihood of permafrost and ground ice.

2-3.1 Polygonal Ground.

Areas of intensive frost action, common in Arctic and Subarctic regions, can result in the formation of surface expressions such as polygonal-patterned ground or polygons. Polygons can range in size from several feet to hundreds of feet in diameter and generally have four to eight sides. Ice-wedge polygons are grouped into either high centered or low centered. Low-centered polygons, where water is ponded in the middle of the polygon, indicate climatic conditions conducive to maintain the environment in the frozen condition. High-centered polygons, where water is not ponded in the middle but along the margins of the polygon, indicate the overall thermal regime is creating a thawing permafrost environment. In general, the existence of polygonal features indicates a very high probability that permafrost exists.

2-3.2 Pingo.

Pingos are good indicators of permafrost as they are very rare outside continuous permafrost zones. They are formed as permafrost creates hydraulic pressure on liquid water beneath an overlying, confining layer of soil, focused on a single area, where it forms a massive ice lens and causes the ground surface to heave upward dramatically.

2-3.3 Thermokarst.

While there are several different types of thaw features, they all have similarly identifiable characteristics, as they are all the result of the same process of permafrost degradation. Thermokarst landform features include hummocks, sinkholes, ravines, caverns, tunnels, thaw lakes, and beaded drainages. Hummocks are mounds many feet in diameter and height and are the result of thaw degradation of the very ice-rich margins of the polygonal terrain. Thawing leaves the soil-rich center of the polygon at a much higher elevation, resulting in recurring mounds across the landscape. Thaw lakes are characterized as rounded or scalloped depressions with sharp or shear banks that often extend into the waterline, with impounded water as evidence of active caving along the edges. These often include trees tilted toward the center of the lake or, in the case of treeless terrain, crevices forming parallel to the edges of the bank. Beaded streams are characterized by a series of small, rounded thaw lakes connected to one another by short waterways. Each rounded thaw lake is the result of both mechanical and thermal erosion. Connecting waterways can follow the strait profile of degrading ice wedges, but this is not always the case. Further evidence of thermokarst and permafrost degradation is the occurrence of “drunken forests,” large numbers of trees at an angle to each other and the ground. Trees off axis are indicative of unstable ground, often due to permafrost in Arctic and Subarctic regions.

2-4 PERMAFROST CHARACTERISTICS.

In Arctic and Subarctic regions, the depth of frost and permafrost is related to both the temperature, duration, and intensity of winter for a given location. Cold regions textbooks provide detailed descriptions of permafrost features. The following summary of the characteristics of permafrost are merely introductory.

2-4.1 Structure.

The structure of permafrost varies and depends on the ground characteristics and local thermal conditions. Permafrost may exist as the following:

- A continuous layer with its upper surface at the bottom of the annual frost zone (active layer) (This is common in Arctic regions.)
- A continuous layer with its upper surface separated from the annual frost zone (active layer) by a residual thaw layer (If the permafrost table is progressively lowering, the subsequent effect is degradation of permafrost.)
- Frozen layers separated by layers of unfrozen material.
- Inclusions of remnants of permafrost in unfrozen ground.

2-4.2 Thickness and Depth.

The thickness of the permafrost layer increases with increasing latitude, being greater in Arctic than in Subarctic regions. The depth to the permafrost layer depends primarily on the magnitude of the air thawing index, the amount of solar radiation that reaches the surface, the surface cover conditions from the previous several years, and the water content and dry unit weight of the soil. Methods for estimating depths of freeze and thaw penetration are described in paragraph 3-5 and are thoroughly discussed in *Frozen Ground Engineering,* by Andersland and Ladanyi.

2-4.3 Factors on Permafrost Structure.

Factors and stability aspects of permafrost must be considered and are described in the following sections.

2-4.3.1 Active Layer.

The active layer refers to the portion of the permafrost soil or soil and rock column from the surface downward, which thaws each summer season to some depth. The depth of thaw is determined by the extent of the previous winter freezing, snow depth, groundwater, soil type, vegetation, slope gradient, and slope aspect. However, the complex nature of the soil thermal regime generally yields varying active layer depths of inches to feet on yearly to decadal scales.

Because the bottom of the active layer transitions to impermeable frozen soils and rock, this confining layer prevents adequate draining of the active layer's moisture, often increasing moisture content to values greater than saturation. During the winter freezing process, the top-down movement of the freeze front creates layers of segregation ice, often inches thick. This segregation ice heaves the active layer soils upwards during the winter season, with subsequent settlement in the next summer's full thawing season. With this repetitive freeze–thaw cycle, active layer soils in the natural or undisturbed state are often very loose with poor bearing capacity and drainage capability.

2-4.3.2 Soil Factors.

As a rule, the characteristics of permafrost will depend on the texture, water content, and temperatures of the soil. Relatively clean sands and gravels located in well-drained positions may not present serious engineering construction problems if they do not contain appreciable amounts of excess ice and are termed thaw stable. Conversely, permafrost consisting of fine-textured soils such as silt, silty-sands, and clays often contain excess volumes of ice in the soil matrix, in lenses, layers, wedges, and veins or other shapes and are termed thaw unstable. See paragraph 3-4 for quantifying soil factors. UFC 3-130-03, Chapter 5, presents information on the strength and other properties of frozen soils. Information on the standard system for classification of frozen soils, frost action, and the strength and thermal properties of frozen soils can be found in cold regions textbooks such as *Frozen Ground Engineering*, by Andersland and Ladanyi.

2-4.3.3 Thaw Stable.

Frozen soils are termed thaw stable if the amount of water contained within a soil matrix (as a direct result of the thawing of ice in the soil) can freely drain away without any settlement and maintain the soil strength.

2-4.3.4 Thaw Unstable.

Frozen soils are termed thaw unstable if they, on thawing, would exhibit loss of strength below normal or exhibit long-term significant settlement as a direct result of the thawing of ice in the soil. Soils that contain an excess of thaw water on melt (greater than available pore space in the material) and soils that do not exhibit particle-to-particle contact in a frozen state due to excess ice, in general, will exhibit settling on thawing.

2-4.3.5 Frost Susceptible Soil.

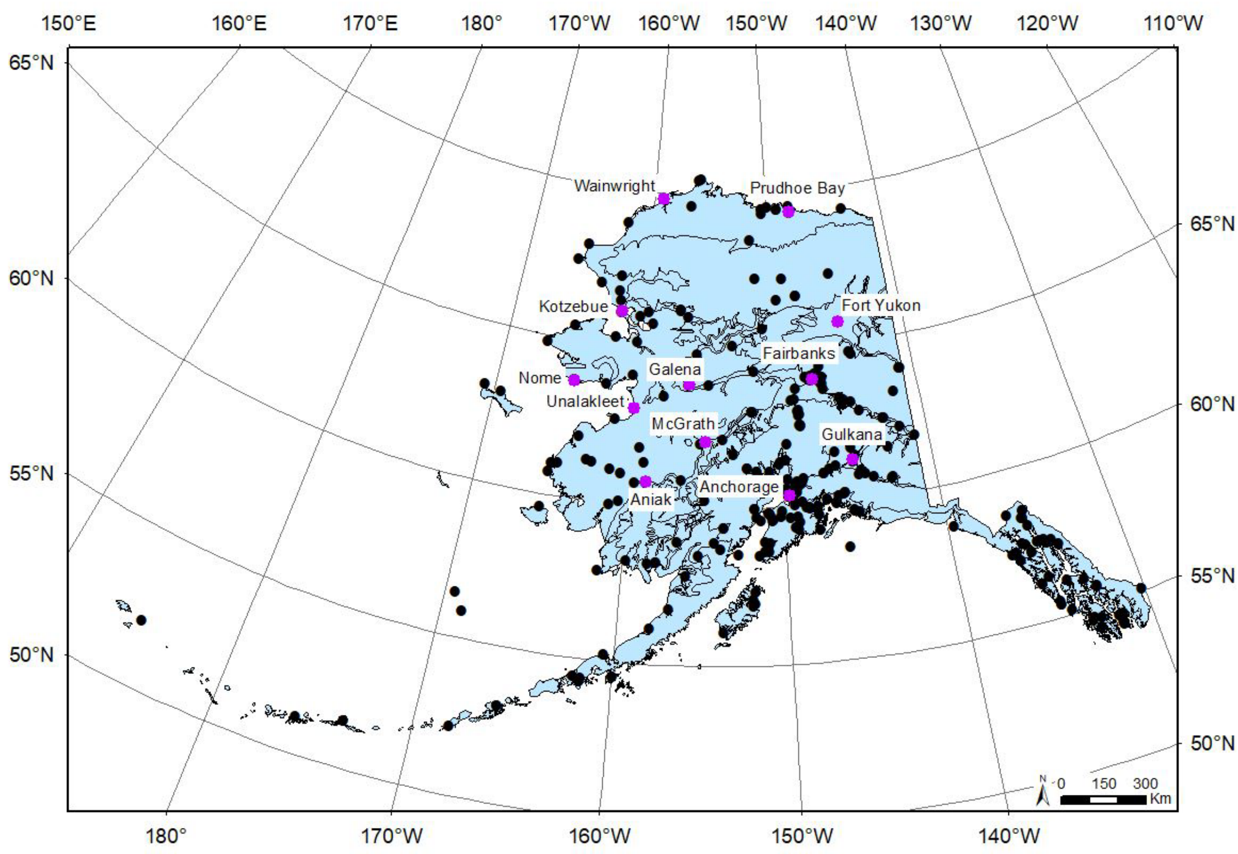
Fine-grained soils such as silty-sands, silts, and clays generally have the ability to wick and retain moisture. Soils located at and near the surface are often inundated with surface and subsurface water flow, so fine-grained soils in the vicinity of these regions will tend to have high moisture levels, with potential to exceed saturation levels. On freezing, the excess amount of soil moisture, when changed to ice, will cause the soil particles to be pushed apart, or disaggregate. The result is the ground surface and any associated structural elements within or on it can be significantly pushed upwards, or heaved. This is most common with pavement materials with poor subsurface drainage but also can occur under foundation elements and floors of structures, causing cracked floors and fractured foundation elements. These soil types are termed frost susceptible.

Structural fill material used for bearing support is considered non–frost susceptible (NFS) when the percentage of the fill material passing the 200 sieve is less than 3% to 5%. Under normal compaction requirements for typical bearing capacity, this low quantity of fines eliminates wicking of moisture and decreases the available pore space volume for water entrainment. Minimizing the entrainment of water also eliminates excess ice development on freezing, preventing disaggregation of the soil particles and frost heaving.

2-5 CLIMATIC CONDITIONS.

Refer to UFC 3-400-02 for an overview of available Engineering Weather Data (EWD) sites and instructions on how to access climate data. A Common Access Card (CAC) is required to access the 14th Weather Squadron's website https://www.climate.af.mil/. For those without a CAC see paragraph 1-6 in UFC 3-400-02 to request EWD. Also, land-based atmospheric observational data, including temperature, dew point, relative humidity, precipitation, and wind speed and direction, are collected and are available online. Ground-based observation records, including those from the Alaska observation stations (Figure 2-3), are available from the National Weather Service (NWS) website; and links to download the data are included in Appendix A, paragraph A-6.

Figure 2-3 Locations of Observation Stations in Alaska



The American National Standards Institute / American Society of Heating, Refrigerating, and Air Conditioning Engineers (ANSI/ASHRAE) Standard 169-2020 covers climate data and climatic zones (based on heating and cooling degree-days) worldwide. For engineering purposes, the general climatic conditions of the Arctic and Subarctic regions are best defined by the prevailing air temperature for the location. The Arctic and Subarctic regions have wide climatic variations; and the climatic conditions differ between the coastal areas and interior locations because of latitude, circulation patterns, and elevation. Atmospheric observations are needed to monitor and examine the climate conditions at a particular location. Definitions based on air temperature are given in Appendix B. See paragraph 2-6 for implications of the changing environments in the Arctic and Subarctic.

2-5.1 Air Temperature.

Air temperatures, which vary significantly from place to place in the Arctic and Subarctic regions, are typically collected by sensors located a few feet above the ground. Distributed air-temperature data sets (minimum, maximum, and mean temperature) for Alaska, and historical 30-year normal data are available online (see Appendix A, paragraph A-6.1, for resources).

2-5.2 Freezing Temperatures.

The patterns of the mean annual temperatures across North American and Eurasian continents are shown in Figures 2-4 and 2-5. On both the North American and Eurasian continents, the lowest mean annual temperature is about 5°F (−15°C). These maps are derived from the WorldIndex database, which is compiled from the Global Surface Summary of Day (GSOD) data. The GSOD data are available at the National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information (NCEI), website https://www.ncei.noaa.gov. The compiled data include the period of record from approximately 1980 to 2017 at various climate stations in North America and in northern Eurasia.[2] See paragraph 2-6 for implications of climate change on air temperatures.

The freezing season, defined as the period when the average daily temperature is below 32°F (0°C), also varies by location. In general, the freezing season begins as early as September in the northern latitudes (Figure 2-6). The freezing season starts when the mean daily temperature stays below freezing for three consecutive days, and it ends when the mean daily temperature begins to remain above freezing for three consecutive days. The average length of the freezing season (in terms of number of days) over the period of record can be more than two hundred days in the northern latitudes (Figures 2-7 and 2-8). Thus, the thawing season can be as late as June (Figure 2-9).

[2] "One-Dimensional Computer Models to Estimate Frost Depth," Barna et al.

Figure 2-4 Distribution of Mean Annual Air Temperature (°F) in North America, Derived over the Period of Record from the WorldIndex Database

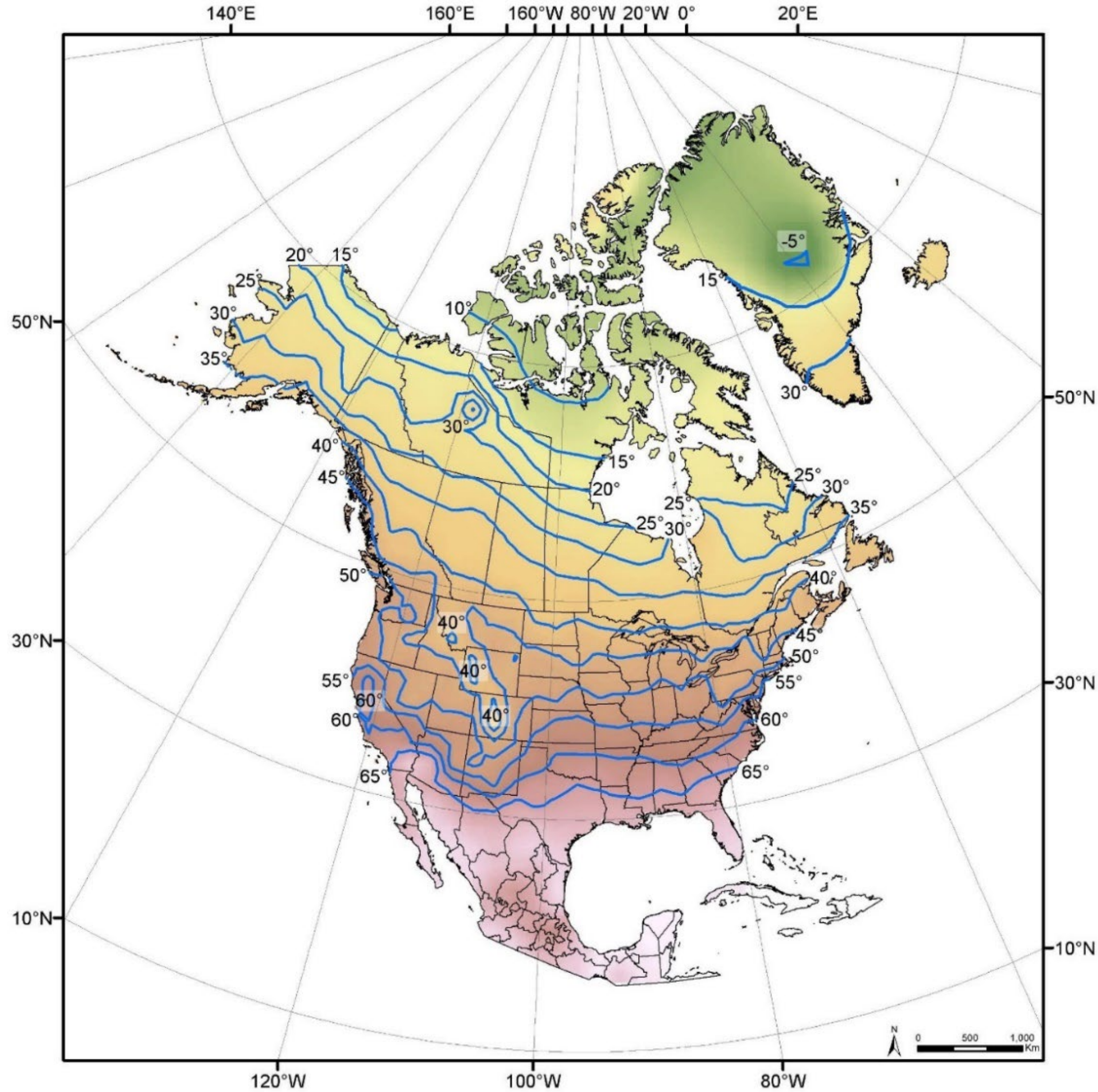


Figure 2-5 Distribution of Mean Annual Air Temperature (°F) in Northern Eurasia, Derived over the Period of Record from the WorldIndex Database

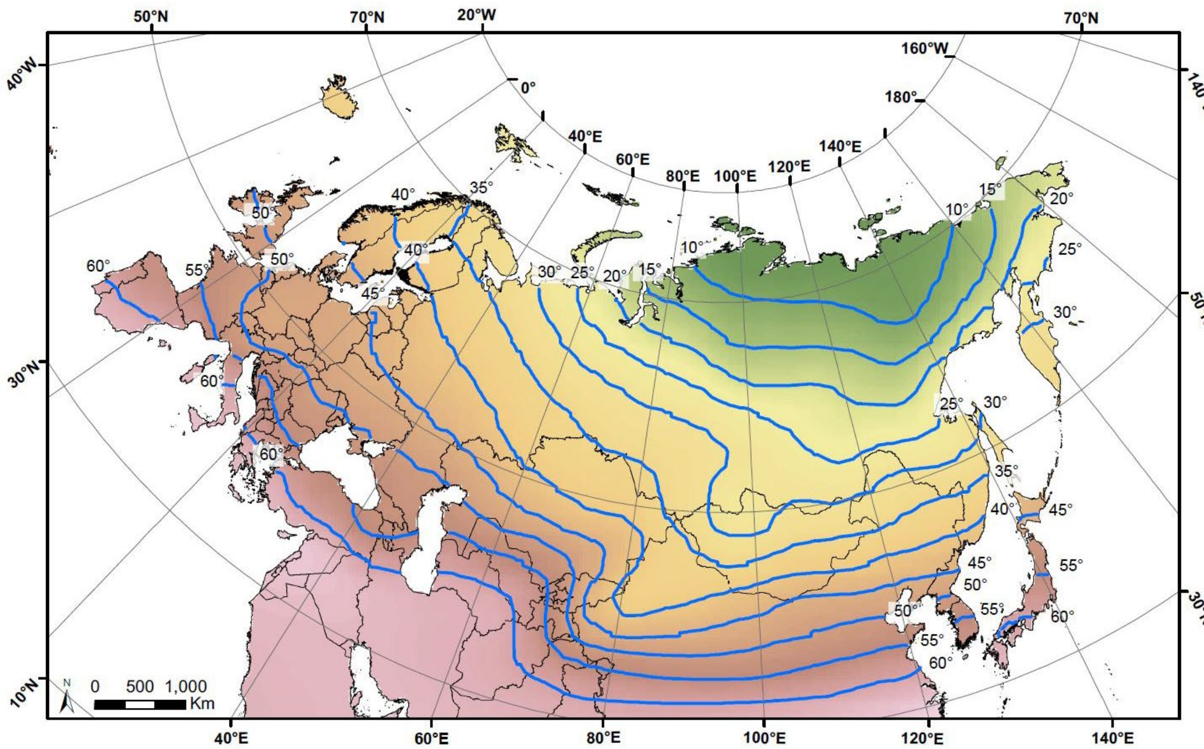


Figure 2-6 Mean Date of the Beginning of the Freezing Season, Derived over the Period of Record from the WorldIndex Database

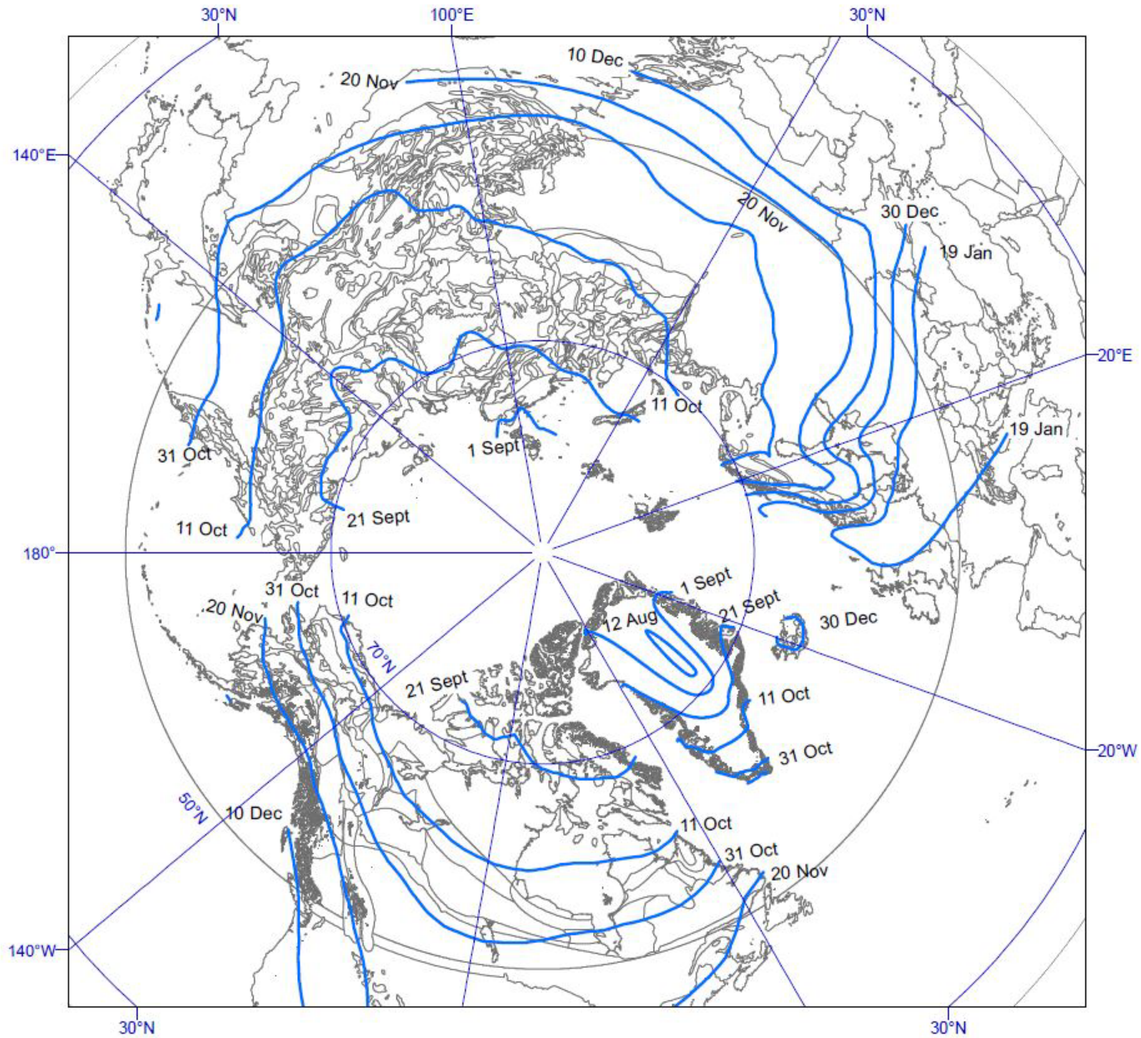


Figure 2-7 Average of the Number of Days in the Freezing Season in North America, Derived over the Period of Record from the WorldIndex Database

