ROADS AND AIRFIELDS CONSTRUCTED ON PERMAFROST

A Synthesis of Practice

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16. Abstract

This synthesis provides the practicing engineer with the basic knowledge required to build roadways and airports over permafrost terrain. Topics covered include an overview of permafrost, geotechnical investigations, slope stability, impacts of climate, and adaptation strategies during the design, construction and maintenance phases. The purpose of the synthesis is not to provide a comprehensive body of knowledge or to provide a complete how-to manual. Rather, the synthesis provides a working knowledge for those working in permafrost regions such that the practicing engineer will be able to work with subject matter experts to obtain the desired project outcomes.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

TABLE OF FIGURES

TABLES

List of Abbreviations

ACCAP	Alaska Center for Climate Assessment and Policy
ACE	Air convection embankments
ACIS	Applied Climate Information System
ACRC	Alaska Climate Research Center
ADNR	Alaska Department of Natural Resources
AKDOT&PF	Alaska Department of Transportation and Public Facilities
APDES	Alaska Pollutant Discharge Elimination System
API	application programming interface
Arctic-EDS	Arctic Environmental and Engineering Data and Design Support System
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
BMP	Best management practice
CCR	Capacitive coupled resistivity
CGP	Construction general permit
DEC	Alaska Department of Environmental Conservation
DGGS	Alaska Division of Geological and Geophysical Surveys
DEM	Digital elevation model
ECS	Erosion control soil
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
EPS	Expanded polystyrene foam insulation
ERT	Electrical resistivity tomography
GCM	Global circulation model
GPR	Ground penetrating radar
GPS	Global positioning system
MAAT	Mean annual air temperature
MADIS	Meteorological Assimilation Data Ingest System
MAGT	Mean annual ground temperature
MAST	Mean annual surface temperature
MS4	Municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
NWS Alaska	National Weather Service Alaska
OHW	Ordinary high water
PDO	Pacific Decadal Oscillation
RCM	Regional climate model
RCP	Representative concentration pathway
SNAP	Scenario Network for Alaska and Arctic Planning
SST	Sea surface temperature
SWPPP	Storm Water Pollution Prevention Plan
TAPS	Trans-Alaskan Pipeline
TTOP	Temperature at the top of permafrost
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UAF	University of Alaska Fairbanks
XPS	Extruded polystyrene foam insulation

Acknowledgments

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Preface

It is important to understand that this synthesis of practice is not intended to be a manual or guideline, primarily because current knowledge does not lend itself to a manual or guideline. Instead, this synthesis is intended to provide those working in permafrost regions a working knowledge of permafrost, and geotechnical exploration in permafrost regions, and a basic knowledge of our changing climate and how that affects the integrity of the permafrost. The synthesis provides a summary of existing techniques for building roadways and airports on permafrost, including what has and has not worked. Because of the nature of permafrost, none of the techniques provided here can be universally applied. Instead, the engineer must adapt to the conditions, budget, and public pressures in finding the best fit solution.

Abstract

This synthesis provides the practicing engineer with the basic knowledge required to build roadways andairports over permafrost terrain. Topics covered include an overview of permafrost, geotechnical investigations, slope stability, impacts of climate, and adaptation strategies during the design, construction, and maintenance phases. The purpose of the synthesis is not to provide a comprehensive body of knowledge or to provide a complete how-to manual. Rather the synthesis provides a working knowledge for those working in permafrost regions such that the practicing engineer will be able to work with subject matter experts to obtain the desired project outcomes.

1. INTRODUCTION

1.1 Objectives of this Guide

This synthesis covers over 100 years of experience and research related to the planning, design, construction, and maintenance of roadways and airports built in permafrost terrain. The information presented here is based on the experience of the authors, published and unpublished papers, and common practices used in global permafrost regions.

This is not to suggest that the synthesis represents guidelines, design standards, or building codes. Rather, it is intended to provide practitioners with a summary of practices, including those that may be debated. Discussions of successes, limitations, and pitfalls of practices are provided so that the practitioner can judge whether a practice may be appropriate.

Because designs for permafrost are evolving, detailed procedures are not provided. Instead, Alaska Department of Transportation and Public Facilities (DOT&PF) relies on subject matter experts. Practitioners are provided with a series of discussions intended to help avoid past failures while taking advantage of the knowledge gained through experience and research.

The sources of information used for this synthesis are provided by chapter. Readers are invited to review these sources for additional information.

1.2 An Alaskan Historical Perspective

Alaskans have been building roads and trails over permafrost since the 1890s. Those pioneers quicklyrealized that even minor disturbances of the terrain could have major impacts on the stability of the permafrost. In 1895 Chester W. Purington noted:

> "A serious detriment to the making of a road in Alaska is the thawing of the ground beneath themoss. It has been the universal experience that whenever the moss is cut into, thawing immediately commences, and the trail which was passable becomes a filthy, slimy mass of mud, roots, and broken stone…" (Judge-Advocate General to the Secretary of War, June 15, 1905, RG94, n.d.)

Purington suggested that the moss be left intact in sections with poor drainage and that the surface be corduroyed with heavy brush or poles on top of which a covering of gravel be laid sufficient to provide necessary insulation.

The same lessons were again learned during the construction of the Alaska Canadian Highway where the pioneer road was constructed using conventional construction technologies.

Against the warnings of Purington and Richardson, the vegetation was stripped from the permafrost. Much of the route was constructed during the winter months, allowing muskeg to be crossed simply because no clearing was required. As the snow melted, so did the muskeg and permafrost, which resulted in much of the route becoming impassable (8igure 1-1). Much of the roadway was rerouted as the pioneer road became permanent.

Figure 1-1 Thawing permafrost during the construction of the Alaska-Canadian Highway (Coates 1982).

In 1950 the Alaska Road Commission formally adopted its philosophy for building on permafrost (Naske, 1983):

- Avoid permafrost when possible, locating on south slopes whenever possible.
- Avoid wet side hills or slopes with seeping water.
- Avoid disturbing moss. When the moss is removed, permafrost melts creating an impassible mire. Place material over undisturbed moss carefully. Even location parties are required to walk.
- Use corduroy over soft areas.

- In cut sections, employ staged construction using a thaw and cut technique, backfilling with porous granular gravel.

While equipment slowly improved, little changed until the construction of the Trans-Alaskan Pipeline (TAPS). TAPS brought a new interest in the application of new technologies to construction over permafrost. Geologists and scientists joined the engineering community in understanding the formation of permafrost, its properties (both frozen and thawing) and surficial manifestations of permafrost. This resulted in a renaissance of permafrost knowledge that continues today.

It was during and shortly after the construction of the TAPS that many of the techniques for building embankments in permafrost terrain were developed. While some of those appear outlandish today, they provided the foundation upon which current designs were developed. Many of these found their way to China, Russia, and other polar regions. For example, the air ducts, thermosyphons, and air convection embankments developed by and for DOT&PF were used extensively to construct the Tibetan Railroad in China (Cheng, 2003).

In the 1980s the recognition of changing climate resulted in a concern for the impact of thawing permafrost, especially in discontinuous permafrost regions. As concern for climate change increases and the demonstrated impact on arctic regions becomes more apparent, engineers are faced with how to adapt. While the fundamentals remain, the environment for which engineers must design is changing. It is therefore critical that everyone associated with the design, construction, and maintenance of roadways and airports understand how their actions, combined with our changing climate, impact the underlying permafrost in the near-term and well into the future.

More recently, the National Science Foundation has and continues to fund studies that focus on the changing arctic and the impact of warming permafrost on infrastructure, the economy, and the lifestyle of those living in the north. The knowledge produced by these studies provides insight into the impacts of these changes on infrastructure.

While research has indicated that the impact of the infrastructure itself on the permafrost is much more rapid than climatic changes, these impacts have been largely ignored by the scientific and political community and to a degree by the engineering community. Infrastructure often causes an immediate impact, whereas climate results in a longer-term impact. Consequently, the engineer must recognize and adapt to both. Unfortunately, it is difficult to separate the two in practice.

An understanding of the history of embankments used in permafrost regions provides the practitioner with wisdom that can only come from the success and failures of those who have preceded them. That said, it is equally important for the engineer to account for anticipated changes moving forward.

1.3 Overview of Impacts of Permafrost on the Design, Construction, and Maintenance of Embankments

Permafrost is defined as soil or rock that is below 0°C (32°F) for two or more years. By this definition, permafrost can range from frozen, ice-rich silts to frozen bedrock. However, note that by this definition, not all the water in the soil is necessarily frozen. As such, the simple definition is not particularly useful to the engineer. To refine the definition, two descriptors of permafrost were developed by the engineering community:

- Ice-rich, thaw unstable permafrost: Frozen soil that contains enough ice to be unstable when melted.
- Ice-poor, thaw stable permafrost: Frozen soil with little ice that shows little change when thawed.

However, the scientific community defines permafrost by how it was formed:

- Syngenetic: Permafrost formed in concert with the deposition of soil layers over time.
- Epigenetic: Permafrost formed by freezing the soil column from the top down.
- Yedoma: Syngenetic permafrost that is mostly ice.

These will be described in more detail in Chapter 2. For now, recognize the relationship between the engineering and scientific definitions of permafrost.

The occurrence of permafrost or the likelihood of permafrost being found is broken down into four regions, which will be discussed in more detail in Chapter 2:

- Isolated
- Sporadic: Permafrost exists in isolated locations.
- Discontinuous: Permafrost occurs frequently, especially on north facing slopes, lowlands, and heavily forested areas.
- Continuous: Permafrost occurs throughout.

Even a basic understanding of the formation and distribution of permafrost and the resulting properties helps the designer understand how permafrost influences the design and performance of embankments over permafrost. Chapter 2 provides insight into the properties of each type of permafrost throughout the three permafrost regions and their distributions across Alaska.

Permafrost found in areas of sporadic permafrost and discontinuous permafrost are generally warm permafrost, i.e., the soil temperatures are slightly below freezing. In these areas, even small increases intemperatures will result in thawing (figure 1-2). Consequently, decisions to employ designs that keep the permafrost frozen should be made carefully. Couple warm permafrost with ice-rich permafrost, and the likelihood of severe damage to the embankment increases. In this case, expect large thaw consolidation, longitudinal cracking, and severe distortion of the surface. While techniques exist that temper these impacts, the designer will be faced with economic decisions concerning when or if to employ available options. Available options are discussed in Chapter 5.

Figure 1-2 Thawing permafrost slopes along the Dalton Highway (photo by DOT&PF)

1.4 The Importance of Using the Right Design to Manage the Impacts of Thawing Permafrost

Dr. Eb Rice (University of Alaska) often stated that there are but four options when constructinginfrastructure over permafrost (Rice, 1975):

- Keep it frozen
- Thaw it
- Remove and replace
- Accept the consequences of thaw beneath the structure.

The engineer must decide which of these make the most sense technically, economically, and in some cases, politically. For example, it often makes little sense to attempt to remove and replace permafrost tens of feet thick, even though it is ice-rich, warm permafrost. Nor does it make sense to attempt to keep warm, ice-rich permafrost a few feet thick frozen. In the first case, accepting the consequences of thawing may be appropriate. In the second case, removing and replacing or pre-thawing the permafrost may be desirable choices.

Only by understanding the permafrost, including both its frozen and thawed properties, and how the design alternatives perform, can the designer select the most appropriate design. There are no standards available. However, this synthesis does provide best practices and suggestions,

1.5 Learning to Think about the Long-Term Impacts of a Design

While the pavement is typically designed for about 15 years, the embankment and its alignment can beexpected to last much longer. Because the overall alignment is unlikely to change, think about the embankment performance over the next 50 or more years.

The temperature regime under the roadway may take decades to reach equilibrium. The changing climate, including changes in temperature and precipitation, may preclude that equilibrium from being reached for the foreseeable future. Figure 1-3 shows an abandoned section of the Richardson Highway near Fairbanks, which had been in place for about 50 years. The roadway still showed signs of settlement due to thawing ice wedges.

Because the climate and its impact on the permafrost is not anticipated to be static, the designer is encouraged to consider the dynamic future in the design of the embankment, especially over permafrost. Chapter 10 provides insight into our future climate. While the predictions are not as precise as we would like, the trends are clear. Used properly, these trends provide general guidance for roadway and airport designers.

Figure 1-3 Roadway damage on an abandoned section of the Richardson Highway east of Fairbanks (photo B. Connor)

1.6 Recognizing When Additional Expertise Is Required

Designers are not expected to know everything about designing roadways and airport embankments over permafrost. Nor does this synthesis provide detailed design procedures. Rather, designers should recognize their personal limitations and seek the help of those trained in the areas of expertise required.These include geotechnical expertise, thermal modeling, climate forecasting, permafrost science and materials testing, and terrain mapping. In many cases multiple subject matter experts may be required. An understanding of the concepts contained in this synthesis aids in asking the right questions and employing the right areas of expertise.

1.7 Knowing What Data May Be Required and How to Use Them

Every design requires data. The more complex the design, the greater the requirement. However, the cost of obtaining and analyzing those data must be managed. Consequently, designers must understand the consequences of the questions they pose and the benefits to the project in obtaining answers to those questions.

The key is to know what information is required to achieve the desired outcome. That defines the data required. There is a big difference in the data required to answer the question of how thick the active layer is and how deep the permafrost will thaw over the next 20 or more years. The thickness of the active layer can be estimated by using the thawing index, soil moisture content, and an n-factor. However, the thaw depth of permafrost over time requires an estimate of daily or weekly air temperatures over the next 20 or more years, soil layer properties including soil type and density, soil moisture profiles as they vary throughout the year, a surface energy balance (or seasonal n-value), and the potential for flowing water. The thickness of the active layer can generally be estimated by the designer, whereas the second question requires someone skilled in thermal modeling.

While some data such as climate data are available through web-based services, care must be taken to ensure the data are of sufficient quality and resolution to be useful. Do not hesitate to work with climatologists to assure the data are adequate or whether improved data may be developed within the scope and budget of the project. More importantly, ask whether more accurate data will improve the design and performance of the project.

1.7.1 Geotechnical Data

Data may be collected by employing several techniques with varying costs. For example, a person skilled in the use of aerial or satellite photo interpretation can glean considerable information concerning the potential for ice-rich permafrost and the spacing of ice wedges by using publicly available geological maps, photos, and satellite imagery. These data, in conjunction with permafrost maps, many of which are contained in this synthesis, provide a wealth of information about the terrain along the project. While ground truthing will be required, this information can provide considerable insight concerning the level of detail required and the appropriate analysis methodology.

As the level of detail increases, so does the cost of the data. The cost of the area information discussed above is quite inexpensive and can be had for the labor cost of a skilled interpreter. Geophysical data such as ground penetrating radar or resistivity methods are more expensive, but often less expensive than drilling. Geophysical methods are particularly good at providing information concerning the uniformity, or lack thereof, of the soil layers, but they generally do not provide detail on the soil properties. That requires drilling. However, if geophysical methods are used to guide more expensive drilling activities, the cost of drilling can be effectively managed.

Only by working with geotechnical engineers, geological engineers, and geologists can an appropriate geotechnical investigation program be developed. It is critical that clear objectives be established early in the process to guide the investigation.

A detailed discussion of geotechnical data is covered in Chapter 3.

1.7.2 Climate Data

Climate data are becoming increasingly important in assessing the long-term performance of the roadway over permafrost. As air temperature and precipitation changes, so does the potential for permafrost thawing. While improving, the scaling and reliability of climate predictions are not absolute, making it critical that the designer understand the variability in the climate models and the consequences of that variability.

Chapter 10 provides an excellent discussion of climate change, including what data are available and the limitations of those data. Because climate data models are constantly evolving, information in that chapter is also evolving. To ensure designers have current information, links to current resources and how to use them are provided in Chapter 10.

1.8 Ensuring Everyone in Design, Construction and Maintenance Understands the Long-Term Strategy Employed

Everyone working on roadways underlain by permafrost must understand the basic concepts of the long-term strategy employed on that section of roadway. Consequently, the more uniformity in the application of overall strategies, the more likely those strategies will be preserved through the construction and maintenance phases. Just as the Alaska Road Commission clearly articulated its philosophy for roadway construction over permafrost, it is important that the roadway and airport design community clearly articulate their overall design philosophy to everyone who works within the rights of way.

For example, a designer may choose to minimize rights of way clearing to reduce thawing of the permafrost outside the roadway prism. If this is not clearly conveyed to construction and maintenance personnel, they may clear to the rights of way limits, negating the designer’s intent. The resulting thermokarsts may alter drainage patterns, causing damage to the embankment that could have been avoided.

However, the design must account for the ability of maintenance personnel to preserve the design. A good example is the employment of widened roadways with 6 percent slopes outside the shoulders (often called the barn roof design). Research proved that the design improves the performance of the travelled way. Unfortunately, lack of funding precluded maintenance personnel from plowing the extended width, rendering the design ineffective.

Stories such as this are more common than one would think. Communication is key to ensuring that the long-term strategy employed is successful. However, that communication must occur in both directions. It is critical that all interested parties are heard before any strategy is employed.

1.9 References

Cheng, 2003

Coates, Ken, 1982, North to Alaska, University of Alaska Press, ISbn 0-912006-55-2, University of Alaska Fairbanks, Fairbanks Alaska

Judge-Advocate General to the Secretary of War, June 15,1905, RG 94, n.d. Records of the Adjunctant General's Office, 1780's to 1917, AGO Doc.File, Various Files pertaining to Alaksa, N.A., s.l.: s.n.

Naske, C. M., June 1983. Alaska Road Commission Historical Narrative, Fairbanks, Alaska: Alaksa Department of Transportation and Public Facilities.

Rice, E., 1975. Arctic Engineering Lecture Notes [Interview] 1975.

2 DESCRIPTION OF PERMAFROST

2.1 Overview

The literature related to permafrost is far too extensive to cover in this chapter. For those wishing a more detailed description of permafrost characteristics related to roadway and airport design, refer to the companion publication *A Permafrost Primer for Highway and Airport Engineers.*

For the sake of brevity, this chapter discusses the conditions under which permafrost may form, the distribution of permafrost, and how permafrost terrain may be recognized. As discussed in Chapter 1, for engineering purposes it is important to know the ice content, the grain size distribution, and the temperature of the soil to gain insight into the impact of the permafrost on the infrastructure should it thaw.

The maps provided along with the descriptions of the distribution of permafrost, anticipated ice content, and temperatures should aid the designer in deciding the likelihood of encountering permafrost, the likelihood and consequences of thaw, and which mitigation techniques may be the most effective.

The information provided here is intended to allow the designer to engage in meaningful discussion with geologists, geological engineers, geotechnical engineers, and permafrost scientists.

2.1.1 Permafrost Occurrence and Thermal Regime

Permafrost is defined as ground (soil or rock, including ice and organic material) that remains at or below 0°C for at least two consecutive years (van Everdingen, 1998). According to this definition, permafrost may or may not contain ground ice. Permafrost regions occupy almost 25 percent of global land area, including about one half of Canada and almost two thirds of Russia. Permafrost also occurs in China, the USA (mostly Alaska), Mongolia, Greenland, Antarctica, and at high elevations in many mountain regions in Eurasia, Africa, and South America (Shur et al., 2011) (figure 2-1).

Permafrost forms when the mean annual surface temperature is perennially below 0 °C; the thermal regime of the ground at various locations is often assessed by using the mean annual ground temperature (MAGT) at the depth of zero annual amplitude (van Everdingen, 1998). The *active layer*—an upper layerof ground that seasonally thaws and freezes—separates the permafrost from the surface. The upper boundary of permafrost is called the *permafrost table*. The thickness of permafrost may range from less than 1 m to more than 1,000 m (van Everdingen, 1998). The typical temperature-depth relationship in permafrost regions is shown in figure 2-2.

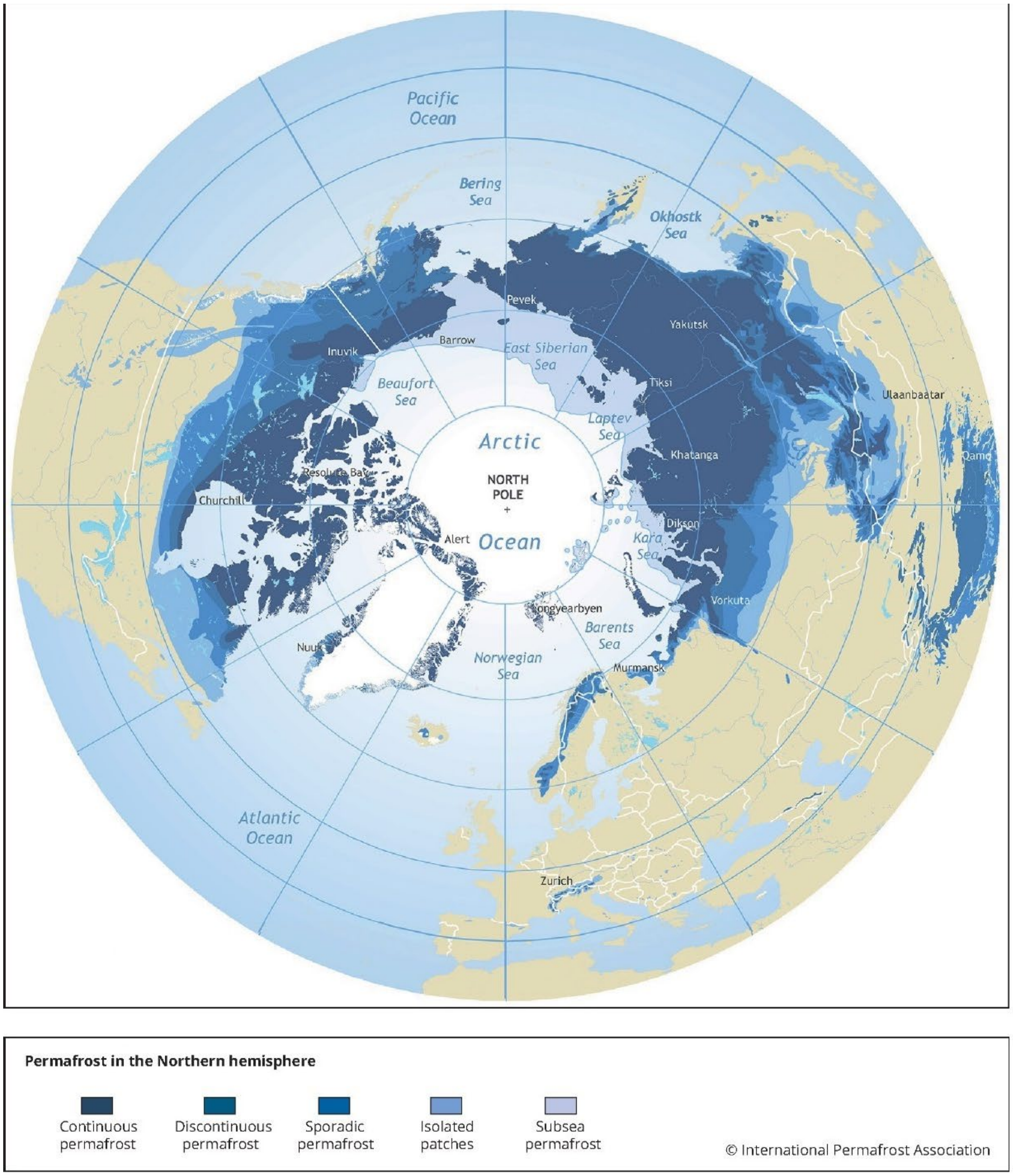


Figure 2-1 Permafrost occurrence in the Northern hemisphere, International Permafrost Association Permafrost Map (https://ipa.arcticportal.org/products/gtn-p/ipa-permafrost-map, based upon Brown etal., 1997).

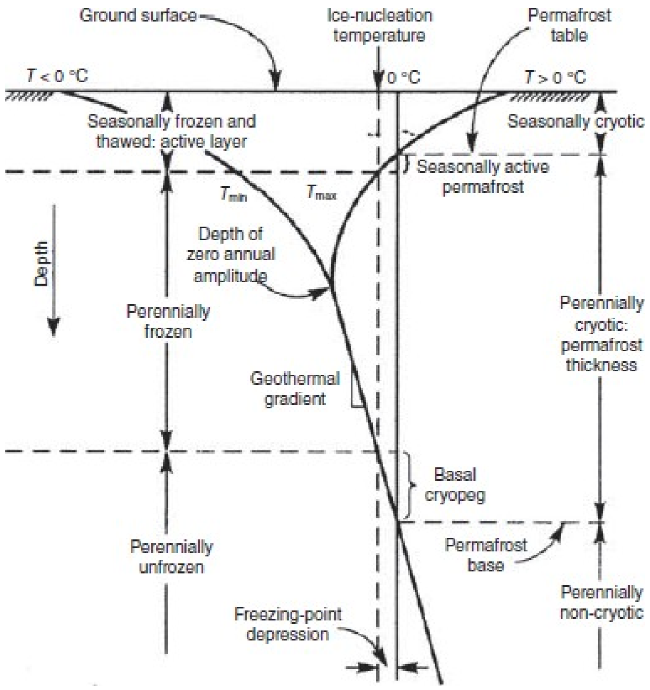


Figure 2-2 Typical ground-thermal regime indicating maximum and minimum temperatures, the decrease in temperature with depth, the geothermal gradient, the depth of zero annual amplitude, andthe depth of seasonal thaw (French, 2018).

There is a strong correlation between the permafrost temperature and mean annual air temperature (MAAT). However, permafrost temperatures also strongly depend on various climatic and environmental factors, including snow cover, vegetation, types of soils, and moisture contents in theactive layer. The climate-permafrost relationship can be represented schematically by the mean annual temperature regimes at three levels (Smith and Riseborough, 2002) (figure 2-3):

1. The air temperature, measured at standard height above seasonal snow cover (MAAT);
2. The temperature at the ground surface (MAGST);
3. The temperature at the top of permafrost (TTOP).