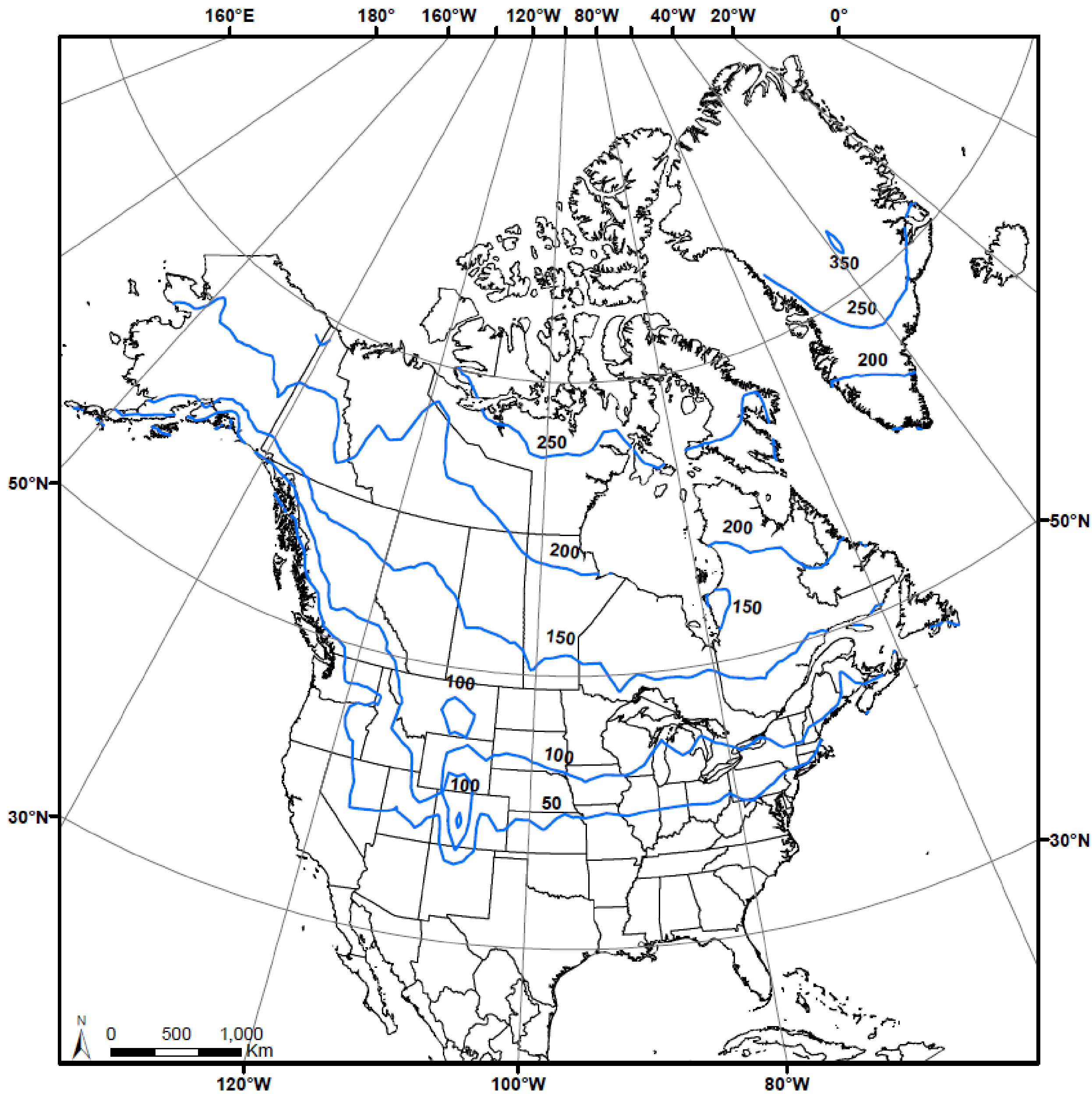


Figure 2-8 Average of the Number of Days in the Freezing Season in Northern Eurasia, Derived over the Period of Record from the WorldIndex Database

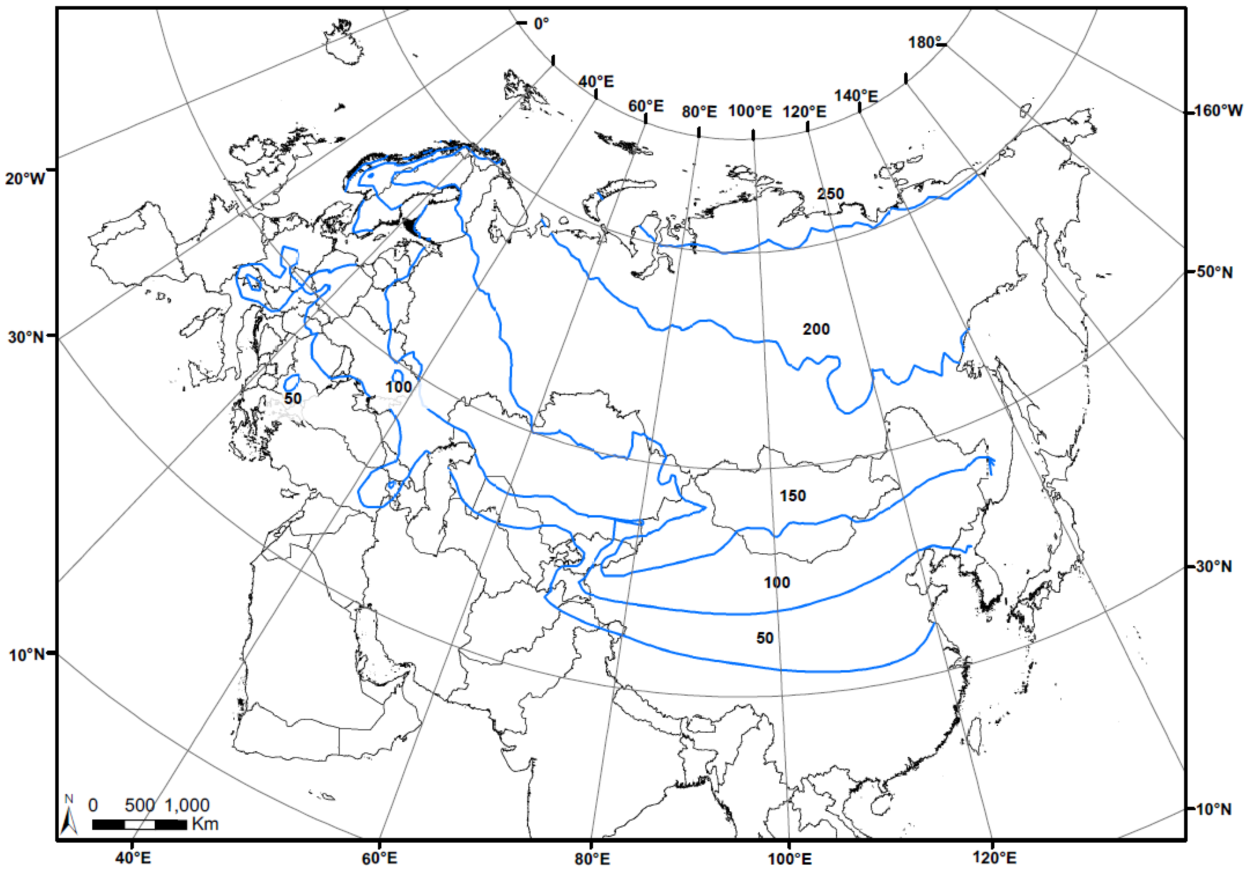
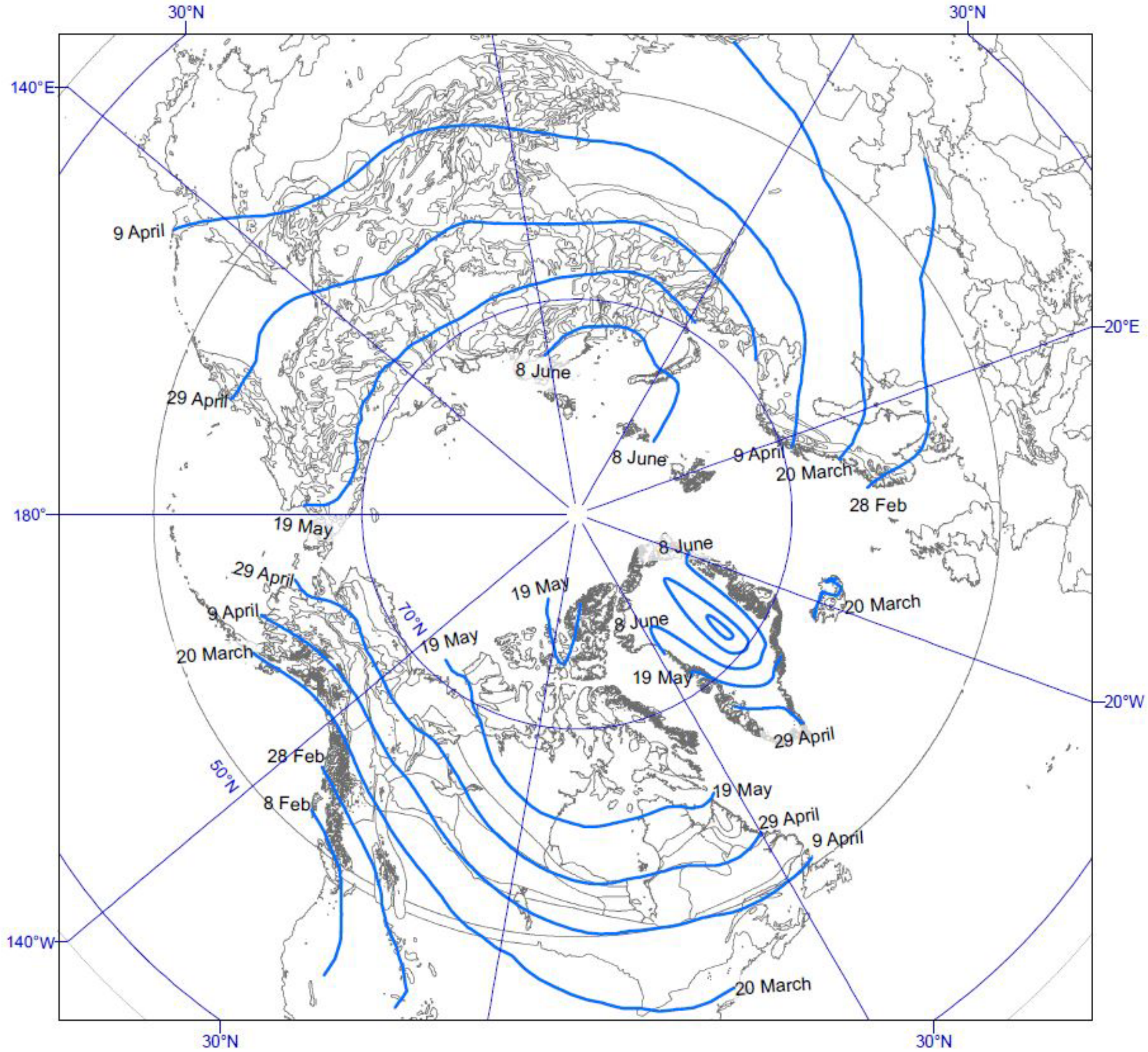


Figure 2-9 Mean Date of the Beginning of the Thawing Season, Derived over the Period of Record from the WorldIndex Database



2-5.3 Freezing Index and Design Freezing Index.

Air-temperature records for a given location are also used to quantify the intensity of temperature variation using the degree-day concept. The freezing index is computed as the sum of the number of degrees that the mean daily temperature departs from the freezing point of bulk water (32°F) during the freezing season. See *Frozen Ground Engineering*, by Andersland and Ladanyi, for graphical illustration of cumulative degree-days versus time for determining the freezing index, as well as thawing index. These indices are affected by the changing climate in the Arctic and Subarctic. See paragraph 2-6 for climate change implications.

The design freezing index is an expanded value of the freezing index and is used to account for climatic variations from year to year. The traditional method for calculating the design freezing index is to average the freezing indices of the three coldest winters in the most recent 30 years of weather records. If the weather records are less extensive, the design freezing index is calculated from the coldest winter in ten years. A more modern approach takes advantage of computers to calculate the design freezing index using the mean freezing index plus the product of 1.5 times the standard deviation of the freezing indices for the winters of record.[3] For pavement and foundation designs, comply with this approach for determining design freezing. Figure 2-10 and 2-11 show the estimated design freezing indices using the more modern approach described in "Computer Assisted Calculations of the Depth of Frost Penetration in Pavement-Soil Structures," by Cortez et al., for North America and northern Eurasia.

2-5.4 Ground Temperature.

Ground temperatures vary from one place to another. Ground temperature is a function of many factors other than air temperature. These factors include solar radiation, surface cover, snow cover, wind, soil type, soil moisture content, groundwater flow, and presence of stationary or moving surface water. The periodic fluctuation of ground-surface temperatures produces the diurnal cycle from day to day, season to season, or year to year. Measurements of subsurface temperature profiles are the most suitable to use for design. However, equations for estimating ground-temperature profiles using surface temperature or mean annual temperature data are in cold regions textbooks such as *Frozen Ground Engineering*, by Andersland and Ladanyi.

Data for ground temperatures is not always available for most locations in the Arctic and Subarctic. However, surface temperatures are available for certain locations and are accessible through global observational networks, observation stations, and from models. See Appendix A, paragraph A-6.2 for data resources. See paragraph 2-6 for climate change implications on ground temperatures.

[3] "Computer Assisted Calculations of the Depth of Frost Penetration in Pavement-Soil Structures," Cortez et al.

Figure 2-10 Design Freezing Index (°F days) in North America Derived Using the More Modern Approach Described in "Computer Assisted Calculations of the Depth of Frost Penetration in Pavement-Soil Structures," by Cortez et al., over the Period of Record from the WorldIndex Database

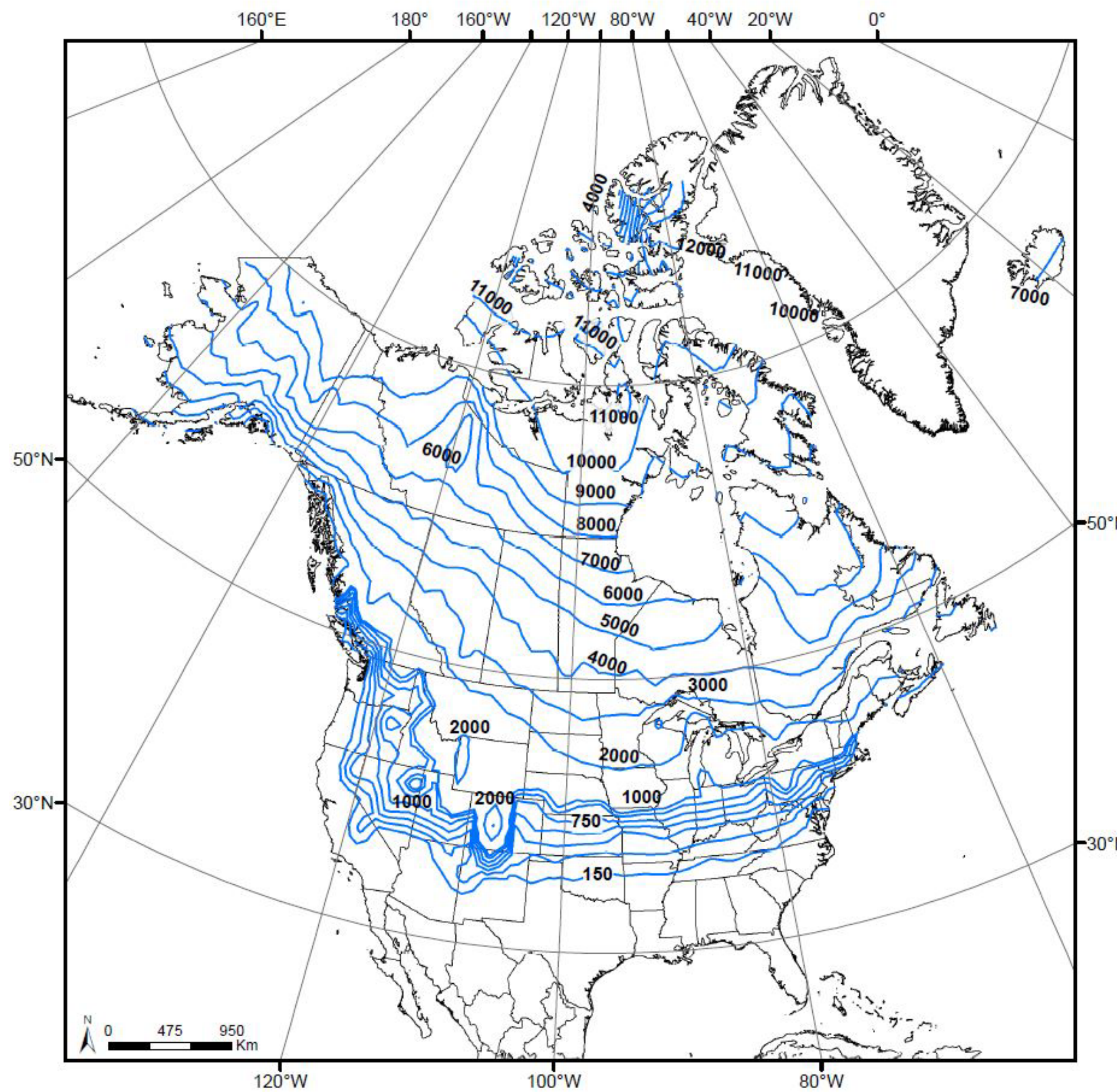
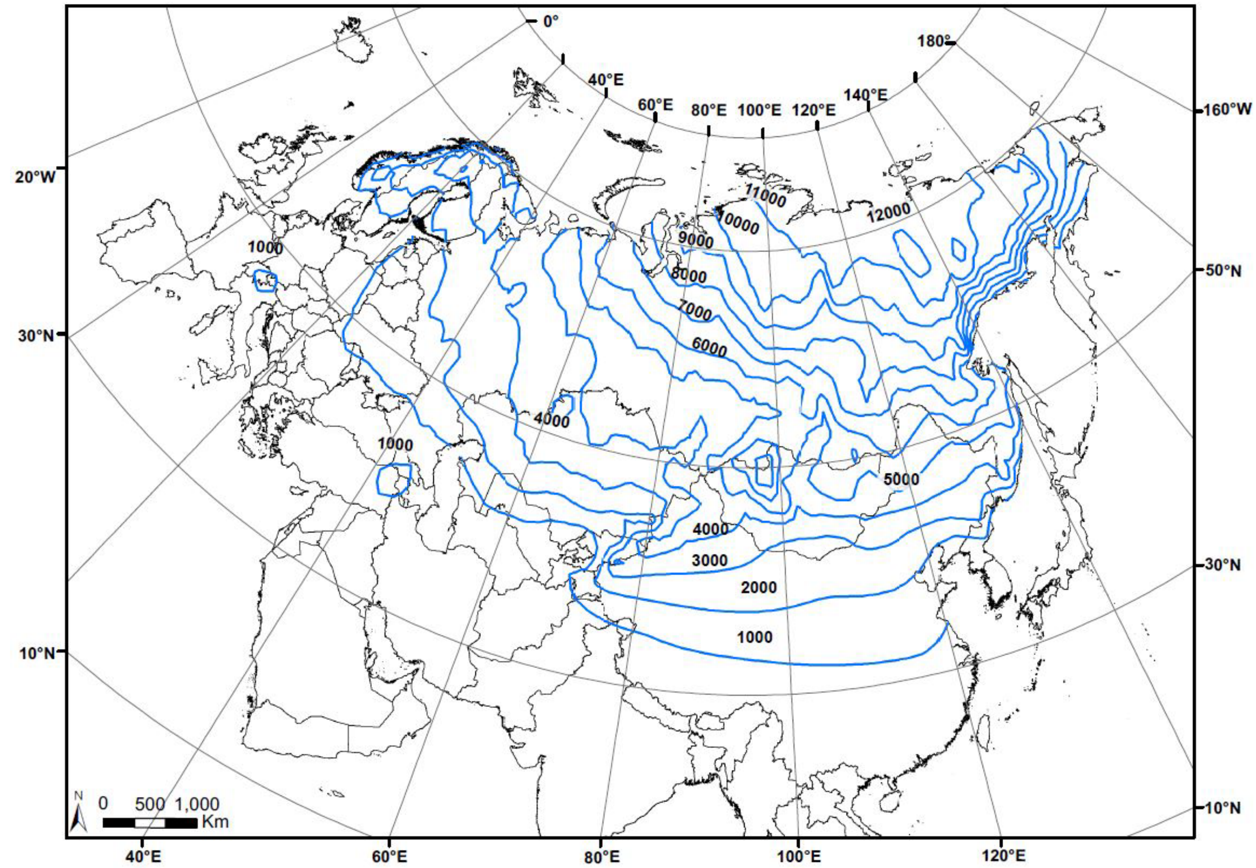


Figure 2-11 Design Freezing Index in Northern Eurasia Derived Using the More Modern Approach Described in "Computer Assisted Calculations of the Depth of Frost Penetration in Pavement-Soil Structures," by Cortez et al., over the Period of Record from the WorldIndex Database



2-5.5 Precipitation and Snow Distribution.

Precipitation and snowfall vary in the Arctic and Subarctic regions due to the complex interactions between the atmosphere, ocean, ice, and snow, as well as global and local processes and environmental changes. Winter has lower rainfall since moisture precipitates as snow. Archives of precipitation observations and other climatic products, like the Operational Climatic Data Summary (OCDS), are available from the U.S. Air Force 14th Weather Squadron for several different stations. Figure 2-12 shows mean monthly and annual precipitation values at selected stations over the observed period of record ending 2020, which are mapped in Figure 2-13. The observed period of record varies by station depending on when the station was established. For Alaska, summaries of climatological conditions such as precipitation, snowfall, and snow depth are also available from NCEI. For additional information, see Appendix A, paragraph A-6.3. Also see paragraph 2-6 for implications of the changing environments on precipitation and snow in the Arctic and Subarctic regions.

Figure 2-12 Mean Monthly and Annual Precipitation in Inches at Selected Stations from the U.S. Air Force 14th Weather Squadron Archived Data

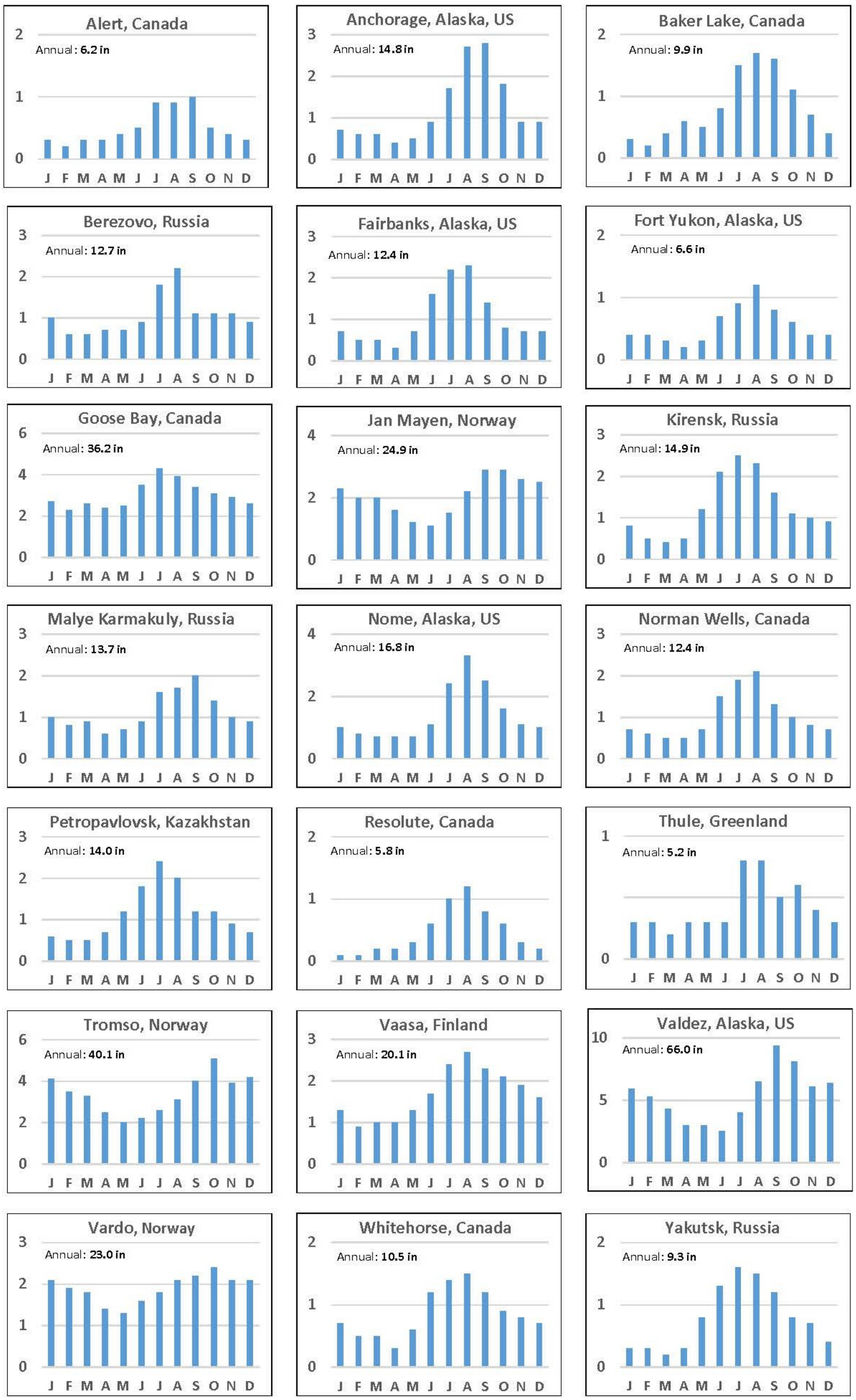
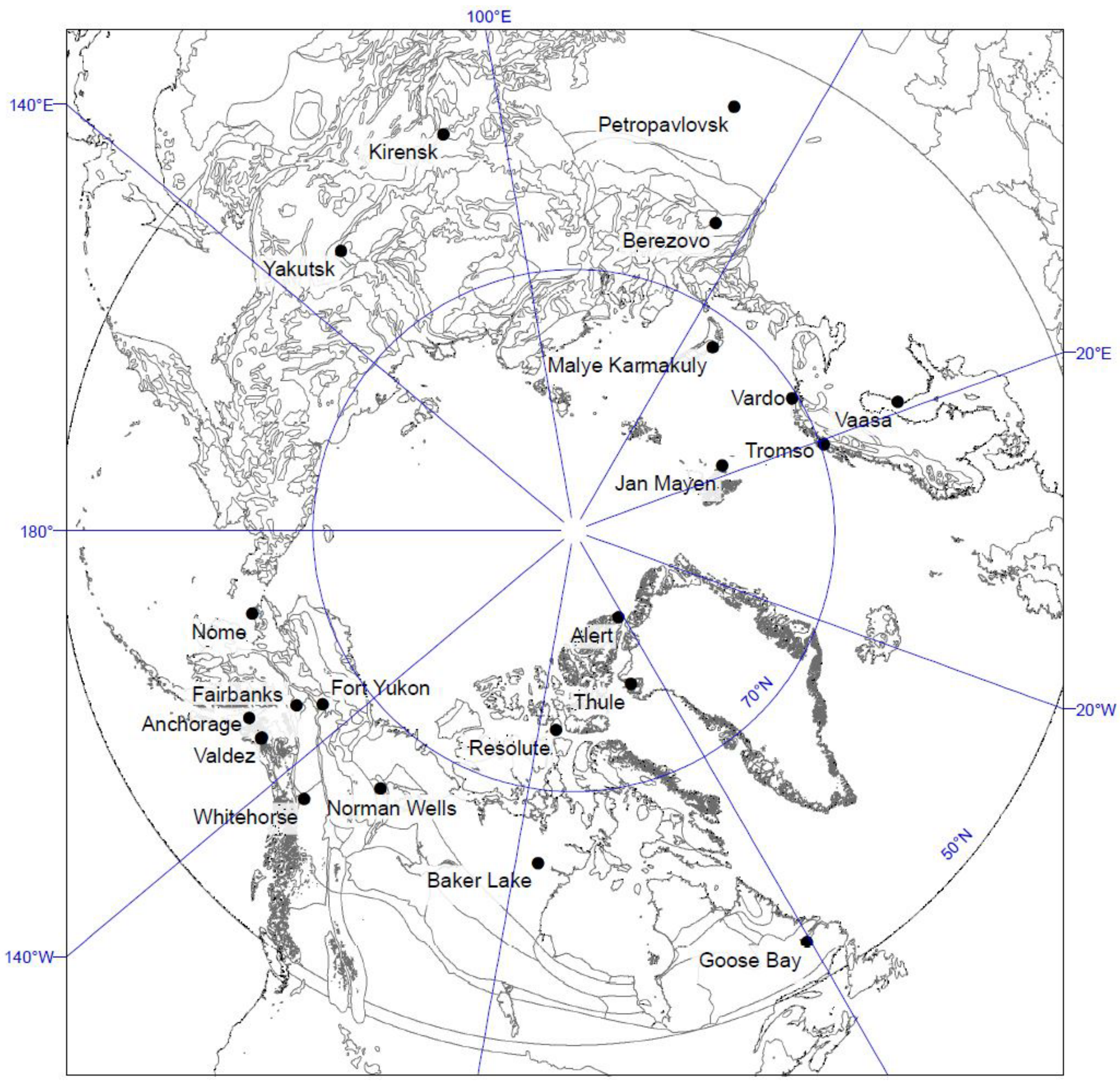


Figure 2-13 Locations of Selected Stations used in Figure 2-12



2-5.6 Snow Loads.

Comply with UFC 1-200-01, UFC 3-301-01, and UFC 3-301-02. Base snow load design on American Society of Civil Engineers (ASCE) guidance ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Ground snow load information is available from the following sites:

- The Structural Load Data Tool (SLDT), hosted on the Whole Building Design Guide website https://www.wbdg.org/ar/tools/sldrt
- The ASCE Hazard Tool (https://asce7hazardtool.online/)
- The Structural Engineers Association of Alaska website https://seaak.net/alaska-snow-loads, which provides values in two

formats: 50 year mean recurrence interval values described in ASCE 7 and reliability-targeted values sorted by risk category

- *Site-Specific Case Studies for Determining Ground Snow Loads in the United States,* by Buska et al., which provides additional locations for site-specific case studies in both the Lower-48 states and Alaska.

Note that ground snow loads in ASCE 7 account for rain-on-snow events and include snow water equivalent (SWE) data as needed in the criteria. At locations where the ground snow load is not provided, use the best locally available criteria. With the approval of the Authority Having Jurisdiction (AHJ), completing snow load case studies may clarify and refine snow loads for site-specific conditions.

2-5.7 Snow Drift.

Wind-induced snow movement, or drifting, is a common occurrence that creates a variety of problems for Arctic and Subarctic infrastructure. Considerable drifting snow deposited adjacent to and on structures can create unanticipated extra snow overburden, potentially accelerating the settlement and deformation of these structures, leading to premature failure. The mechanics of the snow-drifting process deal with snow particles lifted by the dynamic forces of the air flow. General engineering guidance to minimize snowdrift problems is described in publications such as *Introduction to Cold Regions Engineering*, by Freitag and McFadden. An updated summary follows:

- Avoid locations in which snowdrifts form, if possible.
- Before deciding on a final site, evaluate or study snow conditions at proposed locations for at least one winter by using aerial and satellite imagery to identify drift features. Analyze historical meteorological data from the site to determine representative wind directions, speeds (and more importantly, dominant snow transport direction and amount as this may differ from prevailing wind directions).[4]
- Identify potential effects of wind-transported snow on the operation of the facility access roads, sidewalks, and parking areas.
- Consider the entire facility when evaluating snow problems.
- Select locations with the least snow transport by considering the fetch distance, winter precipitation, and wind exposure. Where possible, select sites in the snow erosion zone, 490 to 650 ft (150 to 200 m) downwind from a deposition area.
- Chapter 7 in ASCE 7, Minimum Design Loads, contains design guidance for the calculation of different snow loading conditions, including guidance for drifts, sliding, and rain on snow applied to various roofing configurations and scenarios.

[4] "Blowing Snow Transport Analysis for Estimating Drift Orientation and Severity," Haehnel.

Find design guidelines for controlling blowing and drifting snow in *Design Guidelines for the Control of Blowing and Drifting Snow*, by Tabler. Numerical methods are applicable for modeling and evaluating snowdrift conditions. Procedures and methodology from case studies of snow transport and using computational modeling of snowdrifts around a building are listed in Appendix A, paragraph A-13.

2-5.8 Ice Load and Atmospheric Icing.

Comply with UFC 3-301-01 to design ice-sensitive structures that withstand ice loading caused by freezing rain, snow, and in-cloud icing.

Structures are subject to two categories of ice loadings. The first category includes loads caused by the ice formed on lakes and rivers. Structures affected by these loads include dams, locks, bridges, pile-supported structures, wharves, docks, and all structures located immediately on the shoreline. Infrastructure and structures located adjacent to lakes and rivers, such as channel erosion controls and buildings, are also subject to ice loads. These loads tend to occur during ice ride-up events when wind pushes ice onto shore and during wintertime floods, typically caused by river ice jams. See paragraph 2-5.9 for guidance on ice loads from ice formed in lakes and rivers. The second category includes loads caused by freezing rain, snow, and in-cloud icing. This category is referred to as atmospheric icing. Structures that are sensitive to atmospheric icing include, but are not limited to, lattice structures, guyed masts, overhead lines, light suspension and cable-stayed bridges, aerial cable systems (such as for ski lifts and logging operations), open catwalks and platforms, flagpoles, and signs. ASCE 7 describes the requirements to design these types of structures to withstand atmospheric icing. Electric transmission systems and communications towers and masts are also sensitive to atmospheric icing but are not included in ASCE 7 because other national standards exist for these types of structures. See *National Electrical Safety Code* (Institute of Electrical and Electronics Engineers [IEEE C-2]), *Guidelines for Electrical Transmission Line Structural Loading* (ASCE MOP 74), and *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures* (ANSI/EIA/TIA-222).

2-5.9 Ice Cover and Ice on Water Bodies.

The freezing of lakes, rivers, and coastal waters is a major factor controlling scheduling and effectiveness of field activities in the Arctic and Subarctic. Waterways used for boats or float-equipped aircraft are unusable during the freeze period from September through November. Several weeks of freezing temperatures are required before the ice becomes thick enough to support other types of vehicles. During the winter, ice surfaces, or cover, are often extremely valuable as aircraft landing areas and as smooth, obstruction-free surfaces for tractor trains and other forms of surface transportation. See paragraph 3-2 for guidance on ice-engineering-related ice hydraulics and hydrology and paragraph 3-10.3 for ice or snow roads.

2-5.9.1 Ice Thickness and Bearing Capacity.

When a load is placed on an ice cover, the ice cover deflects downwards in response. The amount of deflection is proportional to the magnitude of the load and the flexural rigidity of the ice cover. The ability of the ice cover to support a load is the bearing capacity of the ice cover. The cover deflects until the water pressure on the bottom of the ice cover increases sufficiently to balance the load. The greater the flexural rigidity of an ice cover, the less it deflects and the larger the area over which the ice cover deflects. The two basic parameters that determine flexural rigidity are the ice cover thickness and its elastic modulus (Young's modulus). In practice, elastic modulus of an ice cover is rarely measured in the field due to practical difficulties. In almost all cases, the bearing capacity is estimated based on the ice thickness, an easily measured parameter.

There are some important considerations when estimating the ice thickness needed to achieve a required bearing capacity.

- **Ice Quality.** It is important that the measured ice thickness be competent blue or black ice and that the ice excludes any unfrozen or partially frozen layers. Snow ice, also called white ice, forms when an ice layer covered with snow floods and the saturated surface snow and water layer freezes. Generally, snow ice has less strength than blue or black ice, and its presence downgrades the ice-cover bearing capacity.
- **Creep.** When a load on an ice layer remains at one location, the deflection of the ice increases with time. The additional deflection is known as creep. In effect, creep reduces the bearing capacity of the ice cover with time. For a load close to or at the maximum bearing capacity of the ice cover, creep can lead to an eventual failure and breakthrough. The occurrence of creep requires treating stationary (or long-term) loads placed on ice differently than moving loads.
- **Risk Factor.** The ratio of the load (pounds force) to the square of the ice thickness (square inches) is often referred to by the symbol *A* and is called the risk factor in using the ice cover. The level of risk increases with increasing *A* values. Operational controls are necessary to implement for managing the risk associated on ice cover with an *A* value of higher than 50. For example, closely monitored, one-of-a-kind missions can tolerate relatively high *A* values of 100 or more. On the other hand, heavily trafficked ice covers such as ice roads require *A* values much closer to 50.
- **Minimum Ice Thickness for Lighter Loads**. Generally, a minimum ice thickness of 4 in. (100 mm) is specified for pedestrians (260 lb or 120 kg), 7 in. (175 mm) for snowmobiles with riders (1,100 lb or 50 kg), and 15 in. (380 mm) for 3/4-ton 4×4 vehicles (up to 11,000 lb). When using the risk factor *A* to estimate the required ice thickness for lighter loads, the estimated ice thickness may not be adequate to support the load because

of normally occurring ice thickness variations (see below), unknown spacing between loads, and other considerations.

See Appendix A, paragraph A-12, for additional guidance on estimating bearing capacity, ice thickness with creep, ice risk, and loads.

2-5.9.2 Ice Thickness Variation.

Ice covers on the surface of a body of water increase in thickness due to the formation of new ice on the underside of the ice layer. The thickness of the ice cover and the resulting ice cover bearing capacity are determined by the climatic conditions. The primary parameters controlling ice thickness are the daily average air temperature and the snow-cover depth.

Ice thickness is also affected by Arctic warming trends due to climate change, with warmer-than-average air temperatures, fewer very cold days, river break-up happening earlier, annual precipitation increase, increase in the occurrence of freezing rain, and a shrinking snow season. Milder winters have resulted in later freeze-up dates, earlier break-up dates, or both, for lakes and water bodies.

2-5.10 Wind and Wind Chill.

Comply with UFC 1-200-01, UFC 3-301-01, and UFC 3-301-02. Identify wind loads at all DoD Installations worldwide by using the structural load data tool hosted on the Whole Building Design Guide website https://www.wbdg.org/ar/tools/sldrt. In many parts of the Arctic and Subarctic, where pressure gradients are weak and temperature inversions are common, surface winds are normally low. Where pressure gradients are more marked, however, near seacoasts and mountains, strong winds are quite common; and wind speeds can attain hurricane velocities. Consider the possibility of strong katabatic winds concentrated in valley outlets during site selection. If strong winds are possible, they may especially affect outdoor activities during the colder months. Worker efficiency decreases with lowering air temperatures, and wind significantly increases this effect. See Appendix A, paragraph A-6.4, for data and online resources.

2-5.11 Visibility and Natural Illumination.

Considerations for adverse weather conditions are necessary when conducting site assessment and surveys, particularly in remote locations. Daylight and seasonal variations affect construction. Poor visibility can disrupt operations and increase safety hazards. Visibility problems may arise from ice fog, blowing snow, and whiteout conditions. Localized fog can form over bodies of water. Ice fog is a type of fog consisting of fine ice crystals suspended in the air. Blowing winter snow can cause severe reductions in visibility, compounded by the shortage of natural daylight. Ground blizzards with winds gusting as high as 40 mph (1.6 km/h) create whiteout conditions in blowing snow. Significant drifting of the snow is likely. Whiteout conditions produce a lack of contrast between the sky and the snow surface and are dangerous and disorienting. See Appendix A, paragraph A-6.5, for hazard warnings and advisory resources.

2-6 CLIMATE CHANGE AND PROJECTIONS.

Global climate change trends are expected to accelerate in the Arctic and Subarctic regions and increase challenges for designing, building, and sustaining infrastructure. These changes are expected to affect many of the climatic factors described in paragraph 2-4. Paragraph 2-6 highlights how future projections of these climatic factors are developed and can affect the infrastructure and facilities criteria in the Arctic.

2-6.1 Overall Climate Observations and Projections.

Climate change trends will present an increasing challenge for infrastructure in Arctic and Subarctic environments with observed changes in air temperatures, ice cover, permafrost, coastal erosion, and other factors. However, translating these trends into the future requires considering climate projections developed from climate models under a range of future greenhouse-gas (GHG) emissions scenarios. These are called projections, rather than specific predictions, because they are “what-if” scenarios, where any of the future GHG emissions scenarios are possible, and actual future trends in emissions may not follow any one of them consistently over time. The future GHG emissions scenarios used in climate projections include low-, moderate-, and high-emission rates under Representative Concentration Pathways (RCPs), for example, 4.5, 6.2, and 8.5, to represent the amount of added infrared greenhouse forcing (in watts per square meter). These projections represent the most comprehensive picture of the expected changes on the climatic factors that would affect Arctic and Subarctic infrastructure.

The Scenarios Network for Alaska and Arctic Planning (SNAP) developed climate projections specifically for the Alaskan and Arctic regions that are applicable to infrastructure and building criteria. SNAP uses global climate model results from the Coupled Model Intercomparison Projects (CMIP3 and CMIP5) for twentieth-century conditions and future low-, moderate-, and high-emissions scenarios out to the year 2100. See Appendix A, paragraph A-7, for additional resources and links to the SNAP future climate projections, reports, and related studies documenting the changing Arctic environment, models, and data. The most likely or significant projected climate impacts affecting the design, building, and sustainability of Arctic and Subarctic infrastructure are summarized in the following sections.

2-6.2 Surface Air-Temperature Projections.

Surface air-temperature increases in the Arctic are projected under all GHG emissions scenarios. Even for low-emissions scenarios, models show on average 5.4°F (3°C) warming over much of Eurasia and North America, and more than 7.2°F (4°C) warming over the Arctic in 2081–2100. The high-emissions scenarios show annual increases of 14.4°F to 18°F (8°C to 10°C) in years 2081–2100 across the Arctic.

The local temperature-change projections developed by SNAP for Alaskan regions and locations assess future changes for criteria infrastructure design for each decade from 2040 to 2100. For coastal northwest Alaska, for example, it shows increasing average temperatures by 12°F (6.6°C) in winter and 8°F (4.4°C) in summer by 2050 in the low-emission scenario and 15°F (8.3°C) in winter and 10°F (5.5°C) in summer in the high-emission scenario.