The difference between the MAAT and MAGST is created by the surface offset, which includes the cooling effect of vegetation in summer (vegetation offset) and the insulating effect of snow cover in winter (nival offset). Usually, the nival offset is much stronger than the vegetation offset. As a result, the MAGST at the depth of zero annual amplitude, which commonly varies between 10 and 20 m, is typically several degrees warmer than the MAAT. There is also a significant difference between the MAGST and TTOP, which is determined by the thermal offset caused by difference in thermal conductivity of soils (especially organic-rich) in frozen and unfrozen states (Kudryavtsev, 1959; Burn and Smith, 1988; Osterkamp and Romanovsky, 1999; Smith and Riseborough, 2002). As a result, the MAGST may be several degrees less than the TTOP and MAGT at the depth of zero annual amplitude if the active layer is composed of peat; under certain conditions, permafrost may be relatively stable even if the MAGST is above 0°C.

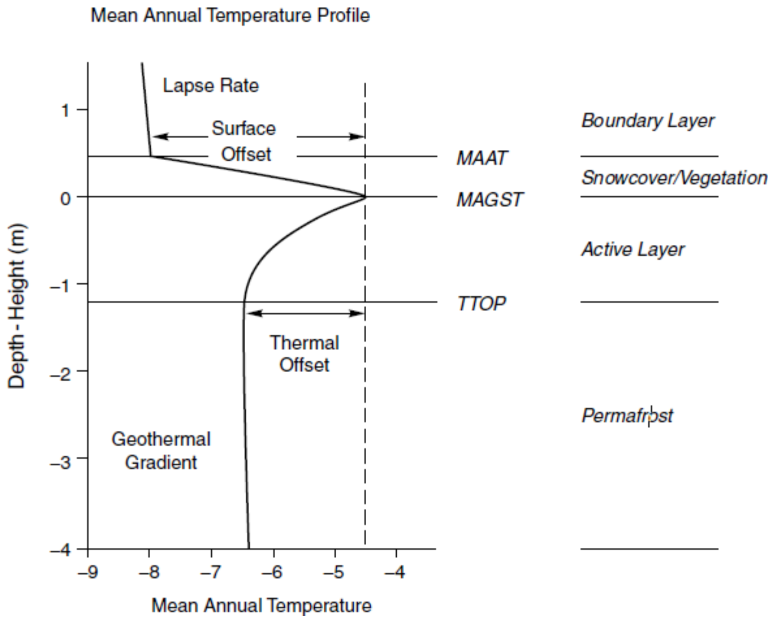


Figure 2-3 Schematic of mean annual temperature profile through the surface boundary layer, showing the relationship between air temperature and permafrost temperature (Smith and Riseborough, 2002).

Permafrost occurrence differs significantly within the permafrost region. The circumarctic map of permafrost and ground ice conditions (Brown et al., 1997) divides the permafrost region into four *permafrost zones* based on the percentage of the area underlain by permafrost (figure 2-4):

1. Continuous,
2. Discontinuous,

3. Sporadic, and
4. Isolated patches of permafrost.

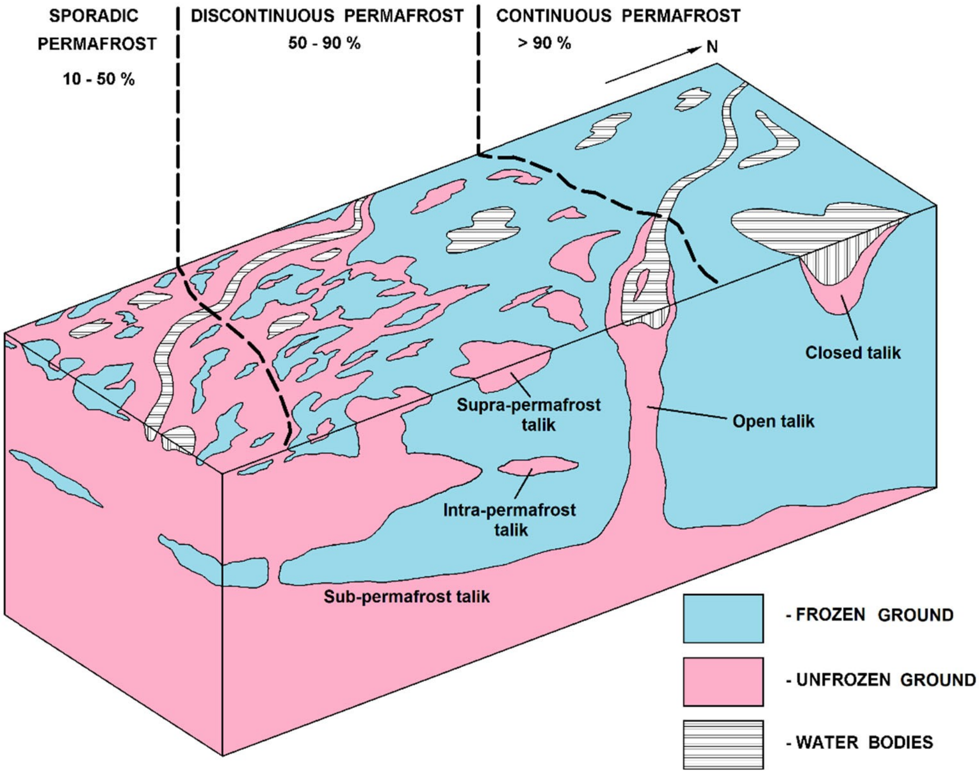


Figure 2-4 Typical permafrost distribution in continuous, discontinuous, and sporadic permafrost zones(modified from Shur et al., 2011).

In the *continuous permafrost zone*, permafrost occupies 90 to 100 percent of the entire area, with closed taliks (layers or bodies of unfrozen ground) developed under big water bodies (deep lakes and rivers) (figure 2-4). Continuous permafrost depends entirely on climate, and the impact of local conditions on permafrost distribution is minimal. In this zone, permafrost exists everywhere beneath the land surfaceand under shallow water (except taliks beneath large water bodies), and it takes only one year to start permafrost formation after soil is newly exposed (e.g., in drained lake basins). Impacts on the soil surface from disturbance, such as fire and development, increase the thickness of the active layer and trigger thawing of ground ice in the upper permafrost, but do not lead to degradation of continuous permafrost. Permafrost temperature in this zone varies widely (MAGTs usually vary from -2 to -10 °C) and greatly depends on snow thickness and water depth. The permafrost table usually merges with the bottom of the active layer; the lowered permafrost table commonly occurs beneath lakes and rivers, and sometimes in areas with a very thick snow cover. During the last several decades, a significant increase in MAGTs has been recorded almost everywhere in the permafrost region (Romanovsky et al., 2017), but in the areas with cold continuous permafrost this warming effect has been the greatest and could reach 2°C and even 3°C (figure 2-5).

Distribution of discontinuous and sporadic permafrost is affected by both climate and local factors; permafrost temperature and distribution strongly depend on topography, soil properties, snow depth, and vegetation; MAGTs usually exceed -3°C (figure 2-5), and in southern areas are close to 0°C.

Conditions of permafrost formation vary from favorable to unfavorable in a sequence of ground types involving peat, clay, silt, sand, and gravel (Shur and Jorgenson, 2007).

In the *discontinuous permafrost zone* permafrost occupies 50 to 90 percent and is interrupted or alternates with areas of unfrozen soil; open and closed taliks are common. In the zone of discontinuous permafrost, the active layer often does not reach the permafrost table. The lowered permafrost table can be a sign of permafrost degradation. In areas with *sporadic permafrost*, permafrost occurs as separate masses surrounded by unfrozen soil and occupies 10 to 50 percent. In areas with *isolated patches of permafrost*, permafrost occurs mainly in peat mounds and ridges surrounded by unfrozen bogs and occupies less than 10 percent of the area (Shur et al., 2011).

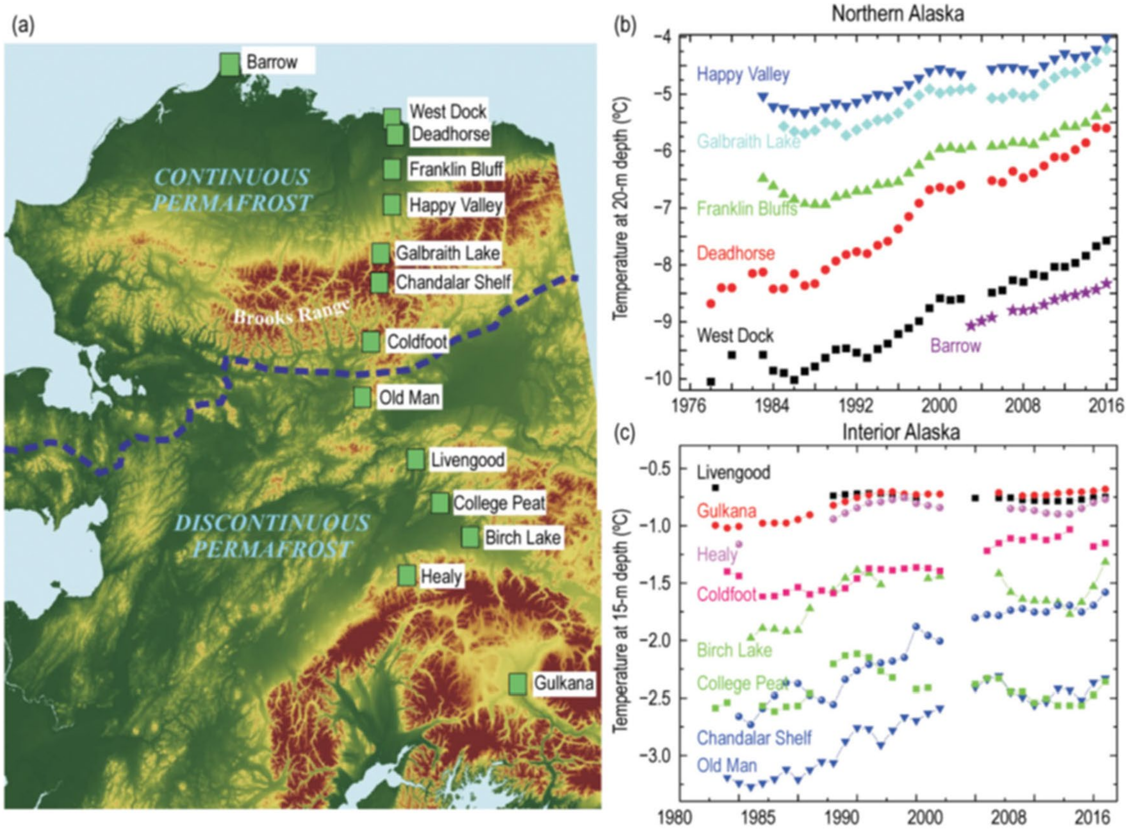


Figure 2-5 Increase in MAGT in Alaska since the 1980s. (a) Continuous and discontinuous permafrost zonesin Alaska (separated by the broken blue line) and location of a north–south transect of permafrost temperature measurement sites; (b) and (c) average annual temperature at depths of 20 m and 15 m below the surface, respectively, at Alaskan measurement sites (Romanovsky et al., 2017).

Permafrost may or may not contain ground ice, which occurs in pores, cavities, voids or other openings in soil or rock. This term refers to all types of ice contained in freezing and frozen ground. Ground ice may occur as lenses, wedges, veins, sheets, seams, irregular masses, or as individual crystals or coatings on mineral or organic particles. Perennial ground ice can only occur within permafrost bodies (van Everdingen, 1998). The volume and type of ground ice is important in determining thaw settlement characteristics and the sensitivity of permafrost to disturbance and thawing. Ice-rich permafrost is defined as thaw-sensitive permafrost containing excess ice (the volume of ice in the ground that exceeds the total pore volume that the ground would have under natural unfrozen conditions) (van Everdingen, 1998). Ice wedges are the most common type of massive ground ice; in some areas, wedge ice can occupy more than 50 percent of volume of the upper permafrost. Ice wedges develop by repeated frostcracking (or thermal contraction cracking) that occurs because of winter cooling of soil and subsequent formation of ice veins because of filling cracks with meltwater in the springtime (Leffingwell, 1915; Lachenbruch, 1962; Dostovalov and Popov, 1966; Mackay, 1972; French and Shur, 2010; Murton, 2013; French, 2018).

The areas with ice-rich permafrost are especially vulnerable to destructive processes of ground-ice degradation, which include thermokarst, thermal erosion, and thermal denudation. Thermokarst is the process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ice (van Everdingen, 1998). It results in subsidence of the soil surface and formation of depressions on the soil surface, as well as the cavities inside frozen soil. Thermal erosion is a process of combined thermal and mechanical action of moving water that results in simultaneous thawing of frozen ice-bearing deposits and their removal by water (van Everdingen, 1998; Shur and Osterkamp, 2007;Kanevskiy et al., 2016a). Thermal denudation is a process of thawing of frozen soils on the exposed bluff surface caused by solar radiation and convective heat exchange between the cold surface and the atmosphere, and subsequent removal of thawed soils from the bluff by gravity (Are, 1988; Shur and Osterkamp, 2007). Thermal denudation is the main process that creates retrogressive thaw slumps—slope failures resulting from thawing of ice-rich permafrost that consist of almost vertical retreating headwalls with exposed ice-rich permafrost and debris flows at the base of headwalls (van Everdingen, 1998).

2.2 Permafrost in Alaska

2.2.1 Permafrost Map of Alaska

Permafrost in Alaska can be encountered almost everywhere—according to the permafrost map of Alaska (Jorgenson et al., 2008) (figure 2-6), about 80 percent of the state belongs to the permafrost region (Jorgenson et al., 2008). The permafrost map contains general information on surficial geology and primary soil texture, permafrost temperature and extent, ground ice volume, distribution of pingos and ice wedges, and primary thermokarst landforms. Permafrost in Alaska includes areas with continuous (29 percent), discontinuous (35 percent), sporadic (8 percent), and isolated (8 percent) permafrost. Permafrost is absent beneath15 percent of the state, with glaciers and ice sheets occupying 4 percent and large water bodies 1 percent of the area (Jorgenson et al., 2008). Only 60 of 187 Alaskan rural communities are located within permafrost-free areas (Kanevskiy et al., 2019).

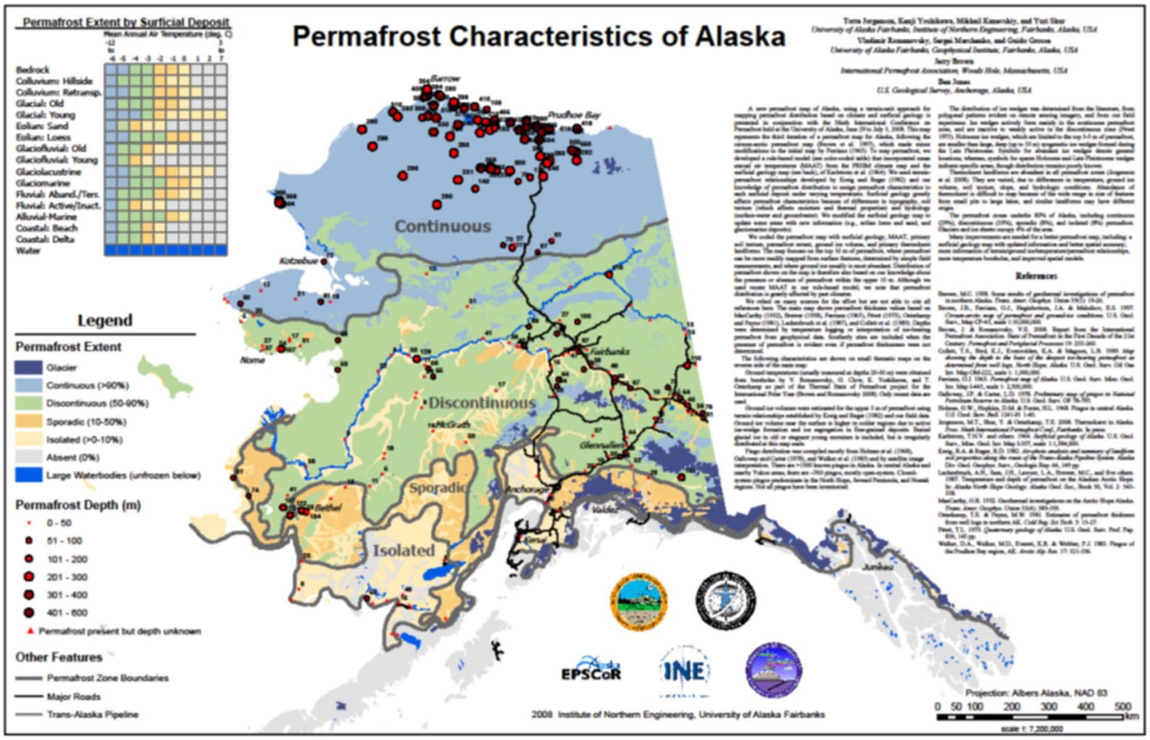
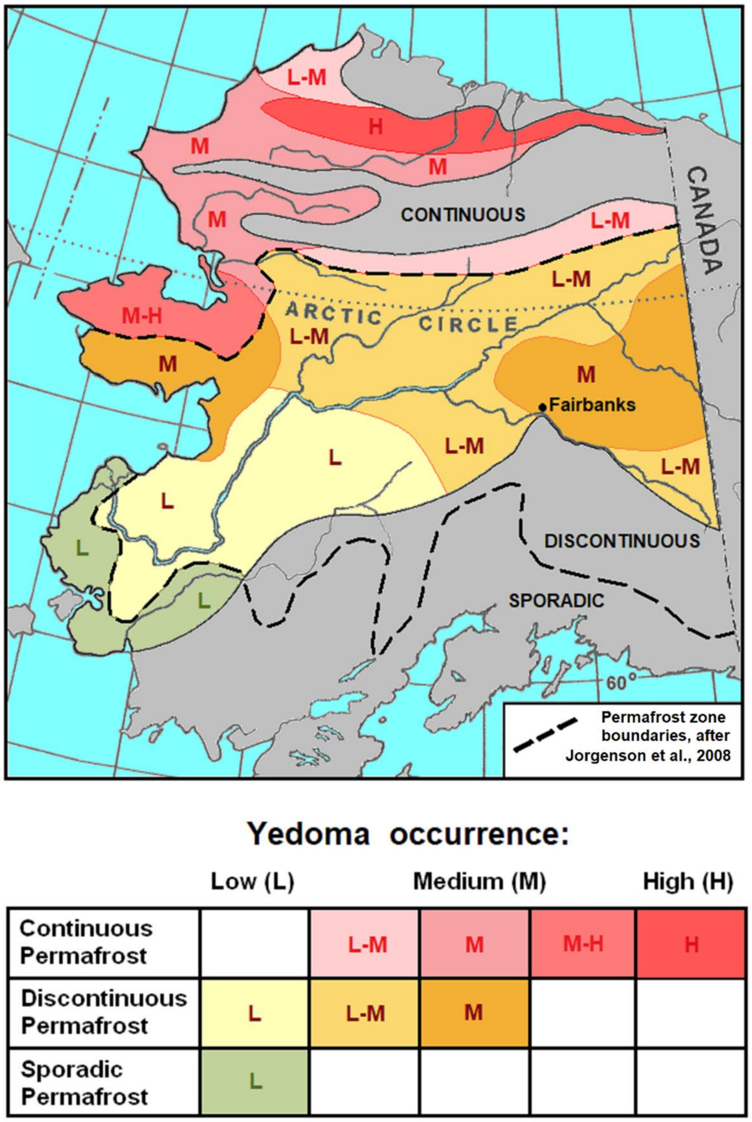


Figure 2-6 Permafrost map of Alaska (Jorgenson et al., 2008).

2.2.2 Yedoma Distribution in Alaska

Yedoma is defined as ice- and organic-rich, syngenetically frozen silty sediments that can be more than 40 m thick; these deposits contain large ice wedges, which can reach up to 10 m in width and more than 40 m in vertical extent (Romanovskii et al., 2004; Kanevskiy et al., 2011a, b; Schirrmeister et al., 2013; Murton, 2013). The occurrence of yedoma presents a great challenge to road construction and should be closely considered during geotechnical investigations (Kanevskiy et al., 2012). Ice-rich yedoma deposits have been observed in many areas with predominantly continuous and discontinuous permafrost that were not glaciated in the late Pleistocene (Kanevskiy et al., 2011a). Within the yedoma region, yedoma is distributed very irregularly (figure 2-7). In some areas it covers only a small percentage, whereas in other areas it may be the dominant terrain unit. In many poorly drained areas yedoma has been strongly reworked by thermokarst since the end of Pleistocene, especially in the discontinuous permafrost zone.The main yedoma areas in Alaska include the “Silt belt” in northern Alaska and the Seward Peninsula with adjacent areas. Yedoma is also abundant in the foothills and valleys of Interior Alaska.



Yedoma occurrence:

	Low (L)		Medium (M)		High (H)
Continuous Permafrost		L-M	M	M-H	H
Discontinuous Permafrost	L	L-M	M		
Sporadic Permafrost	L				

Figure 2-7 Yedoma occurrence within different permafrost zones of Alaska.

2.2.3 Continuous Permafrost

The continuous permafrost zone includes vast areas of northern and northwestern Alaska: the Brooks Range, Arctic Foothills, Arctic Coastal Plain, and the northern part of Seward Peninsula with adjacent areas (figure 2-6). North of the Brooks Range, permafrost thickness generally varies from 200 to 400 m and it reaches a maximum depth of 600 m in the Prudhoe Bay area (Brown and Sellmann, 1973; Lachenbruch et al., 1988; Jorgenson et al., 2008; Jorgenson, 2011). Mean annual permafrost temperatures vary from about -9 to -4°C but may be close to 0°C under shallow lakes. If the water depth exceeds 1.5 m, the mean annual bottom temperature commonly exceeds 0°C, and closed taliks develop under such lakes. Monitoring of permafrost temperatures in deep boreholes showed that is increased significantly during the last decades (Osterkamp and Jorgenson, 2006; Brown and Romanovsky, 2008; Smith et al., 2010; Jorgenson,2011; Romanovsky et al., 2017) (figure 2-5). The thickness of the saturated active layer usually does not exceed 0.5 to 0.6 m, but it can reach 1 to 1.5 m under bare surfaces. The minimal thickness of the active layer (0.2 to 0.3 m) is typical of organic soils. Degradation of ice wedges has occurred during the last decades over vast areas of northern Alaska (Jorgenson et al., 2006, 2015; Raynolds et al., 2014; Kanevskiy et al., 2016b, 2017; Frost et al., 2018).

Yedoma is quite common in the continuous permafrost zone (figure 2-7) and occurs primarily in lowlands and foothills that were unglaciated during the Late Pleistocene. Yedoma is widespread in the Arctic Foothills and adjacent parts of the Arctic Coastal Plain (Lawson, 1982, 1983; Carter, 1988; Brewer et al., 1993; Kanevskiy et al., 2011a, b, 2016a; Jorgenson et al., 2014; Schnabel et al., 2014; Trochim et al., 2016) and in the northern part of Seward Peninsula (Hopkins, 1963; Shur et al., 2012; Stephani et al.,2012; Ulrich et al., 2014). Within poorly drained plains, yedoma has been strongly reworked by thermokarst lakes. Thaw-lake basins are much less frequent in the foothills.

Yedoma sections were described by Carter (1988) in the low foothills of the Brooks Range, where continuous areas of eolian silt (loess) contain large ice wedges. According to Carter, these areas form a *silt belt* 5 to 70 km wide at the boundary between the Arctic Coastal Plain and the Arctic Foothills. We believe that the area of yedoma in northern Alaska is larger than it was mapped by Carter (1988), and isolated yedoma sequences of smaller scale can be found outside the silt belt area as well (Kanevskiy etal., 2011a). Thawing of yedoma deposits in northern Alaska, which started at the end of the Pleistocene, have resulted in the formation of large thaw-lake basins up to 20 to 30 m deep (Livingstone et al., 1958; Williams and Yeend, 1979; Carter, 1988).

Despite complex ground-ice conditions, the cold climate is an important favorable factor for engineeringactivities in northern Alaska. The recent increase in the permafrost temperature itself has not created serious problems because the temperatures of soils in northern Alaska are still quite low. Cold climate and low permafrost temperatures allow for using frozen soils as foundations without expensive technical means. Pads and embankments with a thickness greater than the active layer depth in dry granular soil prevent ice-rich permafrost from thawing.

2.2.4 Discontinuous Permafrost

Discontinuous permafrost is common in Alaska (figure 2-7). Most Alaskan villages are located within the discontinuous permafrost zone. The thickness of permafrost in this zone usually does not exceed 120 m (Jorgenson et al., 2008). Mean annual permafrost temperatures vary from about -3 to 0°C, and closed and open taliks are quite common. Monitoring of permafrost temperatures in deep boreholes showed relatively small (in comparison to the continuous permafrost zone) increases during the last decades (Smith et al., 2010; Romanovsky et al., 2017) (figure 2-5). The active layer thicknesses vary from less than 0.5 m in organic soils to more than 1 m in mineral soils.

Many unfrozen areas in the discontinuous zone of permafrost in Alaska consist of sand and gravel, and the nearby perennially frozen areas consist of silt (Péwé, 1975). Commonly permafrost occurs within areas with thick surface organic layers. Very often permafrost is absent within south-facing slopes, active floodplains, and in areas affected by forest fires and development. Permafrost and ground-ice conditions in the discontinuous permafrost zone are very diverse. Jorgenson et al. (2013) described the four typical landscapes most common across boreal regions of Alaska underlain by discontinuous permafrost: (1) rocky uplands on ice-poor hillside colluvium, (2) silty uplands on extremely ice-rich loess (yedoma), (3) gravelly–sandy lowlands on ice-poor eolian sand, and (4) peaty–silty lowlands on thick ice-rich peat deposits over reworked lowland loess (figure 2-8).