2-6.3 Projections on Permafrost Warming and Thawing.

Increasing air temperatures, both observed and projected, invariably result in warming and thawing permafrost, whose strength and stability are dramatically reduced by warming. The projections of the observed circumpolar degradation of permafrost across North America and Eurasia concluded that nearly 70% of current infrastructure will have damages associated with high thaw potential by 2050.

2-6.4 Precipitation Projections.

Climate projections in all scenarios are highly consistent in showing increasing precipitation in the Arctic and northern latitudes due to higher air temperatures and a northward moisture transport due to a warmer climate. The projected increase for annual precipitation for Alaska is estimated from +10% for low scenarios to +30% for high scenarios. In Fairbanks, for example, the monthly maximum precipitation expected, with a 50-year return period, would increase from 7 in. (175 mm, historical average) to about 10 in. (250 mm) with projected climate change over 2020–2099.

2-6.5 Snow, Rain, and Ice Events.

Future projections of snowfall and snow cover are more variable and uncertain. As greater moisture becomes available for snowfall, and with the increase in mixed precipitation, the SWE would increase. However, increased temperatures also mean a shorter duration of snow cover and an increase in the fraction of rain in storm events, both for “shoulder seasons” (spring and fall) and for winter rain events.

These winter rain events are expected to result in more frequent freezing rain and icing events that impact roadways and damage trees and power lines in regions not previously affected. The increase in SWE and winter rain events may also increase the total weight of snow loads on roofs, compared to historically dry snow. Because ground snow load measurements consider rain-on-snow events, the expected increase in SWE is included in the updated ground snow load criteria.

2-6.6 Sea Ice Cover.

Climate warming dramatically decreases the safety of operating on Arctic Ocean sea ice. The sea ice extent (the area covered by 15% ice concentration) has declined significantly from 1979 to 2021, decreasing by 2.6% per decade for the March maximum extent and decreasing 13.0% per decade for the September minimum extent. In future projections, the Arctic sea ice area steadily decreases significantly by 2050. The Arctic Ocean is likely to be ice-free in summer (less than 0.4 million square miles) at least once before 2050 under all assessed scenarios and consistently ice-free in September by 2050 under the moderate- and high-GHG emissions scenarios.

2-6.7 Coastal Erosion.

The projections of sea level rise, permafrost thawing (paragraph 2-6.3), and sea ice reduction (paragraph 2-6.6) all contribute to an acceleration of coastal erosion rates in the Arctic. The reduction in ice cover along coastlines, specifically during spring and fall, leaves coasts susceptible to greater storm-driven wave activity that can significantly damage coastal infrastructure in addition to eroding the thawing ground.

2-6.8 River Discharge.

The increases in precipitation (paragraph 2-6.4) also appear to be driving an overall increasing trend in river discharge across the Arctic. While there is significant year-to-year variability in the amount of discharge, there are many natural terrestrial effects and water management activities that will affect local river discharge.

2-7 STABILITY AND PERMAFROST DEGRADATION.

Increasing air temperatures and additional frequency of heat waves as discussed in paragraph 2-6 pose risks for irregular thermal thawing of landforms, creating uneven subsidence and thawing of ice-rich permafrost. The degradation processes include inflow of heat energy into the ground, reduction in soil strength or bearing capacity, water migration, and progressive settlement soils containing excess ice. Issues associated with permafrost degradation due to collapse of soil structure include slope instability; coastline and riverbank erosion; and damage to foundations, roads, railways, retaining embankments, and utilities. Consider such potential effects during design. See Appendix A, paragraph A-8, for additional resources.

2-8 VEGETATION AND WILDFIRES.

The three major types of vegetative cover in Arctic and Subarctic areas are tundra, muskeg, and forest. Vegetation types with shallow root systems that occur in wet or poorly drained areas will often occur over shallow depths of permafrost. North American examples of shallow-rooted vegetation commonly overlaying permafrost are black spruce and larch. Ground layers consisting of sphagnum moss (North America) and other thick, spongy insulating ground layers are also high-probability indicators of permafrost. Vegetation types with deeper root systems and requiring better drained soils will occur in areas with deeper occurrences of permafrost, if present. Generally, deciduous tree cover indicates a low probability of shallow permafrost occurrence. Vegetation profiles are useful as indicators of potential permafrost occurrence but should be interpreted in concurrence with other indicators. It is reasonable to assume that areas of homogenous vegetation share similarly homogenous conditions across the same area. UFC 3-130-02 provides further guidance on vegetation for site assessment.

Wildfires or forest fires affect vegetation, promote permafrost thawing, and may alter permafrost conditions over many years. In the Alaskan interior, summer is typically the driest and warmest season and, as such, is prone to wildfires. Appendix A, paragraph

A-9 contains information on fire-weather conditions and fire impact on vegetation and soil in the Arctic.

2-9 WETLANDS.

Wetlands are common in the Arctic and Subarctic environments. Approximately 40% of the State of Alaska is considered wetlands (Alaska Department of Environmental Conservation, Division of Water website https://www.fws.gov/wetlands/Documents/Status-of-Alaska-Wetlands.pdf, and Hall et al. 1994). Some of these wetland types are bottomland forests, bogs, wet meadows, potholes, and wet tundra. In the winter months, these areas are frozen and covered with snow and ice. Executive Order 11990 directs all Federal agencies to avoid wetlands development wherever there is a practicable alternative. Also, see UFC 3-201-01 for basic site development, design, and planning requirements and for specific issues such as wetlands, flood hazards, and tidal zones.

2-10 SEISMIC.

Comply with UFC 1-200-01, UFC 3-301-01, and UFC 3-301-02. Assess location-specific seismic parameters using the structural load data tool hosted on the Whole Building Design Guide (WBDG) website https://www.wbdg.org/ar/tools/sldrt.

2-10.1 Seismic Loading.

Design codes for the dynamic loads imposed by earthquakes are applicable to frozen soil conditions; however, the presence of permafrost can significantly alter the ground-motion characteristics. Stress-wave velocities are much higher and damping is lower in frozen soils. Propagation of stress waves through permafrost is faster and of a higher intensity than for nonfrozen soils. The average response in spectra vary depending on the depth of permafrost, local soil conditions (unfrozen soils above the frozen layer), and the interaction between distributed blocks of isolated frozen soil. See Appendix A, paragraph A-10, for additional literature on how these affect ground motion in Arctic and Subarctic areas. Site exploration must include a seismic survey to quantify spectral values for seismic parameters because the stratigraphy and geotechnical properties of soil profiles affect seismic responses.

2-10.2 Design.

Infrastructure in the Arctic and Subarctic includes seismic design by considering the probability, severity, frequency, and potential damage of seismic ground shaking or tsunamis, in addition to designing for dead, live, snow, and wind structural loads. The U.S. Geological Survey (USGS) Earthquake Hazards Program website posts and archives seismic activities worldwide. The University of Fairbanks (UAF), Alaska Earthquake Center, posts earthquake activities in Alaska. Alaska is a seismically active region with frequent earthquakes. Ground motion can be characterized as moderate to high, depending on location and proximity to faulting. See Appendix A, paragraph A-10, for additional resources.

The National Institute of Building Sciences Building Seismic Safety Council, along with the U.S. Department of Homeland Security, Federal Emergency Management Agency (FEMA), publishes *An Introduction to the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA P-749), highlighting earthquake effects and design requirements. FEMA P-749 also provides a seismic design category map for Alaska.

2-11 GEOSPATIAL DATA.

Geospatial data are valuable for site planning, reconnaissance, and initial site characterization of ground conditions. Geospatial data sets including the digital elevation model (DEM), digital surface model (DSM), soils, and other terrain features in Arctic regions are available. See Appendix A, paragraph A-11, for other resources.

CHAPTER 3 ENGINEERING FACTORS AFFECTING DESIGN AND CONSTRUCTION

3-1 INTRODUCTION.

This chapter introduces specific requirements for planning, design, and construction procedures for Arctic and Subarctic regions and identifies issues associated with the extreme cold region conditions. Full discussions of these topics are found in the other volumes of the UFC 3-130 series.

3-2 ICE ENGINEERING.

Water infrastructure in cold regions, such as piers, bridges, dams, and riprap, are included in the field of ice engineering. Resources for various ice engineering topics to consider in the design and construction of water infrastructure are available in Appendix A, including practical recommendations for modeling ice-jam floods. Additional considerations, such as freezing of lakes and streams, ice and snow in hydrology, and ice and snow in hydraulics, are discussed in *Introduction to Cold Regions Engineering*, by Freitag and McFadden. Climate change may affect river ice, including ice-jam floods.

3-3 HYDROLOGY: SNOW AND SNOWMELT.

In general, hydrology in Arctic and Subarctic environments is highly dynamic, is seasonally and climatically dependent, and varies greatly in extent for both surface and subsurface conditions across the regions. The important characteristics for hydrology in Arctic and Subarctic environments include considerations with surface energy balance, snow process, snow insulation, snowmelt, infiltration, soil temperature, soil moisture, permafrost, active layers, and other aspects. Surface hydrology is influenced by permafrost depth (the active layer) and snow loading as well as the potential retention of winter or late-season rain events. Also, permafrost greatly influences subsurface hydrology (groundwater), causing reduced ground permeability, which in turn affects the distribution and movement of subsurface water.

Snow hydrology and estimating snowmelt runoff produced by a watershed over a specified time are important factors to consider for groundwater flow and drainage design. There are three basic components required to estimate snowmelt runoff. The first is the spatial distribution of the SWE throughout the watershed at the start of the snowmelt period. SWE is the depth of water produced by melting the entire depth of snow over a unit area of the watershed. The second is a snowmelt model that estimates properties of the snowpack (temperature and liquid-water saturation) and the heat transfer into the snowpack from the atmosphere and calculates the amount of the liquid water that reaches the soil surface over the specified time period. The third is a routing model to determine the time for watershed channels to transport surface water to a point of interest, generally the watershed outlet. See Appendix A for more resources and best practices on SWE measurements and snowmelt estimation.

3-3.1 Aufeis.

Aufeis is a phenomenon in which liquid water (stream or ground source) overflows and refreezes on a frozen surface or near-surface confines and atop existing terrain or ice pack. Aufeis is considered an infrastructure geohazard. It affects infrastructure by accumulating on road surfaces; eroding stream channels; contributing to ground uplift; subsidence due to ice accumulation; and thaw and frost sorting ground materials, which leads to unstable soil conditions. Aufeis generally forms in the same areas annually or can form randomly one season and never appear again in the same location. Changes in climatic, geological, or hydrological conditions can cause abrupt variance in occurrence and severity of aufeis formation. In general, the formation is controlled by local or regional surface topography, groundwater, climate, soil conditions, and permafrost presence and distribution. Practical mitigation options include removing the ice buildup by ripping with heavy equipment, installing ice fences, and installing ice storage areas or interceptor systems to divert water flow. See Appendix A for more resources on best practices.

3-3.2 Avalanche.

Mountainous terrain has the potential to pose avalanche hazards. Avalanches are the result of high-altitude structural failure of snowpack and the resulting movement of snow, ice, and debris from higher to lower altitude. Avalanche hazards include the mechanical hazards of large amounts of moving material, as well as air blast and shockwave hazards.

3-4 FROZEN GROUND ENGINEERING.

Frozen ground engineering factors affecting design and construction of facilities in Arctic and Subarctic environments are briefly introduced below. Comply with the more-detailed requirements in UFC 3-130-03 and UFC 3-130-05. Discussions of fundamental concepts and advances in the field of frozen ground engineering are available in various textbooks such as *Frozen Ground Engineering*, by Andersland and Ladanyi, and *Introduction to Cold Regions Engineering*, by Freitag and McFadden.

3-4.1 Physical Properties and Soil Factors.

As a rule, the engineering characteristics of permafrost depend on the texture, water content, salinity, and temperature of the soil. Clean sands and gravels located in well-drained areas may not present serious engineering construction problems if they do not contain appreciable amounts of excess ice. Conversely, permafrost consisting of fine-textured soils, such as silt, often contains large formations of ice lenses, wedges, veins, or other shapes. Cold regions textbooks such as *Frozen Ground Engineering*, by Andersland and Ladanyi, contain information on the standard system for classification of frozen soils, frost action, and the strength and thermal properties of frozen soils. Investigate and evaluate frozen soil index properties (for example, soil type, moisture content, ice content, and density) in accordance with accepted engineering practices, including the following:

- ASTM D4083, *Standard Practice for Description of Frozen Soils (Visual-Manual Procedure)*
- ASTM D2216, *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soils and Rock by Mass*
- ASTM D2487, *Standard Practice for Classification of Soils for Engineering Purposes*
- ASTM D7015/D7015M, *Standard Practice for Obtaining Intact Block (Cubical and Cylindrical) Samples of Soils*
- ASTM D7099, *Standard Terminology Relating to Frozen Soil and Rock*

ASTM publishes symposia and technical papers on the latest information on frozen soil properties and measurements of soil indices. Since frozen saline soils are widely distributed, particularly along the Arctic coast, consider the special engineering properties of these soils. See Appendix A for an additional list of information.

3-4.2 Heat Flow at the Ground Surface.

Permafrost remains stable if its natural cover of trees and other vegetation remain intact or undisturbed and if the mean annual temperature of that location is maintained. However, one of the most important things to consider in any civil engineering work in the Arctic and Subarctic is the effect of a change in surface condition on the thermal regime in the ground. Transfer of heat at the air–ground interface depends on such time-varying factors as the thermal properties of the soil, the albedo (reflectivity) and insulating properties of the ground cover at the surface, the amount of solar radiation reaching the surface, the wind structure and velocity above the surface and the surface roughness, the air temperature and humidity as a function of height above the surface, precipitation, snow cover, and evapotranspiration from vegetation. Heat flow toward the ground surface from the soil below is also a factor. Alteration by stripping away, compressing, or otherwise changing the existing vegetative ground cover, erecting structures, or constructing pavements, pipelines, or other features alters the thermal balance in the ground, changing the depth of annual freeze and thaw and, in permafrost areas, alters the depth of the permafrost table. Cold regions textbooks discuss permafrost degradation or aggradation due to ground-surface alteration in more detail, specifically *Frozen Ground Engineering*, by Anderson and Ladanyi (see Appendix D).

3-4.3 Mechanical Properties.

The mechanical properties of frozen soils are influenced by soil temperature, water content, density, applied load, and specimen orientation. See Appendix A for additional resources on mechanical properties. While certain data sets of soil mechanical properties are available, experienced field geotechnical engineers and technicians must identify and conduct the required tests for site-specific soil and loading conditions.

3-4.3.1 ASTM Standards.

Use the following ASTM standards that are specific to frozen soil material properties:

- ASTM D5520, *Standard Test Method for Laboratory Determination of Creep Properties of Frozen Soil Samples by Uniaxial Compression*
- ASTM D5780, *Standard Test Method for Individual Piles in Permafrost Under Static Axial Compressive Load*
- ASTM D5918, *Standard Test Method for Frost Heave and Thaw Weaking Susceptibility of Soils*
- ASTM D6035, *Standard Test Method for Determining the Effect of Freeze–Thaw on Hydraulic Conductivity of Compacted or Intact Soil Specimens Using a Flexible Wall Permeameter*
- ASTM D7300, *Standard Test Method for Laboratory Determination of Strength Properties of Frozen Soil at a Constant Rate of Strain*

3-4.3.2 Other Standards.

Aside from ASTM standards, the following are other commonly used, nonstandardized frozen soil test methods:

- Thaw-consolidation test
- Compressibility of thawing soils
- Shear stress test
- Triaxial compression test
- Pile pullout test for field measurement

See Appendix A for additional resources and sources of experimental data for soil properties for ice-soils.

3-5 CALCULATION OF DEPTH OF FREEZE AND THAW IN SOIL.

It is essential to understand the thermal properties that influence soil heating and cooling in cold region design and construction. The parameters include thermal conductivity, heat capacity, latent heat, thermal diffusivity, and thermal expansion and contraction as described in detail in cold regions engineering textbooks (see list in Appendix A). Heat transfer and the depths to which soils freeze and thaw are particularly important when designing structures, utilities, and pavements in areas of seasonal frost and permafrost. Methods for calculating such depths are based on heat-transfer principles and are presented in cold regions textbooks such as *Frozen Ground Engineering*, by Andersland and Ladanyi, and *Cold Region Structural Engineering*, by Erranti and Lee. The methods include one-dimensional linear, multiple-plane, and two-dimensional radial heat flow. Use UFC 3-130-03, Chapter 6, for numerical modeling of ground thermal response.

3-5.1 One-Dimensional Linear Heat Flow.

The modified Berggren equation is a mathematical construction over Fourier's Law for one-dimensional heat conduction through a homogeneous soil. The solution to the modified Berggren equation requires numerical methods. Use the modified Berggren equation for (1) calculating the depth of frost penetration in Subarctic and seasonal frost regions where the ground freezes during winter and thaws during spring and (2) for calculating the depth of seasonal thaw penetration (active layer thickness) in permafrost areas.[1] See Appendix A, paragraph A-16, for a list of one-dimensional models used in cold regions.

3-5.2 Multiple-Plane and Two-Dimensional Radial Heat Flow

Thermal problems dealing with multiple planes and radial heat flow are common for foundation and utilities design. Comply with UFC-3-130-03 for foundation design, including pile foundations, in permafrost and UFC-3-130-05 to design and construct utility supply lines including water and sewage transport in permafrost and seasonal frost areas.

See *Frozen Ground Engineering*, by Andersland and Ladanyi, and *Cold Region Structural Engineering,* by Erranti and Lee, for steady-state heat-flow equations to quantify thermal resistance and temperature conditions for multiple layers and cylindrical or spherical heat flow. The steady-state solutions include heat flow

- through several layers of different thicknesses and material conductivity, such as floor systems or a concrete pad over soil, soil layers with insulation, pavements, buried insulated utilities, and other scenarios;
- for effective thickness with a cylindrical cross section;
- of two infinite areas, with one heated and one cooled, for estimating the radial geothermal gradient between them such as temperature gradients near shores, beneath rivers, and around heated or cooled structures.

Note that these solutions can over- or underestimate results due to the variability of surface temperature or surface cover, the effects of phase change, moisture (in the frozen and thawed soil), and salinity.

3-6 SITE SELECTION AND GEOTECHNICAL INVESTIGATIONS.

Comply with UFC 3-201-01, Chapter 2, for planning and conducting geotechnical investigations during the various stages of development for civil and military projects.

Geotechnical investigations must be tailored to the individual projects. Comply with UFC 3-130-02 for site selection and development procedures specific to cold regions. The requirements and information for site selection and geotechnical assessment described in UFC 3-130-02 are unique to the Arctic and Subarctic regions. Moreover, all designs

[1] *Frozen Ground Engineering*, Andersland and Ladanyi.

for construction in Arctic and Subarctic regions are preceded by thorough site or route investigations to obtain any existing information on the proposed location and to identify new field data requirements on surface and subsurface features, drainage, permafrost, and other conditions. The importance of thorough site investigations before construction cannot be overemphasized. Sites with non-frost-susceptible subsurface conditions or foundations are much easier to develop for than those having frost-susceptible materials or permafrost. Soil investigations (sampling, testing, and evaluation) must be in accordance with UFC 3-220-01, UFC 3-250-01, and UFC 3-260-02 as discussed in UFC 3-201-01, paragraph 2-4.1. Comply with UFC 3-130-02 for site selection and geotechnical investigations, specifically on frozen and permafrost soils. Also see Appendix A, paragraph A-17, for other guidance and other standard practices.

3-6.1 Site Selection.

Arctic and Subarctic site selection and development is much more complex than in temperate regions because of the remoteness of the locations, the large distances sometimes involved, the limited support facilities, and the seasonal and environmental constraints on field activities. Over large areas of the Arctic and Subarctic, specific terrain or local climatic information is limited. The use of existing geospatial and remote-sensing data sets is beneficial. Access to proposed site or route locations is difficult and expensive, may require careful seasonal scheduling, and may involve severe restraints on sizes and weights of survey equipment that can be brought in. Field working conditions are difficult, considering that very low temperatures persist for several months of the year. Costs of site selection and development studies are high, but do not allow these costs to justify inadequate investigations.

3-6.2 Soil Sampling.

Sampling for frozen ground requires greater attention to avoid thermal disturbance. Select suitable sampling techniques and equipment based on project-specific needs and as determined by an experienced field engineer. Obtain samples that represent the subsurface conditions. Special care is required to maintain samples in their frozen state in the field, in transit, and in storage. Take specific care when machining samples, particularly for mechanical tests. For more information on field sampling, as well as sample handling of frozen soils, field testing, and instrumentations in frozen ground, see *Frozen Ground Engineering*, by Andersland and Ladanyi.

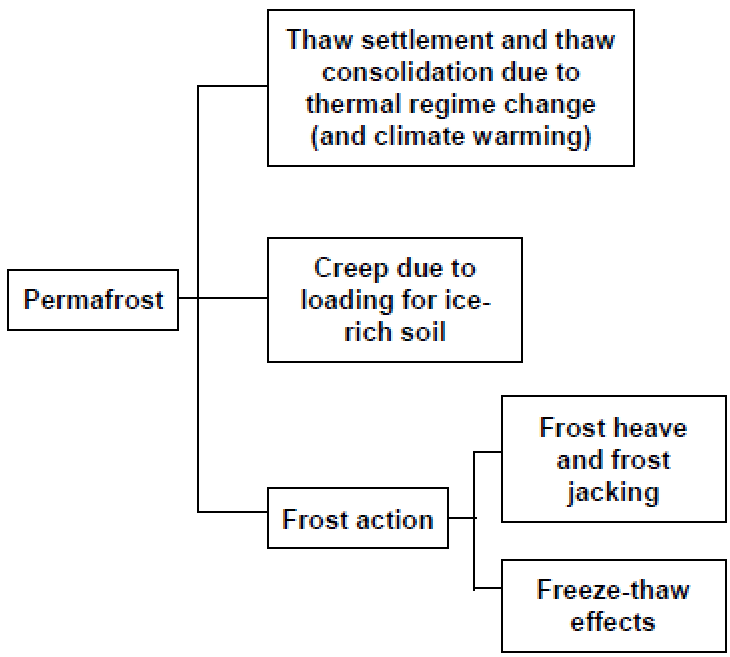
3-6.3 Geophysical Methods.