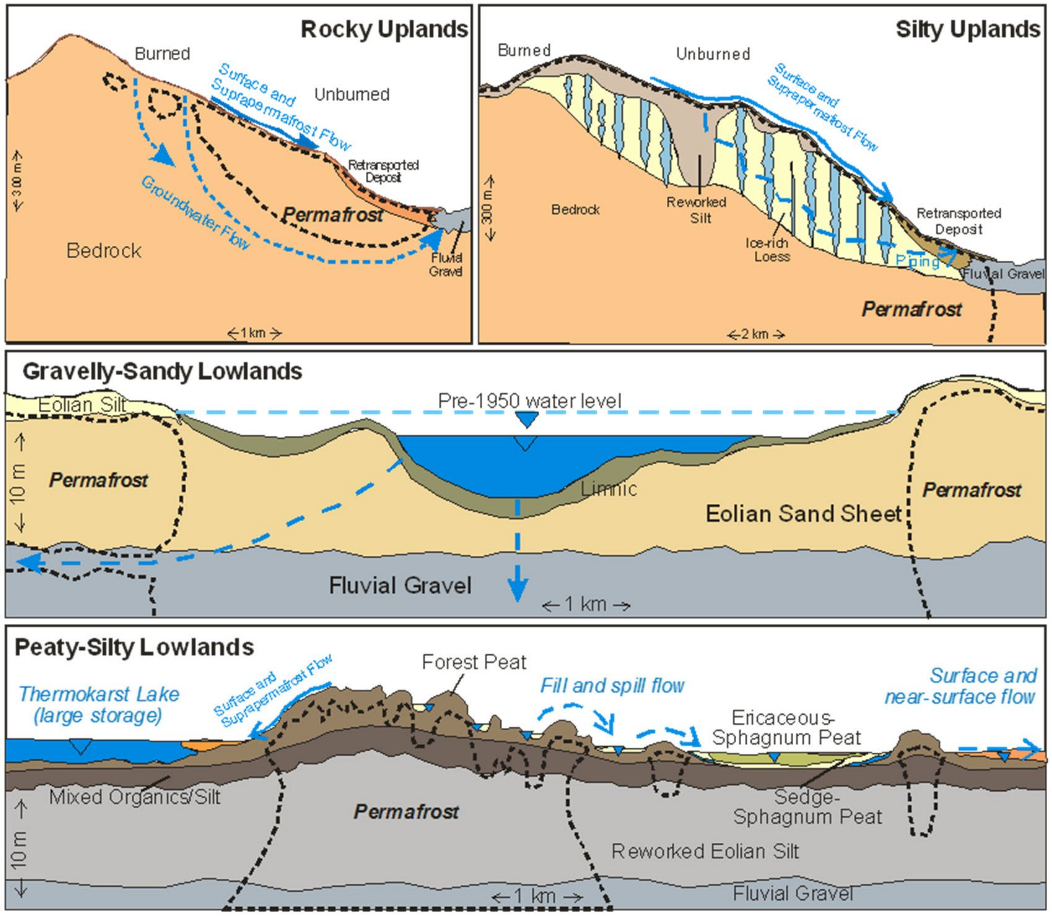


Figure 2-8 Topographic profiles illustrating relationships among topography, hydrology, soils, permafrost, and vegetation within rocky upland, silty upland, gravelly-sandy lowland, and peaty lowlandlandscapes (Jorgenson et al., 2013).

Ice wedges are mainly inactive or weakly active (Péwé, 1975). Modern ice wedges develop mainly within peatlands with relatively low permafrost temperatures (Hamilton et al., 1983; Bjella et al., 2017).

Inactive ice wedges commonly occur in yedoma, which can be encountered mainly in foothills and valleys within the uplands and low mountains, unglaciated during the Late Pleistocene. Wedge-ice contents in yedoma deposits of interior Alaska vary from 10 to >50 percent by volume, and the vertical extentof ice wedges may exceed 25 m (Kanevskiy et al., 2008, 2012; Shur et al., 2010). In many cases, ice wedges in yedoma are buried under a layer of relatively ice-poor silt up to 5 m thick (Péwé, 1975; Hamilton et al., 1988; Shur et al., 2004; Bray et al., 2006; Kanevskiy et al., 2008, 2012; Jensen et al., 2013; Jorgenson et al., 2013; Nossov et al., 2013).

It is difficult to distinguish yedoma terrain in the discontinuous permafrost zone because it is obscured in boreal forests. Baydzherakhs (conical thermokarst mounds) that indicate the presence of yedoma are visible mainly in drained thaw-lake basins or old agricultural fields. They also can be detected in LIDAR images. In most cases yedoma sites may be detected only by drilling.

Main yedoma areas in the discontinuous permafrost zone include the southern part of the Seward Peninsula and adjacent areas, the Yukon-Tanana upland, and parts of the Yukon Flats adjacent to foothills. Yedoma has been described at numerous sites in interior Alaska, primarily within the Yukon-Tanana upland (Péwé, 1975;Kanevskiy et al., 2012; Jensen et al., 2013; Jorgenson et al., 2013; Nossov et al., 2013).

Yedoma remnants exist mostly in the well-drained areas adjacent to foothills or large river valleys. Within poorly drained plains (e.g., Koyukuk Flats, Innoko Flats), yedoma has been almost completely reworked by thermokarst and thermal erosion since the end of the Pleistocene, and permafrost occurs mainly within uplifted peat plateaus, interspersed with unfrozen bogs and fens (Jorgenson et al., 2012;O'Donnell et al., 2012). The mean annual soil temperature at the base of the active layer within permafrost plateaus is close to 0°C. Surficial deposits often comprise frozen organic soils up to 4.5 m thick underlain by ice-rich lacustrine silt (presumably reworked yedoma). The volume of visible segregated ice in silt in these areas locally exceeds 50 percent, with ice lenses up to 10 cm thick (Kanevskiy etal., 2014). Modern ice wedges are not typical of this area, though Weber and Péwé (1961, 1970) reported the presence of ice wedges up to 1 m wide and 4.5 m tall in the Yukon-Koyukuk lowland.

Buried glacier ice and ice-rich glacio-lacustrine sediments can be encountered in the mountains and large valleys that developed during the late Pleistocene glaciation. Investigations at the Gulkana Airport (Copper River Basin, Alaska) revealed ice-rich, glacio-lacustrine silty clay at depths of 7 to 11 m with icelenses up to 15 cm thick and spacing from 10 to 30 cm (Shur and Zhestkova, 2003).

Destruction of vegetation in the discontinuous permafrost zone leads to degradation of permafrost (Douglas et al., 2008). Thawing of ice wedges under the roads (figure 2-9), agricultural fields, or buildings often results in significant differential thaw settlement. In the areas with ice-rich permafrost, relatively high permafrost temperatures complicate the use of frozen soils as foundations. Mitigation techniques are discussed in Chapter 5.

Figure 2-9 Thermokarst mounds (baydzherakhs) developed because of ice-wedge degradation under the abandoned part of the Dalton Highway, interior Alaska.

2.2.5 Sporadic and Isolated Permafrost

Areas with sporadic and isolated permafrost cover approximately 15 percent of Alaska, where the ground is mostly unfrozen. Permafrost thicknesses usually do not exceed 50 m. However, in some areas (e.g., around Bethel) they can be more than 100 m (Jorgenson et al., 2008) (figure 2-6). Permafrost temperatures are close to 0°C, and permafrost exists mostly in organic soils or in the areas with a very thick surficial organic layer.

In many areas with sporadic and isolated permafrost, mean annual air temperatures (MAAT) are above freezing, leading to permafrost degradation. For example, the mean annual air temperature in Anchorage exceeds +2°C, which is unfavorable to the existence of permafrost. However, isolated masses of relic permafrost in this area are protected from rapid thawing by a thick layer of moss and peat. According to Lee (1977), in the 1970s permafrost existed in about 2 to 5 percent of the Anchorage area. Permafrost bodies usually occurred at depths from 4.5 to 10 m; some of them were ice-rich with ice lenses from 2 to 30 cm thick (Lee, 1977). Frozen soils found at the study site near Birchwood, which is located between Anchorage and Wasilla, include silty clay of glacio-lacustrine origin with numerous layers of segregated ice up to 70 cm thick (Kanevskiy et al., 2013). The average volume of visible ice is 42.5 percent, and total gravimetricwater content is 68 percent. With an average permafrost thickness of 9.5 m and an average thaw strain of 40 percent, the thaw settlement of the surface is expected to be at least 3.8 m after complete degradation of permafrost, an unacceptable deformation for any engineered structure on these soils. Riddle and Rooney (2012) provided a comprehensive review of permafrost occurrence and its impact on structures in the Anchorage area.

In the coastal area of the Yukon-Kuskokwim Delta, ice-rich permafrost widely occurs in abandoned-floodplain deposits within elevated plateaus with a thick surficial organic layer (Jorgenson, 2000). Residual, currently degrading permafrost plateaus exist in the western Kenai Peninsula lowlands of south-central Alaska, a region with a MAAT of +0.5 to +2.5°C; the thickness of ice-rich peat in this area may exceed 5 m (Jones et al., 2016).

Yedoma-like terrain (supposedly yedoma hills and thaw-lake basins) has been detected within the Yukon-Kuskokwim delta and adjacent areas. Information is also available on massive ice (presumablylarge syngenetic ice wedges) at several sites (e.g., near the village of Chevak). However, there is no confirmed evidence of yedoma occurrence in these areas.

Most villages within the sporadic and isolated permafrost zones are located on unfrozen ground, but occurrence of the ice-rich permafrost mentioned above shows that permafrost-related hazards still mayexist in these areas and may affect either some parts of communities or adjacent areas. Warm permafrost temperatures and MAAT above freezing make preservation of soils in a frozen state extremely difficult.

2.2.6 Mountain Permafrost

In the mountain areas, a significant part of terrain is exposed bedrock, which is generally ice poor. Ice-rich weathered bedrocks containing golets ice may be encountered. Ice-rich sediments are localized mostly at the bases of gentle slopes and in the bottoms of river valleys. During the late Pleistocene, the mountain areas of Alaska were mainly glaciated, so no ice wedges could form at that time. Small Holocene ice wedges occur in the mountains mainly within the continuous permafrost zone (e.g., the Brooks Range). Buried glacier ice and ice-rich glacio-lacustrine sediments may be encountered in large glacial valleys (Kreig and Reger, 1982; Brown and Kreig, 1983; Kanevskiy et al., 2011b). Mass-wasting processes such as solifluction, creep of frozen soils, and the formation of rock glaciers and frozen debris lobes are active in these areas, as is the formation of frost blisters and icings.

2.3 References

Are, F.E. 1988. Thermal abrasion of sea coasts (Parts 1 and 2). Polar Geography and Geology, 12(1 and 2): 1-86, 87–157. http://dx.doi.org/10.1080/10889378809377352.

Bjella, K., Kanevskiy, M., and Hinkel, K. 2017. The Use of Electrical Resistivity Methods for Ground Ice Characterization for Engineering. 17th International Conference on Cold Regions Engineering. Congress on Technical Advancement 2017: Cold Regions Engineering. Zufelt, J.E. (Ed.), 59–70. doi:10.1061/9780784481011.006

Bray, M.T., French, H.M., and Shur, Y. 2006. Further cryostratigraphic observations in the CRREL permafrost tunnel, Fox, Alaska. Permafrost and Periglacial Processes, 17(3): 233–243.

Brewer, M.C., Carter, L.D., and Glenn, R. 1993. Sudden drainage of a thaw lake on the Alaskan Arctic Coastal Plain. Proceedings of the 6th International Conference on Permafrost, July 5–9, Beijing, China. South China University of Technology Press, 48–53.

Brown, J., and Kreig, R.A. (Eds.). 1983. Guidebook to Permafrost and Related Features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska, 230 pp.

Brown and Sellmann, 1973

Brown, J., and Romanovsky, V.E., 2008. Report from the International Permafrost Association: state of permafrost in the first decade of the 21st century. Permafrost and Periglacial Processes, 19(2): 255–260.

Brown, J., Ferrians, O.J., Heginbottom, J.A., and Melnikov, E.S. 1997. Circum-Arctic Map of Permafrost and Ground-Ice Conditions. Reston: U.S. Geological Survey.

Burn, C.R., Smith, C.A.S. 1988. Observations of the “thermal offset” in the near-surface mean annual ground temperature at sites near Mayo, Yukon Territory, Canada. Arctic 41(2): 99–104.

Carter, L.D. 1988. Loess and deep thermokarst basins in Arctic Alaska. Proceedings of the 5th International Conference on Permafrost. Tapir Publishers, Trondheim, Norway, 706–711.

Dostovalov, B.N., and Popov, A.I. 1966. Polygonal systems of ice-wedges and conditions of their development, pp. 102–105. In: Permafrost International Conference, 1963, Lafayette, Indiana. National Academy of Sciences-National Research Council, Washington, DC, Publication 1287.

Douglas, T.A., Jorgenson, M.T., Kanevskiy, M.Z., Romanovsky, V.E., Shur, Y., and Yoshikawa, K. 2008. Investigations into permafrost dynamics at the Fairbanks Permafrost Experimental Station near Fairbanks, Alaska. In: Proceedings of the 9th International Conference on Permafrost, June 29–July 3, 2008, Fairbanks, Alaska. Kane, D.L., and Hinkel, K.M. (Eds.). Institute of Northern Engineering, University of Alaska Fairbanks, Vol. 1: 373–378.

French, H.M. 2018. The Periglacial Environment. 4th ed. John Wiley and Sons Ltd., Chichester, UK, 515 pp.

French, H., and Shur, Y. 2010. The principles of cryostratigraphy. Earth-Science Reviews, 110: 190–206. doi: 10.1016/j.earscirev.2010.04.002.

Frost, G.V., Christopherson, T., Jorgenson, M.T., Liljedahl, A.K., Macander, M.J., Walker, D.A., and Wells, A.F. 2018. Regional patterns and asynchronous onset of ice-wedge degradation since the mid-20th century in Arctic Alaska. Remote Sensing, 10, 1312.

Hamilton, T.D., Ager, T.A., and Robinson, S.W. 1983. Late Holocene ice wedges near Fairbanks, Alaska, USA: Environmental setting and history of growth. Arctic and Alpine Research, 15(2): 157–168.

Hamilton, T.D., Craig, J.L., and Sellmann P.V. 1988. The Fox permafrost tunnel: A late Quaternary geologic record in central Alaska. Geological Society of America Bulletin, 100, 948–969.

Hopkins, D.M. 1963. Geology of the Imuruk Lake area, Seward Peninsula, Alaska. U.S. Geological Survey Bulletin, 1141-c, 101 pp.

Jensen, B.J.L., Reyes, A.V., Froese, D.G., and Stone, D.B. 2013. The Palisades is a key reference site for the middle Pleistocene of eastern Beringia: New evidence from paleomagnetics and regional tephrostratigraphy. Quaternary Science Reviews, 63: 91–108.

Jones, B.M., Baughman, C.A., Romanovsky, V.E., Parsekian, A.D., Babcock, E.L., Stephani, E., Jones, M.C., Grosse, G., and Berg, E.E. 2016. Presence of rapidly degrading permafrost plateaus in south-central Alaska. The Cryosphere, 10: 2673–2692.

Jorgenson, 2000

Jorgenson, M.T. 2011. Coastal region of northern Alaska, Guidebook to permafrost and related features: Alaska Division of Geological & Geophysical Surveys Guidebook 10, 188 pp.

Jorgenson, M.T., Shur, Y.L., and Pullman, E.R. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. Geophysical Research Letters, 25(2), L02503.

Jorgenson, T., Yoshikawa, K., Kanevskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J., and Jones, B. 2008. Permafrost characteristics of Alaska. In: Proceedings of the 9th International Conference on Permafrost, Extended Abstracts. June 29–July 3, 2008, Fairbanks, AK. Kane, D.L., and Hinkel, K.M. (Eds.), Institute of Northern Engineering, University of Alaska Fairbanks: 121–122.

Jorgenson, T., Kanevskiy, M., Shur, Y., Osterkamp, T., Fortier, D., Cater, T., Miller, P. 2012. Thermokarst lake and shore fen development in boreal Alaska. In: Proceedings of the Tenth International Conference on Permafrost, June 25-29, 2012, Salekhard, Russia. The Northern Publisher, Salekhard, Russia. Vol. 1: International contributions. Hinkel, K.M. (ed.): 179-184.

Jorgenson, M.T., Harden, J., Kanevskiy, M., O'Donnell, J., Wickland, K., Ewing, S., Manies, K., Zhuang, Q., Shur, Y., Striegl, R., and Koch, J. 2013. Reorganization of vegetation, hydrology, and soil carbon after permafrost degradation across heterogeneous boreal landscapes. Environmental Research Letters, 8(3), 035017, doi:10.1088/1748-9326/8/3/035017.

Jorgenson, M.T., Kanevskiy, M., Shur, Y., Grunblatt, J., Ping, C.L., and Michaelson, G. 2014. Permafrost database development, characterization, and mapping for northern Alaska. Report for Arctic Landscape Conservation Cooperative by Alaska Ecoscience and

University of Alaska Fairbanks, 45 pp. http://alaska.portal.gina.alaska.edu/catalogs/9630-2014- permafrost- database-development-charact

Jorgenson, M.T., Kanevskiy, M., Shur, Y., Moskalenko, N., Brown, D.R.N., Wickland, K., Striegl, R., and Koch, J. 2015. Role of ground ice dynamics and ecological feedbacks in recent ice wedge degradation and stabilization. Journal of Geophysical Research – Earth Surface, 120: 2280–2297. doi:10.1002/2015JF003602.

Kanevskiy, M., French, H., and Shur, Y. (Eds.) 2008. Late-Pleistocene Syngenetic Permafrost in the CRREL Permafrost Tunnel, Fox, Alaska. A guidebook prepared for Ninth International Conference on Permafrost, June 29-July 3, 2008, Fairbanks, Alaska, 22 pp.

Kanevskiy, M., Shur, Y., Fortier, D., Jorgenson, M.T., and Stephani, E. 2011a. Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure. Quaternary Research, 75: 584–596, doi:10.1016/j.yqres.2010.12.003.

Kanevskiy, M., Shur, Y., Jorgenson, M.T., Ping, C.-L., Fortier, D., Stephani, E., and Dillon, M. 2011b. Permafrost of northern Alaska. In: Proceedings of the 21st International Offshore and Polar Engineering Conference Maui, Hawaii, USA, June 19–24, 2011: 1179–1186, ISBN 978-1-880653-96-8 (Set); ISSN 1098- 6189 (Set); www.isope.org.

Kanevskiy, M., Shur, Y., Connor, B., Dillon, M., Stephani, E., and O'Donnell, J. 2012. Study of the ice-rich syngenetic permafrost for road design (Interior Alaska). In: Proceedings of the 10th International Conference on Permafrost, June 25–29, 2012, Salekhard, Russia. The Northern Publisher, Salekhard, Russia. Vol. 1: International contributions. Hinkel, K.M. (Ed.): 191–196.

Kanevskiy, M., Shur, Y., Krzewinski, T., and Dillon, M. 2013. Structure and properties of ice-rich permafrost near Anchorage, Alaska. Cold Regions Science and Technology, 93: 1–11. doi:10.1016/j.coldregions.2013.05.001.

Kanevskiy, M., Jorgenson, M.T., Shur, Y., O'Donnell, J.A., Harden, J.W., Zhuang, Q., and Fortier, D. 2014. Cryostratigraphy and permafrost evolution in lacustrine lowlands of west-central Alaska. Permafrost and Periglacial Processes, 25(1): 14–34, doi: 10.1002/ppp.1800.

Kanevskiy, M., Shur, Y., Strauss, J., Jorgenson, M.T., Fortier, D., Stephani, E., and Vasiliev, A. 2016a. Patterns and rates of riverbank erosion involving ice-rich permafrost (yedoma) in northern Alaska. Geomorphology, 253: 370–384. doi: 10.1016/j.geomorph.2015.10.023

Kanevskiy M., Shur, Y., Walker, D.A., Buchhorn, M., Jorgenson, T., Matyshak, G., Raynolds, M.K., Peirce, J.L., and Wirth, L.M. 2016b. Evaluation of Risk of Ice-Wedge Degradation, Prudhoe Bay Oilfield, AK. In: Abstracts of the 11th International Conference on Permafrost, June 20–24, 2016, Potsdam, Germany: 1007–1009.

Kanevskiy, M., Shur, Y., Jorgenson, T., Brown, D.R.N., Moskalenko, N.G., Brown, J., Walker, D.A., Raynolds, M.K., and Buchhorn, M. 2017. Degradation and stabilization of ice wedges: Implications for assessing risk of thermokarst in northern Alaska. Geomorphology, 297: 20–42. doi: 10.1016/j.geomorph.2017.09.001.

Kanevskiy M., Connor, B., Schnabel, W., Bjella, K., and Trochim, E. 2019. Determination of Communities At-Risk from Thawing Permafrost. Proceedings of the 18th International

Conference on Cold Regions Engineering and the 8th Canadian Permafrost Conference, Quebec City, Quebec, Canada, August 18–22, 2019: 588-596.

Kreig, R.A., and Reger, R.D. 1982. Air-photo analysis and summary of landform soil properties along the route of the Trans-Alaska Pipeline System. DGGS, College, Alaska, Geologic report 66, 149 pp.

Kudryavtsev, V.A. 1959. Temperatura, moshchnost’ i preryvistost’ tolshch merzlykh porod [Temperature, thickness, and discontinuity of permafrost]. In Osnovy geokriologii merzlotovedeniya) [Fundamentals of Geocryology (Permafrost Science)], Part 1, Shvetsov, P.F., Dostovalov, B.N. (eds). USSR Academy of Sciences: Moscow, 219–273 (in Russian).

Lachenbruch, A.H. 1962. Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Geological Society of America, Special Papers, 70, 69 pp.

Lachenbruch, A.H., Sass, J.H., Lawver, L.A., Brewer, M.C., Marshall, B.V., Munroe, R.J., Kennelly Jr., J.P., Galanis Jr., S.P., and Moses Jr., T.H. 1988. Temperature and depth of permafrost on the Arctic slope of Alaska. In: Gryc, G. (Ed.), Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, pp. 645–656.

Lawson, D.E. 1982. Long-term modifications of perennially frozen sediment and terrain at East Oumalik, northern Alaska. CRREL Report 82-36, 33 pp.

Lawson, D.E. 1983. Ground ice in perennially frozen sediments, northern Alaska. In: Proceedings of the 4th International Conference on Permafrost. National Academy Press, Washington, DC, 695–700.

Lee, H.R. 1977. Permafrost in Anchorage. Proceedings of the 2nd International Symposium on Cold Regions Engineering. August 12–14, 1976. University of Alaska Fairbanks, pp. 283–289.

Leffingwell, E. de K. 1915. Ground-ice wedges, the dominant form of ground-ice on the north coast of Alaska. Journal of Geology, 23: 635–654.

Livingstone, D.A., Bryan, K., Jr., and Leahy, R.G. 1958. Effects of an Arctic environment on the origin and development of freshwater lakes. Limnology and Oceanography, 3: 192–214.

Mackay, J.R. 1972. The world of underground ice. Annals of the Association of American Geographers, 62(1): 1–22.

Murton, J.B. 2013. Ground ice and cryostratigraphy. In: Treatise on Geomorphology, Vol. 8, Glacial and Periglacial Geomorphology, Schoder, J.F. (editor-in-chief), Giardino, R., Harboor, J. (volume Eds.). Academic Press, San Diego: 173–201.

Nossov, D.R., Jorgenson, M.T., Kielland, K., and Kanevskiy, M. 2013. Edaphic and microclimatic controls over permafrost response to fire in interior Alaska. Environmental Research Letters, 8(3), 035013, doi:10.1088/1748-9326/8/3/035013.

O’Donnell, J.A., Jorgenson, M.T., Harden, J.W., McGuire, A.D., Kanevskiy, M.Z., and Wickland, K.P. 2012. The effects of permafrost thaw on soil hydrologic, thermal, and carbon dynamics in an Alaska peatland. Ecosystems, 15(2): 213–229. doi: 10.1007/s10021-011-9504-0.

Osterkamp, T.E., and Jorgenson, J.C., 2006. Warming of permafrost in the Arctic National Wildlife Refuge, Alaska. Permafrost and Periglacial Processes, 17: 65–69.

Osterkamp, T.E., and Romanovsky, V.E. 1999. Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost and Periglacial Processes 10: 17–37.

Péwé, T.L. 1975. Quaternary geology of Alaska. U.S. Geological Survey, Professional Paper 835, 145 pp.

Raynolds, M.K., Walker, D.A., Ambrosius, K.J., Brown, J., Everett, K.R., Kanevskiy, M., Kofinas, G.P., Romanovsky, V.E., Shur, Y., and Webber, P.J. 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. Global Change Biology, 20(4): 1211–1224. http://dx.doi.org/10.1111/gcd.12500.

Riddle, C.H., and Rooney, J.W. 2012. Encounters with relict permafrost in the Anchorage, Alaska, area. Proceedings of the 10th International Conference on Permafrost, Salekhard, Yamal-Nenets Autonomous District, Russia, June 25–29, 2012, 1, pp. 323–328.

Romanovskii, N.N., Hubberten, H.-W., Gavrilov, A.V., Tumskoy, V.E., and Kholodov, A.L. 2004. Permafrost of the east Siberian Arctic shelf and coastal lowlands. Quaternary Science Reviews, 23: 1359–1369.

Romanovsky, V.E., Smith, S.L., Shiklomanov, N.I., Streletskiy, D.A., Isaksen, K., Kholodov, A.L., Christiansen, H.H., Drozdov, D.S., Malkova, G.V., and Marchenko, S.S. 2017. Terrestrial permafrost [in "State of the climate in 2016"]. Bulletin of the American Meteorological Society, August 2017, pp. S147– S149.

Schirrmeister, L., Froese, D., Tumskoy, V., Grosse, G., and Wetterich, S. 2013. Yedoma: Late Pleistocene ice-rich syngenetic permafrost of Beringia. Encyclopedia of Quaternary Science, 2nd ed., pp. 542–552.

Schnabel, W., Fortier, R., Kanevskiy, M., Munk, J., Shur, Y., and Trochim, E. 2014. Geophysical applications for arctic/subarctic transportation planning. Final report prepared for Alaska University Transportation Center, Project # 410018, INE/AUTC 13.01.

Shur, Y., and Jorgenson, M.T. 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes, 18: 7–19.

Shur, Y., and Osterkamp, T. 2007. Thermokarst. Report INE 06.11. University of Alaska Fairbanks, Institute of Northern Engineering, Fairbanks, AK (50 pp.).

Shur, Y., and Zhestkova, T. 2003. Cryogenic structure of a glacio-lacustrine deposit. Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland, July 21–25, 2003, 2, pp. 1051–1056.

Shur, Y., French, H.M., Bray, M.T., and Anderson, D.A. 2004. Syngenetic permafrost growth: cryostratigraphic observations from the CRREL Tunnel near Fairbanks, Alaska. Permafrost and Periglacial Processes, 15(4): 339–347.

Shur, Y., Kanevskiy, M., Dillon, M., Stephani, E., and O'Donnell, J. 2010. Geotechnical investigations for the Dalton Highway innovation project as a case study of the ice-rich syngenetic permafrost. Report # FHWA-AK-RD-10-06, prepared for ADOT&PF, AUTC assigned project # 207122.

Shur, Y., Jorgenson, M.T., and Kanevskiy, M.Z. 2011. Permafrost. In: Singh, V.P., Singh, P., and Haritashya, U.K., (Eds.): Encyclopedia of Earth Sciences Series, Encyclopedia of Snow, Ice and Glaciers: 841–848. doi:10.1007/978-90-481-2642-2.

Shur, Y., Kanevskiy, M., Jorgenson, T., Dillon, M., Stephani, E., and Bray, M. 2012. Permafrost degradation and thaw settlement under lakes in yedoma environment. In: Proceedings of the 10th International Conference on Permafrost, June 25–29, 2012, Salekhard, Russia. Vol. 1 International contributions, Hinkel, K.M. (Ed.). The Northern Publisher, Salekhard, Russia: 383–388.

Smith, M.W., Riseborough, D.W. 2002. Climate and the limits of permafrost: a zonal analysis. Permafrost and Periglacial Processes 13: 1–15.

Smith, S.L., Romanovsky, V.E., Lewkowicz, A.G., Burn, C.R., Allard, M., Clow, G.D., Yoshikawa, K., and Throop, J. 2010. Thermal state of permafrost in North America: A contribution to the International Polar Year. Permafrost and Periglacial Processes, 21: 117–135. http://dx.doi.org/10.1002/ppp.690.

Stephani, E., Kanevskiy, M., Dillon, M., Bray, M., and Shur, Y. 2012. Cryostratigraphy of yedoma (ice complex) in Seward Peninsula, Alaska. In: 10th International Conference on Permafrost, June 25–29, 2012, Salekhard, Russia. Vol. 4/2: Extended abstracts. Fort Dialog-Iset: Ekaterinburg, Russia: 569–570.

Trochim, E.D., Schnabel, W.E., Kanevskiy, M., Munk, J., and Shur, Y. 2016. Geophysical and cryostratigraphic investigations for road design in northern Alaska. Cold Regions Science and Technology, 131: 24–38. doi: 10.1016/j.coldregions.2016.08.004.

Ulrich, M., Grosse, G., Strauss, J., and Schirrmeister, L. 2014. Quantifying wedge-ice volumes in yedoma and thermokarst basin deposits. Permafrost and Periglacial Processes, 25(3): 151–161.

van Everdingen, R.O. (Ed.) 1998. Multi-Language Glossary of Permafrost and Related Ground-ice Terms. International Permafrost Association. The Arctic Institute of North America, University of Calgary, Calgary, 268 pp.

Weber, F.L., and Péwé, T.L. 1961. Engineering geology problems in the Yukon-Koyukuk lowland, Alaska. In: Short Papers in the Geologic and Hydrologic Sciences, Articles 293–435. U.S. Geological Survey Professional Paper 424-D: 371–373.

Weber, F.L., and Péwé, T.L. 1970. Surficial and engineering geology of the central part of the Yukon- Koyukuk lowland, Alaska. U.S. Geological Survey Miscellaneous Investigations Geologic Map I-590, 2 sheets.

Williams, J.R., and Yeend, W.E. 1979. Deep thaw lake basins in the inner Arctic Coastal Plain, Alaska. U.S. Geological Survey in Alaska: Accomplishments during 1978, Johnson, K.M., and Williams, J.R. (Eds.). USGS Circular 804-B, B35-B37.

3 GEOTECHNICAL INVESTIGATIONS

3.1 Overview

Geotechnical data are crucial to project success by helping engineers to

- Design to meet performance and maintenance expectations during the life of the structure
- Ensure that contracting milestones and spending limits are met during the construction phase
- Reduce the numbers of change orders and cost over-runs.

The design of roadways and airfields in Alaska requires an understanding of permafrost, surficial properties, and potential impacts of thawing permafrost on infrastructure. Key parameters affecting performance are the extent and quantity of ice (gravimetric moisture content), soil type, frozen condition, and active layer thickness (Andersland and Ladanyi 2013, Johnson 1981). More importantly, however, perennially frozen materials most often have highly variable ice content, laterally and vertically because of the permafrost and ecosystem geomorphology (Jorgenson and Kreig 1988, Shur and Jorgenson 2007).

Management of risk and cost requires a systematic approach that characterizes the site. Drilling of regularly spaced boreholes provides indispensable exploratory and confirmatory site data. However, drilling is costly, and each borehole provides information about a single point. Drilling can miss criticalvariability and spatial relationships between the boreholes, especially in the boundary zones where critical bearing capacity changes occur between ice-rich vs. ice-poor conditions, or frozen and thawed areas.

Employing a strategic, comprehensive approach that maximizes the value of each borehole while allowing interpretation between those boreholes can often reduce the risk of claims and change orders during construction. Geotechnical data may be acquired through multiple methods, including analysis of aerial and satellite imagery, geophysical measurements, and geologic and topographic maps to include digital elevation models (DEMs), or through remote sensing techniques.

Chapter 3 provides an overview of the geotechnical investigation tools available. In keeping with the theme of this synthesis the information presented here allows the designer to understand the strengths and weaknesses of each method and when they may be applied. There is no method that works in everycase. Consequently, the primary goal is to allow the designer to engage in a meaningful discussion with subject matter experts who can assist in the development of a geotechnical investigation plan to meet the needs of the project.

3.1.1 Terrain Units

Geotechnical investigations in the permafrost region are often based on the terrain-unit approach (Kreig and Reger, 1982). *Terrain (or geomorphic) units* are distinguished on the basis of geomorphology and surficial geology. This approach is based on a close correlation of ground-ice volume and other permafrost characteristics with terrain units because the process of ground-ice accumulation is controlled by soil texture and properties, geologic history, and conditions of permafrost formation. Such correlation has been proven during permafrost studies throughout Alaska (Shur and Jorgenson, 1998).

Terrain analysis assumes that the geomorphic, geologic, and geotechnical properties of terrain are closely related, and that terrain units formed during the same time, under the same climatic conditions, and affected by similar processes. Climatic conditions during the formation of terrain units are especially important for geotechnical investigations in the permafrost region. For example, in Alaska, the textures of soils of modern floodplains in the continuous and discontinuous permafrost zones may be identical, but the permafrost properties of soils, including thermal state, ground-ice content, existence of massive ice, and permafrost-related processes, may be completely different (Schnabel et al., 2014). Much of this is discussed in Chapter 2 and in more detail in the companion publication *A Permafrost Primer for Highwayand Airport Engineers.*

Mapping of terrain units is based mainly on interpretation of aerial photographs, satellite imagery, and topographic maps, as well as analysis of previous studies (geological, geomorphological, and vegetation maps,geotechnical reports, scientific papers, etc.). Preliminary terrain-unit maps (figure 3-1) depict the main landforms.

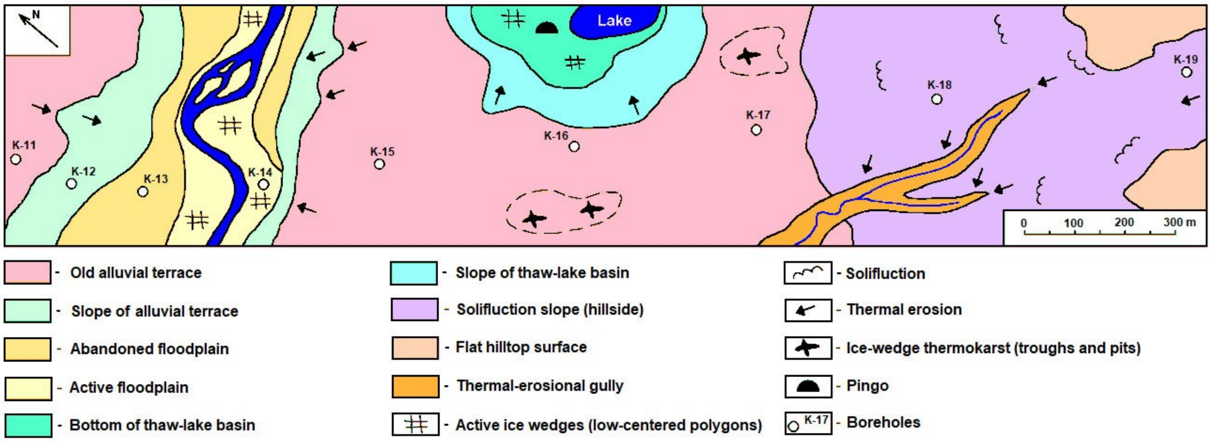


Figure 3-1 Example of a terrain-unit (landform) map.

3.1.2 Satellite Imagery and Air Photo Interpretation

Interpretation of imagery is widely used in geotechnical investigations in permafrost-affected areas because of the close relationship between permafrost properties and surface features (Schnabel et al.,2014). Sources include satellite images, air photos, and aerial light detection and ranging (lidar).

An abundance of satellites constantly capture the state of the Earth, many of which have freely available data. Each satellite has different sensors, and spatial and temporal resolutions.

Therefore, it is important to understand what is needed for an analysis before a data search begins.

Aerial lidar is another method used for a terrain analysis. Laser returns map the surface of the earth to create a high-resolution picture of the ground and elevation. Lidar series collected over time can be differenced to detect elevation changes due to permafrost melt. Many municipalities, boroughs, and government agencies such as the U.S. Geological Survey (USGS) and the Alaska Division of Geological and Geophysical Surveys (DGGS) collect aerial lidar and make these data available to the public. Private companies provide customized aerial lidar at a specific area of interest. Unmanned aerial vehicles carrying inexpensive lidar cameras are becoming more common. As a result, lidar data are becoming increasingly available at lower costs.

3.1.3 Engineering-Geological Maps and Sections

Engineering-geological maps are compiled on the basis of the terrain-unit approach. The data on permafrost conditions and soil properties may be obtained through detailed geophysical and other subsurface investigations (drilling, excavation, description of natural exposures, etc.) along selected transects. With sufficient information on permafrost and surficial geology, terrain-unit maps can be transformed into engineering-geological maps (figure 3-2). Terrain-unit maps can then be transformed into engineering-geological cross-sections that contain important geotechnical information (figure 3-3).

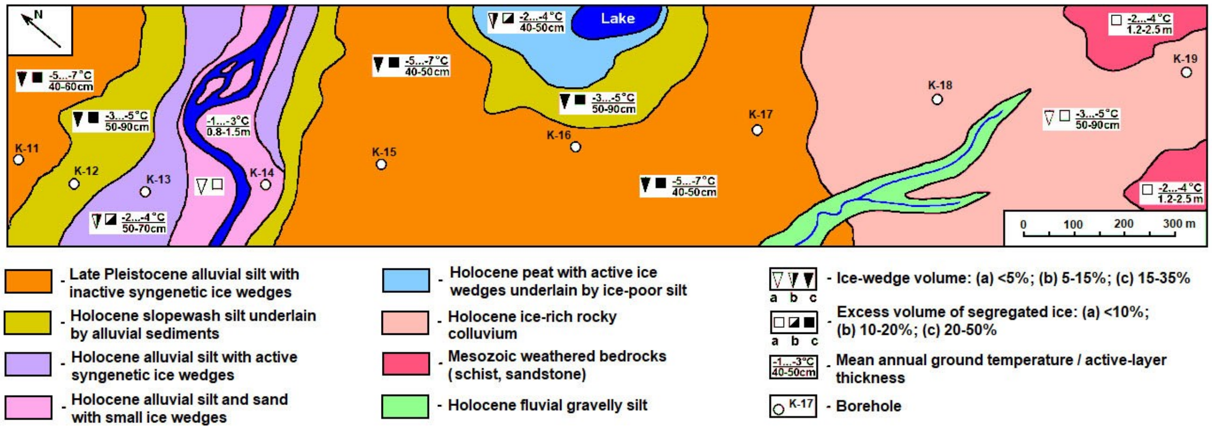


Figure 3-2 Example of an engineering-geological map that was modified from the terrain-unit map (see figure 3-1).

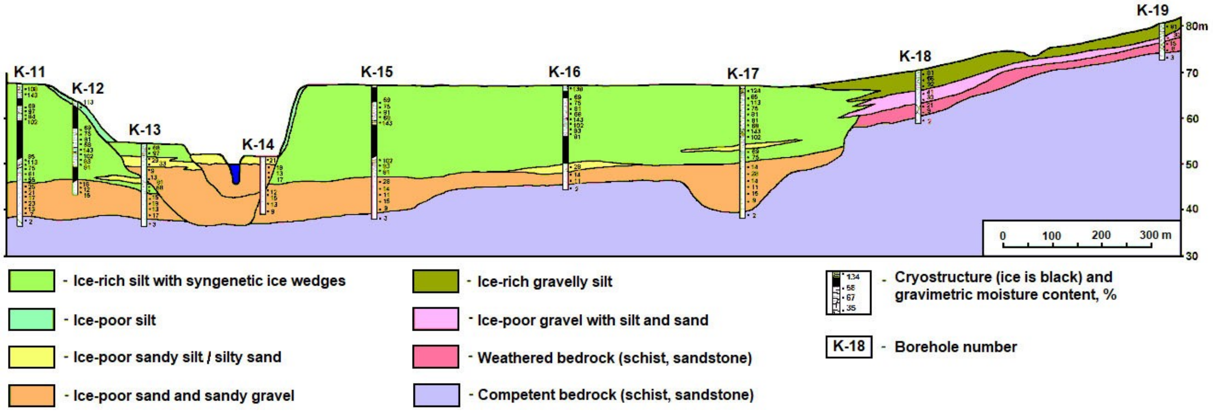


Figure 3-3 Example of an engineering-geological cross-section

Engineering-geological mapping is impossible without field studies. These start with detailed mapping and descriptions of surficial features and include characterization of vegetation, measurements of thaw depth, mapping of various permafrost-related landforms (e.g., ice-wedge troughs and other polygonal features, thermokarst ponds, sinkholes, thermo-erosional gullies, pingos, solifluction lobes, etc.), and characterization of adjacent infrastructure (permafrost engineered versus non-permafrost engineered, road deformations, etc.). These surficial features, some of which may be detected on the basis of interpretation of aerial photographs and satellite images, may indicate the occurrence and sometimes properties of the near-surface permafrost. However, characterization of subsurface conditions is impossible without detailed geotechnical investigations, namely drilling. Several boreholes, their locations along the selected transects, and depth of drilling should be determined on the basis of the diversity of terrain conditions and results of geophysical investigations.

3.2 Introduction to Geophysical Investigations

Geophysical techniques such as electrical resistivity tomography (ERT) and ground penetrating radar (GPR) have been used successfully for subsurface profile imaging of many types of earth materials, both in sediments and bedrock. These techniques specifically provide unique visualization of the subsurface in frozen environments resulting from electrical contrast between water and ice. ERT measures the transient response of subsurface materials to an electrical impulse, as frozen ground is higher in resistivity whereas thawed or wet soils are low in resistivity (high conductivity). Resistivity has been proved to delineate between frozen vs. thawed, and ice-rich vs. ice-poor terrain. The energy is input to the subsurface either by direct electrical conductors (galvanic) or via capacitive coupled systems. The latter allows for long continuous transects.

GPR measures the velocity changes of radar frequency impulse into the subsurface. Differences in dielectric permittivity cause velocity and polarity changes of the signal, indicating the depth and location of major subsurface changes. Sub-horizontally layered strata such as sediments and man-made earthen projects are easily discernable, particularly where phase change boundaries exist at the top of the permafrost and water tables. It is important to understand that GPR provides only horizons where changes occur. It does not provide information concerning what those changes are without additional information.

The equipment for these techniques is commercially available and easily operated with a modest amount of training. In the case of GPR, some complexity can arise when details in complex subsurface structure are discerned, requiring expertise for refined processing.

Once the user becomes familiar with these technologies, information becomes immediately apparent. This not only provides data for the areas between ground truth locations (test pits, boreholes, outcrops), but it optimizes geotechnical investigation by providing information related to the variability of the soil structure. The decision to utilize surface geophysics is often predicated on the end user's familiarity with the techniques and the anticipated information provided to the project. However, it is often influenced by the budget.

Project team members, particularly geologists and geotechnical/materials engineers, readily understandthe requirement for subsurface sampling via boreholes or test pits. Geophysical methods are rapidly demonstrating the benefits of inclusion in a geological/ geotechnical investigation, particularly on linear projects in frozen terrain. However, the utilization of surface geophysics—including which technology, how they are used, and when—is evolving.

3.3 Electrical Resistivity Tomography (ERT)

3.3.1 Capacitive Coupled Resistivity (CCR)

Capacitive coupled resistivity (CCR) is a type of ERT survey that uses the earth as one conductor of a parallel plate capacitor. The transmitter and receivers are connected via coaxial cables, creating a dipole antenna. The transmitter sends a continuous-current sine wave through the dipole antenna, polarizing the surrounding earth material. A passing receiver measures the induced polarization from which the resistivity can then be calculated. This system does not require inserted electrodes and can continuously collect pulsed readings at a frequency of 10 Hz (figure 3-4) while traveling along the surface. The transmitter dipole antenna is separated from the series-connected receiver dipoles antennae with a non-conducting rope.Increasing the separation increases the survey depth up to 20 m. The system can be pulled on foot, or by snow-machine, all-terrain vehicle, or full-size vehicle. The overall length of the CCR array to be towed can exceed 100 m (330 ft) when the 10-m dipoles and a rope separation of 25 m are used. The system can collect data throughout the year and under damp conditions, including rain. Global positioning system (GPS) information is incorporated in the data to allow for transect location. Processing of the data is the same as that for directly coupled ERT, through utilization of inversion to provide a pseudo-section of the subsurface resistivity with either commercially available or user written software and an image of the profile produced.

Figure 3-4 CCR system pulled by a snowmobile on a packed trail

The image is composed of a color index coded and contoured to illustrate areas of high or low resistivity, with red-purple indicating high resistivity and blue-green indicating low resistivity (high conductivity), although these can be modified on the basis of end-user preference. Details of dramatic changes in resistivityare limited to a 2- to 3-meter resolution. The change from thawed to frozen ground occurs abruptly, especially for the thawed active layer over permafrost. Fortunately for geological investigations, extreme detail of the horizontal and vertical location of the dramatic changes is less important during a preliminary assessment, and greater precision will be attained with ground truth drilling or test pit excavation.

In figure 3-5, a pseudosection is shown of a portion of a 13-km survey northwest of Fairbanks, Alaska, for the relocation of the Dalton Highway 0 to 8 mile. The CCR survey was conducted along the proposed centerline after clearing and grubbing. Borehole drilling was conducted along the centerline during the CCR survey at 100-m (300-ft) intervals per

AKDOT&PF field protocols. The location consisted of discontinuous warm permafrost. Drilling of the lower portion of the alignment in the West Fork of the Tolovana River encountered numerous thawed areas and areas with ice-poor permafrost. The boreholes were overlain with the resistivity, to include gradation, frozen condition, and ice volume.

3.3.2 Galvanic (Electrode Coupled)

The galvanic method of ERT utilizes metal electrode stakes driven into the soil or rock at equal intervals along the surface to be surveyed. Resistivity is determined by injecting current directly into the subsurface via two current electrodes and then reading the resultant voltage via two potential electrodes (figure 3-6). Increasing the electrode spacing increases the depth. Thirty-meter depths or more are achievable with electrode separations of 6 m. Set-up is time consuming, requiring electrodes to be hammered into the ground. Each survey is limited to the length of the cables at maximum electrode spacing. Data can be collected all seasons of the year; however, electrode installation in frozen earth materials in the winter requires considerable effort, and the electrodes must be potted in saline solution to facilitate lower contact resistance. Operators should take appropriate precautions when working around water to avoid electrical shock. Electrode location is topographically mapped with conventional mapping equipment, optical or GPS. Averaging algorithms are used to calculate the apparent resistivity over a range of depths along the electrode line, producing a two-dimensional, pseudo-section of inversion results.

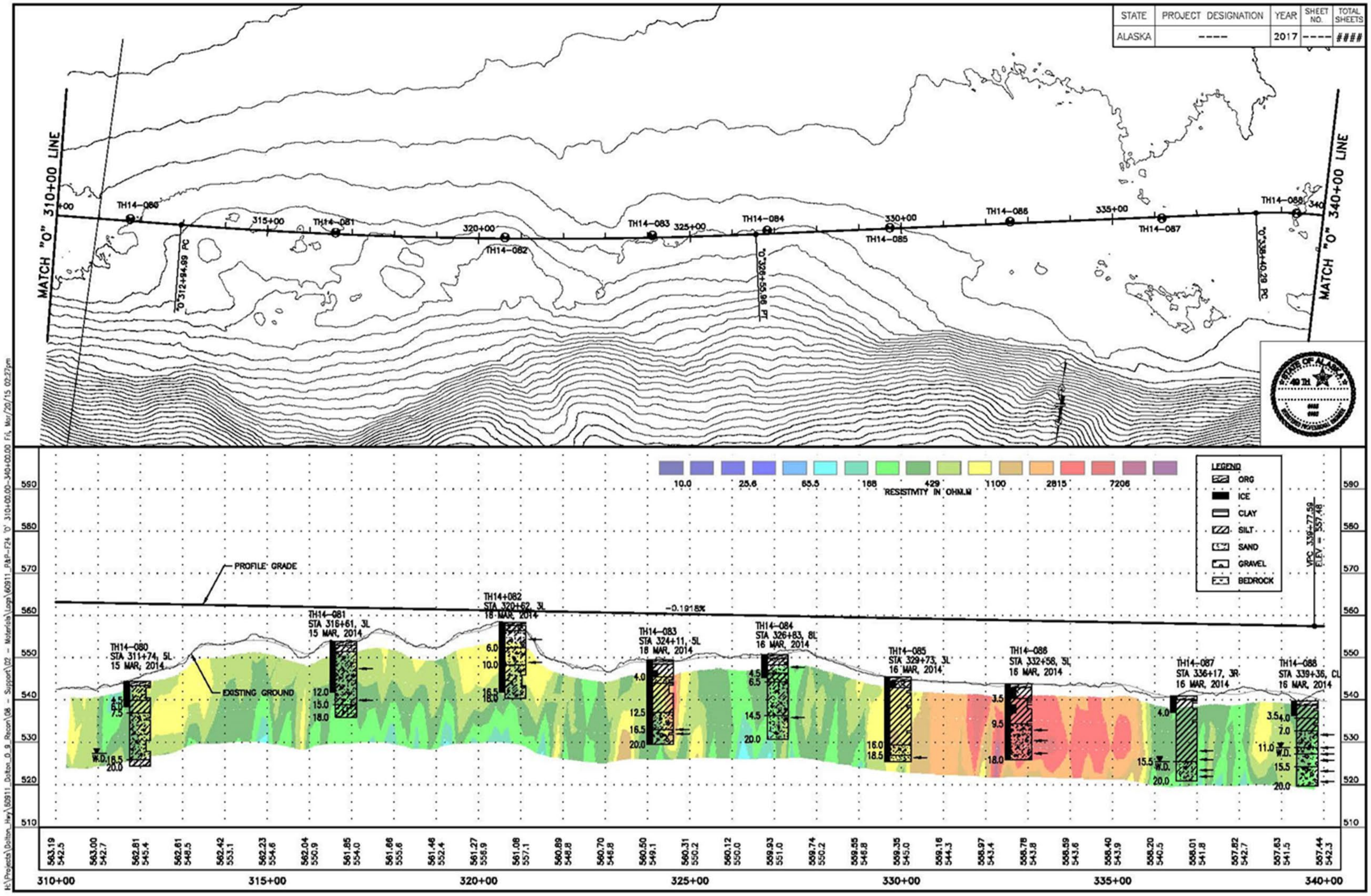


Figure 3-5 Station 310+00 to 340+00, 0 to 8 mile Dalton Highway Realignment. The ERT-CCR survey was conducted before the borehole drilling (units are imperial).

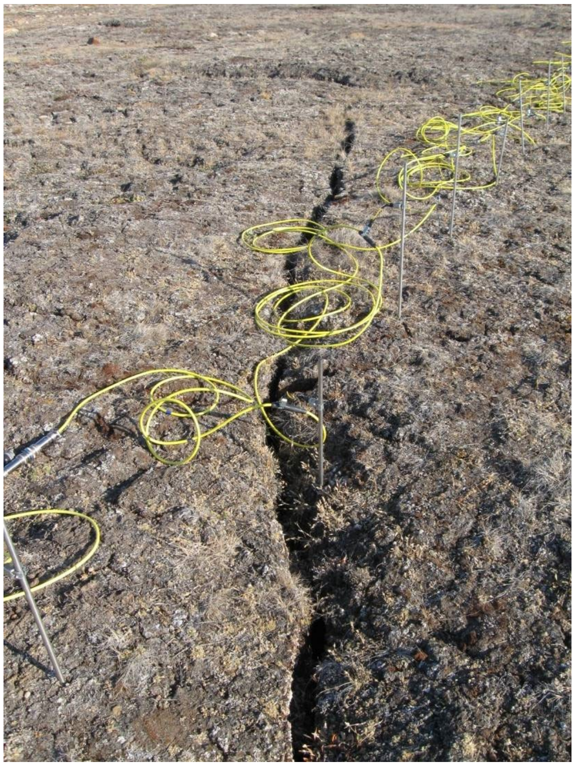


Figure 3-6 Direct coupled ERT system installed in tundra terrain.