The use of geophysical methods to characterize the permafrost and ground ice has increased in recent decades. Because physical properties depend on freezing of interstitial water in soils and rocks, successful delineation of permafrost requires supplementary information (such as core data) and knowledge of geophysics methods for frozen ground. Find further information on using geophysics in frozen ground in *Frozen Ground Engineering*, by Andersland and Ladanyi, and *Improving Design Methodologies and Assessment Tools for Building on Permafrost in a Warming Climate*, by Bjella et al.

3-7 FOUNDATIONS FOR STRUCTURES.

Planning, design, and construction of Arctic and Subarctic foundations requires a thorough consideration of ground characteristics as well as the physical, mechanical, and thermal properties of the foundation soil (Figure 3-1). Permafrost and frozen soils respond to foundation loads differently than normal, unfrozen soils, requiring the appropriate type of foundation to address those differences. Comply with UFC 3-130-03 and references therein for requirements of foundation planning, design and construction in cold regions.

Figure 3-1 Consideration Factors for Foundation Design



3-7.1 Considerations.

The major principles to consider for foundation design are bearing capacity and settlement. Because foundation soils vary, the following are additional factors to consider:

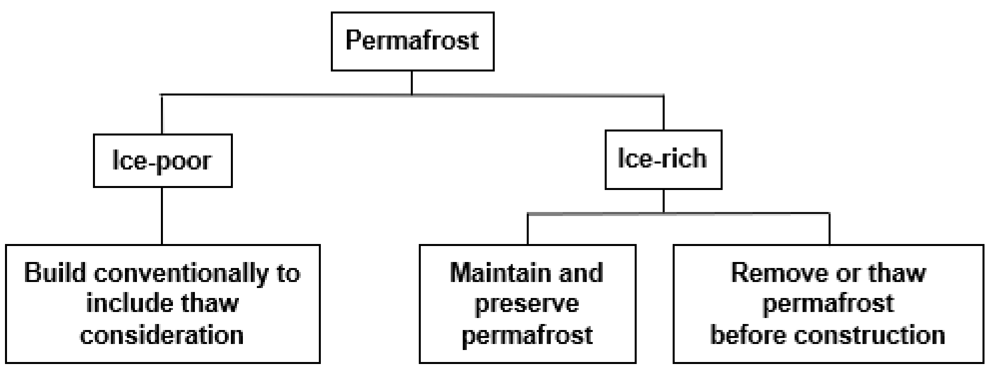
- Thaw settlement and thaw consolidation associated with thermal changes—When thaw settlement occurs, the volume of the soil structure decreases due to melting ground ice or permafrost and the subsequent draining of meltwater, causing ground settlement and creating uneven ground. Thaw consolidation occurs when frozen soil thaws but meltwater is trapped and soil remains undrained, reducing soil strength.
- Long-term strength and creep—The presence of ice causes frozen soil to take on stress-strain behavior characteristics like ice. The strength and deformation of frozen soils depend on loading, temperature, and time.

Therefore, frozen soil subjected to load responds with an instantaneous deformation and a time-dependent deformation. Determine allowable loads by conducting laboratory creep tests (such as ASTM D5520).

- Frost action—Frost action is the process of alternate freezing and thawing of moisture in soil, rock, and other materials and evaluating the resulting effects on materials and on structures placed on, or in, the ground. The process can involve frost heave, frost jacking, and other freeze–thaw effects. Frost heave is an upward ground movement due to ice formation in the underlying soil. Frost jacking is a cumulative upward displacement of objects embedded in the ground, caused by frost action. Freeze–thaw effects not only cause displacement but also change the hydraulic and strength properties of the thawed soil.

The principles for foundation design in permafrost are divided into two categories: ice-poor permafrost and ice-rich permafrost (Figure 3-2).

Figure 3-2 General Approach for Foundation Design



3-7.2 Foundation Design for Permafrost Under Ice-Poor Conditions.

Conditions under ice-poor permafrost are not adversely affected by thaw as they contain little or no ground ice. Materials within this permafrost are clean, granular soils or rocks. Consider the following principles for foundation design in permafrost areas with ice-poor conditions:

- Place foundation below the active layer with protection as needed against uplift acting in adfreezing shear and against frost overturning or sliding produced by frost thrust.
- Design with proper drainage to continue to remove water prior to freezing.
- Support the structure on a compacted, non-frost-susceptible fill capable of limiting freeze and thaw effects.
- Use normal temperate zone approaches if the foundation-supporting conditions will not be adversely affected by thaw.

3-7.3 Foundation Design for Permafrost Under Ice-Rich Conditions.

Ice-rich permafrost conditions are usually fine-grained soils or rocks with significant ground ice, which are adversely affected by thaw. These materials are found in continuous and discontinuous permafrost zones. Consider the following principles for foundation design in permafrost areas with ice-rich conditions:

- Maintain the existing thermal regime.
- Modify the foundation conditions prior to construction.
- In the design and construction, identify and account for the thermal regime changes.

Further, consider this additional guidance:

- Support the structure on a compacted, non-frost-susceptible fill capable of limiting freeze and thaw effects.
- Use thermal insulation, foundation loading, foundation soil replacement, heat to thaw ice-rich soil or removal of heat by freezing the soil, or combinations of these.

3-8 BUILDING DESIGN PRACTICES.

Specialized cold regions building design criteria and guidance are discussed in UFC 3-130-04*,* and design criteria and guidance pertinent to foundations are presented in UFC 3-130-03. General considerations include building type or use, building materials, doors, entrances, roofs, windows, sliding snow and falling ice, wind, snowmelt, icing, drifting of snow, and many other aspects of building design for Arctic and Subarctic environments. Consider requirements as part of a system of interrelated elements under broad design, construction, operation, and maintenance of facilities. Give special attention to foundations, exposure, and adaptation to the extreme environmental conditions.

3-9 UTILITIES.

Use UFC 3-130-05 for criteria and guidance for utilities in the Arctic and Subarctic*.* Connections of utilities to buildings are discussed in UFC 3-130-04. Utilities include water, wastewater, utilidors, fire protection, electrical, and communication systems. Many elements of these systems, such as electric generators and water-treatment mechanical equipment, are standard items that require no modifications for use in the Arctic and Subarctic if they are appropriately protected from extreme temperatures, snow, and ice and if back-up systems or power are provided as necessary. However, other items require special approaches. For example, protect water distribution pipes in the Arctic from freezing to maintain flow, prevent bursting, and withstand differential thaw settlement or frost heave. Design wastewater treatment facilities to resist frost heave or thaw; settlement damage to pipes, tanks, and other structural elements; and adverse effects of low temperatures on treatment processes. Achieve acceptable grounding conditions by finding areas where soils are less likely to freeze, by installing ground rods or piles in warmer soils, or both; UFC 3-130-05, paragraph 11-2, discusses this further.

3-10 HORIZONTAL INFRASTRUCTURE (AIRFIELD PAVEMENTS AND ROADS).

3-10.1 Airfields and Roadways.

Comply with the cold regions requirements for road, pavement, and airfield design in UFC 3-250 and UFC 3-260 series as listed in the references. In addition, several cold regions textbooks present detailed information on pavement-specific topics

- *Cold Regions Pavement Engineering*, Doré and Zubeck;
- *Introduction to Cold Regions Engineering*, Freitag and McFadden;
- *Permafrost Engineering Design and Constructio*n, Johnston; and
- *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers*, McFadden and Bennett.

Several factors affect roadway and airfield surface performance in cold regions. Factors include loading, surface characteristics, subsurface drainage, freeze and thaw, subgrade properties, resilient modulus, moisture change, icing, snow and ice removal, and many others. Consider the following detrimental effects when designing airfield pavements and roads in the Arctic and Subarctic:

- Seasonal frost heave and settlement, commonly differential
- Reduced bearing capacity during and after thaw
- Pavement pumping (the ejection of water and base and subgrade material through joints and cracks or at the pavement edge under traffic loading)
- Pavement cracking
- Deterioration of pavement surfacing
- Progressive increase of pavement roughness
- Loss of compaction
- Restriction of subsurface drainage by frozen ground
- Wintertime surface drainage problems
- Snow removal and icing problems
- Degradation settlement from thawing of permafrost, commonly differential
- Adverse surface drainage effects from permafrost degradation

All but the last two effects are observed to some extent in temperate zone frost areas. The most difficult conditions are in areas near the boundary between permafrost and unfrozen soils. Here the depth of seasonal freezing is at a maximum and permafrost, where present, is the least thermally stable. The detrimental effects of seasonal frost action on pavements are discussed in cold regions textbooks, particularly in *Cold Regions Pavement Engineering*, by Doré and Zubeck. In permafrost regions, the change of ground-surface conditions caused by construction can initiate permafrost degradation and invariably create differential settlement.

3-10.2 Unsurfaced Airfields and Roadways.

Unsurfaced roads and airfields have unbound, aggregate surfaces as an uppermost layer, meaning there is no asphalt or cement layer as a wearing surface. The typical material used for an aggregate wearing surface is compacted gravel with a specified gradation. Guidance for basic design elements, construction, and maintenance of gravel roads is listed in the Federal Highway Administration (FHWA-OTS-15-002). The Alaska Department of Transportation also provides guidance for gravel roads design and maintenance. Army and Air Force only, use UFC 3-250-09FA cold regions requirements for designing unsurfaced roadways and unsurfaced airfields.

3-10.3 Winter—Ice, and Snow Roads.

In very cold and remote areas, winter roads constructed using snow and ice, or both, are viable. Snow roads are built with compacted snow. Ice-capped snow roads use water to produce a bond between snow particles, adding stability to the road.[2] Design, construction, and maintenance techniques for ice and snow roads are described in *Introduction to Cold Regions Engineering*, by Freitag and McFadden, *Permafrost Engineering Design and Construction*, by Johnston; and *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers,* by McFadden and Bennett. Ice and snow roads are viable only when sufficient ice thickness forms on the surface of a body of water to carry the vehicle loading or enough snow cover and sufficiently frozen layers exists in the ground. Snow roads (compacted snow) are common in the high Arctic and at McMurdo Station in Antarctica. See Appendix A, paragraph A-18, for snow roads best practices and procedures used by other agencies.

3-10.4 Ice and Snow Runways.

Ice and snow runways are successfully constructed in cold regions. Snow runway design is based on strength properties and bearing capacity similar to that of conventional roads and runways. The design for an ice runway is like a snow runway, except the stress loading characteristics are based on the flexural strength of the ice rather than the shear resistance of a snow layer. The complex nature of snow and ice mechanics presents unique challenges to constructing snow and ice runways. Detailed information on the design and construction methods of a first-of-its-kind snow runway capable of supporting a wheeled aircraft as heavy as a C-17 is documented in *A Snow*

[2] "Winter Roads in Manitoba," Kuryk.

Runway for Supporting Wheeled Aircraft: Phoenix Airfield, McMurdo, Antarctica, by Haehnel et al. Guidance for snow and ice runways, specifically for Antarctica, is in FC 3-260-06F, *Air Force Design, Construction, Maintenance, and Evaluation of Snow and Ice Airfields in Antarctica*. See APPENIDX A, paragraph A-18, for other methodology on the design and construction for snow and ice runways.

3-11 DRAINAGE AND GROUNDWATER.

Although annual precipitation intensity rates are relatively light in much of the Arctic and Subarctic, except in coastal regions, control of surface and subsurface water movement around structures is necessary to prevent icings, erosion, and permafrost degradation. Sources of surface water include snowmelt (see paragraph 3-3), rain, groundwater seepage, and flooding. Also, sources of groundwater may include melting subsurface permafrost ice. In this context, icing is a sheetlike mass of layered ice formed on the ground surface by freezing of successive flows of water that seep from the ground. UFC 3-130-03 provides criteria and guidance for surface drainage design and to control icing in Arctic and Subarctic regions. UFC 3-130-03 presents criteria and guidance for drainage around structures, including brief guidance for seepage control.

3-11.1 Surface Water.

A frequent cause of damaging floods in cold regions is the temporary damming of rivers by ice jams formed by melting winter snowpack along river and tributary areas. The following are two examples of guidance for flood design:

- FEMA developed the *Design Guide for Improving Critical Facility Safety from Flooding and High Winds* (FEMA 543), which includes recommendations incorporating hazard mitigation measures into all stages, and at all levels, of critical facility planning and design for new construction, reconstruction, and rehabilitation of existing facilities.
- The Department of Commerce, Community and Economic Development, which is a department within the state of Alaska, provides *The Floodplain Management in Alaska Quick Guide*.

The frozen condition of the ground during much of year makes it necessary to assume that the rate of infiltration in the Arctic, for surface drainage design, is zero. Construct relatively deep and narrow surface channels to direct and carry away surface water to reduce the channel surface area and minimize heat loss that leads to ice formation and reduces flow capacity. Preferably, line the channels to prevent excess infiltration into the soil and prevent permafrost degradation. Oversize culverts to account for ice. Flowing surface water in channels can be a significant cause of permafrost thawing. In Subarctic regions, such channels, once formed, may continue to thaw and deepen year after year. Avoid drainage ditches that cut into ice-rich permafrost.

3-11.2 Groundwater Seepage.

Icings generally occur in upland areas where seeps or springs provide a continuous source of groundwater to the surface during winter. Icings are undesirable near buildings, roadways, culverts, or other structures as they are a serious problem when they interfere with road travel or drainage. Control of icings can be surprisingly difficult to achieve. Icing impacts can sometimes be circumvented if the flow can be redirected to locations where it does no harm. Include a steam pipe in culverts susceptible to icing to allow culvert thawing when necessary.

3-11.3 Groundwater.

Control groundwater flow where possible to prevent erosion, or permafrost degradation, and differential settlement. In practice, there are few options for controlling groundwater. Some control over the direction of summer drainage flow in the active layer is possible by modifying surface conditions to selectively control depth of thaw. Modifying downstream water levels can influence the flowrate of groundwater. Injecting water into the ground, such as from leaking water, sewer, or steam pipes, can seriously degrade permafrost and must be avoided. When wells drilled through permafrost encounter water under artesian pressure, great care is necessary to stabilize the unstable soil around the casing to avoid losing control of the well.

3-12 EARTHWORK: EXCAVATION, GRADING, AND FILL.

Conduct a site assessment before performing any earthwork and excavation activities to characterize ground conditions and identify the appropriate methods for excavation. Comply with requirements for site assessment in UFC-3-130-02.

3-12.1 Excavation.

Techniques used for excavation of frozen soils depend on the time of the year and ground conditions. Mechanical methods to fracture, break, and rip frozen materials include excavating by machine and cutting equipment, hydraulic dredging, drilling, and controlled explosive loading or blasting. Other approaches, such as thawing frozen ground, are applicable under certain conditions. Methods for thawing frozen ground include solar thawing, steam injection, water injection, and electric heating. Detailed discussion on excavation techniques and other related factors are described in various cold regions textbooks (see Appendix D).

3-12.2 Earthwork and Fill Placement.

Earthwork of frozen soil is feasible, but significant care and effort are required. Earthwork and placement of fill material can be extremely challenging if conducted during freezing temperatures. Relative compaction varies depending on temperatures, soil type, and ice contents. See cold regions textbooks such as *Introduction to Cold Regions Engineering*, by Freitag and McFadden, *Frozen Ground Engineering*, by Andersland and Ladanyi, *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers*, by McFadden and Bennett, and *Permafrost*

Engineering Design and Construction, by Johnston, for detailed information and guidance, including handling on earthwork, placement, and compaction of frozen materials. Use required tests and standards, including ASTM D4253, for determining the minimum thawed dry density of a material.

In general, the placement of frozen materials is prohibited unless the materials can be satisfactorily compacted and maintained in a frozen state for the life of the structure.[3] If material contains a significant amount of ground ice, instability due to thaw settlement will result from melting. Frost heaving can be an issue if the fill materials used are frost susceptible. Whenever possible, use non-frost-susceptible soils for fill materials. The magnitude of frost heave and subsequent thaw weakening is determined by the frost susceptibility of the soils. The frost design classification of soils provides an approximation of frost susceptibility. However, when accurate measurements are needed, ASTM D5918 provides the procedures to determine the frost-heave and thaw-weakening susceptibility of soils.

3-13 EROSION CONTROL.

Adapting to coastal erosion and bank erosion resulting from increased disturbances in hydrological cycles is an evolving field in higher-latitude areas. No specific design guidelines are currently available; however, base erosion-control designs on a solid understanding of the erosion processes involved (fluvial versus terrestrial), the mechanisms of the permafrost environment, and other applicable environment factors. Special consideration of sea ice and sea ice dynamics is necessary for coastal design. Attention to unique issues, such as river overflow during the breakup period and of formation of strudel scour for structures near rivers, is a must. Published erosion-control approaches are listed in Appendix A, paragraph A-19.

3-14 EMBANKMENTS.

Deformation such as settlements and lateral spreading of materials are common embankment failures in cold regions. Settlement of embankments in permafrost regions are attributed to thaw settlement, creep, and freeze–thaw cycling. Consider engineering measures during design to protect the permafrost underneath the embankment. Analysis such as numerical modeling is a viable approach to analyze the embankment deformation for heat transfer, creep, soil compression, and thaw consolidation. Other embankment design techniques are described in Appendix A, paragraph A-20.

3-15 GROUND AND SLOPE STABILITY.

Use general requirements for slope stability in UFC 3-220-01, paragraph 2-4.10. Ice-rich permafrost slopes can create significant creep deformation. Find analyses and design considerations for slopes in thawing permafrost and in frozen soils as well as slope stabilization methods in *Frozen Ground Engineering*, by Andersland and Ladanyi. Comply with UFC-3-130-03 to mitigate slope failures and stability of slopes during thaw.

[3] *Permafrost Engineering Design and Construction*, Johnston.

3-16 CONSTRUCTION MANAGEMENT AND PRACTICES.

Designs, cost estimates, and construction management and procedures in the Arctic and Subarctic regions differ from those in temperate regions because of deep seasonal frost, permafrost, and extreme climate. The environment and short construction season critically affect field operation schedules. Remote, isolated construction sites served by long and difficult supply lines mean that mistakes in planning are time-consuming and costly. A highly competent management team, with decentralized authority and centralized support, must carefully plan and organize field activities and conduct an intensive field inspection effort.

3-16.1 Methods of Transportation.

3-16.1.1 Air.

Air transport is a principal mode of transport to Arctic and Subarctic field sites. If a landing strip does not exist near the site, use helicopters or float-, ski- or wheel-equipped small planes in initial project stages, depending on available surface conditions. In winter, heavy wheel-equipped planes can use ice landing surfaces. Constructing a serviceable conventional runway facilitates regular heavy plane operations.

3-16.1.2 Water.

A suitable road or waterway, or an expedient access road, allows delivery of construction materials and equipment to the construction site. However, rivers and the Arctic coastal waters have only limited ice-free periods for water transport. Sometimes a north-flowing river may be open for upstream navigation before its mouth becomes sufficiently ice-free in the breakup period that permits entrance from the sea.

3-16.1.3 Ground.

Low-ground-pressure tractor trains can transport personnel, materials, and equipment over frozen, snow-covered terrain in winter. Frozen lakes and rivers are frequently used very effectively for such transportation. Wheeled, tracked, or sled equipment can use ice bridges to cross rivers and lakes. Stockpile materials at convenient locations during the summer for surface transport in winter. For protection of the terrain, operations on the natural tundra surface in summer are prohibited in Alaska. Vehicles with low-ground-pressure rubber tires (1 to 2 lb/in^2 [7 to 14 kPa]) are an exception. In some areas, such as nature preserves, other restrictions or permit requirements may apply.

3-16.2 Construction Equipment.

Heavy equipment is essential in Arctic and Subarctic construction. Winterize all motorized equipment, including insulated cabs and facilities, fire-retardant engine shrouds, and heaters to protect personnel from severe cold, wind, and snow. Removable cleats on tracked vehicles (such as grousers) or other special traction devices and winches are frequently necessary. Preventive maintenance plays a key role in equipment operation. Maintain a strict lubrication schedule on all equipment. Equipment operators must adhere to freezing-weather preoperation, starting, warm-up, and operating procedures. Unused “cold-soaked” hydraulic systems are especially vulnerable to failure on start-up at about 30°F (−1.1°C) or lower. Tires in extremely low temperatures become brittle and are easily punctured. Metal parts are vulnerable to brittleness at temperatures around 40°F (4.4°C) or lower and can lead to potential safety and operation problem. Inspect all equipment regularly to locate cracks and breaks. Repair all cracks when first observed by preheating before welding and replacing broken parts. Additional information on the effects of cold on equipment performance are described in *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers*, by McFadden and Bennett.

3-16.3 Cold and the Worker.

The efficiency of labor on construction projects in the Arctic and Subarctic varies with the experience, attitude, and morale of the workers, as well as working conditions. Cold and darkness during the winter months create safety and operational problems that directly limit productivity. The degree of worker climate acclimation and their cold adaptability is important across all classes of labor and directly affect productivity.

3-16.4 Construction Operations.

The special conditions that prevail in the Arctic and Subarctic impact all aspects of construction, such as excavating frozen soil or frozen rock; placing embankments, backfill, or concrete; and protecting the work. The following are examples of factors that require careful consideration:

- Difficulty of excavating frozen materials
- Difficulty of handling wet, thawed material in summer
- Adherence of ice-filled frozen materials to equipment at low temperatures
- Direct effects of low temperatures on equipment, including brittle fracture of metal
- Shortness of the above-freezing summer season
- Shortness of daylight hours in fall and winter
- Difficulty of achieving satisfactory fills and backfills when temperatures are below freezing
- Problem of placing concrete and achieving adequate strength gain without thaw of underlying permafrost
- Problems protecting work from cold, heat, drying, dust, wind, and precipitation
- Enclosure of work to maintain worker efficiency
- Fire safety and fire protection

3-16.5 Placing Concrete.

Whenever possible, conduct concrete placement work during above-freezing temperatures. Refer to UFC 3-301-01, paragraph 2-7, for requirements.

A combination of several techniques and methods are used to prevent damage to concrete placement during freezing conditions. These techniques include enclosures or tents, insulation, heating of materials, additives, and others that are described in various cold regions textbooks (see Appendix D). Refer and conform to the American Concrete Institute (ACI) *Guide to Cold Weather Concreting* (ACI 306R-16) for recommendations, test methods, mixing, placing, and preparation for cold weather concreting.

3-17 MAINTENANCE AND MONITORING CONSIDERATIONS.