Ground penetrating radar (GPR) is a common geophysical method used for subsurface imaging of stratified geological formations (figure 3-7) or isolated natural or manmade features such as buried utilities. GPR uses short pulses centered within the radio frequency spectrum, typically between 50 and 3000 MHz. Higher frequencies provide higher vertical resolution at the expense of penetration depth. Reflections are the result of changes in electrical properties defined by the relative dielectric constant ofeach material. Transitions from frozen to unfrozen and from wet to dry provide the strongest reflections, creating the utility of GPR in cold regions. Antenna units are typically dragged along the ground surface, recording the position every 50 or 100 m using non-differential GPS.

Good success in penetrating permafrost has been obtained in areas of floodplain alluvial sands and gravels (Delaney et al. 1990; Arcone et al. 1992, 1998). Penetration in ice-rich sands has reached 80 m and 40 m in deeply frozen moraines (Arcone et al. 2002). GPR measurements are routinely made along potential road corridors and existing pavements, gravels, or other substrates. In permafrost regions both thaw settlement and frost heaving cause degradation, for which investigation and mitigation are greatly aided by GPR surveys (Bjella, 2020).

Late winter frozen, well-graded, and gravel fill embankments in interior Alaska afford more than 10 m of signal penetration when an antenna frequency of 400 MHz is used. As such, GPR is useful in helping to route and design roads and in investigating problem spots along existing embankments. The results of GPR conducted over fine grained sediments, such as the air-borne silt (loess) of Interior Alaska, are mixed.

The mineralogical component of the glacially derived sediments can cause extreme attenuation of the GPR signal, specifically in the wet or frozen state (Arcone, 2008).

Figure 3-7 200-MHz antenna pulled over an airfield embankment.

Post processing of ground penetrating radar data can be time consuming and complicated depending onthe subsurface composition and desired features to be imaged. In general, GPR will provide good result where non-mineralogical clay minerals are present, such as in layered structures of manmade embankments, alluvial gravel deposits, and bedrock outcroppings. Where massive deposits of clay or siltare present, these strata attenuate the GPR signal, greatly decreasing resolution of features at even shallow depths. The presence of ground water also attenuates the signal, and fine-grained sediments such asclay and silt (loess) can be excellent harbingers of ground water, further attenuating the signal.

In figure 3-8, a radargram of a section of the Elliott Highway is seen before the most recent reconstruction. The layered structure is the repeated infilling of asphalt at a location experiencing continued and dramatic permafrost thaw settlement approximately 0.5 km north of Haystack Mountain Road. This survey was conducted with a 400-MHz antenna pulled behind a vehicle on a specially designed plastic cart.

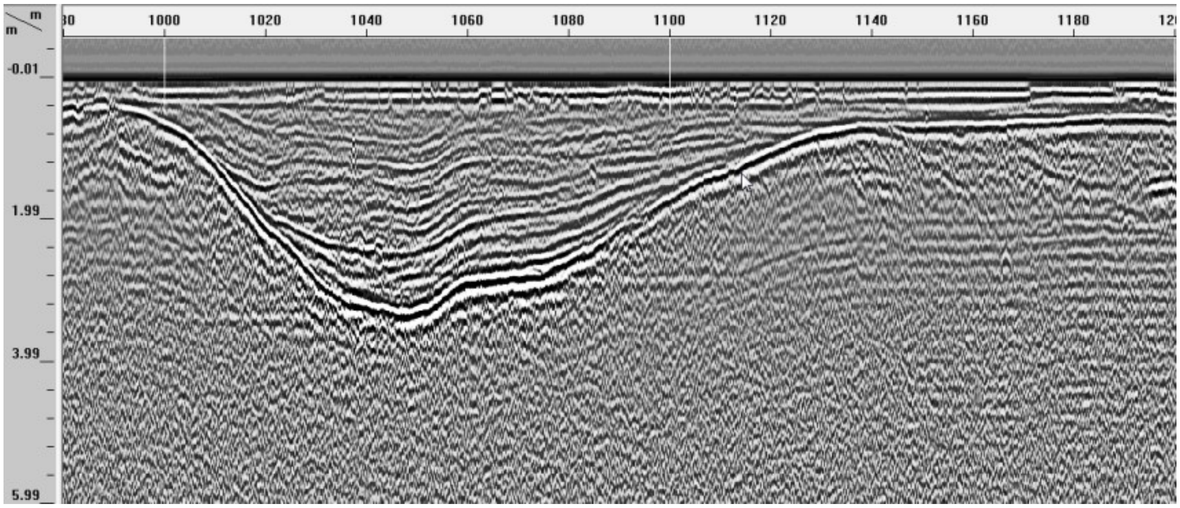
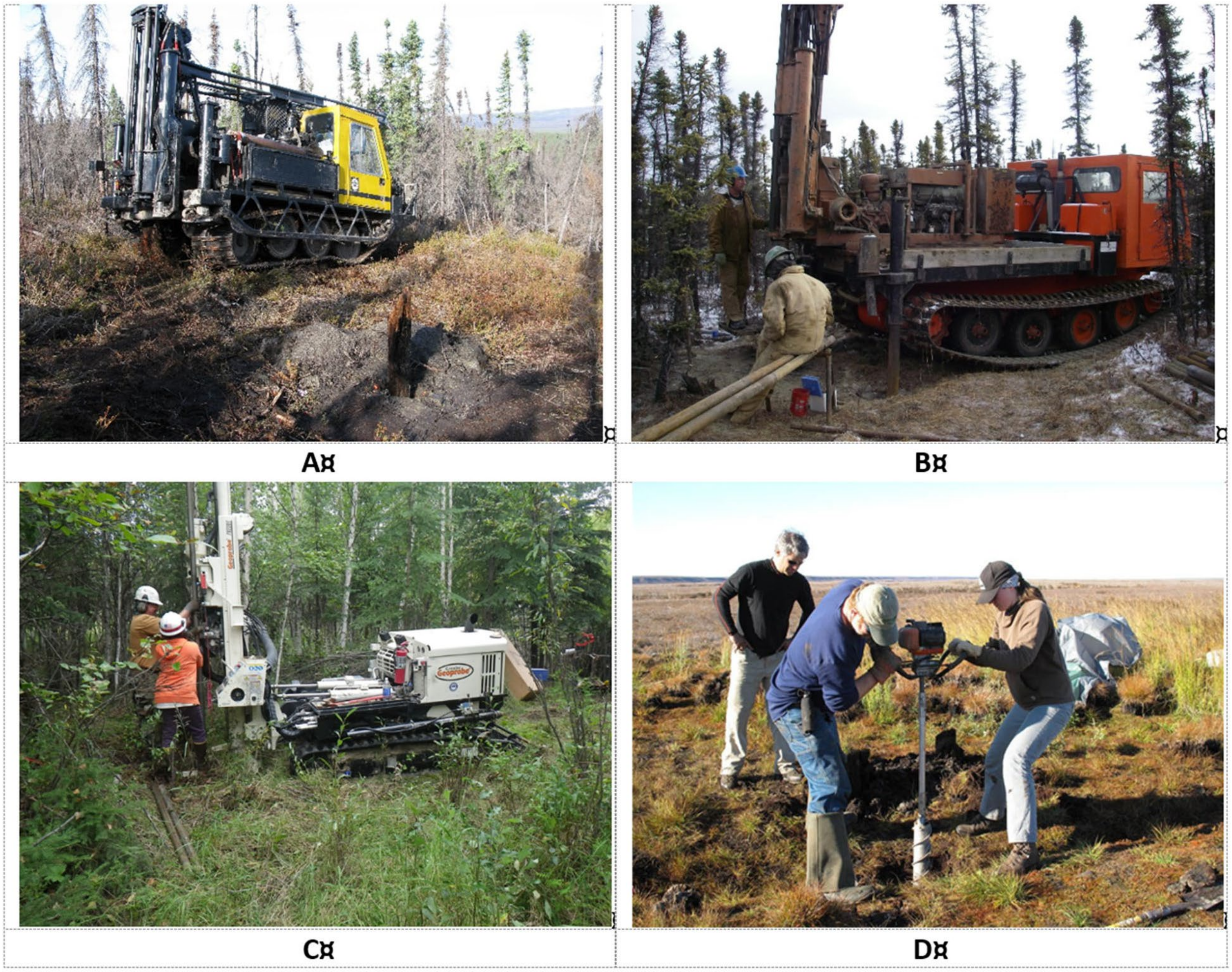


Figure 3-8 400-MHz GPR profile on the Elliott Highway, Fairbanks, Alaska. Deep thaw settlement can be seen.

3.4 Drilling, Logging, and Sampling

3.4.1 Drilling

Drilling remains the primary means of getting soil profile data even when geophysical data are collected, primarily because of the ease of soil property interpretation by visual means or by testing (figure 3-9). The most common practice is the use of a solid stem, hollow stem, or flight auger to bore and recover soil samples. Solid-stem drilling is relatively inexpensive and fast, allowing soil classifications, moisture content determination, and the ability to detect relative ice content. In areas where natural or artificial permafrost exposures are rare, drilling becomes a main source of geotechnical information. In many cases, this provides adequate information for the embankment design.


A

B

C

D

Figure 3-9 Drilling methods used for geotechnical studies in permafrost areas of Alaska.
A – Drill rig performing solid-stem and hollow-stem drilling at the Dalton Highway Innovation Project field site, May 2008; operated by DOT&PF crew; equipped with a modified CME sampler (2-in. inside diameter); depth of drilling – up to 30 m;
B – Drilling with a Nodwell mounted CME 55 drill rig with a 154-kg automatic hammer for split-spoon sampling at the HAARP field site, October 2007; performed by Discovery Drilling Inc. crew; depth of drilling – up to 20 m;
C – Direct-push Geoprobe drilling performed by CRREL crew, CCHRC field site, August 2014; depth of drilling – up to 20 m;
D – Drilling with the SIPRE corer, UAF AUTCproject, field site AR-6, Anaktuvuk area, September 2010; SIPRE corer (7.5-cm inner diameter) was equipped with a small (1.89 cu. in., 1.3 h.p.) two-stroke Tanaka TIA-340 engine; depth of drilling – up to 6 m.

Soil descriptions and samples obtained from the auger cuttings cannot be used for appropriate evaluation of permafrost structure and associated properties. Several drilling methods are commonly used in the permafrost region (Rand and Mellor, 1985; ADOT&PF,

2007; National Standard of Canada CAN/BNQ, 2017). The common practice of geotechnical investigation in permafrost areas of Alaska includes augering with solid flights (hollow-stem drilling) as a main drilling method and sampling of frozen soils with split spoons. Several split-spoon samples are usually taken from each solid-stem borehole. These samples are suitable for describing cryogenic structure, evaluating visible ice volume, and soil testing; however, information from several samples cannot be extrapolated to the whole section. Thesame problem exists for other drilling methods (rotary drilling, air drilling/downhole hammer)

For reliable geotechnical information, consider drilling boreholes by using continuous-coring methods in at least some part of a study area. A detailed description of boreholes helps clarify permafrost structure and origin and furthers the study of frozen soils properties with undisturbed samples. Without a good-quality core, it is impossible to distinguish the nature of ground ice. For example, massive ice bodies encountered by augering at different depths can be interpreted either as layers of tabular massive ice (figure 3-10A) or as syngenetic ice wedges (figure 3-10B). This problem can be solved only by studying undisturbed samples of ice obtained by a corer, or moderately disturbed samples of ice obtained by split spoons, hollow-stem drilling, or direct-push Geoprobe drilling.

The most significant consideration for augering in frozen soils is maintaining in situ temperatures below -3 degrees Celsius. Otherwise, the augers may conduct heat and melt the pore ice. Sampling with hollow-stem augers should be used with caution because the auger may become frozen in the hole. Thawing the device with a brine or antifreeze solution may release it, but this may cause the borehole walls to thaw and destabilize. The SIPRE ice corer has notable success coring both frozen soils and ice. These corers are motor-driven augers that are raised and lowered by hand, and they consist of 3-foot-long stainless-steel coring barrels with quick release drive heads and cutting heads with replaceable, carbide-tipped cutting bits. They return undisturbed cores typically 0.5-m long and 76 mm in diameter. SIPRE corers are portable with an average shipping weight of about 85 pounds, and do not require fluids. One disadvantage is that excess cuttings tend to accumulate above the barrel, which may jam the auger in hole.

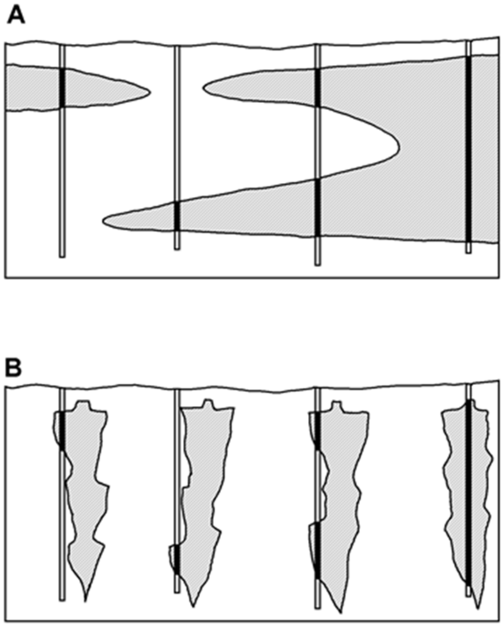


Figure 3-10 Alternative interpretations of massive ice bodies based upon drilling results: A – tabularmassive ice; B – syngenetic ice wedges.

Direct-push Geoprobes are forced into the ground by hydraulically powered presses or hammers. No rotational augering occurs, producing little to no cuttings. Typical probe depths are 9 to 18 meters. Probe heads can be either sampling or driving heads, where the small diameter probes do not disturb the surface as much as other drilling methods. This is important for drilling through roadways or runways, but the Geoprobes do tend to compress the soil horizons below the surface. Direct-push Geoprobes are most applicable for unconsolidated soils, but they have limited penetration in semi-consolidated soils and almost nopenetration in soils containing excess cobbles or boulders. Operators report effective penetration in frozen soils and permafrost conditions (Geoprobe Systems, 2019). Thus, while other drilling and sampling methods may have difficulty in keeping the soil frozen at depth without chilled drilling fluids, this method has future promise.

Wireline coring, a method commonly utilized for rock coring, can be used on frozen soils. One disadvantage is the potential for the latches on the core barrel to become frozen, preventing the cable from properly seating at the time of withdrawal. The benefit of not having to remove the drill assemblyeach time still makes this a good option, provided that the latches can be prevented from freezing.

The drill bits have a profound effect on the success of the operation in frozen ground. Chisel-edge, wedge-shaped, finger-style bits, diamond or tungsten tipped, have proved the most effective in frozen soils for rotational drilling. However, the soil-ice matrix must remain as solid as possible; otherwise, the material may crumble, become soft, with some localized thawing of the ice freezing to the drill string. This often prevents further cuttings from migrating up auger flights and prevents the drill bit from cutting and penetrating. Drill bits should be full-faced and stable (US Army Corps of Engineers, 2001). The cutters on the bit should not be irregular, chipped, or broken. Gouges and irregularities could develop on the core, and frictional melting could destabilize the core, the borehole or both.

Aggressive penetration rates could cause the core to break or the fluid ports in the bits' core barrel to become clogged or frozen. However, if the rate is too slow, or the bite is ineffective, small chips could melt and refreeze (US Army Corps of Engineers, 2001).

Frictional melting and heat conduction are additional concerns when drilling occurs in frozen soils. As mentioned earlier, drilling fluid acting as a coolant is sometimes used. In the past the type of fluid was often petroleum based, but this has been replaced with chilled brine solutions.

3.5 References

Alaska Department of Transportation and Public Facilities, Alaska Geotechnical Manual, (2007), Juneau, Alaska

Andersland, Orlando B. and Ladanyi, Branko (2004). Frozen Ground Engineering, second edition, John Wiley & Sons, Inc. & American Society of Civil Engineers, ISBN 0-471-61549-8

Arcone, S., Grant, S., Boitnott, G., & Bostick, B. (2008). Complex permittivity and clay mineralogy of grain-size fractions in a wet silt soil. Geophysics, 73(3), J1-J13.

Arcone, S. A., Prentice, M. L., & Delaney, A. J. (2002). Stratigraphic profiling with ground-penetrating radar in permafrost: A review of possible analogs for Mars. Journal of Geophysical Research: Planets, 107(E11), 18-1.

Arcone, S. A., Chacho, E. F., & Delaney, A. J. (1998). Seasonal structure of taliks beneath arctic streams determined with ground-penetrating radar. In Proceedings of the seventh International Permafrost Conference (pp. 19-24). International Permafrost Association, Canadian National Committee.

Arcone, S. A., Chacho Jr, E. F., & Delaney, A. J. (1992). Short-pulse radar detection of groundwater in the Sagavanirktok River floodplain in early spring. Water Resources Research, 28(11), 2925-2936.

Bjella, K., Ellison, A., & Maakestad, J. (2020). Allen Army Airfield Frost Heave. In Shoop, S. A. (Ed.). (2020, March). Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate. American Society of Civil Engineers.

Cao, Y., Dai, S., Labuz, J., & Pantelis, J. (2007). Implementation of ground penetrating radar.

Delaney, A. J., Arcone, S. A., & Chacho Jr, E. F. (1990). Winter short-pulse radar studies on the Tanana River, Alaska. Arctic, 244-250.

Johnson, G.H., (1981). Permafrost Engineering Design and Construction, Associate Committee on Geotechnical Research Council of Canada, John Wiley & Sons, ISBN 0-471-79918-1

Jorgenson, M.T. and Kreig, R.A., (1988). A model for mapping permafrost distribution based on landscape component maps and climatic variables. In 5th International Conference on Permafrost. Proceedings. Tapir Publishers, Trondheim, Trondheim, Norway (pp. 176-182).

Geoprobe (2019). Geotek Alaska Sonic Succeeds at Subzero. The Probing Times, Salina, Kansas, USA

Kreig, R.A., and Reger, R.D. (1982). Air-photo analysis and summary of landform soil properties along the route of the Trans-Alaska Pipeline System. DGGS, College, Alaska, Geologic report 66, 149 pp.

National Standard of Canada Can/BNQ 2501-500/2017 (2017). Geotechnical Site Investigations for Building Foundations in Permafrost Zones, Bureau De Normalisation Du Quebec, Standards Council of Canada, ICS 91.080.01;93.020

Rand, J. and Mellor, M., (1985), Ice Coring Augers for Shallow Depth Sampling. CRREL, Report 85:21,

Schnabel, W., Fortier, R., Kanevskiy, M., Munk, J., Shur, Y., and Trochim, E. (2014). Geophysical applications for arctic/subarctic transportation planning. Final report prepared for Alaska University Transportation Center, Project # 410018, INE/AUTC 13.01.

Shur, Y., and Jorgenson, M.T. (2007). Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes, 18: 7–19.

Shur, Y. L., & Jorgenson, M. T. (1998). Cryostructure development on the floodplain of the Colville River Delta, northern Alaska. In Proceedings of the Seventh International Conference on Permafrost (Vol. 57, pp. 993-1000). Centre d'études nordiques, Université Laval, Québec: Yellowknife, Canada.

US Army Corps of Engineers, Engineering and Design (2001). Geotechnical Investigation, Manual 1110-1- 1804, January, US Department of Engineers, Washington, DCTransportation Center, Project # 410018, INE/AUTC 13.01.

4.. THERMAL MODELING

4.1 Overview

Thermal modeling allows designers to understand the thermal impact of their designs. However, if the models are not used properly, they can also mislead the designer. This chapter discusses various techniques for estimating the soil temperature profile so that the designer can understand what method is appropriate. The chapter also discusses potential pitfalls and how to avoid them. The chapter does not instruct the designer on the details of running thermal models. It is assumed that they will reach out to others with the appropriate expertise. Rather the intent is to allow the designer to understand the limits of thermal models and to help them interpret the results.

4.2 Introduction to Thermal Modeling

In the paragraphs that follow a summary of basic heat transfer and thermal modeling is provided. Thegoal is to provide the designer with a basic knowledge of the physical processes involved, the various ways of approximating the thermal impacts of roadway designs, both simplified analytical approaches andnumerical models—and finally—the various pitfalls and complexities that can complicate modeling and interpreting results.

4.2.1 Physical Processes: Heat Transfer Modes

The movement of heat within a typical roadway structure is governed by three fundamental physical processes. These include thermal conduction, thermal convection or advection, and thermal radiation. Within the granular materials of a roadway embankment and its supporting foundation soils, the most prevalent heat transfer process is thermal conduction (also known as thermal diffusion), which is typically modelled with Fourier's Law of Heat Conduction. In its most general form, Fourier's Law can bewritten as a multi-dimensional vector equation:

$$\vec{q} = -k\,\vec{\nabla}\mathrm{T}$$

where $\vec{q}$ is the conduction heat flux vector, k is the thermal conductivity of the granular material, and ∇T is the temperature gradient. In the most simplified case (e.g., the vertical heat transfer into or out ofthe ground through the soil surface), Fourier's Law can be written as:

$$q_z = -k\,\frac{dT}{dz}$$

where q_z is heat flux in the vertical direction, and z is the depth below the ground surface. Fourier's Law represents the theoretical expression that governs the movement of heat through the granular roadwayembankment and foundation soils in response to temperature differences. It dictates that the movement of heat is directly proportional to the thermal conductivity of the material and the temperature gradient. Note that the negative sign in the expression simply indicates that heat will always flow from warmer to colder zones, in exact opposition to the direction of the thermal gradient.

The other two heat transport mechanisms, convection and radiation, are typically less common within the bulk of a granular material (either the embankment prism or foundation soils), but they can and dohave a big impact on boundary temperatures. One exception arises when the roadway structure is subjected to the flow of a fluid (either a liquid such as water or a gas such as air) through the granular material. Examples might include the seepage of melt water downslope through the base of an embankment, or the convection of pore air as occurs in air convection (ACE) embankments (to be discussed later). In such a case the moving fluid can carry a substantial amount of heat with it, either depositing or removing heat from the embankment structure as it flows. Such a process is known as heat convection, and when it occurs, it must be recognized and accounted for in the thermal modelingprocess.

More commonly, convection and radiation are processes that primarily affect boundary temperatures such as the temperature of the roadway surface or the embankment side slope. In this context, convection can be considered to be the physical process that connects surrounding atmospheric air temperatures to the temperature at the surface of the ground or embankment. In this case, the convective heat transfer that occurs between the ground/embankment surface and the surrounding air is a function of surface conditions, wind speed, and embankment orientation. Newton's Law of Cooling is often used to express convective heat transfer that occurs at a solid boundary:

$$Q = h\ (T_a - T_s)$$

where q is the heat flux into (or out of) the surface, h is the heat transfer coefficient, T_a is the air temperature, and T_s is the ground or embankment surface temperature. Note that the larger the heat transfer coefficient, h, the closer the surface temperature is to the air temperature. However, determining a value for h is complicated by wind speed and surface conditions, as mentioned above.

Thermal radiation is the result of thermally induced emission of electromagnetic radiation. All objects emit thermal radiation as a function of their absolute temperature. Thus, the ground/embankment surface will emit thermal radiation, sending it away, typically toward the sky. At the same time, the skyand or sun will emit thermal radiation that is received by the ground/embankment surface.

Fundamentally the radiation process is governed by the Stefan-Bolzmann Law:

$$q = \varepsilon \sigma T^4$$

where q is the heat flux away from the surface, ε is the surface emissivity, σ is the Stefan-Bolzmann constant, and T is the absolute temperature of the surface. In terrestrial applications, radiation transfer is typically broken into long-wave and short-wave contributions. As a result of Plank's Law, the wavelength of emitted radiation is tied to the temperature of the surface, with surfaces at environmental temperatures (such as the ground/embankment surface or atmospheric air masses) emitting long-wave radiation and very hot objects (such as the sun) emitting short-wave radiation. At the ground/embankment surface, it is the net radiation flux that becomes important in determining surface temperatures.

Convective and radiative heat transfer at the ground/embankment surface will be discussed further in Section 4.3.2 in relation to surface boundary conditions for thermal modeling applications.

4.2.2 Energy Balance

To formulate a numerical model that can be utilized to solve for embankment and foundation soil temperatures, it is necessary to carry out an energy balance on a representative volume of the granular material. Thinking for a moment about a small control volume of the granular material that forms either the embankment or foundation soil structure, the temperature within that volume will be determined by how much thermal energy (heat) enters the volume in comparison to the material's ability to store that energy. Adding heat to the control volume will generally cause its temperature to increase, or, if ice exists within the control volume, it may cause some melting to occur. Conversely, removing heat may cause a temperature reduction or freezing to occur. Both the solid granular particles and any pore waterpresent in the material can store thermal energy, but only the pore water will undergo freezing or thawing. Energy storage associated with freezing or thawing of the material is known as latent heat, whereas energy storage that increases or decreases the temperature of the material is known as sensible heat.

Collectively, the ability of the material to store heat is measured by its volumetric heat capacity, which can have both sensible and latent heat components.