Once facilities or structures are in use, maintenance and monitoring are important given the extreme temperatures and change in thermal properties that impact a facility’s life cycle in the Arctic and Subarctic environments. Maintenance includes a collection of actions as well as monitoring to ensure the continued function and sustained service of facilities or structures. There are two aspects to monitoring infrastructure in cold regions: (1) monitoring ground conditions around a building and (2) monitoring the intrinsic aspects of the structure itself. Monitoring is the process of measuring to assess whether facilities or structures are performing as intended. Monitoring can include, but is not limited to, qualitative (like visual observation) assessments and quantitative measurements (such as using sensors).

For foundations and utilities, the most important factor influencing the performance in permafrost is the ground thermal regime.[4] In addition, accumulated snow and ice build-up adjacent to foundations and utilities can disrupt airflow, drainage, or surface flow. Monitoring results can identify performance failures due to factors influencing the distribution or existence of permafrost, the properties and behavior of frozen soil, or freezing and thawing effects. Regular inspection and monitoring programs are essential to ensure that the ground thermal regime is stable and identifies any concerns that affect structures. Note the following signs:

- Subsidence of fills
- Sloughing of natural and manufactured slopes
- Settlement of foundations
- Differential movement of structures
- Ponding of water
- Cracking of the ground and water flowing from under the fill
- Other indications of potential thawing, frost action, or drainage problems

[4] *Permafrost Engineering Design and Construction*, Johnston.

Soil temperature measurements conducted at critical locations beneath a structure (load-bearing points, heating-source proximity, and building geometry) measure the performance of subgrade foundation soils. Consider an early warning detection system consisting of temperature sensors installed at various locations to provide managers and engineers advance knowledge of changing conditions that risk foundation damage as discussed in *Improving Design Methodologies and Assessment Tools for Building on Permafrost in a Warming Climate*, by Bjella et al. More importantly, identify the limiting performance tolerances for which monitoring is being performed. This includes tolerance criteria such as allowable total and differential settlement for structures, limiting stress and strain criteria during pile driving, and minimum acceptable embankment fill compaction. The intent is to identify possible approaching adverse performance conditions and prepare options for engineering mitigation.

CHAPTER 4 RISK AND RESILIENCE CONSIDERATIONS

4-1 INTRODUCTION.

Currently, there is no standard or approach for risk assessment explicitly for Arctic and Subarctic conditions. The harsh Arctic and Subarctic conditions contain inherently significant risks to engineering and construction. The risks are heightened due to natural disasters and climate change. In Arctic and Subarctic regions, resilience is an increasingly important factor in developing and maintaining infrastructure against both the intrinsically extreme environmental conditions and potential climate change impacts. Some overarching updates on risk and resilience directives are available in the following:

- *Army Climate Resilience Handbook*, by Pinson et al., provides methodology and processes to assess climate hazards and incorporate risk into existing Installation Master Plans.
- *Air Force Civil Engineer Severe Weather/Climate Hazard Screening and Risk Assessment Playbook*, by the U.S. Air Force, provides a framework for screening and assessing severe weather, climate hazards, and their associated current and future risks.

Updates to the DoD Installation adaptation and resilience planning handbook and resources on resilience planning are available in the Whole Building Design Guide website.

4-2 RISK ASSESSMENT AND DESIGN FOR RELIABILITY.

Risk assessment is an analysis of a project that identifies and quantifies specific risks according to a hazard probability of impact, while design for reliability refers to the performance of a system within a given environment for the expected life cycle and the likelihood of success or failure in the operation when the system is subjected to hazards. The fundamental guidance for risk assessment is highlighted in the following UFCs:

- UFC 1-200-02 addresses climate change risk consideration and requirements.
- UFC 2-100-01 includes potential risks associated with climate change and formulates potential solutions. Paragraph 2-2.17 has risk-related planning and climate resilience that include processes for an Installation Climate Resilience Plan (ICRP).
- UFC 3-201-01, Chapter 2, includes flood-hazard-related risks.
- UFC 3-220-01 includes geotechnical-related risks.
- UFC 3-301-01 covers risk categories of building types.

Best practices and other guidance on risk assessments used by various agencies are available and listed in Appendix A, paragraph A-21.

4-3 RISK IN THE ARCTIC AND SUBARCTIC.

The general hazards that incur risk in Arctic and Subarctic areas include, but are not limited to, changes in earthquake frequency, precipitation patterns, higher temperatures and more frequent heat waves, potential flooding, wildfires, and thawing of permafrost. Higher temperatures and more heat waves pose risks for irregular thermal thawing of landforms, creating uneven thawing of ice-rich permafrost or permafrost degradation. Other risks include an increased thawing active layer, potentially destructive collapse of slopes because of thawing of near-surface permafrost, and thaw slumping. All of these affect the ground stability and induce changes in the soil’s mechanical behavior, such as bearing capacity for the support of infrastructure, which must be evaluated and considered. Apply appropriate risk methodology by using the literature to quantify factors such as thermal stability, thaw sensitivity, and stability of the permafrost landscape, as well as other factors affecting ground instability due to climate change.

4-3.1 Methods.

4-3.1.1 Risk Methodology.

Apply appropriate risk assessment methods to identify various risk factors for design and construction in cold regions. There are two types of risk assessment methods applicable for cold regions (and see Appendix A for more details):

- Qualitative evaluation is based on experienced experts’ judgment and evaluation of on-site risks. This method is simple, subjective, and develops a risk index value.
- Quantitative evaluation typically uses methods that analyze the interactions between various factors and quantifies the degree of influence of these factors on the stability and safety of infrastructure for predicting and evaluating the risks to infrastructure.

4-3.1.2 Design for Reliability.

The traditional steps in the design for reliability theory include (1) outline performance objectives, (2) select the mathematical formulation of limit state function or define random variables affecting the limit states of the problem and their probabilistic distributions, (3) create a structural model and conduct analysis to evaluate the limit state functions, and (4) compute the probability of failure and reliability index. See Appendix A for additional information and find examples that are appropriate to use for the project.

4-3.2 Risk Factors Associated with Permafrost.

4-3.2.1 Thermal Stability.

The risk to thermal stability includes factors such as the characteristics of permafrost and its phase changes (such as annual mean ground temperature and radiation balance), the thermal disturbance caused by engineering activities and construction, and the damages due to deformation. Thermal stability analysis includes a comprehensive consideration of climate factors, surface conditions, soil conditions, topography and geomorphology, engineering disturbance, and other influencing factors.

4-3.2.2 Thermal Thaw Sensitivity.

The factors influencing the permafrost thermal thaw sensitivity include the annual mean ground temperature, the permafrost table temperature, the freezing and thawing process, the seasonal thawing depth, and characteristics of ice content in the frozen soil.

4-4 RESILIENCE.

UFC 2-100-01 provides guidance that includes processes for the ICRP. Currently, there is no guidance or approach explicitly for Arctic and Subarctic conditions for assessing the vulnerability or resilience of engineering infrastructure. However, best practices are available that are applicable to military projects in cold regions environments and are listed in Appendix A, paragraph A-22. Incorporating resilience techniques into the design and construction of facilities in the Arctic and Subarctic environment is site or Installation focused and project specific.

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APPENDIX A BEST PRACTICES

A-1 INTRODUCTION.

The Best Practices Appendix is 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 infrastructure planning, design, and construction in the Arctic and Subarctic. 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. For Best Practices guidelines not discussed in a UFC, the DoR must submit to the Government Project Manager a list of the guidelines or requirements being used for the project with documentation sufficient for review and approval prior to completing the design.

A-2 WHOLE BUILDING DESIGN GUIDE.

The Whole Building Design Guide (WBDG) provides additional information and discussion on practice and facility design, including a holistic approach to integrated design of facilities. The WBDG provides access to all Construction Criteria Base criteria, standards and codes for the DoD Military Departments, and other agencies. These standards include UFC, UFGS, Performance Technical Specifications, design manuals, and specifications. For approved government employees, it also provides access to nongovernment standards.

Installation Facilities Standards are also available on the WBDG website https://www.wbdg.org/airforce/ifs. Installation Facilities Standards provide guidance on

- Installation elements (such as streets, open and spaces),
- site develop (such as utilities, parking areas, stormwater management, sidewalks, bikeways and trails, landscaping, site furnishings, signage, and exterior lighting),
- and facilities design (both interior and exterior elements).

A-3 ENGINEERING RESOURCES.

The Colleges of Engineering at both the University of Alaska Anchorage and UAF offer fundamental courses in Arctic Engineering that address cold regions engineering problems and current solutions. These courses are approved and required by the State of Alaska Board of Registration for Architects, Engineers, and Land Surveyors. Their websites are given in Appendix C.

A-4 COLD REGIONS PUBLICATIONS.

There are several online sources for cold regions publications and databases. The ASCE Cold Regions Engineering Division, formerly the Technical Council on Cold Regions Engineering, sponsors conferences, publishes reports on the effects of cold regions environments on engineering design and on construction and operations, and publishes the *Journal of Cold Regions Engineering* (https://ascelibrary.org/journal/jcrgei). Another source of Arctic and Subarctic papers is the *Cold Regions Science and Technology* journal (https://www.journals.elsevier.com/cold-regions-science-and-technology). The Cold Regions Research and Engineering Laboratory (CRREL) library maintains an extensive collection of cold regions scientific and technical literature on the U.S. Army Engineer Research and Development Center (ERDC) Library Resources website https://www.erdc.usace.army.mil/Library/. In addition, the International Permafrost Association (IPA) disseminates from national and international members information pertinent to cold regions science and engineering. The IPA has a network of permafrost data sets and publications, including conference proceedings.

A-5 PERMAFROST AND GROUND ICE.

A-5.1 Distribution and Features.

The IPA defines Arctic and Subarctic limits in accordance with permafrost distribution and then divides these regions into classifications based on geographic continuity within the landscape (IPA website https://www.permafrost.org/what-is-permafrost/). Permafrost extent is also classified by ground-ice content (Figure 2-1 and 2-2). Data to derive these maps is available from the National Snow and Ice Data Center (NSIDC) (search for “frozen ground” at https://nsidc.org/). A permafrost map for Alaska is available from “Permafrost Characteristics of Alaska,” by Jorgenson et al.

Estimations of permafrost distribution are modeled across the northern hemisphere in “Northern Hemisphere Permafrost Map Based on TTOP Modelling for 2000–2016 at 1 km^2 Scale,” by Obu et al., and throughout Alaska in “Distribution of Near-Surface Permafrost in Alaska: Estimates of Present and Future Conditions,” by Pastick et al., and in “Permafrost of Northern Alaska,” by Kanevskiy et al. These papers discuss factors affecting permafrost existence and distribution.

A-5.2 Resources.

Several textbooks and papers discuss the different types of landforms and the cryostructures, or frozen ground structures, present in cold regions. These include *Cold Climate Landforms*, by Evans, *The Periglacial Environment*, by French, and “Permafrost of Northern Alaska,” by Kanevskiy et al.

Cold Region Structural Engineering, by Erranti and Lee, *Construction in Cold Regions: A Guide for Planners, Engineers, Contractors, and Managers*, by McFadden and

Bennett, and *Frozen in Time: Permafrost and Engineering Problems*, by Muller, discuss the associated challenges for engineering and design that ground ice presents.

A-5.3 Databases.

Archived data of permafrost conditions from the global network of permafrost observatories are available from IPA (https://www.permafrost.org/data/). The IPA website provides global and regional data sources, including active layer information and permafrost temperature and distribution.

A-6 CLIMATE DATA SOURCES.

Ground-based observation records are available from NOAA NCEI (https://www.ncei.noaa.gov/products/land-based-station). Numerous Alaska observation stations (Figure 2-3) are listed by NWS (https://www.weather.gov/aawu/stnlist).

Several global observational networks are searchable on the internet. Historical weather, climate data, and related information for numerous locations across Canada are available at Government of Canada, Historical Climate Data (https://climate.weather.gc.ca/). The Danish Cooperation for Environment in the Arctic publishes temperature and wind conditions for Arctic Sea ice and the Greenland ice sheet at the Polar Portal website http://polarportal.dk/en/greenland/. The “Frozen Ground” link at this website provides ground-temperature profiles at two southern sites, Sisimiut and Kangerlussuaq, and the colder northern site of Ilulissat.

Databases with compiled climate data exist. For example, the WorldIndex database provides global climate data and is used in the Pavement-Transportation Computer Assisted Structural Engineering (PCASE) software.[1] The climate data compiled in the WorldIndex database is obtained from NOAA through NCEI (https://www.ncei.noaa.gov/). The PCASE database includes the station name, coordinates, number of years of data used to calculate the average air temperature, number of years of data used to calculate the freezing index, yearly average temperature, and other climatic trends or information used for designing and evaluating pavements on military Installations.

A-6.1 Air Temperature.

Distributed air-temperature data sets (minimum, maximum, and mean temperature) for Alaska for the period 1981–2010 and historical 30-year normal data are available online from Parameter-Elevation Regressions on Independent Slopes Model (PRISM). These downloadable data are produced by the Spatial Climate Analysis Service, Oregon State University (https://prism.oregonstate.edu/projects/public/alaska/grids/). The current set of 30-year normal data covering the period 1991–2020 is available at “NCEI U.S. Climate Normals Quick Access” (https://www.ncei.noaa.gov/access/us-climate-normals/).

[1] “One-Dimensional Computer Models to Estimate Frost Depth,” Barna et al.

A-6.2 Ground Temperatures.

Surface temperatures are available for certain locations and are accessible through global observational networks and observation stations.[2] In Alaska, the Department of the Interior developed a permafrost monitoring network on federal lands in northern Alaska as part of the Global Terrestrial Network for Permafrost. These data sets are also from IPA (https://www.permafrost.org/data/). Simulated ground temperatures near the surface from numerical modeling are available for Alaska[3] and the northern hemisphere.[4]

A-6.3 Precipitation and Snow Distribution.

Precipitation and snowfall vary in the Arctic and Subarctic regions due to the complex interactions between the atmosphere, ocean, ice, and snow, as well as global and local processes and environmental changes.[5] There are a variety of papers focused on satellite-based characterization of snowfall in the Arctic over both land and ice surfaces such as

- "Arctic Snowfall from CloudSat Observations and Reanalyses," by Edel et al.;
- "Status of High-Latitude Precipitation Estimates from Observations and Reanalyses," by Behrangi et al.; and
- "Intercomparison of Precipitation Estimates Over the Arctic Ocean and its Peripheral Seas from Reanalyses," by Boisvert et al.

For example, "Arctic Snowfall from CloudSat Observations and Reanalyses," by Edel et al., examined the frequency and phase of precipitation as well as the snowfall rates from CloudSat (a polar orbiting satellite) over the 2007–2010 period. They indicated that the mean surface snowfall rates are particularly high on the Alaska Range (approx. 40 in. [1,000 mm] per year) and extremely high over the southeastern coast of Greenland (ranging from 80 in. [2,000 mm] to 160 in. [4,000 mm] per year).

Summaries of climatological conditions such as precipitation, snowfall, and snow depth for Alaska are also available from NOAA NCEI (https://www.ncei.noaa.gov/). NCEI also provides data sets on the "Global Precipitation Climatology Project (GPCP) Clearinghouse" website https://www.ncei.noaa.gov/products/global-precipitation-climatology-project. The GPCP data sets include monthly and daily precipitation data

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[2] "Thermal State of Permafrost in North America: A Contribution to the International Polar Year," Smith et al.

[3] "Numerical Modeling of Permafrost Dynamics in Alaska Using a High Spatial Resolution Data Set," Jafarov et al.; *Permafrost Characteristics of Alaska*, Marchenko et al.

[4] "Northern Hemisphere Permafrost Map Based on TTOP Modelling for 2000–2016 at 1 km^2 Scale," Obu et al.; "A Ground Temperature Map of the North Atlantic Permafrost Region Based on Remote Sensing and Reanalysis Data," Westermann et al.

[5] "Arctic Snowfall from CloudSat Observations and Reanalyses," Edel et al.; "Winter Northern Hemisphere Weather Patterns Remember Summer Arctic Sea-Ice Extent," Francis et al.; "Processes and Impacts of Arctic Amplification: A Research Synthesis," Serreze and Barry.

derived from surface and satellite measurements for 1979–present (1997–present for daily). Also, the NWS's National Operational Hydrologic Remote Sensing Center produces real-time snow-cover-extent maps for the U.S. and the rest of the Northern Hemisphere. The satellite observations are available on NOAA "U.S. and Northern Hemisphere Snow Cover" (https://www.nohrsc.noaa.gov/nh_snowcover/).

A-6.4 Wind and Wind Chill.

The relationship between human temperature tolerance and wind factors are found in literature such as "A New Approach to an Accurate Wind Chill Factor," by Bluestein and Zecher, and "The New Wind Chill Equivalent Temperature Chart," by Osczevski and Bluestein. A wind-chill chart and wind-chill calculator are both available online through NOAA NWS (https://www.weather.gov/safety/cold-wind-chill-chart).

A-6.5 Visibility.

Weather-related hazard warnings and advisories (such as storm, wind, and so on) are available online. For example, alerts for Alaska are available from the "NWS Forecast Office: Anchorage, AK" website https://www.weather.gov/afc/ and for Canada from the Government of Canada "Alerts" website https://weather.gc.ca/mainmenu/alert_menu_e.html. Information on blizzards is available at the NWS "What is a Ground Blizzard?" website https://www.weather.gov/safety/winter-ground-blizzard.

A-7 CLIMATE CHANGE AND PROJECTIONS.

Recurring official reports from the Intergovernmental Panel on Climate Change (IPCC) such as "Climate Change 2021: The Physical Science Basis," by Masson-Delmotte et al., and from NOAA such as *Arctic Report Card 2022*, by Druckenmiller et al., document the changing Arctic environment. The SNAP program at UAF developed climate projections and uses global climate model results from CMIP3 and CMIP5 for twentieth-century conditions and future low-, moderate-, and high-emissions scenarios out to the year 2100.[6] The SNAP future climate projections can be found at the SNAP website https://uaf-snap.org. The IPCC, NOAA reports, and related studies estimate the most likely or significant projected climate impacts affecting the design, building, and sustainability of Arctic and Subarctic infrastructure as described below:

- Projections on permafrost warming and thawing: "Impacts of Permafrost Degradation on Infrastructure," by Hjort et al., summarizes the observed circumpolar degradation of permafrost and the associated damages to infrastructure across North America and Eurasia. They concluded that nearly 70% of current infrastructure in the permafrost domain is in areas with high thaw potential of near-surface permafrost by 2050. Data related to projected permafrost temperature for Alaska is available from the Arctic Environmental and Engineering Data + Design Support System website

[6] "Downscaling of Climate Model Output for Alaskan Stakeholders," Walsh et al.

https://arcticeds.org/physiography/permafrost/ or at the SNAP website https://uaf-snap.org.

- Precipitation projections: Under the SNAP projections, Fresco et al., in *Future Projections of Precipitation for Alaska Infrastructure: Final Report,* developed future projections of the maximum precipitation (as both snow or rain) in 1-hour, 1-day, and 1-month periods, expected over return periods of 2 years to 50 years. In nearly all future model projections from 2020 to 2099, the projections are consistently towards an increasing maximum precipitation across Alaska.

- Sea ice cover: The extent of multiyear sea ice, which is older than 1 year and generally thicker and more stable for on-ice operations, has also decreased from 2.7 million square miles to only 0.6 million square miles (7.0–1.5 million km^2), and sea ice older than 4 years has nearly disappeared.[7]

A-8 PERMAFROST DEGRADATION.

Higher temperature and more heat waves pose risks for irregular thermal thawing of landforms, creating uneven subsidence and thawing of ice-rich permafrost.[8] These changes in the thermal regime produce dynamic responses to changes in soil moisture, collapse of soil structure, vegetation change, or land surface response to thawing permafrost. “Synthesis of Physical Processes of Permafrost Degradation and Geophysical and Geomechanical Properties of Permafrost,” by Liew et al., describes the physical processes of permafrost degradation and its effects on physical and mechanical properties.

A-9 VEGETATION AND WILDFIRES.

The literature such as “A Raster Version of the Circumpolar Arctic Vegetation Map (CAVM),” by Raynolds et al., “Evidence for Widespread Wildfires and Their Environmental Impact in the Late Cretaceous Canadian Arctic,” by Synnott et al., and “The Circumpolar Arctic Vegetation Map,” by Walker et al., provides more current information on vegetation.

Wildfires or forest fires affect vegetation, promote permafrost thawing, and may alter permafrost conditions over many years.[9] In the Alaskan interior, summer is typically the driest and warmest season and, as such, is prone to wildfires. Studies and research on fire-weather conditions and fire impact on vegetation and soil currently under development include “Impacts of Wildfire and Landscape Factors on Organic Soil Properties in Arctic Tussock Tundra,” by He et al., “Estimates of Temporal-Spatial Variability of Wildfire Danger Across the Pan-Arctic and Extra-Tropics,” by Justino et al., “Circumpolar Spatio-Temporal Patterns and Contributing Climatic Factors of Wildfire Activity in the Arctic Tundra from 2001 to 2015,” by Masrur et al., and “Evidence for

[7] “Sea Ice,” Meier et al.
[8] “Arctic Landscapes in Transition: Responses to Thawing Permafrost,” Rowland et al.
[9] “Divergent Shrub-Cover Responses Driven by Climate, Wildfire, and Permafrost Interactions in Arctic Tundra Ecosystems,” Chen et al.

Widespread Wildfires and Their Environmental Impact in the Late Cretaceous Canadian Arctic," by Synnott et al.

A-10 SEISMIC.

Studies and discussions on ground-motion characteristics and stress-wave velocities in frozen soils are available in the literature. Because the average response spectra vary depending on depth of permafrost,[10] local soil conditions (unfrozen soils above the frozen layer), and the interaction between distributed blocks of isolated frozen soil,[11] consider these effects on ground motion in Arctic and Subarctic areas.

Posts and archives of seismic activities worldwide are available on the USGS, Earthquake Hazards Program website. The International Federation of Digital Seismograph Networks (https://www.fdsn.org/networks/detail/DK/) provides similar global data, including Arctic regions. The UAF Alaska Earthquake Center posts earthquake activities in Alaska on their website https://earthquake.alaska.edu/earthquakes.

The National Institute of Building Sciences Building Seismic Safety Council, working for FEMA, published FEMA P-749, which provides an introduction to recommended seismic provisions for new buildings and other structures. FEMA P-749, Chapter 5, describes the seismic design category map for Alaska.

A-11 GEOSPATIAL DATA RESOURCES.

The following are some sources of geospatial data:

- "Arctic DEM Explorer" (https://livingatlas2.arcgis.com/arcticdemexplorer/) automatically produces a high-resolution, high quality DSM of the Arctic by using optical stereo imagery, high-performance computing, and open-source photogrammetry software and allows users to export a particular area of interest.
- NSIDC "Data" (https://nsidc.org/data) is a repository of geographic information systems (GIS) data on snow, ice, and frozen ground.
- Arctic Research Consortium of the United States (https://www.arcus.org/gis/maps-data/metadata) publishes geospatial data on their website.
- Find satellite and remotely sensed data at the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/), a National Aeronautics

[10] "Numerical Analysis of Permafrost Effects on the Seismic Site Response," by Yang et al.
[11] "Seismic Behavior of Buried Energy Pipelines in Northern Permafrost Regions," "Experimental and Analytical Study of Seismic Site Response of Discontinuous Permafrost," "Vulnerability of Buried Energy Pipelines Subject to Earthquake-Triggered Transverse Landslides in Permafrost Thawing Slopes," Dadfar et al.

and Space Administration (NASA)/USGS website. Products include multispectral and hyperspectral imagery for mapping land cover.

Additional sources for topographic maps are commercially available. Sources also include state or federal agencies or other topographic service agencies such as NASA Earth Observations (https://neo.gsfc.nasa.gov). DEM data sets for Alaska, including a 5 m resolution, are available online from the USGS Science Data Catalog (https://data.usgs.gov/datacatalog/data/USGS:e250fffe-ed32-4627-a3e6-9474b6dc6f0b). Other DEM data, such as for Greenland, is available from NSIDC (http://nsidc.org).

A-12 ICE ENGINEERING.

Resources for ice engineering topics are available in EM 1110-2-1612. EM 1110-2-1612 covers information and equations on the following topics:

- Ice processes and properties
- Ice control structures for both nonstructural and structural ice control
- Hydraulic computation and modeling of ice-covered rivers
- Analyses of ice-affected stages and flooding
- Ice forces on structures
- Sediment transport
- Bearing capacity of floating ice sheets, including ice blocks, short-term loads, moving loads, and long-term loads
- Model tests in ice
- Ice jams and mitigation measures
- Winter navigation on inland waterways, river ice management, river ice problem identification, ice forecasting, ice-related hydrometeorological data collection and monitoring, and ice control
- Control of icing on hydraulic structures

In “Modelling of Ice Jam Floods Under Past and Future Climates: A Review,” Rokaya et al. provide practical recommendations for modeling ice-jam floods.

The relationship between bearing capacity and ice thickness is described in EM 1110-2-1612. Arctic warming trends associated with climate change are increasing fall and winter air temperatures, causing fewer very cold days, river breakup to happen earlier, annual precipitation increase, an increase in the occurrence of freezing rain, and a shrinking snow season.[12] Milder winters have resulted in later freeze-up dates, earlier breakup dates, or both, for lakes in the northern United States and Canada.[13]

A-13 SNOWDRIFTS.

Procedures and methodology from case studies in Greenland and Antarctica for analyses of snow transport are found in

- South Pole Station Snowdrift Simulations, by Allen et al.;
- Snow Drift Management: Summit Station Greenland, by Haehnel and Bigl;
- Antarctic Camps Snow Drift Management Handbook, by Haehnel and Weatherly;
- “Blowing Snow Transport Analysis for Estimating Drift Orientation and Severity,” by Haehnel;
- “Spatial Snowdrift Modelling for an Open Natural Terrain Using a Physically Based Linear Particle Distribution Equation,” by Ohara et al.; and
- “Diagnosing Changes in Glacier Hydrology from Physical Principles Using a Hydrological Model with Snow Redistribution, Sublimation, Firnification and Energy Balance Ablation Algorithms,” by Pradhananga and Pomeroy.

Computational methods, such as two-phase computational fluid dynamics modeling of snowdrift around a building, are available to use for estimating the increased rate of drift accumulation on structures in *South Pole Station Snowdrift Simulations*, by Allen et al., and “CFD Modeling of Snowdrift Around a Building: An Overview of Models and Evaluation of a New Approach,” by Tominaga et al.

A-14 SNOW HYDROLOGY AND SNOWMELT.

An overview on the distinct aspects of Arctic hydrology, snow, and permafrost hydrology can be found in “Arctic Terrestrial Hydrology: A Synthesis of Processes, Regional Effects, and Research Challenges,” by Bring et al., “A Review of Hydrological Models Applied in the Permafrost-Dominated Arctic Region,” by Bui et al., and “Progress in Permafrost Hydrology in the New Millennium,” by Woo et al. Surface hydrology is influenced by permafrost depth (active layer), snow loading, and the potential retention of winter or late-season rain events.[14] Refer to “A Review of Hydrological Models Applied in the Permafrost-Dominated Arctic Region,” by Bui et al., for a comprehensive review and comparison of various hydrological models for limitations, suitability, and functionality.

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[12] “Alaska Terrestrial and Marine Climate Trends, 1957–2021,” Ballinger et al.
[13] “Historical Trends in Lake and River Ice Cover in the Northern Hemisphere,” Magnuson et al.
[14] “Hydrological Response of a High-Arctic Catchment to Changing Climate Over the Past 35 years: A Case Study of Bayelva Watershed, Svalbard,” Nowak and Hodson.

Snow hydrology and snowmelt with a hydrologic routing model is available at USACE Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) (https://www.hec.usace.army.mil/software/hec-hms/). The U.S. Army guidance on snowmelt estimation is found in EM 1110-2-1406.

The formation of aufies is controlled by local or regional surface topography, groundwater, climate, soil conditions, and permafrost presence and distribution.[15] Aufeis plagues infrastructure, including accumulation on road surfaces;[16] erosion of stream channels; [17] ground uplift and subsidence due to ice accumulation and thaw; and frost sorting of ground materials, leading to unstable conditions. The fundamental characteristics are available in the textbooks, and practical mitigation options to reduce icing are presented in "Denali Park Access Road Icing Problems and Mitigation Options," by Vinson and Lofgren, and "Observations of Arctic Snow and Sea Ice Cover from CALIOP Lidar Measurements," by Lu et al.

A-14.1 SWE Spatial Distribution.

Estimate the SWE spatial distribution in watersheds of interest using ground-based measurements or gridded estimates of SWE.

A-14.1.1 Ground-Based Measurements of SWE.

Ground-based measurements of SWE are typically made using a snow sampler. It is a hollow rod that is driven through the snowpack from top to bottom to extract a representative sample of snow. The filled snow sampler is then weighed to determine the SWE, Figure A-1.[18] The measurements are generally made at up to 10 separate locations along a line and averaged to account for variations in the snowpack depth and density. This is known as a snow course or snow survey. Samples are also retrieved and melted to determine SWE. In many cases, only the snow depth is measured, generally using a ruler or other measuring tool. Use the procedure in "Estimating Snow Water Equivalent Using Snow Depth Data and Climate Classes," by Sturm et al., to convert snow depth measurements to SWE if required.

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[15] "The Distribution and Dynamics of Aufeis in Permafrost Regions," Ensom et al.
[16] "Denali Park Access Road Icing Problems and Mitigation Options," Vinson and Lofgren.
[17] *Aufeis Formation in Jarvis Creek and Flood Mitigation,* Daly et al.; "Aufeis Formation and Remediation," Zufelt and Daly.
[18] *Snow-Survey Sampling Guide*, U.S. Department of Agriculture (USDA).

Figure A-1 Weighing a Snow Sample in the Field to Measure SWE

A-14.1.2 Sources of Ground-Based Measurements of SWE.

The Global Historical Climatology Network is a worldwide database of daily weather data from over 107,000 surface stations compiled by NOAA's NCEI and available at "Global Historical Climatology Network Daily" (https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily). The depth of snow on the ground is one of five core elements reported. More than 15,000 of these stations also report the water equivalent of the snow on the ground as the depth of the melted snow. The Global Historical Climatology Network includes data from four networks that provide snow information: CoCoRaHS, COOP, SNOTEL, and WBAN networks.

- CoCoRaHS—The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) (https://www.cocorahs.org/) started in 1998. The network is sponsored by NOAA and the National Science Foundation and includes locations in all 50 states. Canada locations were added in 2012. Observers use a snow ruler to measure the snow depth on the ground and record the average depth to the nearest 0.5 inch. Reporting the water equivalent of total snow on the ground is optional.
- COOP—The NWS's Cooperative Observers Program (COOP) (https://www.weather.gov/coop/Overview) records daily United States observations. Snow depths are recorded in whole inches, and the water content of the snow on the ground is reported to the nearest 0.1 in. (2.5 mm).
- SNOTEL—The USDA Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) network comprises over 865 automated sites at remote,

high elevations in the western U.S. states, including Alaska. Data is available at the National Weather and Climate Center (https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=swe). Site instrumentation includes a sonic snow depth sensor and a snow pillow instrumented with a pressure transducer. The snow depth sensor has 0.5 in. resolution. The snow water equivalent is calculated from the snow pillow measurements with a 0.1 in. resolution up to 250 in. (6.35 m) of water as a maximum limit.

- WBAN—Weather Bureau Army Navy (WBAN) network consists of over 430 stations in the U.S. and over 83 stations outside the U.S. Snow depth is reported in whole inches whenever there is more than a trace of snow on the ground. The water equivalent of snow on the ground is reported with a 0.1 in. (2.5 mm) resolution at designated stations at 1800 UTC if the average snow depth is at least 2 in. (50 mm).

A-14.1.3 Gridded Estimates of SWE.

Gridded estimates of SWE are produced using observations and models. Typically, the models ingest surface observations, satellite data, and other data sources to determine the snowpack state at each model time step. In choosing a gridded snow product, it is important to ensure that the model spatial resolution, time step, time period, and level of accuracy are appropriate for the project. Typically, gridded snow products are distributed as large digital files that require special knowledge to process. There are many gridded snow products available. Listed below are three useful gridded snow products for snow hydrology:

- SNODAS—The NWS National Operational Hydrologic Remote Sensing Center (NOHRSC) provides a near-real-time 1 km^2 spatially distributed estimate of SWE and other snow properties across the continental United States through its SNODAS (Snow Data Assimilation System) data set available from NOHRSC (https://www.nohrsc.noaa.gov/). SNODAS data cover 2003 to the present. SNODAS integrates combined downscaled forcing data, an energy balance snow model, and assimilated observations in the SNODAS daily gridded SWE product to arrive at the best estimate of the snow characteristics over the United States and to minimize error associated with any individual method.

- University of Arizona SWE—The University of Arizona developed a 4 km gridded daily SWE data set covering 1982 to 2017 for the continental U.S. as presented in *Daily 4 km Gridded SWE and Snow Depth from Assimilated In-Situ and Modeled Data Over the Conterminous U.S. Version 1*, by Broxton et al. This data set interpolates SWE and snow depth from SNOTEL, the NWS COOP network sites, and other precipitation and temperature data.

- MERRA-2—The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), is available from NASA's Global Modeling and Assimilation Office, Modern-Era Retrospective Analysis for Research

Applications, Version 2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). The MERRA-2 data set begins in 1980, offers worldwide coverage, provides estimates several times a day, and has a spatial resolution of ½° latitude by ⅝° longitude. MERRA-2 includes many parameters, including snow data.

A-14.1.4 Snow Mapping.

Snow mapping describes the process of analyzing ground-based measurements of snow, gridded snow products, satellite imagery, or other data to produce spatial distribution maps of the SWE for the watersheds of interest at the start of the snowmelt period. In general, GIS techniques are used to produce the maps. Required information includes base maps, a DEM, watershed boundaries, stream-channel layout, and land cover data. There are several considerations:

- Variation of SWE with elevation—In areas with significant elevation range, the snowpack depth is likely to increase as the elevation increases. Interpolation schemes using point measurements of SWE or other snow properties must take the relationship between elevation and snow depth into account.

- Variation of SWE with land cover—In areas with abrupt changes in land cover, such as forested "tree islands" found in prairies, snow conditions found in the tree islands are not representative of the general land cover found in the standard areas. Point measurements of SWE in these types of locations can produce erroneous results if used in interpolation schemes. (See *Wintertime Snow and Precipitation Conditions in the Willow Creek Watershed Above Ririe Dam, Idaho,* by Giovando et al., for an example.)

- Areas with no significant elevation range—It is difficult to produce accurate snow maps for large watersheds with no significant elevation range. In these areas, the snow spatial distribution is strongly influenced by wind, storm tracks, and other processes that are difficult to capture by interpolation. In these areas, gridded snow products produce better results than ground-based measurements.

- Determination of snow-covered area (SCA)—It is difficult when using an interpolation scheme to accurately estimate the spatial limits of the SCA in a watershed. In these cases, additional information provided by the MOD10A1 Cloud-Gap-Filled Snow-Covered Area (referred to as CGF-SCA) product is useful. CGF-SCA is a gridded, global, fractional SCA product based on satellite imagery that provides cloud-free daily estimates of snow-covered area.[19] It is produced daily by the NSIDC (https://nsidc.org/data/MOD10A1F/versions/61).

A-14.2 Snowmelt Modeling and Flow Routing.

As mentioned in paragraph A-14, USACE HEC-HMS (https://www.hec.usace.army.mil/software/hec-hms/) combines snowmelt models and a

[19] "MODIS Snow and Sea Ice Products," Hall et al.

variety of loss method, transform methods, baseflow estimation methods, and routing schemes to estimate snowmelt runoff. The model is GIS based and has extensive capabilities for performing many types of hydrologic analysis. A brief description of its snowmelt capabilities follows. For more information, see the HEC-HMS manuals available online.

- HEC-HMS has two spatial modes for snowmelt modeling. Snowmelt is estimated on a gridded or an elevation-band basis. The gridded approach divides the watershed into grids that are of constant size but can change to match project conditions. The snowmelt is estimated separately for each grid cell. Separate meteorological conditions driving the snowmelt are required for each grid cell. The gridded approach is appropriate for watersheds with significant elevation ranges or watersheds with significant spatial variations of weather during snowmelt events. The elevation-band approach divides the watershed into several bands, with each band covering a specific range of elevation. Snowmelt is estimated separately for each band. HEC-HMS estimates the temperature for each band based on an observed temperature at a known elevation and a known lapse rate of air temperature with elevation. The elevation-band approach is appropriate for mountainous watersheds.

- A temperature index (TI) snowmelt model is available in HEC-HMS. The TI model is empirically based and requires only air temperature to drive the basic melt calculation. The TI model is based on a linear relationship between snowmelt and air temperature.[20] This method was widely used by federal, state, and local agencies, as well as private engineering firms. For best results, it is important to calibrate the relationship between snowmelt and air temperature for each location where the model is applied.

A-15 FROZEN GROUND.

A-15.1 Engineering Properties.

Methods to quantify soil indexes are available in EM 1110-2-1906, which describes testing procedures for determining soil properties. ASTM standards and technical papers also provide additional information on frozen soil testing and properties.

Since frozen saline soils are widely distributed, particularly along the Arctic coast, the unique engineering properties of these soils must be considered.[21] Further discussion can be found in

- *Frozen Ground Engineering*, by Andersland and Ladanyi;

- "Strength Characteristics of Frozen Saline Soils," by Aksenov et al.;

[20] *Snow Hydrology*, U.S. Army, North Pacific Division.
[21] "Frozen Saline Soils of the Arctic Coast: Their Distribution and Engineering Properties," Brouchkov.

- "Long-Term Pile Load Testing System Performance in Saline and Ice-Rich Permafrost," by Biggar et al.;
- "Frozen Saline Soils of the Arctic Coast: Their Distribution and Engineering Properties," by Brouchkov;
- "Design of Vertical and Laterally Loaded Piles in Saline Permafrost," by Nixon and Neukirchner; and
- "Strength of Frozen Saline Soils," by Hivon and Sego.

A-15.2 Mechanical Properties.

Aside from ASTM standards, other common, nonstandardized frozen-soil test methods used are found in "Practice of Testing Frozen Soils," by Oestgaard and Zubeck, and in "Triaxial Testing of Frozen Soils—State of the Art," by Kornfield and Zubeck. The mechanical properties of frozen soils are available in various textbooks and literature such as *Frozen Ground Engineering*, by Andersland and Ladanyi, "Mechanical Properties of Naturally Frozen Ice-Rich Silty Soils," by Ge et al., and "Sampling, Machining and Testing of Naturally Frozen Soils," by Zubeck and Yang. Additional experimental data for soil properties for ice soils are available in literature (for example, "Sampling, Machining and Testing of Naturally Frozen Soils," by Ge et al., and "Experimental Study on Influences of Water Content and Temperature on Mechanical Properties of Ice-Rich Frozen Soil," by Huo et al.).

A-16 MODELS FOR ESTIMATION OF FREEZE AND THAW IN SOIL.

ModBerg, a one-dimensional linear model, may be used to calculate the depth of frost penetration in pavement structures or in soils.[22] Also, a method called FROST Modeler is available for estimating frost depth.[23] Both the ModBerg and FROST are available within PCASE (https://transportation.erdc.dren.mil/pcase/).

A-17 SITE SELECTION AND GEOTECHNICAL INVESTIGATIONS.

Standards and methods for site selection and geotechnical investigations are available. EM 1110-1-1804 is a guide for planning and conducting geotechnical investigations during the various stages of development for civil and military projects. EM 1110-2-1906 is for general guidance on sampling and storage of soil samples collected in the field.

For frozen soils, special care is required to maintain samples in their frozen state in the field, as well as in transit and storage. "Sampling, Machining and Testing of Naturally Frozen Soils," by Still et al., discusses maintaining samples in their frozen state and

[22] "Computer Assisted Calculations of the Depth of Frost Penetration in Pavement-Soil Structures," Cortez et al.; "One-Dimensional Computer Models to Estimate Frost Depth," Barna et al.
[23] *Pavement-Transportation Computer Assisted Structural Engineering (PCASE) Implementation of the Modified Berggren (ModBerg) Equation for Computing the Frost Penetration Depth Within Pavement Structures*, Bianchini and Gonzalez.

machining frozen samples. An introduction to geophysical exploration for engineering, geological, and environmental can be found in EM 1110-1-1802.

A-18 SNOW AND ICE ROADS.

Snow roads (compacted snow) are common in cold regions. The complex nature of snow and ice mechanics presents unique challenges to constructing snow and ice runways. In "Review of Ice and Snow Runway Pavements," White and McCallum reviewed the methodology on the design and construction for snow and ice runways. In *McMurdo Snow Roads and Transportation: Final Program Summary* and in *Snow-Road Construction and Maintenance*, Shoop et al. provide examples of standard operation procedures and guidance for constructing, maintaining, or repairing snow roads at McMurdo Station, Antarctica. Procedures for ice road construction and a winter road operations handbook are available for northern regions in *Field Handbook Version of the Winter Roads Manual*, from the Ministry of Highways and Infrastructure, and *Overview of Ice Roads in Canada: Design, Usage and Climate Change Adaptation*, by Barrette. Additionally, "Design Considerations for the Use of Ice as a Construction Platform," by Hicks and Fayek, has practical design guidance and ice-loading criteria for short-term (less than 3 minutes) and long-term loading.

A-19 EROSION CONTROL.

Erosion-control approaches are published by the U.S. Arctic Research Commission Permafrost Task Force, in *Climate Change, Permafrost, and Impacts on Civil Infrastructure*, and in

- *Responses to Coastal Erosion in Alaska in a Changing Climate: A Guide for Coastal Residents, Business and Resource Managers, Engineers, and Builders*, by Smith and Hendee;
- "Mapping Sea Ice Overflood Using Remote Sensing: Alaskan Beaufort Sea," by Dickins et al.; and
- "Riverbank Erosion in Cold Environments: Review and Outlook," by Chassiot et al.

A-20 EMBANKMENTS.

Air convection embankments (ACEs) were used successfully for road embankments in Russia[24] and in several other countries, such as the United States, Canada, and Greenland. The ACE design concept is a mitigation approach to prevent permafrost degradation under transportation infrastructure.[25] Traditional ACEs use a highly porous,

[24] Roads and Airfields in Cold Regions: A State of the Practice Report, Vinson et al.
[25] "Modeling the Performance of an Air Convection Embankment (ACE) with Thermal Berm over Ice-Rich Permafrost, Lost Chicken Creek, Alaska," Darrow and Jensen.

poorly graded granular material to construct the main portion of the embankment.[26] The design results in a passive cooling or a natural convection system in a porous embankment with sufficient air permeability. Others have used a modified ACE with ventilation pipes installed in the embankment.[27] Canada applied and assessed methods, guidelines for thermal analysis, and mitigation design techniques for thermal stabilization of embankments built on thaw-sensitive permafrost.[28] Settlement of embankments in permafrost regions are attributed to thaw settlement, creep, and freeze–thaw cycling.[29] Analysis and numerical models are viable approaches to analyze the embankment deformation for heat transfer, creep, soil compression, and thaw consolidation.[30]

A-21 RISK METHODOLOGY.

A-21.1 USACE Risk Management Center.

The USACE Risk Management Center (https://www.rmc.usace.army.mil/) provides resources on risk assessments for various civil works projects, including best practices, software and tools, hazardous substance release, human and ecological effects, and remedial action (EM 200-1-4).

A-21.2 International Organization for Standardization.

Other guidance for risk management is published by the International Organization for Standardization (ISO):

- ISO 31000, *Risk Management—Guidelines*
- ISO/IEC 31010, *Risk Management—Risk Assessment Techniques.*

[26] “Convective Cooling in Open Rock Embankments,” “Passively Cooled Railway Embankments for Use in Permafrost Areas,” Goering; “Design of Passive Permafrost Cooling System for an Interior Alaska Roadway,” Goering and Saboundjian.
[27] “Optimization in the Use of Air Convection Embankments for the Protection of Underlying Permafrost,” Jørgensen and Ingeman-Nielsen.
[28] *Thermal Stabilization of Embankments Built on Thaw-Sensitive Permafrost*, Kong and Doré.
[29] “Large-Scale Direct Shear Testing of Compacted Frozen Soil Under Freezing and Thawing Conditions,” De Guzman et al.; “Structural Stability of Highway Embankments in the Arctic Corridor,” De Guzman; “Optimization in the Use of Air Convection Embankments for the Protection of Underlying Permafrost,” Jørgensen and Ingeman-Nielsen; “In-Situ Monitoring of Settlement at Different Layers Under Embankments in Permafrost Regions on the Qinghai–Tibet Plateau,” Yu et al.
[30] “Investigation of Embankment Deformation Mechanisms in Permafrost Regions,” Ming et al.