For steady state heat transfer in a granular soil system (i.e., temperatures do not change with time), the energy balance is simplified because there is, by definition, no change in energy storage over time within the granular material. However, steady state heat transfer generally does not occur in roadway embankment situations because of the changing yearly and daily ambient temperatures. For unsteady heat transfer it is necessary to balance the net heat flux into a representative volume with the material's ability to store that heat. For instance, for materials with high heat capacity values or materials that are undergoing freeze/thaw (and thus have a large latent heat capacity), the representative volume may be able to absorb or reject a large amount of heat with only a minimal change in temperature. By formulating a basic energy balance using the first law of thermodynamics (conservation of energy), a numerical equation can be derived for the temperature change of the representative control volume as a function of how much heat is entering or leaving to neighboring control volumes. These control volume equations can then be stepped forward in time, producing a time series of control volume temperatures and providing the designer with a picture of how temperatures vary throughout the embankment and foundation soil over time. This is the essence of how a numerical thermal model is developed. The details of control volume construction depend on the geometry of the problem and the type of numerical model (typically finite difference or finite element) that is being employed. In the end the model will produce a collection of control volume temperatures at varying times as the surface temperatures of the embankment or ground change. For most embankment thermal modeling applications, net heat transfer into each of the control volumes is governed by thermal conduction.

However, as mentioned above, if there is a moving fluid, such as percolating or flowing ground water, or moving pore air, as in an ACE embankment, then thermal convection can play a dominant role in transferring heat between the control volumes and, therefore, must be accounted for in the model.

4.2.3 Physical Domain

Most highway embankment analyses can be considered two-dimensional (2D). That is, the temperatures in the embankment and underlying foundation soils vary substantially with depth and vary across the embankment cross-section from centerline to toe and out into the undisturbed ground. Near the embankment centerline, temperatures will be affected by annual variations of the driving surface temperature and by the thermal properties of the embankment material, which are generally quite different than the properties of the underlying native foundation soils. In some cases, however, it may be possible to simplify the problem to one dimension (1D, typically this would be the vertical direction), or it may be necessary to include heat transfer in the centerline direction, making the problem three-dimensional (3D). A 3D analysis may be necessary, for instance, if there is substantial ground water flow and temperature variation in the direction of the road centerline.

The question of whether to use a 1D, 2D, or 3D analysis essentially boils down to a question of anticipated temperature differences in the embankment and foundation soils. Generally, the largest temperature differences occur between the upper surface and the layers of granular materials below. This, in turn, implies that the largest and most significant heat transfer will occur in the vertical direction. On the other hand, sometimes there are large differences in temperature between the embankment centerline and the shoulder area. As an example, this could be the case for a paved highway that is plowed in the winter, with most of the snow then accumulating on the side slope. For this situation, low winter air temperatures would result in a relatively cold asphalt surface, but warmer shoulders because of the insulating effect of the snow. In this case, which is somewhat typical, there can besubstantial horizontal temperature differences and, thus, important heat transfer effects in both the vertical and horizontal directions, making the problem 2D.

1D problems are sometimes amenable to simplified modeling solutions. Some of these 1D techniques are discussed in section 4.4. On the other hand, 2D problems require some sort of numerical solution that will entail much more work on the part of the designer or consultant than a simplified 1D analysis.Looking to even more complex problems, it is possible to conduct a numerical analysis of a 3D problem, but the resources required to do so will be substantial and may not be justified or even be possible within typical design budgets.

Once the dimensionality has been settled on, an appropriate model domain must be determined. For a 2D model, the model domain should extend from the upper surface of the embankment/ground to some depth. The depth should generally be set large enough that no appreciable annual temperature fluctuations are expected at the lower boundary of the model. The lateral boundaries could be set at the embankment centerline (so long as symmetry about the centerline can be assumed) and at a distance significantly away from the edge of the embankment toe such that the thermal influence of the embankment no longer impacts temperatures. This implies that the heat transfer at the outer lateral boundary should be 1D, in the vertical direction only. Understanding these requirements will allow the designer to determine whether an adequate model domain has been utilized by simply examining the temperatures produced by the thermal model.

4.2.4 Time Domain

Given that roadway embankments are subjected to substantial surface temperature variations, we can anticipate that the temperatures within the granular embankment materials and foundation soils will be variable, depending on the time of year or perhaps even the time of day. The important time scales can vary from hours to many years, but typically the annual temperature cycle with thawing occurring duringsummer and re-freezing occurring in the winter is of greatest interest. With that in mind, a numerical thermal model would typically be run for several seasons, with a time step on the order of a day to obtain an idea of annual thaw or freeze depths.

When determining the time scales to use for thermal modeling of a roadway embankment, several important factors must be considered. These include the purpose of the modeling effort, which might be to control frost heave beneath an embankment, to avoid annual thaw into an ice-rich permafrost layer, or to avoid long-term thaw of warm permafrost. In addition, the time scale of the modeling program could be affected by the level of knowledge regarding the initial temperatures of the embankment material and underlying foundation soil. This results from the fact that the model will start with these measured (or approximated) initial temperatures and then trace out future thermal behavior on the basis of that initial temperature distribution. If the initial temperatures are only poorly known, then a longer simulation run time (many yearly annual cycles) may be needed to reduce the impact of the approximated initial temperature distribution.

For roadways that are constructed in non-permafrost areas, the primary reason to conduct a thermal modeling effort would be to avoid potential frost heave due to freezing of frost susceptible materials at the base of the embankment. For a problem such as this, a numerical analysis could be performed by using measured pre-construction ground temperatures and a total run time of a few years. In this case the model should quickly converge (within a few annual cycles) to a repeatable annual freeze/thaw pattern,thus giving the designer a good idea of whether freezing might reach frost susceptible material.

For roadways constructed in permafrost areas, two potentially problematic scenarios are possible. For locations with cold permafrost (defined here as permafrost that is cold enough that it is unlikely to experience large-scale thawing), the designer needs to be concerned about the annual thaw depth to ensure that it does not penetrate the surface of the pre-existing permafrost layer. In this case it may also be possible to conduct a sufficient numerical analysis by using the measured pre-construction ground temperatures and a model run time of a few years. As for the non-permafrost case, this type of modeling effort could be expected to converge to a repeatable annual freeze/thaw pattern within a few annual cycles, thus indicating whether thawing into the permafrost layer will be an issue.

For roadways constructed in warm permafrost areas, as found in much of interior Alaska, the purpose of the modeling effort might be different still. In this case, it is likely that the warm embankment surfaces may cause large-scale, long-term thawing of the permafrost layer underlying the roadway. To accuratelydetermine the extent of any large-scale thawing, a model simulation time of many years (maybe as many as 30 to 50 years) may be needed. This is a result of the fact that thawing of a large permafrost mass will require the addition of a substantial amount of heat, which will happen only slowly over time, particularly if insulation is used in the roadway. Conducting a multi-year thermal analysis such as this may give the designer an idea of the level and intensity of maintenance problems to expect, which could influence the types of mitigation strategies considered in the design process.

4.3 Data Requirements

Several types of data are needed to conduct a thermal modeling analysis. These include the thermal properties of the materials that make up the embankment and foundation soils, appropriate boundary condition data, and initial temperature data. The thermal properties can generally be determined from a knowledge of the soil and embankment material types and moisture content. Boundary conditions include the temperatures at the upper surface of the ground and embankment as a function of time, and information regarding the geothermal flux of heat that enters the bottom boundary of the model.

Initial temperatures are probably most appropriately based on direct measurement of temperatures before/during the construction process. For example, these could include pre-construction soil temperature profiles as measured by a temperature string and embankment material temperatures measured during construction (or assumed on the basis of handling and ambient air temperatures).

4.3.1 Material Properties

Thermal properties of soils and granular materials are a function of mineralogy, texture, porosity, and moisture content. With a knowledge of these material parameters, it is possible to use a variety of different correlations or charts to determine thermal conductivity, heat capacity, latent heat, and permeability (important for modeling the convection of ground water or pore air), which are the suite of thermal properties needed to support thermal modeling. Depending on the amount of moisture presentin the material, the thermal conductivity and sensible heat capacity will vary substantially between the frozen and thawed states. This is a result of the fact that liquid water and ice have different thermal conductivities and sensible heat capacities.

One common source of thermal conductivity data is the earlier work of (Kersten, 1949), who produced graphical correlations for soil thermal conductivity data. Kersten produced thermal conductivity plots forsands and gravels, for silt and clay soils, and for peat and organic soils, for both the frozen and unfrozen states. In the graphical correlations, the thermal conductivity values were given as a function of the material's dry density and moisture content. Kersten's original work has been reanalyzed and reformatted by several subsequent authors and is also available in Andersland and Anderson, 1978, as well as Farouki, 1981. In addition to Kersten's graphical data, Johansen provided several correlations for thermal conductivity, including correlations for the thermal conductivity of crushed rock, which may be important when air convection embankments are modeled (Johansen, 1975).

While thermal conductivity is complicated to determine because of the microscopic heat conduction path through a mixture of solid material grains, pore air, and pore water/ice, heat capacity values are a more straightforward function of the constituents. As a result, the thawed and frozen sensible heat capacity of a granular material system can be calculated simply on the basis of knowledge of the dry density of the material and the water and/or ice content. Similarly, latent heat values can be calculated simply on the basis of the moisture content of the material. Equations and methods for calculating sensible and latent heat for soils and other granular materials can be found in in the geotechnical engineering literature, see for example Andersland and Anderson (1978) or Andersland and Ladanyi (1994).

For situations in which the flow of a pore fluid (water or air) is suspected, it will be necessary to add the permeability to the list of important material properties. Where ground or surface water flow is expected to affect the thermal regime beneath the embankment, analysis options are limited and often complicated by lack of knowledge of exact geometries, particularly if water channeling is expected in a confined zone beneath the embankment. On the other hand, for air circulation in air convection embankments or ventilated shoulders (see Chapter 5 for further details), it is often possible to define geometries and material properties accurately enough that a thermal modeling study can be completed. However, these analyses are also more complicated because of the need to solve the governing equation for air flow as well as for temperatures.

From the designer's perspective, the important consideration is that an accurate thermal analysis will rely on accurate knowledge of both the foundation soil properties and the properties of the embankment materials. These will include soil type, dry density, moisture content, and in some cases accurate gradation curves. During site investigation it will be necessary to do adequate testing to ensure that, for instance, foundation soil properties are known from the surface to depths of approximately half the embankment width. In addition, some amount of source pit sampling will also be needed to accurately characterize the properties of the embankment materials themselves. If substantial changes in moisture content occur throughout the annual cycle or are expected during the lifetime of the project, this should also be characterized as completely as possible and passed on to those who may be conducting the thermal modeling analysis.

4.3.2 Boundary Conditions and the Surface Energy Balance

In addition to accurate characterization of material properties, a thermal model will also be reliant on detailed knowledge of temperature behavior at the boundaries of the model, including the ground or embankment surface, and the lateral and lower boundaries of the model. As indicated in section 4.2.2,the lower boundary of a model domain should be placed at a sufficient depth below the surface that minimal annual temperature variations are expected. Under those circumstances, the governing boundary condition at the lower boundary will consist of a geothermal heat flux specification.

Geothermal heat flux is generally on the order of 0.06 W/m^2 but can vary across the state. See Batir, etal. (2013) for more details.

For the lateral boundaries of a 2D (or 3D) model, it is usually possible to assume zero heat flux (implying temperature changes only in the vertical direction), so long as the lateral boundaries are located at a symmetry plane (e.g., potentially the embankment centerline) or moved outward away from the embankment into the undisturbed native vegetation zone.

By far the most complicated boundaries are those of the ground and embankment surfaces. Temperatures at these surfaces are governed by interaction with the atmosphere and are complicated by changing surface conditions throughout the yearly cycle, such as the presence or absence of a snowlayer. They may also be even further complicated by climate change, depending on the lifetime of the project and expected changes in atmospheric conditions over that time.

The most comprehensive and most accurate way to treat the upper surface boundary condition is to carry out a comprehensive surface energy balance. In such an analysis the entire array of important heat transfer interactions between the surface and the atmosphere are considered and balanced to calculate the heat entering or leaving the upper boundary of the model domain. Important components of the surface energy balance include the net incoming radiation (both short-wave and long-wave components), convective heat transfer between the surface and the air, and any energy transfer associated with evaporation/condensation/sublimation of surface moisture. A common form of the surface energy balance equation can be represented as follows:

$$Q_g = Q_{net\ rad} - Q_{conv} - Q_{evap}$$

where Q_g is the heat entering the ground or embankment surface, $Q_{net\ rad}$ is the net radiation heat flux arriving at the surface, Q_{conv} is the convective heat loss from the surface to the atmospheric air, and Q_{evap} is the energy loss from the surface associated with evaporation/ sublimation/ condensation of moisture. The net radiation term is driven primarily by incoming solar radiation, but long-wave radiation away from the surface (especially during clear nights) also has a big impact on surface heat transfer. The convective heat transfer is determined by the difference between surface and air temperatures and the heat transfer coefficient (see the discussion of Newton's Law of Cooling above). The heat transfer coefficient is a complex function of surface roughness, wind speed, and buoyancy. Finally, the energy transfer from the surface due to evaporation/sublimation/condensation is a function of surface moisture conditions and relative humidity in the atmospheric air mass. Many researchers have reportedon the importance of these various surface energy balance terms in arctic conditions (Hinzman, et al., 1998).

As is evident from the discussion above, carrying out a complete surface energy balance for a typical roadway embankment modeling exercise is both analytically challenging and data intensive. To characterize the surface energy balance terms accurately, comprehensive meteorological data are neededat the site. Meteorological data are collected with a data station that includes air temperature and relative humidity instruments at multiple elevations above the ground, in addition to wind speed anemometers and net radiometers. These instruments would typically be polled multiple times per day and records would need to be available for the entire yearly annual cycle. If such data are available, they can often be used in commercial thermal modeling packages to provide an accurate simulation of surface conditions and, thus, improve the quality of the thermal model output. Unfortunately, such comprehensive data are usually not available, so modeling efforts often must utilize simplified methods for handling the surface boundary condition.

The most common method for simplifying surface boundary conditions involves the use of a surface N-factor. A comprehensive description of the N-factor methodology was published by Lunardini (1981). The method recognizes the fact that the most important factor in determining surface temperatures is the atmospheric air temperature. However, the correlation is not exact because of the other terms in the surface energy balance. Measurements have indicated that ground or embankment surface temperatures are often warmer than air temperatures during both winter and summer. During winter conditions this situation can result from the insulating effect of snow cover, which tends to keep the ground surface warmer than the winter air. During summer, the warmer surface conditions can be traced to heating of the surface by solar radiation.

In the N-factor approach, the fine details of the surface energy balance described above are included only in an approximate, yearly average sense. This allows treatment of the surface boundary condition based on knowledge of air temperatures alone, which are often easier to acquire for a given project site than all the individual surface energy balance components. For the winter freezing season, the freeze N-factor is defined as:

$$N_f = \frac{I_{sf}}{I_{af}}$$

where N_f is the freeze N-factor, I_{sf} is the surface freezing index, and I_{af} is the air freezing index. The air freezing index for the winter season can easily be determined from air temperature measurements as the sum of the number of integrated degree-days that the air temperature is below freezing. Given freeze N-factor data appropriate for the conditions being considered, the surface freezing index can then be calculated by using the equation above. Similarly, for the thawing season:

$$N_t = \frac{I_{st}}{I_{at}}$$

with parameters defined the same as above for the thawing season. Using the same considerations as for the freezing case, the equation above allows the calculation of the surface thawing index. The surface freezing and thawing indices, thus obtained, can then be used to establish surface boundary conditions for the thermal modeling effort.

While the N-factor approach described briefly above can dramatically simplify the treatment of the ground/embankment surface for the purposes of thermal modeling, there are potential pitfalls with this method that the designer should be aware of. First, the existing N-factor data are based on field measurements and are categorized by surface type; see Lunardini (1981) for data for various types of surfaces. Snow cover has a large impact on heat transfer between the ground/embankment surface and the atmosphere, so it is particularly important to understand how the effects of a potential snow cover have been included (or excluded) from N-factor data for the freezing season. In addition, average wind speed in each location also has a strong influence on N-factors. The U.S. Army Corps of Engineers completed a study of thawing N-factors and showed that N_t decreases by about 50 percent as average wind speed increases from 1 to 15 mph (Department of the Army, 1966). As a practical approach, it may be advisable to bracket model calculations by using a range of N-factor data to better understand the influence of the surface boundary condition on the output of the thermal model.

4.4 Analytical Modeling

If the design conditions warrant a more simplified modeling approach, then an analytical thermal model (as opposed to a numerical model) may be a viable option. In general, analytical modeling will be limited to 1D situations where the important heat transfer occurs only in the vertical direction. As discussed above, roadway modeling situations often violate this condition because of the differences in the thermal behavior of the driving surface, as opposed to the snow-covered embankment side slopes and native ground cover. This variation of surface conditions across the right-of-way leads to a significant amount of lateral/horizontal heat transfer and tends to reduce the accuracy of 1D analytical modeling. However, the effort associated with 1D modeling is dramatically lower than that required fora multi-dimensional numerical model and may be a better choice for projects that are deemed to be more insensitive to thermal impacts or for cases in which limited project funding is available. As an example, 1D models may be adequate to predict the annual thaw depth at the centerline of an embankment located in an area of continuous permafrost.

In the following sections a summary is provided for four different analytical modeling techniques, ranging from the simpler to the most complex. The intention here is to provide the designer with an appropriate background so that decisions can be made regarding model complexity, rather than providing detailed instructions on employing the modeling techniques.

4.4.1 Stefan and Whiplash Solutions

The two most simplified 1D models are the Stefan freeze/thaw analysis and the Whiplash curve solution. Each of these methods can be used to estimate an annual depth of freeze or thaw, but both have significant simplifications that limit the accuracy of the results for a given set of circumstances. For both methods, the surface boundary conditions as discussed above, typically characterized by the surface freezing and thawing indices, are used to drive the analysis. Both methods rely on accurate knowledge of the material properties and both assume that the material is uniform in the vertical direction. This may be a reasonable assumption for a gravel embankment with a uniform type of material between the upper surface and embankment base.

The primary difference between these two methods lies in the way that they incorporate the effect of the heat capacity of the material (refer to section *4.3.1* above). In the Stefan analysis, the sensible heat of the material is neglected, and the fundamental assumption is that all the heat either added or removed fr [illegible] ancing either the thawing front or the freezing front, depending on the [illegible] approach, the Stefan analysis tends to be more accurate for materials that are highly saturated with water. In this case the heat entering or leaving a given material volume will be used primarily for thawing or freezing of the material, with relatively little energy used to change the temperature away from the freezing point. As such the Stefan method can be used accurately to calculate the depth of a forming ice layer on a lake surface. For the thawing case the Stefan solution can be written as follows:

$$X = \sqrt{\frac{2\,k\,(T_s - T_f)\,t}{L}}$$

where X is the depth of thaw after a time interval t when the surface is exposed to a temperature T_s that is above the thawing temperature T_f. In the equation above, k is the thermal conductivity of the material and L is the latent heat. Also, note that $(T_s-T_f)t$ can be replaced with the surface thawing index. See Andersland and Anderson (1978) for more discussion on how to use this model equation and its limitations.

As opposed to the Stefan solution, the Whiplash curve analysis neglects latent heat and includes only the sensible heat effect. As a result, this method is more accurate for very dry materials that do not contain a substantial moisture content, such that all heat energy added or removed from the material goes toward changing its temperature as opposed to freezing or thawing. Such an analysis could be relatively accurate, for instance, in the case of solid bedrock with little water content. This solution is often illustrated as a sinusoidal annual temperature fluctuation at the ground surface with an exponentially decaying amplitude with depth. See Andersland and Ladanyi (1994) for a discussion of the Whiplash curve equations and graphical illustrations.

4.4.2 Neumann Solution

For real-world roadway problems, it is unlikely that the conditions for use of the Stefan or Whiplash curve methods will be met (i.e., extremely wet or extremely dry materials). As a result, it is valuable to move up one level in 1D model complexity and consider the Neumann problem. In the Neumann analysis it is assumed that the problem starts with a uniform soil column that is initially either frozen or thawed. At the beginning of a given time period the ground surface is then exposed to a temperature either above or below the freezing point, and the soil column begins thawing or freezing from the top down, respectively. The added complexity occurs because the Neumann analysis includes consideration of both sensible and latent heat and can also account for differences in the frozen and thawed properties of the soil. An analytical solution to this problem was derived by Neumann in 1860 and is reported on in detail in Carslaw and Jeager (1959), with applications to geotechnical freeze/thaw problems discussed in Andersland and Anderson (1978). While the mathematics are a bit more complicated with the solution including the Error Function, it is possible to implement the Neumann solution in a spreadsheet for use in soil freeze/thaw calculations.

4.4.3 Modified Berggren Method

The Modified Berggren method can be thought of as a layered version of the Neumann solution that allows the calculation of freeze or thaw depths in layered systems. This method is more applicable to roadway embankment problems because the embankment prism usually consists of horizontal layers ofdifferent material types, perhaps even including insulation layers. For a freeze depth situation, the Modified Berggren Method allows the designer to calculate the amount of surface freezing index needed to freeze each layer of the system. Once all the surface freeze index has been used for a given winter season, the final freeze depth can be obtained. A similar procedure can be utilized for calculating the annual depth of thaw in a permafrost area. The Modified Berggren method does account for both sensible and latent heat, so it is a fairly accurate method for calculating annual depth of freeze/thaw, in a layered system, albeit it is limited to 1D vertical freeze/thaw as are the other analytical modeling methods discussed here. Andersland and Landanyi (1994) provided a practical guide and some examples for using the Modified Berggren method to solve foundation problems. This method is also amenable to spreadsheet implementation.

4.5 Numerical Modeling

While the analytical methods discussed in Section 4.4 offer the designer a relatively simple way to estimate freeze or thaw depths in 1D situations, there are no known analytical solutions for the more complex 2D or 3D situations associated with modeling of an entire embankment profile. As discussed in section 4.2.2, roadway embankment problems typically have differences in surface conditions across the embankment profile that result in 2D heat transfer. Under these circumstances it will be difficult to ensure accurate freeze/thaw depth analysis using the 1D analytical solutions described above. As a result, all comprehensive thermal modeling studies of roadway embankments are completed by using numerical methods. The advantage of utilizing numerical methods is that any level of detail or complexity can be incorporated in the model so long as adequate knowledge of material characteristics and boundary conditions can be obtained. On the other hand, the disadvantage is the amount of effort required to build a comprehensive numerical model of a real-world situation and the time it typically takes to obtain and analyze the results. Once obtained, however, the results will offer the designer the knowledge of specific temperatures throughout the embankment and foundation soils as a function of time. If thawing of an underlying permafrost layer is a concern, the numerical model output should be able to provide a timeline for such thaw and would also indicate zones where the thaw rate is highest.

Such information could be valuable in terms of designing mitigating measures such as placement ofinsulation or use of ACE structures.

At a fundamental level, all numerical thermal modeling procedures begin by determining the physical boundaries of the spatial domain to be simulated and then breaking that domain up into small control volumes by using some sort of discretization scheme. In general, the discretization ends up generating a set of nodal points that are associated with the control volumes and dispersed throughout the model domain. A set of numerical equations are then developed for each of the control volumes and solved simultaneously to advance the temperature solution from time step to time step. In this way the temperature behavior at each of the nodes is traced out over time, giving the designer a detailed view of the temperatures throughout the embankment and foundation soils as time evolves.

4.5.1 1D Finite Difference/Finite Element Models

1D numerical models are substantially simpler than their 2D or 3D counterparts, mostly because the discretization scheme is quite simple and will consist of a series of nodal points starting at the upper surface boundary and extending down into the soil column to depth. Given the 1D nature of such models, they suffer from the same issues as the 1D analytical methods discussed above in that they are unable to account for differences in surface conditions between the driving surface, side slopes, and native ground cover that likely result in lateral heat transfer. For this reason, 1D numerical models do not offer much advantage over the analytical methods described above and are not used very often in practice. However, one potential advantage is that they can be configured to incorporate many of the complexities in surface boundary conditions and material characteristics that are hard for analytical methods to deal with. For example, if meteorological data are available for the site, it would be possible to drive the surface boundary condition with a full surface energy balance model. In addition, a 1D numerical model can easily incorporate multiple layers of materials with different properties and is capable of tracing out the thaw/freeze behavior over a multi-year period, thus indicating the potential for long-term thaw of a pre-existing permafrost layer.

4.5.2 2D and 3D Finite Element Models

Thermal modeling of a complete roadway embankment profile will require at least a 2D analysis (see discussion of model physical domains in Section 4.2.2). Modern 2D and 3D numerical models are generally based on the Finite Element method because of the flexibility of the method's discretization techniques. The flexible elements that are used to represent the domain consist of different geometricalshapes and sizes that allow the modeler to accurately represent complex boundaries and to use smaller elements in areas where sharper temperature changes are expected. This allows efficient and accurate solutions to be obtained.

The complexity of 2D/3D numerical modeling generally requires the use of pre-existing commercial (or potentially public domain) software. These methods are not amenable to spreadsheet implementation by a designer or consultant. It is also likely that supporting software will be needed to visualize the results, both over the spatial extent of the simulated domain and over time. Depending on the purpose of the analysis, output may be needed over a series of many annual cycles. This is particularly true if climate change impacts or long-term multi-year thaw of permafrost are being investigated.

Several commercial simulation packages are available to help analyze typical roadway geotechnical problems (more about those in section 4.5.6). In their simplest forms, these models begin with known or assumed initial temperatures for the domain and then use the entered material properties and boundary conditions to calculate temperatures within the modelled domain as time evolves. If it is anticipated that there will be no pore fluid motion within the domain (no ground water flow nor substantial movement of pore air), then the modeling package solves the heat transfer equation assuming that only thermal conduction occurs within the domain. This is generally a good assumption for normal, well-graded embankment materials and foundation soils as long as no concentrated groundwater (or surface water) flow pathways exist.

4.5.3 Modeling Advection

In some cases, it may be necessary to consider the impact of flowing pore fluids (advection). Doing so requires quite a bit of additional knowledge regarding the type of moving fluid (water or pore air) and the mechanism(s) responsible for fluid movement. Pore water moves in reaction to some sort of hydraulic gradient, perhaps due to impoundment of surface water on an uphill embankment toe. If this type of water flow occurs it could have incredibly significant impacts on temperatures beneath the embankment. In this case, the equations governing pore water flow need to be solved as part of the numerical simulation because the thermal model needs to include the impact of any heat carried through the domain by the moving pore water. Most finite element modeling packages are capable of modeling pore water flow and the impact of that flow on the temperature field, but the model inputs now need to include information regarding material permeability and hydraulic gradients across thedomain. Theoretically this information could be gathered through material testing and stand tubes in the field to record water head at the boundaries of the model domain, but this adds significant complexity to the modeling exercise.

Another possibility for advection includes the effect of moving pore air. Generally substantial pore air motion only occurs in materials that have extremely high air permeabilities, such as those used for the construction of air convection embankments (ACE). ACE materials typically consist ofpoorly graded aggregate with a large particle size (on the order of 2 inch (5 cm) or above). In such cases,pore air motion usually only occurs because of temperature-induced buoyancy differences within portions of the embankment, although wind-driven air circulation is a possible as well. As in the case of pore water flow, the impact of pore air flow needs to be considered by the numerical model, and the pore air flow equation needs to be solved simultaneously alongside the heat transfer (energy) equation. For density driven pore air flow (also referred to as natural convection) it is the variation in temperature throughout the domain that results in pore air motion. This situation is somewhat simpler than the case of ground water flow (which is driven by external hydraulic gradients). For a situation suchas encountered in an ACE embankment, the problems become coupled in that the pore air flow vectors must be calculated on the basis of the current temperature distribution, and the calculation of the temperature distribution requires knowledge of the air flow vectors. Several commercial packages can solve the pore air flow and temperature equations simultaneously, thus allowing the designer to examine the impacts of pore air motion on the thermal behavior of the embankment and underlying foundation soils.

4.5.4 Model Verification and Numerical Resolution

Before the results of a numerical modeling study are relied upon, two important aspects of the model analysis should be considered carefully. The first involves verification that the model is capable of correctly solving the physical equations that are needed to obtain the relevant solutions and that the material property and boundary condition data have been incorporated correctly. Assuming that a commercial software package is being utilized, it is likely that the developer has verified that the critical equations and solution methodology are working properly, and developers will often provide a suite of example outputs that demonstrate the capabilities of the software. However, if the designer or consultant is using such a package for the first time, it would be wise to run a simplified problem, perhaps one with a known analytical solution (based on the Nuemann solution for instance), so that the model output can be compared with a known/expected result. Successful completion of this exercise will verify not only that the software package has correctly implemented the appropriate equations, but also that the designer or consultant has mastered use of the software. Similarly, experimenting with a few different boundary conditions and different types of materials would be a worthy exercise when learning to use a thermal simulator for the first time.

The second important check on the output of a numerical simulation has to do with a method for ensuring that the numerical resolution of the model is adequate. Fundamentally, the accuracy of anynumerical model is a function of the size of the control volumes used to represent the domain. More control volumes (or elements) result in more nodal points with smaller spacing and, thus, a better ability to represent the temperature variations across the domain. Essentially, more elements/nodes lead to a more accurate solution. The critical question then becomes, how many elements is enough? This is an important question because adding elements ad nauseam increases the computing requirements and makes the resulting data analysis more challenging. One way of addressing this issue is to conduct a grid resolution study. In such a study, a base solution is obtained for the problem by using an element spacing that seems adequate based solely on experience and the expected temperature profile in the domain. Once the base solution has been obtained, another numerical simulation is obtained for at least one test case that uses significantly more elements (perhaps twice as many). Then the base solution is compared to the solution obtained with the expanded grid. Minor differences between the two solutions would tend to indicate that the base-level numerical grid is sufficient to obtain accurate results. Some commercial software packages have automatic grid refinement modules that can aid in conducting this type of grid resolution study.

Related to the size/number of elements used to represent the spatial domain, some consideration should also be given to the time domain. If only large times steps are used in the simulation, then the results will also become inaccurate. As a result, it may also be important to consider a time step resolution study, like that described above, for the spatial domain. A base solution would be obtained with a time step size considered adequate by the designer or consultant, and then a second solution for at least one test case could be obtained by using a time step size that is substantially smaller. Again, comparisons between the base solution and the solution obtained with a smaller time step would indicate the adequacy of the time step size used.

If the designer is relying on numerical solutions to make significant design decisions, then these issues of model verification and grid/time step resolution should be considered and discussed with whoever is responsible for producing the model results.

4.5.5 Quick Introduction to Commercial Software

While there are several commercial and public domain finite element simulation packages available, only a few have been designed with a focus on the type of geotechnical problems faced by designers of roadways in areas with extensive freeze/thaw or permafrost foundation soils. Please note that this discussion does not provide an endorsement of any software, commercial or otherwise; it is simply intended to provide the designer with a quick summary of existing software that may be of use for modeling the types of roadway design problems typically encountered in Alaska.

Two packages that are well-suited for northern transportation situations are the Geoslope suite by Seequent, and the Soilvision suite by Bentley. Both companies offer comprehensive geotechnical engineering software packages that include finite element modeling capabilities for problems that incorporate freezing and thawing soils, atmospheric boundary conditions, and material characterizations that support different frozen and thawed properties of constituent materials. In particular, the Temp/W simulator (part of the Geoslope suite) is configured to use N-factor-based surface boundary conditions or a complete surface energy balance model, depending on the level of data available. It also has comprehensive material routines that include the impact of freezing/thawing moisture. If advection is present, the Geoslope suite is also capable of coupling the Temp/W module to either Seep/W (for groundwater flow coupling) or Air/W (for pore air flow coupling). These capabilities are also present in the Soilvision software suite. In addition, both packages include routines that can be used to handle the impacts of thermosyphons. More information can be obtained from the respective company web sites (Bentley, 2020, Seequent, 2020).

4.6 Real-World Modeling Challenges

The methods and thermal models discussed above are well developed and are more than capable of solving the fundamental equations governing heat transfer and freeze/thaw in geotechnical settings. However, the complexity of real-world situations can sometimes undermine the ability of these models to re-produce what is observed in the field. Problems include changing conditions or arise from the difficulty of knowing all the material properties and field conditions accurately. As a result, the designers should use output from thermal modeling in combination with other available information as a general guide, as opposed to considering model output an exact indication of how the thermal conditions withinan embankment and its foundation will evolve over time. Some of the complexities that can lead to a mismatch between thermal model output and observed conditions in the field are outlined in the paragraphs that follow.

4.6.1 Material Properties Including Heterogeneity

Accurate thermal modeling relies on detailed knowledge of the materials that are used for embankment construction and those that make up the foundation soils. While models can consider complex spatial variations in materials, it is seldom possible to conduct a sampling regimen that is really capable of capturing this complexity. More commonly. one set of properties is used for the foundation soils and two or three other sets of properties are used for the presumed embankment construction materials. In addition, while it is possible to characterize construction materials at the source site, these often end upbeing quite variable, and the embankment material properties as placed may be quite different than those assumed for modeling during the design phase. Furthermore, changes in conditions throughout a typical annual cycle or over many years can also cause departures between predicted temperatures and those experienced in the field. A significant potential error source has to do with changing moisture conditions over time. Particularly, because the freeze/thaw process will liberate or absorb a large amount of latent heat, small discrepancies between moisture contents used for modeling as opposed to the actual moisture conditions in the field, can have a large impact on predicted temperatures. In some cases, annual variations in moisture conditions (e.g., wetter in spring and dryer during fall) may be known anecdotally, but quantifying these variations and incorporating them in a modeling effort can be difficult even though the impact on model output can be large. An example might include the impact of water saturation in an organic-rich active layer. A highly saturated active layer will substantially slow the freezing process in the fall or the thaw penetration in the spring. One approach to improve model output would be to run a 1D numerical model of the undisturbed site and compare the model output to field measurements. This exercise allows some amount of "tuning" and verification of the native foundation soil characteristics before the embankment is added to the surface. Related to this is a consideration of the alteration of the active layer behavior once the embankment has been placed. Compressed organic active layer materials will have significantly altered thermal properties in comparison to those in the natural uncompressed state.

4.6.2 Boundary Condition Uncertainty

As discussed in section 4.3.2, the upper boundary where the road and native surfaces interact with the atmosphere is quite complex. It is also variable. For instance, in Interior Alaska, mean annual air temperatures can easily vary by 5°F from year to year. As a result, a string of warmer than normal years could well produce more thawing than that predicted by a thermal model using long-term average data to drive the upper boundary condition. One approach for including this in a modeling effort is to bracket the surface conditions by running a simulation model with warmer than normal air temperatures for several years in a row to assess the impact of a warm period.

In addition to atmospheric air temperatures, variations in precipitation patterns can also have a big impact on the thermal state of an embankment and its foundation. As with air temperatures, large interannual variations in snow depth are possible. If N-factors are used to set upper surface boundary conditions, then a particularly heavy snow year will cause a significant reduction in the freeze N-factor. Again, a modeling approach to account for snow layer variation might be to run a series of thermal models with different freeze N-factors to examine the impact of variable snow depths.

4.6.3 Appropriate Initial Conditions

Another significant uncertainty that can result in variations between thermal model output and real-world observations has to do with the initial condition of the embankment and foundation soil layers at the time of construction. To accurately characterize initial soil temperatures, a foundation soil monitoring study should be carried out ahead of time. If exact soil temperature data are not available, it may be possible to estimate the soil column temperatures on the basis of known air temperatures and surface conditions, but this is likely to be less accurate. Data are also needed that characterize the temperature of the embankment materials at the time of placement, but this is sometimes poorly known ahead of time during the design process. Still, placing warm embankment material during the middle of a summer construction season can have a big impact on foundation temperatures for several years after project completion. This is a particularly important consideration for embankments placed over permafrost. Thermal modeling may be an effective method for examining tradeoffs regarding winter (or fall/spring) construction timing for these situations. However, poor or inaccurate assumptions regarding the initial temperatures of embankment or foundation materials can result in poor agreement between model outputs and real-world observations.

4.6.4 Climate Variability

While interannual climate variability was discussed above, the potentially larger issue of climate change is also something that the designer may need to be concerned with, depending on the expected lifetime of the project. This is where appropriate use of thermal modeling can be a big advantage because models can be run out for thirty years or more with gradually increasing air temperatures included in the surface boundary conditions. Clearly, there may be a compounding impact if interannual variability (e.g., several warm years in a row) is combined with an overall warming climate. Again, appropriate model scenarios can be worked out to give the designer an idea of how a particular embankment configuration might react 25 years from now in the face of several unusually warm years, but deciding on the exact parameters of such a thermal modeling experiment will likely be challenging.

4.7 References

Andersland, O. B. & Anderson, D. M., 1978. Geotechnical Engineering for Cold Regions. New York: McGraw-Hill.

Andersland, O. B. & Ladanyi, B., 1994. An Introduction to Frozen Ground Engineering. 1st ed. London: Chapman & Hall, Inc..

Batir, J. F., Blackwell, D. D. & Richards, M. C., 2013. Updated surface heat flow map of Alaska. GRC Transactions, Volume 37, pp. 927-932.

Bentley, 2020. Soilvision. [Online] Available at: https://www.bentley.com/en/products/brands/soilvision

Carslaw, H. S. & Jeager, J. C., 1959. Conduction of Heat in Solids. 2nd ed. New York: Oxford University Press.

Department of the Army, 1966. Arctic and subarctic construction calculation methods for determination of depths of freeze and thaw in Soils, s.l.: Department of the Army.

Farouki, O. T., 1981. Thermal Properties of Soils, Hannover, NH: Cold Regions Research & Engineering Laboratory.

Hinzman, L. D., Goering, D. J. & Kane, D. L., 1998. A distributed thermal model for caclulating soil temperature profies and depth of thaw in permafrost regions. Journal of Geophysical Research, 103(D22), pp. 28,975-28,991.

Johansen, O., 1975. Thermal conductivity of soils., Hannover, NH: Cold Regions Research & Engineering Laboratory.

Kersten, M. S., 1949. Thermal Properties of Soils, St. Paul Minneapolis: University of Minnesota Engineering Experiment Station.

Lunardini, V. J., 1981. Heat Transfer in Cold Climates. New York: Van Nostrand Reinhold. Seequent, 2020. GeoStudio. [Online] Available at: https://www.geoslope.com/products/geostudio

Seequent, 2020

5. DESIGN ALTERNATIVES

5.1 Overview

Numerous technologies have been applied to construction of embankments over permafrost. These have ranged from avoidance of permafrost, to passive cooling systems, to purposely thawing the permafrost. Those that have proved to work may or may not be practical for an application. Except for avoidance, none is cost effective on a large scale. That often leaves the engineer with a single choice: accept the consequences of thawing permafrost.

The use of any of the mitigation techniques is predicated on the benefits derived from the increased costs. The engineer is consequently burdened with justifying those potential benefits. This becomes increasingly difficult as the result of changes in our climate. Questions concerning whether a solution to keep the permafrost frozen will work in 10 or 20 years are a critical part of the decision process.

The techniques presented in this chapter are simply tools available to the engineer. They may or may not work in a specific application. Nor are they necessarily cost effective. Whether to use these or other technologies is left to the engineer in consultation with subject matter experts. Consequently, design alternatives are presented here for the engineer to consider. Each alternative is discussed in turn, providing the engineer with information concerning best uses and when to avoid their use. Detailed design information is not provided here. It is assumed that the design engineer will either seek out appropriate expertise or take the time to learn the required design methodology. References provide detailed information.

5.2 Avoiding Permafrost

Avoidance of permafrost was a critical part of route selection established by the Alaska Road Commission during the upgrade of the Richardson Highway in 1910. It is still considered the preferred approach by AKDOT&PF. While this policy may increase the cost of the initial route selection, the cost of maintenance and reconstruction of embankments over permafrost will likely be more expensive over time.

There are, however, exceptions. If the thaw sensitive permafrost layer is thin, removal and replacement may be more attractive. For example, a thin layer of ice-rich silt over frozen gravel is common in the upper and middle Tanana Valley. If the frozen gravel is thaw stable, removing the ice-rich silt may prove cost effective.

Indeed, if the embankment can be constructed on thaw stable material, then that alternative should beconsidered.

5.3 Acceptance of the Consequences of Thaw

In many cases, especially in areas of widespread permafrost, little can be done to eliminate the impacts of thawing permafrost. Consequently, the resulting impacts must be accepted (figure 5-1). This does not mean nothing can be done to reduce the severity of the impacts.

First, minimize the disturbance, whether a new construction or reconstruction. This means minimize disturbance of vegetation, the existing embankment, and especially drainage patterns. The goal is tominimize changes to the energy balance.

Finally, consider how the surface, side slopes, and cut slopes will be maintained. This may mean flattening side slopes, increasing the embankment thickness, or increasing culvert sizes. Decisions during the design process greatly affect construction and maintenance activities.

Figure 5-1 Roadway damage resulting from thawing permafrost. Photo by Thomas Kinney

5.4 Shoulder and Side Slope Modification

There are essentially three shoulder and side slope modifications: slope flattening, stabilization berms,and shoulder widening. The value of these treatments continues to be debated. The philosophy of all these treatments is that by adding material to the slopes, the thaw consolidation and the resulting longitudinal cracking will occur in the slopes or shoulder areas instead of the travelled way. As with insulation, an understanding of the thermal regime will aid in the determination of whether modifications will work.

Two factors determine whether modifications will be effective: mean annual surface temperature (MAST) and water (advection). If the MAST of the shoulder or fore slopes is above freezing, the permafrost below the shoulders or fore slopes can be expected to ultimately thaw. Consequently, areas of sporadic permafrost, south facing slopes in areas of discontinuous permafrost, and areas where the snowfall is sufficient to insulate the shoulders and slope enough to raise the MAST above freezing are poor candidates for these techniques. In the Fairbanks area, mean annual roadway surface temperatures are typically around 30°F, while the side slopes are typically around 37°F (McHattie, 1983).Consequently, side slopes whether modified or not, will thaw the permafrost beneath them, which is typically around 31°F.

5.5 Pre-thawing and Consolidation

Pre-thawing has its roots in the mining industry, which used steam points. Hot water injection and finally cold-water injection proved more effective in later years. Miners would simply thaw and remove the overburden above the ore-bearing layer.

The Alaska Road Commission used the thaw and cut method for roadway cuts. Available equipment simply would not allow removal of frozen material (Naske, 1983). It was critical that the thaw not get ahead of the removal of the material in the cut. Doing so would result in increased volumes of material removed would have to be replaced. With the advent of larger equipment, this method is generally avoided.

More recently, the material is thawed by simply clearing the soil of vegetation and allowing it to thaw over one or more summers. Between 4 and 5 feet of thaw can be expected in ice-rich soils (Esch, 1982). The time to thaw and drain must be sufficient to achieve the desired results. While the method is inexpensive, the project schedule may not provide adequate time.

5.6 Preservation of Permafrost

Most of the development of construction on permafrost has focused on the preservation of permafrost.Techniques range from insulation which thermally protects the permafrost, to passive freezing techniques, including thermosyphons, air ducts, and air convection embankments. While all of these can reduce the ground temperature, they may not have the capacity to keep the permafrost frozen, especially in areas of warm permafrost. The designer must carefully evaluate each alternative considered to ensure that the technique is cost effective over the life of the embankment.

5.6.1 Insulation

Insulation has proved to be an effective means of reducing or eliminating both thawing of permafrost and frost heave. The use of insulation in Alaska began in 1968 at the Anchorage International Airport with the use of Dow Chemical Company Styrofoam^{TM} (Kelner, June 18, 1968). Kelner noted that the installation proved the value of insulation and recommended its use in other applications. The report also indicated that the development of Insulfoam by Western Insulfoam was in progress.

That same year the Department of Highways first used expanded foam insulation for control of frost heave 11 miles south of Anchorage (Esch, 1986). The study concluded that expanded plastic foam was not acceptable because of water uptake. Between 1968 and 1986, insulation was used at 39 sites for both frost heave protection and for the preservation of permafrost (figure 5-2). Two types of insulation emerged as the preferred alternatives: extruded polystyrene foam insulation and expanded polystrene foam insulation (Esch, 1986).

5.6.1.1 Comparison of the Performance of Extruded Polystyrene Foam Insulation (XPS) and Expanded Polystyrene Foam Insulation (EPS)

Both extruded polystyrene foam insulation (XPS) and expanded polystyrene foam insulation (EPS) have performed well in embankments over time. Neither tend to absorb water when submerged, as defined by ASTM C-518-91. However, EPS tends to take on more water in the soil becauseof vapor pressure produced when one side is warmer with a high humidity and the other is cold and dry, such as when the embankment is freezing (Connor, 2019).

Extruded polystyrene foam insulation used in embankments is manufactured with an extrusion process that produces a relatively dense, closed cell, ridged insulation with compressive strengths typically in the range of 40 to 100 psi. Depending on the manufacturer, the dimensions are generally 2ft. x 8 ft. x 2 in. The color may be blue, pink, or yellow representing the manufacturer. The primary advantage of XPS is that the water uptake resulting from vapor transport is less than that of expanded foam insulation (EPS), and the R-value of XPS is less sensitive to moisture content (figure 5-2).

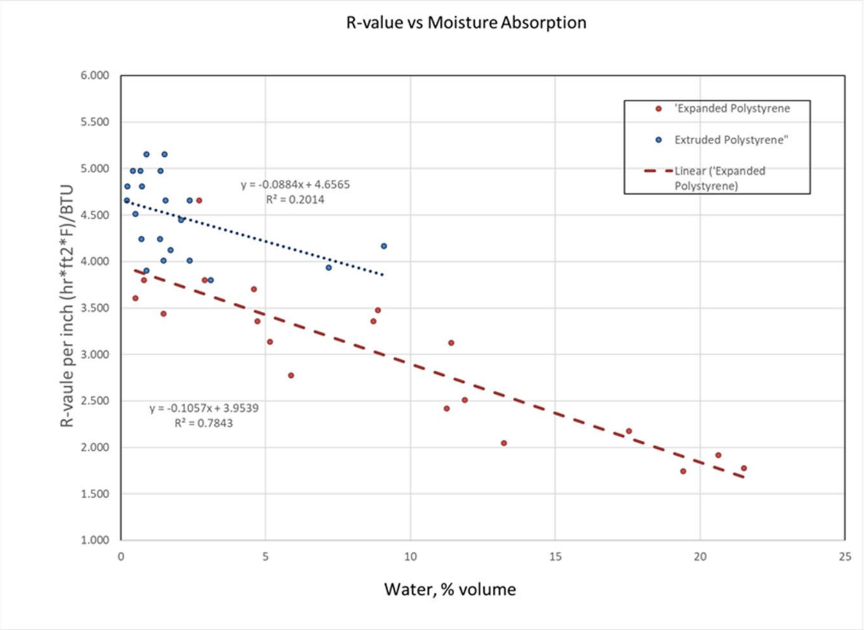


Figure 5-2 R-value - moisture relationships (Connor, 2019)

The designer may wish to consider using an in-service R-value rather than the published R-values of foam insulation. Unfortunately, in-service R-value data are quite limited. However, the available data are reasonably consistent (Connor, 2019).

5.6.1.2 Installation Depth

The depth at which the insulation should be placed continues to be debated. The optimal depth depends on several factors, including preservation of permafrost or slowing the thaw, winter or summer construction, surface energy balance, and soil conditions. A conceptual overview is provided here. It issuggested that the design engineer consult experts in thermal modeling to guide the final decisions.

First determine whether insulation will have economic value through either preserving the permafrost or slowing the rate of thaw, thereby reducing the annual maintenance costs. A first approximation looks at the ratio of the thawing and the freezing index at the surface, which can be estimated by using the following equation.

$$\frac{Surface\ TI}{Surface\ FI} = \frac{n(Air\ TI)}{n(Air\ FI)}$$

where

TI= Thawing Index
FI= Freezing Index
$n_{freezing}$=0.7 to 0.85
$n_{thawing}$ = 1.6 to 2.0

If the ratio is equal to or greater than 1, one can expect thawing of the permafrost to occur. As the ratio gets larger, the rate of thaw can be expected to increase. If the geothermal gradient is considered, then the thaw rate will increase as insulation is added. Consequently, the best that can be achieved with the use of insulation if the ratio is near or greater than 1 is to slow the rate of thaw. An economic analysis is required to determine whether the benefit-cost ratio is attractive. In this case, a better approach is to use long-term thermal modeling, as discussed in Chapter 4, to determine the value of using insulation.

If the thaw-freeze ratio is below 1, then the likelihood of preserving the permafrost in the near term is good. If climate change is accounted for, the ratio will likely change over time.

Once the decision has been made to include insulation in the design, the location of the insulation must be determined. This is best explained by using the cooler analogy. First, it makes no sense to mix warm and cold items in the cooler. Similarly, it makes no sense to place warm material between the insulation and the cold permafrost. Consequently, if the desire is to place the insulation higher in the embankment, then the material between the insulation and the permafrost should be cold (figure 5-3). This means material placed below the insulation should be placed in the winter and allowed to freeze before the installation of the insulation. If the embankment is already frozen, this work can be done in late winter or early spring when construction is easier.

Like the cooler, the greater the cold mass and the colder the mass, the longer it will take to thaw. Placing a cold mass between the permafrost and the insulation significantly reduces or eliminates the thaw rate beneath the insulation.

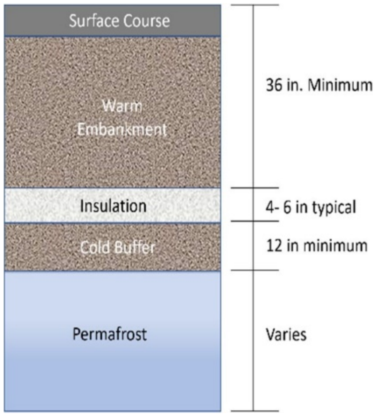


Figure 5-3 Typical section for installation of insulation

However, winter construction may not be appropriate. The engineer may decide on summer or fall construction. Like the cooler, only cold material should be beneath the insulation. This requires excavating the warm material and placing the insulation near the permafrost. Ideally this work should be done in late fall or early spring so that additional thawing is minimized. Depending on the location, mid-summer or late summer work may result in unacceptable thawing, leading to the development of a talik between the permafrost and the insulation. The rate of thaw may increase, reducing the value of the insulation.

Experience has shown that a 12-inch buffer between the permafrost and the insulation performs better than if the insulation is placed directly on the permafrost. Again, this encourages the installation in early spring or late fall so the temperature of the buffer is low.

If the insulation is placed too close to the surface, then the thermal mass over the insulation will be so small that the material rapidly freezes, causing differential icing. This can lead to an unacceptable increase in vehicle crashes. Experience has shown that 36 inches of embankment above the insulation will minimized differential icing.

Finally, the thickness at the ends of the insulation section should be tapered as a transition. An abrupt ending often results in an unacceptable bump. Figure 5-4 depicts proper installation of the insulation.

Figure 5-4 Installation of DOW extruded foam insulation at Fairhill Road near Fairbanks, Alaska

5.6.2 Techniques Using Air Convection

Air convection techniques are proving to be among the most effective means of maintaining permafrost.Three techniques are being used: air convection embankments, air convection culverts, and heat drains. Each, when properly installed, provides good results. The choice depends on the location, climate, and availability of rock.

The descriptions provided here give a general understanding of how these systems are configured, with their variations and how they work. However, it is best to engage someone skilled in these systems to ensure that they are properly designed.

5.6.2.1 Air Convection Embankments (ACE)

Air convection embankments (ACE) are proving to be one of the most effective means of preserving permafrost. The principles behind ACE are conceptually simple and computationally complex. During the winter months, the relatively warm soil at the bottom of a porous embankment material heats the air.

The warmer, lighter air rises until it reaches the cold surface of the roadway, where it cools, becoming heavier, and then begins to fall, creating air convection cells shown in figure 5-5 (Goering, 1994). The process cools the soil, preserving the permafrost. When the driving surface approaches the temperatureof the soil, the air ceases to circulate, creating a mildly insulative layer.

ACE has been used effectively on several projects in Alaska, on the Qinghai Tibet Railway in China, and in the Yukon Territory, Canada.