A-21.3 Methods Used in Cold Regions.

There are two types of risk assessment methods applicable for cold regions:[31]

- Qualitative evaluation methods are simple, subjective, and develop a risk index value. An example of this can be found in "Qualitative Risk Assessment and Strategies for Infrastructure on Permafrost in the French Alps," by Duvillard et al., which discusses the risk induced by permafrost warming and thawing on the stability of infrastructure built in mountainous areas.
- Quantitative methods include finite element analysis, the analytic hierarchy process, sensitivity analysis, Monte Carlo simulation, artificial neural networks, the catastrophe progression method, and others. Use a sensitivity analysis method to derive a specific risk value for various influencing factors of engineering risks, followed by an analytic hierarchy process and comprehensive evaluation method to analyze the weight of each influencing factor.[32] Various textbooks provide guidance for using a finite element method for a comprehensive risk assessment to simulate and predict the stability and failure probability.

A-21.4 Design for Reliability.

ISO provides general standards of reliability for structures (ISO 13822 and ISO 2394). There are also various methods used for design reliability. Examples of using Monte Carlo simulations include

- "A Probability-Based Reliability Assessment Approach of Seismic Base-Isolated Bridges in Cold Regions," by Nassar et al., for evaluating bridge structures regarding earthquake response in cold regions;
- "Reliability-Based Assessment of Deteriorating Performance to Asphalt Pavement Under Freeze–Thaw Cycles in Cold Regions," by Si et al., for asphalt pavement deterioration under freeze–thaw cycles in cold regions; and
- "Quantitative Risk and Optimal Design Approaches in the Snow Avalanche Field: Review and Extensions," by Eckert et al., on optimal infrastructure design with risk frameworks for snow avalanches.

[31] "Engineering Risk Analysis in Cold Regions: State of the Art and Perspectives," Yu et al.
[32] Ibid.

A-22 RESILIENCE.

A-22.1 Assessments.

Best practices for resilience assessments can be found in the following:

- *USACE Guide to Resilience Practices* as described in EP 1100-1-5
- ASCE *Hazard-Resilient Infrastructure: Analysis and Design* (Ayyub)
- ASCE *Climate-Resilient Infrastructure: Adaptive Design and Risk Management* (Ayyub)

A-22.2 Resources.

Academic papers on general resilience concepts include

- "Practical Resilience Metrics or Planning, Design, and Decision Making," by Ayyub;
- Adapting Infrastructure and Civil Engineering Practice to a Changing Climate, by Olsen; and
- "A Novel Framework for Risk Assessment and Resilience of Critical Infrastructure Towards Climate Change," Kumar et al.,

"Resilience and Vulnerability of Permafrost to Climate Change," by Jorgenson et al., focuses on cold regions environments; "Reliability-Based Assessment of Deteriorating Performance to Asphalt Pavement Under Freeze–Thaw Cycles in Cold Regions," by Si et al., on transportation systems; and "Best Practices for HVAC, Plumbing, and Heat Supply in Arctic Climates," by Winfield et al., on utilities. Preliminary guides on thermal resilience for buildings, with general recommendations for the building envelopes and foundations, as well as best practices for HVAC, plumbing, and heat supply in Arctic conditions, are presented in *Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates,* by Zhivov, and in "Best Practices for HVAC, Plumbing, and Heat Supply in Arctic Climates," by Winfield et al. At a geological scale, in "Resilience and Vulnerability of Permafrost to Climate Change," Jorgenson et al. (2010) assessed the interdependent factors of air temperatures and ecological variables affecting the resilience or vulnerability of permafrost stability due to climate change.

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APPENDIX B GLOSSARY

B-1 INTRODUCTION.

The following acronyms and terms used in this document and are specific to cold regions engineering, design, and construction. ASTM D7099 also provides an excellent reference for these and additional terms.

Additionally, a glossary of permafrost and other terms related to ground ice are available in the Glossary of Permafrost and Related Ground-Ice Terms from IPA (https://www.permafrost.org/publication/glossary-of-permafrost-and-related-ground-ice-terms/).

B-2 ACRONYMS.

ACE	Air convection embankments
ACI	American Concrete Institute
AFCEC	Air Force Civil Engineer Center
AHJ	Authority Having Jurisdiction
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BIA	Bilateral Infrastructure Agreement
CGF	Cloud-Gap-Filled
CAC	Common Access Card
CATEX	Categorical Exclusion
CCR	Criteria Change Request
CIMP	Coupled Model Intercomparison Projects
CoCoRaHS	The Community Collaborative Rain, Hail, and Snow Network
COOP	Cooperative Observer Program
CRREL	Cold Regions Research and Engineering Laboratory

CX	Categorical Exclusion
°C	Degrees Celsius
°F	Degrees Fahrenheit
DEM	Digital elevation model
DoDI	Department of Defense Instructions
DoR	Designer of Record
DSM	Digital surface model
ERDC	Engineer Research and Development Center
EWD	Engineering Weather Data
FEMA	Federal Emergency Management Agency
ft	Feet
GHG	Greenhouse gas
GIS	Geographic information system
GPCP	Global Precipitation Climatology Project
GSOD	Global Surface Summary of Day
h	Hours
HEC-HMS	Hydrologic Engineering Center’s Hydrologic Modeling System
HQUSACE	Headquarters, U.S. Army Corps of Engineers
HNFA	Host Nation Funded Construction Agreements
IBC	International Building Code
ICRP	Installation Climate Resilience Plan
in.	Inches
$in.^2$	Square inches
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change

ISO	International Organization for Standardization
kg	Kilograms
km	Kilometers
kPa	Kilopascal
km^2	Square kilometers
lb	Pounds
m	Meters
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Ver. 2
mm	Millimeters
mph	Miles per hour
NAVFAC	Naval Facilities Engineering Command
NCEI	National Centers for Environmental Information
NEPA	National Environmental Policy Act
NFS	Non–frost susceptible
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
OCDS	Operational Climatic Data Summary
OSHA	Occupational Safety and Health Administration
PCASE	Pavement-Transportation Computer Assisted Structural Engineering
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
RCP	Representative Concentration Pathway
SCA	Snow-covered area
SLDT	Structural Load Data Tool

SNAP	Scenarios Network for Alaska and Arctic Planning
SNODAS	Snow Data Assimilation System
SNOTEL	Snowpack Telemetry
SOFA	Status of Forces Agreements
SWE	Snow water equivalent
TI	Temperature index
UFC	Unified Facilities Criteria
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UAF	University of Alaska Fairbanks
WBAN	Weather Bureau Army Navy

B-3 DEFINITION OF TERMS.

B-3.1 General.

Installation: With a capital "I," this refers to any DOD post, base, station, camp, fort, ranges or training areas.

B-3.2 Regions.

Arctic: The northern region in which the mean temperature for the warmest month is less than 50°F (10°C) and the mean annual temperature is below 32°F (0°C). In general, Arctic land areas coincide with the tundra region north of the limit of trees.

Subarctic: The region adjacent to the Arctic in which the mean temperature for the coldest month is below 32°F (0°C), the mean temperature for the warmest month is above 50°F (10°C), and there are less than four months having a mean temperature above 50°F (10°C). In general, Subarctic land areas coincide with the circumpolar belt of dominant coniferous forest.

Seasonal frost: Those areas of the earth having significant ground freezing during the winter but without development of permafrost. In seasonal frost areas, seasonal temperatures cause frost that affects earth materials and keep these frozen during only the winter; the occurrence of ground temperatures below 0°C appear only part of the year.

B-3.3 Soil and Frost Terms.

For common cold regions' soil terminology, see ASTM D7099, *Standard Terminology Relating to Frozen Soil and Rock*.

Active layer: The top layer of ground subject to annual freezing and thawing with a permafrost layer below.

Aggradation: Progressive increase in the thickness of permafrost, taking place over a period of years due to a change in climate or terrain conditions.

Annual frost zone: The top layer of ground subject to annual freezing and thawing. In Arctic and Subarctic regions where annual freezing penetrates to the permafrost table, the active layer, suprapermafrost, and the annual frost zone are identical.

Closed system: A condition in which no source of free water is available during the freezing process beyond that originally contained in the voids of soil.

Creep: Extremely slow, continuous strain deformation of materials under stress, at rates so slow as to usually be imperceptible except by observations of high precision or of extended duration.

Degradation: Progressive lowering of the permafrost table, occurring over a period of years.

Excess ice: Ice in the ground that exceeds the total volume of the pores that the ground would have under natural unfrozen conditions.

Free water: That portion of the pore water that is free to move between interconnected pores under the influence of gravity.

Freeze–thaw cycle: A freezing followed by thawing of a material over time.

Freezing (of ground): The changing of phase from water to ice in soil or rock.

Freezing front: The advancing boundary between frozen (or partially frozen) and unfrozen ground.

Freezing point: The temperature at which a pure liquid solidifies under atmospheric pressure; the temperature at which a ground material starts to freeze.

Freezing-point depression: The number of degrees by which the freezing point of an earth material is depressed below 0°C (32°F).

Freezing pressure: The positive pressure developed at ice–water interfaces in a soil as it freezes.

Frost action: A general term for the alternate freezing and thawing of moisture in materials, such as soil. It also covers the effects on these materials and on structures of which they are a part of or with which they are in contact. The term "frost" is often used to refer to frost action in general.

Frost boil: The breaking of a limited section of a highway or airfield pavement under traffic and ejection of soft, semiliquid subgrade soil. This is caused by the melting of the segregated ice formed by frost action. May also occur on unpaved ground surfaces, resulting in a small soil mound.

Frost creep: The ratchet-like downslope movement of particles because of frost heaving and subsequent ground settling on thawing. The heaving is normal to the slope and the settling more vertical.

Frost heave: The upward or outward movement of a ground surface (or objects on or in the ground) due to ice formation in the underlying soil. As the freeze front progresses downward, moisture migrates to the front, producing accelerated expansion and heaving.

Frost penetration: The movement of the freezing front into the ground during freezing.

Frost slough: A shallow slide that occurs when the stability of frost-loosened and moisture-saturated fine-grained soils on slopes is reduced during thaw.

Frost-stable ground: Soil or rock in which little or no segregated ice forms during seasonal freezing.

Frost-susceptible soil: Soil that will experience significant ice segregation when the requisite moisture and freezing conditions are present.

Frozen fringe: The zone in a freezing, frost-susceptible soil between the warmest isotherm at which ice exists in pores and the isotherm at which the warmest ice lens is growing.

Frost table: The surface, usually irregular, that represents the level, at any time in spring and summer, to which thawing of seasonal frozen ground has penetrated.

Frost thrust: A force due to frost action.

Frozen zone: A range of depth within which the soil is frozen.

Ground ice: A body of soil-free ice within frozen ground, including ice in pores, cavities, voids, or other openings in soil or rock, including massive ice; a general term referring to all types of ice in freezing and frozen ground.

Ground settlement: The downward movement of the ground, lowering the ground surface, resulting from the melting of ground ice more than that contained in pore fillings.

Hard-frozen ground: Frozen soil or rock which is firmly cemented by ice.

Heat capacity: The amount of heat required to raise the temperature of a unit mass of a substance by one degree. It is commonly expressed in Joules per kilogram per degree Kelvin.

Heterogeneously frozen soil: A soil with part of its water frozen as macroscopic ice occupying space more than the original voids in the soil.

Homogeneously frozen soil: A soil in which water is frozen within the material voids without macroscopic segregation of ice.

Ice lens: A lens-shaped body of ice ranging in thickness from hairline to 0.3 m. Ice layers more than 0.3 m in thickness are better termed massive ice beds.

Ice lenses: Lenticular formations of ice in soil occurring parallel to each other, normal to the direction of heat loss, and commonly in repeated layers.

Ice-rich permafrost: Perennially frozen ground that contains ice more than that required to fill pore spaces.

Intrusive ice: Ice formed from water intruded or injected under pressure into soils and rocks.

Ice segregation: The growth of ice within soil more than the amount produced by in-place conversion of the original void moisture to ice. Ice segregation occurs most often as distinct lenses, layers, veins, and masses, commonly, but not always, oriented normal to the direction of heat loss.

Ice wedge: A wedge-shaped ice mass, usually with its apex pointing downwards, in permafrost. Usually associated with fissures on trough-type polygons.

Ice wedge polygon: Any polygon surrounded by troughs underlain by ice wedges.

Latent heat of fusion: The amount of heat required to melt all the ice (or freeze all the pore water) in a unit mass of soil or rock.

Non-frost-susceptible materials: Cohesionless materials such as crushed rock, gravel, sand, slag, and cinders in which there is no significant ice segregation under normal freezing conditions.

Normal period: The time of the year when there is no alteration in strength of foundation materials because of frost action. In seasonal frost areas, it extends from mid- or late spring to mid- or late fall.

Open system: A condition where more free water than originally contained in the voids of the soil is available to move within the soil and to form segregated ice in frost-susceptible soil.

Percent heave: The ratio, expressed as a percentage, of the amount of heave to the depth of frozen soil.

Permafrost: Perennially frozen ground. A thermal condition in soil or rock where temperatures below 32°F persist over at least two consecutive winters and the intervening summer; moisture in the form of water and ground ice may or may not be present.

Permafrost base: The lower boundary surface of permafrost, above which temperatures are below 32°F, and below which temperatures are above 32°F.

Permafrost, continuous: Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region, except for widely scattered locations.

Permafrost, discontinuous: Permafrost occurring in some areas beneath the ground surface throughout a geographic region where other areas are free of permafrost.

Permafrost table: An irregular surface within the ground that represents the upper boundary surface of permafrost.

Residual thaw layer: A layer of thawed or unfrozen ground between the permafrost and the annual frost zone. This layer does not exist where annual frost (active layer) extends to permafrost.

Seasonally active permafrost: The uppermost layer of the permafrost that undergoes seasonal phase changes due to the lowered thawing temperature and freezing-point depression of its pore water.

Segregated ice: Ice formed by the migration of pore water to the freezing plane, where it forms into discreet lenses, layers, or seams, ranging in thickness from hairline to greater than 10 m (32 ft). The ice is formed by ice segregation.

Snowdrift: An accumulation of wind-blown snow, often much thicker than the surrounding snow cover.

Snowline: The boundary of a highland region in which snow never melts.

Snowmelt: Melting of the snow cover; the period during which the melting of the snow cover occurs at the end of winter.

Solifluction: The perceptible, slow downslope flow of saturated unfrozen soil over a base of impervious or frozen material. Movement takes place primarily when melting of segregated ice or infiltration of surface runoff concentrates excess water in the surface soil, which then behaves like a viscous fluid. Solifluction features lobes, stripes, sheets, and terraces.

Suprapermafrost: The entire layer of ground above the permafrost table.

Sporadic permafrost: A subzone of the zone of discontinuous permafrost: In North American usage, it is permafrost underlying less than 30% of the exposed land surface; in Russian usage, it is permafrost underlying from 3% to 20% of the exposed land surface.

Tangential adfreeze shear: Tangential shear between frozen ground or ice and another material to which it is bonded by freezing.

Thaw consolidation: The process by which a reduction in volume and increase in density of a soil mass occurs, following thaw, in response to the escape of water under the weight of the soil itself, an applied load, or both. Thaw consolidation may proceed for many years.

Thaw-sensitive permafrost: Perennially frozen ground that, on thawing, will experience significant thaw settlement and suffer loss of strength to a value significantly lower than that of a similar material in an unfrozen condition.

Thaw settlement: The differential downward movement of the ground surface resulting from the escape of water on melting of excess ice in the soil and the thaw consolidation of the soil mass.

Thaw slumping: A type of mass movement caused by the conversion of ice into water in a soil by ground thaw, creating the kind of landslide that most closely resembles the more temperate climate earth flow with a well-developed breakaway scarp front.

Thaw-stable frozen soils: Frozen soils that do not, on thawing, show loss of strength below normal, long-time thawed values nor produce detrimental settlement.

Thaw-unstable frozen soils: Frozen soils that show, on thawing, significant loss of strength below normal, long-time thawed values or significant settlement as a direct result of the melting of excess ice in the soil.

B-3.3.1 Temperature-related Terms.

Average annual temperature: The average of the average daily temperatures for a particular year.

Average daily temperature: The average of the maximum and minimum temperatures for one day or the average of several temperature readings taken at equal time intervals for one day, hourly.

Average monthly temperature: The average of the average daily temperatures for a particular month.

Breakup period: The period of the spring thaw during which the ground surface is excessively wet and soft and ice is disappearing from streams and lakes. Duration of the breakup period usually varies usually from 1 to 6 weeks, depending on regions or local climatic conditions.

Degree-days: The degree-days for any one day equal the difference between the average daily air temperature and 32°F. The degree-days are negative when the average daily temperature is below 32°F (freezing degree-days) and positive when above 32°F (thawing degree-days). Degree-days may be computed in either Fahrenheit or Celsius units; this manual uses Fahrenheit degree-days.

Design freezing index: For design of permanent pavements, the design freezing index is the average air freezing index of the three coldest winters in the latest 30 years of record. If 30 years of record are not available, substitute the air freezing index for the coldest winter in a 10-year period. For design of foundations for average permanent structures, compute the design freezing index for the coldest winter in 30 years of record, or estimate to correspond with this frequency if the number of years of record is limited. Use the latest available periods of record. To avoid the necessity for adopting a new and only slightly different freezing index each year, the design index at a site with continuing construction need not change more than once in five years, unless the more recent temperature records indicate a significant change.

Design thawing index: The design thawing index is computed on the same frequency and basis as the design freezing index, except that summer thaw conditions are used.

Freeze-up period: The period during which the ground surface freezes and an ice cover is forming on streams and lakes. The duration of the freeze-up period varies from 1 to 3 months, depending on regional or local climatic conditions.

Freezing index: The number of degree-days between the highest and lowest points on a curve of cumulative degree-days versus time for one freezing season. It is a measure of the combined duration and magnitude of below-freezing temperatures occurring during any given freezing season. The index determined for air temperatures at approximately 4.5 ft above the ground surface is commonly designated as the air freezing index, while that determined for temperatures at, or immediately below, the ground surface is known as the surface freezing index.

Freezing season: That period during which the average daily temperature is below 32°F.

Frost-melting period: An interval of the year during which ice in the ground is returning to a liquid state. It ends when all the ice in the ground melts or when freezing starts again. Although in the generalized case there is only one frost-melting period, beginning during the general rise of the air temperatures in the spring, one or more significant frost-melting intervals may take place during a winter season.

Geothermal gradient: The temperature gradient in the ground below the zone of annual temperature fluctuations, produced by the continuous flow of heat from the Earth's hot interior toward the Earth's cool surface.

Mean annual temperature: The average value taken from several years of annual temperature averages.

Mean daily temperatures: The average taken from the averages of the daily temperatures for a given day for several years.

Mean freezing index: The freezing index determined from mean temperatures.

Mean monthly temperature: The average taken from the averages of the monthly temperatures for a given month for several years.

Mean thawing index: The thawing index determined from mean temperatures.

Period of weakening: An interval of the year that starts at the beginning of the frost-melting period and ends when the subgrade strength has returned to normal-period values or when freezing starts again. In seasonal frost areas, the period of weakening may be longer than the frost-melting period; but in permafrost areas, the periods coincide.

Strudel scour: An Arctic phenomenon that occurs every spring when the fresh-water rivers melt and form off-river deltas when river discharge drains through holes in the sea ice cover. Strudel scours constitute a major design consideration for subsea pipelines or other structures near rivers.

Thawing index: The number of degree-days between the lowest and highest points on a curve of cumulative degree-days versus time for one thawing season. It is a measure of the combined duration and magnitude of above-freezing temperatures during any given thawing season. The index determined for air temperatures at 4.5 ft above the ground is commonly designated as the air thawing index, while the temperature at or immediately below the ground surface is known as the surface thawing index.

Thermal regime: The pattern of temperature variations found in the ground with time and at a certain depth from the surface.

Thermal erosion: The erosion of ice-rich permafrost by the combined thermal and mechanical action of moving water or air (sublimation).

Thermal expansion (or contraction) coefficient: The volume change per unit volume of a substance due to a one-degree change in its temperature.

Thermal pile(s): Structural piling modified to passively remove heat from the ground whenever the ambient air temperature is lower than the ground temperature.

Total annual freezing index: The cumulative number of degree-days, calculated by adding all the negative mean daily air temperatures (in degrees Celsius) for a specific station during a calendar year.

Total annual thawing index: The cumulative number of degree-days, calculated by adding all the positive mean daily air temperatures (in degrees Celsius) for a specific station during a calendar year.

Wind chill: The excess rate of removal of body heat from exposed skin by moving air compared to still air at low temperatures. It is often expressed as a lower equivalent air temperature that is a function of actual air temperature and wind speed.

B-3.4 Terrain Terms.

Frost mound: A localized mound-shape on the land surface caused by frost action with or without hydrostatic pressure.

Icing: A surface ice mass formed by freezing of successive sheets of water from seepage, flow from a spring, or emergence from below river or lake ice through fractures.

Muskeg: Poorly drained organic terrain consisting of a mat of living vegetation overlying an extremely compressible mixture of partially decomposed peat, varying in thickness from a few inches to many feet.

Patterned ground: A general term describing ground patterns that result from frost action, such as polygons, circles and nets, stripes, and solifluction features.

Pingo (hydrolaccolith): A large ice-cored frost mound, often 100 ft high or more, consisting of a core of massive ice, produced primarily by injection of water and covered with soil and vegetation.

Strudel scour: A localized, seasonal scour formation that occurs in the spring when melting fresh water in rivers and streams flows over the surface and drains through holes of frozen shore-fast ice.

Thermokarst: The irregular topography resulting from differential thaw settlement or caving of the ground because of excess ice melting in thaw-unstable permafrost; the process by which characteristic landforms result from the thawing of ice-rich permafrost.

Tundra: Treeless terrain of grasses and shrubs characteristic of the Arctic, found at both high latitudes and high altitudes.

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APPENDIX C SUPPLEMENTAL RESOURCES

The following references are reliable sources for information related to infrastructure planning, design, and construction in the Arctic and Subarctic. 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.

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