A second configuration of ACE is the ventilated shoulder, shown in figure 5-6. The concept is the same except only the shoulders are treated. The ventilated shoulder works well when the center of the embankment is frozen, but the shoulder is thawed. Because only the shoulders are covered in rock, the cost is considerably less.Unlike the ACE shown in figure 5-5, the cold air is drawn in at the toe of the slope and the warm air is exhausted higher in the embankment. Unfortunately, the performance of the ventilated shoulder maybe compromised during the summer months in windy areas. This can be overcome by placinggeosynthetic over the rock, which is then covered by topsoil.

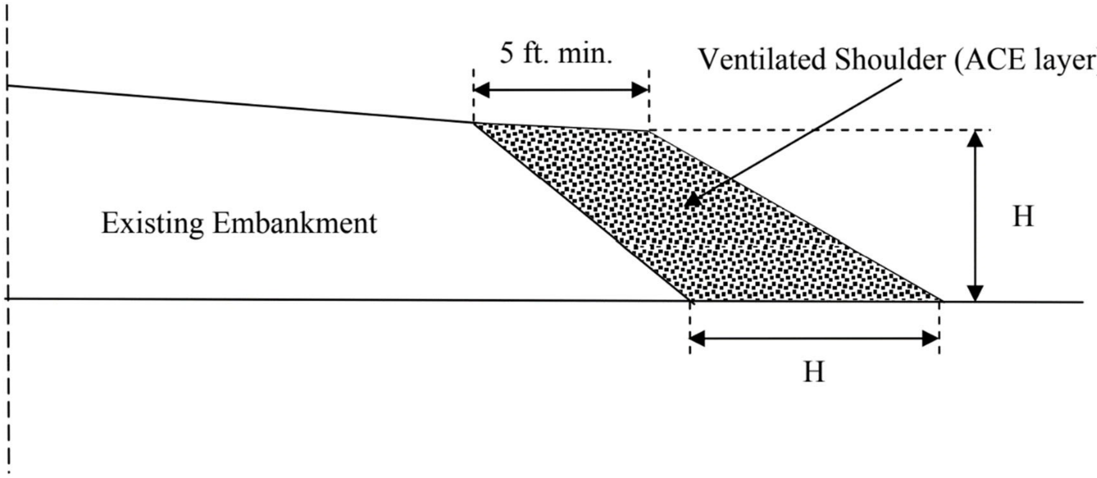


Figure 5-6 Ventilated shoulder section (Mchattie, 2009)

Using a full ACE on high fills is unnecessarily expensive. By combining the two configurations discussed, a cost-effective configuration can be constructed as shown in figure 5-7. This system keeps both the center of the roadway and the shoulders frozen.

Where appropriate rock is readily available, ACE is an attractive alternative. However, where there is no rock, it becomes prohibitively expensive. Consequently, cost is the primary consideration when ACE maybe a viable solution.

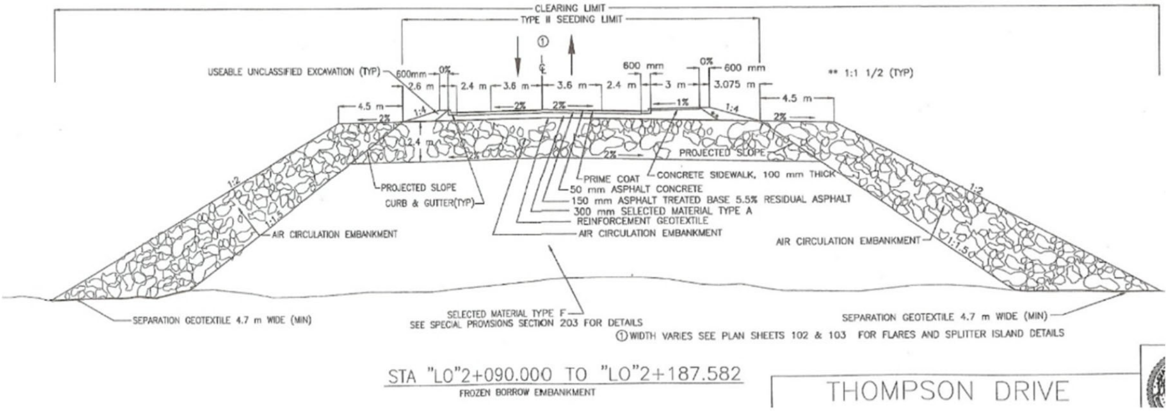


Figure 5-7 ACE on a high fill (Alaska Department of Transportation and Public Facilities , 2003)

5.6.2.2 Air Convection Culverts

There are two types of air convection culverts. The first is simply a culvert, typically 18 to 24 inches in diameter, placed high in the embankment oriented in the direction of the prevailing wind (Nixon, 1978).

These systems cool the embankment but not the shoulders. The Qinghai-Tibet Railway used this system extensively. (Cheng, 2003)

The second type of air convection culverts work in much the same way as the ACE ventilated shoulders discussed in Section 5.6.2.1. As the air in the culvert is heated by the ground, air is drawn into the inlet. The air then flows through the pipe and rises in the vertical standpipe when the air temperature is cold enough, in much the same way as the air in the chimney on a furnace (figure 5-8 and figure 5-9). Through this process, the ground is cooled (Zarling, 1984). Like the ventilated shoulder, air convection culverts cool only the shoulders. The primary advantage of the air convection culverts is that they can be used where there is no rock.

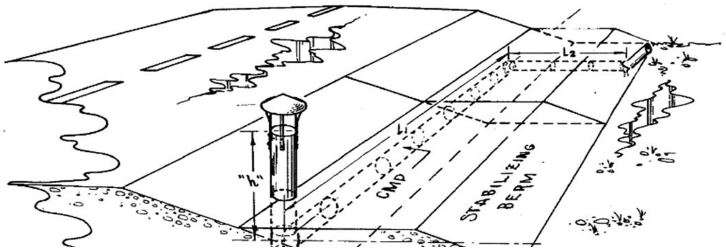


Figure 5-8 Air Convection Culverts with Chimney
(Zarling, 1984)

Figure 5-9 Air Convection culverts at Beaver Creek, Yukon Territory, Canada (photo by B. Connor)

Air convection culverts have proved effective in reducing thawing beneath the shoulders. As a result, longitudinal cracking due to shoulder rotation is also reduced or eliminated (Braley, 1991). Take care to place the inlet and the horizontal run well above the water to ensure the pipe remains open as the embankment settles. Ideally, the inlet and outlet should be closed during the summer months to keep air from flowing because of wind.

5.6.2.3 Heat Drains

Heat drains are being used in Canada to remove heat from the embankment by using air convection and have proved quite effective (figure 5-10). They consist of a highly permeable composite drainage geosynthetic that uses the air layer between the outer geosynthetic layers to convey air (Dore, 2009). An air intake is located at the foot of the embankment with a complementary outlet located near the top of the embankment, both attached to the geocomposite (figure 5-11). The geocomposite may be placed underneath the embankment, with the inlet and outlet located on opposite sides of the embankment. As an option, the geocomposite may be placed in the shoulder with the inlet and outlet placed on the same side of the embankment. As in the air convection culverts and the air convection embankment, the warm ground heats the air, which creates air circulation through convection.

It is critical that the heat drain be placed in the embankment above the water table. Anticipated settlement of the embankment must be accounted for to ensure that water does not get into the geocomposite.

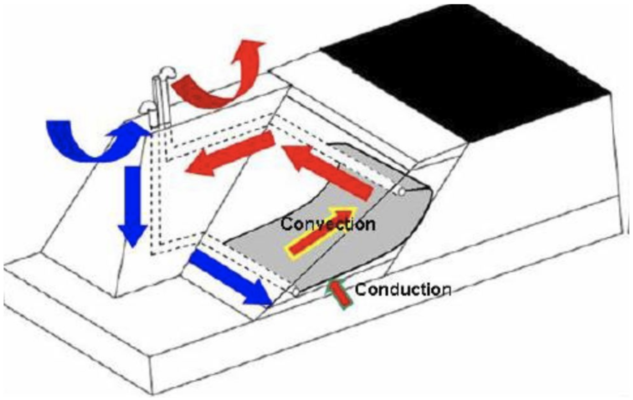


Figure 5-10 Schematic of heat drain (Dore 2007)

Figure 5-11 Heat drains in Salluit, Nunavik, Canada (photo B. Connor)

5.6.3 Shading with Snow Sheds

Removing solar insolation during the summer months is a valid means of skewing the thermal balance toward cooling of the surface. In nature, vegetation provides shade, allowing the underlying permafrostto remain frozen. It is well known that south facing slopes have much greater sun exposure that north facing slopes. Consequently, permafrost is more likely to exist on northern slopes, again, because of the presence or lack of shading.

Snow removal and storage on roadway embankments increase the surface temperature by insulating the slopes from winter temperatures. As a result, thawing of the permafrost beneath the slopes and at the toe of slope occurs. This results in longitudinal cracking migrating up the slope into the traveled way, often called shoulder rotation.

Snow sheds were developed to combat both solar insolation by shading the slopes and insulation due to snow removal (Zarling, 1986). Snow sheds are constructed by using trusses to hold a roof off the ground, allowing air to flow under the shed. Zarling concluded that the snow sheds reduced the mean annual ground surface temperature from 39°F to 28°F.

More recently the Yukon Territory Department of Highways and Public Works constructed a test site nearBeaver Creek consisting of several of the techniques described in this chapter. One of those was an updated snow shed, figure 5-12. The ground surface temperatures under the snow shed were 13ºF colder during the winter and 9 ºF cooler during the summer (Fortier, 2018). Fortier noted that the clearance beneath the snow shed should be sufficient to allow air convection during the winter.

Figure 5-12 Snow shed installed near Beaver Creek, Canada (Photo B. Connor)

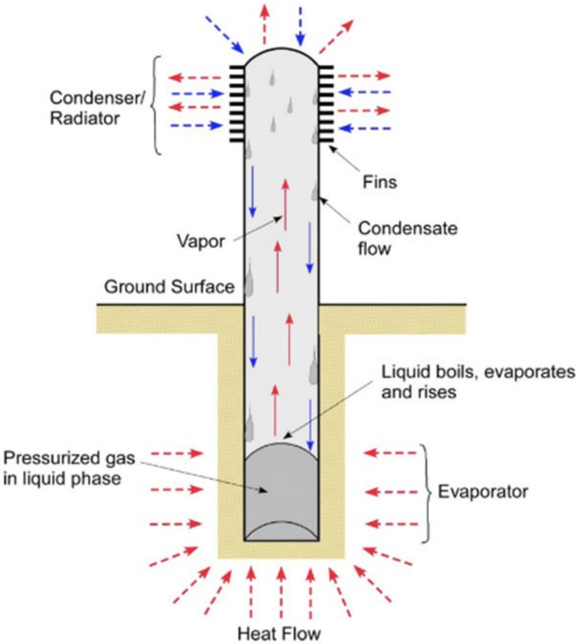
The primary disadvantage of the snow sheds is that they may require a guard rail if they are within the clear zone. Using the Beaver Creek design, the Yukon Department of Highways and Public Works did not feel that a guard rail was necessary.

It is important to recognize that snow sheds affect only the slopes upon which they are placed and have little thermal impact on the roadway surface. They do, however, reduce the longitudinal cracking that results from thawing under the slopes.

5.6.4 Thermosyphons

Thermosyphons were originally developed by Erv Long in 1956 and first used in 1960 (Wagner, 2014). Thermosyphons are a two-phase, passive system commonly used to transfer heat. Applications include cooling of spacecraft, cooling of electronic components, and maintaining permafrost beneath buildings and embankments.

The principles behind the thermosyphon are simple (figure 5-13). A tube is filled with a pressurized gas such that the pressurized gas resides



as a liquid in the bottom of the tube with the gas above. When the temperature at the condenser at the top is sufficiently cold, the heat is released to the environment, cooling the gas, which then liquifies and moves to the evaporator at the bottom. The relatively warm soil at the bottom heats the liquid, which then becomes a gas, which then returns to the condenser. The gas and pressures are designed to work at the desired working temperature range of the system. For use in permafrost regions the temperature range is around 31°F for the evaporator and around 0°F for the condenser. While propane and ammonia have been used, CO_2 is commonly used today.

Thermosyphons can be placed in embankments using several configurations, including vertical, sloped evaporators, sloped fin, hairpin, and flat loop (Wagner, 2014). The configuration depends on the application. Consequently, the design engineer should work closely with those with expertise and experience in the design of thermosyphons.

Figure 5-13 Two-phase thermosyphon (Wagner, 2014)

5.6.4.1 Vertical Thermosyphons

Vertical thermosyphons, as depicted in figure 5-13, are typically used in building foundations, for pile foundations, or for vertical appurtenances such as utility poles or light standards. They may be installed alongside the pile or foundation or within the pile = foundation.

5.6.4.2 Flat Evaporator Thermosyphons

Flat evaporator thermosyphons use flat evaporators. These are the most used in embankments because of the ease of installation and good performance. Flat evaporator thermosyphons were used on the Bethel airport in the 1970s and more recently on Chena Hot Springs Road near Fairbanks in 1998 (McFadden, 1985, Forstrom, 2003). Insulation over the evaporator may improve the performance of the system.

The condensers may be either vertical or sloped, depending on winds, snowfall, and other environmental factors.

5.6.4.3 Flat Loop Thermosyphons

Flat loop thermosyphons are like flat evaporator thermosyphons except that the evaporator forms a loop, which has been found to increase the efficiency of the system by around 40 percent. To date these systems have been used beneath slab-on-grade foundations and beneath crawl spaces. While the primary use is under buildings, they do have application within roadways (see the Chena Hot Springs test section discussion below).

5.6.4.4 Buried Condenser Thermosyphons

As their name implies, buried condenser thermosyphons are completely buried. The primary advantage of these thermosyphons is that they are protected from damage caused by vehicles leaving the roadway. The disadvantage is that they are not as efficient as thermosyphons, which have their condensers exposed to the winter air (Wagner, 2014). There are two installations in Alaska, one on Chena Hot Springs Road and one on Thompson Drive on the UAF campus. Both reduced the thawing under the roadway (Forsstrom, 2003). The hairpin thermosyphons installed at UAF reduced the amount of ice on the roadway immediately above the thermosyphon, which is an advantage to traffic. While there arecracks above each thermosyphon, these cracks have not been detrimental to the performance of the roadway.

Because of their cost, thermosyphons are generally appropriate for small, localized problems.

5.6.5 Winter Construction

Winter construction can help ensure that the underlying permafrost remains frozen by shielding it from summer temperatures. However, winter work requires planning and often increases the cost. Several techniques are available.

One approach is to prepare the subgrade after freeze-up and construct the embankment by using frozen material. Unfortunately, it is impossible to get the same levels of compaction that can be achieved by using thawed material. It is best to use dry sandy material to obtain maximum compaction and to minimize settlement. Compacting materials with high moisture content will result in low compaction. If this material thaws, loss of soil strength and high settlement can be expected.

A better approach is to place the material in a thawed state and allow it to freeze in place before placing the next layer. This is generally achievable by placing the material in about 1-foot layers and allowing it to freeze overnight. This technique may be difficult in areas of continuous permafrost.

A third technique is to place a layer of material during the first winter to protect the permafrost and to continue construction during the summer.

In any case the decision to use winter construction must be made with a full understanding of the difficulties involved and the potential gains in performance, including the impact on the underlying permafrost.

5.7 Geosynthetics

Geosynthetics have been used in embankments since the 1970s with good success throughout the world. Their use in permafrost regions has been to reduce the impact of thawing permafrost. The most effective use has been to minimize longitudinal cracking due to shoulder rotation and lateral spreading as shown in figure 5-14 (Johnson, 1983). However, the use of geosynthetics has not been effective in reducing vertical displacement over permafrost.

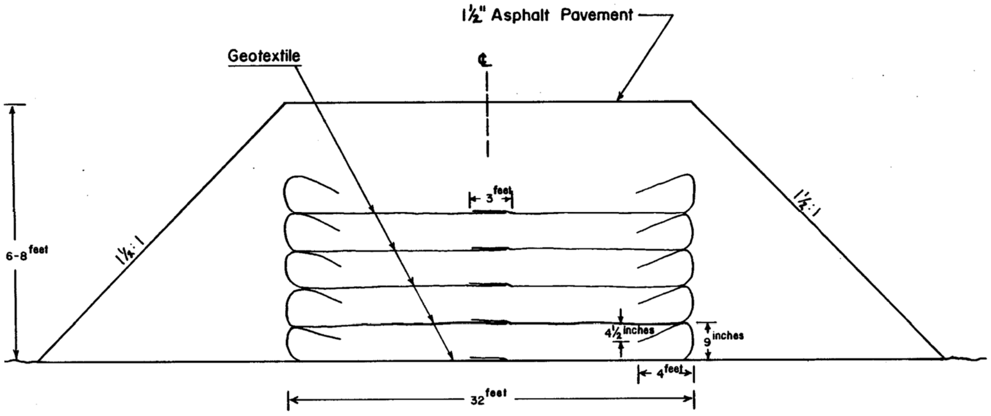


Figure 5-14 Wrapped geotextile reinforcement (Johnson, 1983)

Geosynthetics are effective as a separator between fine grained soils and courser materials used in embankments. Care must be taken over permafrost to select a material that will allow water to most out as the permafrost thaws and to accommodate movement. There have been instances in which the water has caused the fabric to act much like a water balloon, which ultimately burst. In other cases, the fabric has ripped, rendering it ineffective.

5.8 Summary

The mitigation techniques do not necessarily represent all the techniques available. They do represent the most used at the time of the writing of this synthesis. Not included in this synthesis are conceptual mitigation techniques that have not been proven. The reader may be struck by the cost of most of these techniques and that the techniques listed here address only localized problems. This is not to say that these techniques are not cost effective. In many cases, they have proved cost effective. The designer should work with the geotechnical staff to determine the best technique and analyze the costs and the benefts to be derived.

5.9 References

Alaska Department of Transportation and Public Facilities , 2003. Plans for UAF/New Geist Road Access (STP-MGE-MGS-0002(90)/60395. Fairbanks, Alaska: State of Alaska (DOT&PF).

Braley, A. C. B. R. M. a. Z. J., 1991. Evaluation of Garder Creek Air Ducts, Fairbanks, Alaska: Alaska Department of Transportation and Public Facilities.

Connor, B., 2019. Comparison of Polystyrene Expanded and Extruded Foam Insulation in

Roadway and Airport Embankments, Fairbanks, Alaska: Alaska University Transportation.

Dore, G. a. Z. H. K., 2009. Cold Regions Pavement Engineering. 1st edition ed. Reston, Virginia: ASCE Press.

Esch, D. C., 1982. Permafrost Prethawing by Surface Modification, Juneau, Alaska: Akaska Department of Highways.

Esch, D. C., 1986. Insulation Performance Beneath Roads and Airfields in Alaska, Fairbanks, Alaska: Alaska Department of Transportation and Public Facilities.

Forstrom, A. L. E. L. Z. J. P. K. S., 2003. Thermosyphon Cooling on Chena Hot Springs Road, Fairbanks , Alaska: Alaska Department of Transportation and Public Facilities.

Fortier, D. S. M. a. R. K., 2018. Performance assessment of the thermo-reflective snow-sun sheds at the Beaver Creek road experimental site, Montreal: Geocryolab.

Goering, D. J. K. P., 1994. Roadway Stabilization Using Air Convection Embankments, Fairbanks, Alaska: Institute of Northern Engineering.

Johnson, E. G., 1983. Application of Geotextiles in Alaska, Anchorage, Alaska: Alaska Department of Transportation and Public Facilities.

Kelner, J. P., June 18, 1968. Thermal Test of 4 Pavements (including Insulation, Anchorage, Alaska: State of Alaska Division of Aviation.

McFadden, Terry, 1985, Performance of the Termotume Permafrost Stabilization System in the Airport Rundqy at Bethel, Alaska, State of Alaksa Department of Transportation and Public Facilities Division of Planning Research Section

McHattie, R. L. E. D. C., 1983. Benefits of a Peat Underlay Used in Roadway Construction on Permafrost. Washington D.C., National Academy Press..

Mchattie, R. L. G. D. J., 2009. Air convective Embankment (ACE) Design Guide, Juneau, Alaska: Alaska Department of Transportation and Public Facilities.

Naske, 1983

Nixon, J., 1978. Geothermal Aspects of ventilated pad design. Ottawa, National Research Council of Canada, pp. 841-84.

Wagner, A. M., 2014. Review of Thermosyphon Applications, Washington D.C.: US Army Corps of Engineersm Engineer Research and Development Center/Cold Regions Research and Engineering Laboratory.

Zarling, J. P. B. A. W., 1986. Thaw Stabilization of Roadway Embankments Constructed over Permafrost, Fairbanks, Alaska: Institute of Northern Engineering.

Zarling, J. P. C. B. G. D. J., 1984. Air Duct Systems for Roadway Stabilization Over Permafrost Areas, Fairbanks, Alaska: Alaska Department of Transportation and Public Facilities.

6. SLOPE STABILITY

6.1 Introduction

Environmental regulations regarding work in permafrost areas have reached such a high level of legal importance that they can compete with the need for the road project itself—and may exceed that need without a convincing demonstration of competent permafrost engineering. Engineers now working on road or airfield projects in permafrost areas of Alaska have no choice but to learn how some kinds of disturbed permafrost can degrade and how to confront that problem in an acceptable way.

Ice-rich permafrost is often encountered during construction of roads and other projects in the arctic and subarctic. This type of permafrost is typically silt with segregated ice and/or massive ground ice. Thawing of ice-rich permafrost causes problems on Alaska transportation projects, including reduced equipment mobility, uncontrolled erosion, dirty runoff, and slope failures unless special measures havebeen taken. See Chapter 2 for a comprehensive discussion of permafrost as a naturally occurring material, as well as its general characteristics and distribution within Alaska.

Water quality on construction projects is of such great concern that resource agencies are concerned with the by-products of the thawing process—particulate-rich effluent and accompanying terrain disfigurement. Consequences of environmental distress include project delays, change orders, and contractor claims. Added to these initial construction site problems are needs for (1) managing legal environmental issues associated with exposed ice-rich permafrost, and (2) ways of properly disposing of excavated ice-rich material.

Throughout this chapter, the working definition of "ice-rich" is permafrost that has a frozen water content high enough to cause "problems" upon thawing. Given the recent direction of environmental regulation, monitoring, and enforcement, the definitions of "ice-rich" and "problem" will likely change with time.

Engineers have basically only two methods for dealing with icy cut slopes should they be encountered. They can (1) preserve the ice-rich soil in its frozen state, or (2) accommodate thawing by using design methods that minimize thawing's most negative effects. Preservation requires expensive passive refrigeration or an even more expensive active refrigeration system. However, it would certainly be too expensive to preserve the frozen state of materials except perhaps in some unusual situations.

Preservation would be especially difficult throughout the areas of warm permafrost of Alaska DOT&PF's Interior, Central, and Southcentral regions. The alternative approach, the one addressed in this chapter, isto accommodate thawing with environmentally acceptable design measures.

Chapter 6 provides practical engineering guidance when ice-rich cut slopes are considered the best, if not only, alternative. The word "practical" is stressed for good reason. Engineers are used to calculating their way toward solutions for difficult problems. Ice-rich cut slope solutions require a combination of common sense-based engineering judgment plus guidance from experience. The exact 3D distribution of non-ice-rich soil/massive ice/ice-rich soil is usually unknown before making a construction cut is made into the icy material. Knowing the exact distribution of these material types is vital to any standard engineering analysis. This kind of exploration would require extraordinary expense and effort far beyond normal geologic exploration methods for roadways and airfields. Specifically, standard slope stability analysis and runoff prediction is not possible for the following reasons:

- Distribution of massive ice or ice-rich materials along the cut face is not known before exposure.
- 3D distribution of ice/icy soils behind the cut face remains unknown even after exposure.
- Thaw-consolidation cannot be predicted before thaw.
- Thaw-consolidation across icy cut faces likely will be very non-uniform.
- Soil drainage appearance, duration, and total volume cannot be predicted before thaw.
- Silt load and chemistry of the runoff cannot be predicted before thaw.

Figure 6-1 shows a Dalton Highway example of surprises encountered when a cut slope is constructed in icy materials (before thawing). Figure 6-2 shows examples of cuts at different locations after thawing has progressed.

Figure 6-1 Three material types exposed in a permafrost cut slope, before any thaw.

Figure 6-2 Massive ice exposed in a cut slope (left) and runoff from a thawing ice-rich cut slope (right).

The following sections first describe how ice-rich materials exposed in a construction cut thaw and degrade, followed by an overview of past and present methods for dealing with thaw unstable slopes. Finally, several methods are recommended for dealing with ice-rich cut slopes and excavated materials, accompanied by a summary of Alaska's regulatory environment that guides development of these and future methods. The reader must understand that past methods that worked mechanically/thermally would not be allowed today if done in the old way because of changes in environmental laws and regulations. Only one of the treatment methods recommended in this chapter has a documented history of repeated use in Alaska. Even that treatment has been modified in this version to control runoff and improve water quality.

This chapter is generally based on *Documenting Best Management Practices for Cut Slopes in Ice-rich Permafrost* (Vinson and McHattie 2009). As used in that report, recommended best management practices (BMPs) offered the best possibilities for practical and effective solutions to icy cut slope problems. Except for the first of several icy cut slope treatments discussed in detail later in this chapter, none of the treatments benefits from well documented, repeated histories of successful use.

This chapter focuses on the problem of ice-rich cuts. In addition, it briefly discusses disposal of ice-rich materials excavated from those cuts and formation of embankments using that ice-rich material.

6.2 How Ice-Rich Permafrost Cut Slopes Degrade

A much more complete picture of permafrost science and theory is presented in other chapters of this synthesis. This section only provides a cursory discussion of ice-rich permafrost degradation as it pertains to icy cut slopes.

6.2.1 Erosion Mechanisms

The rate of erosion is affected by several variables. The most significant are soil type, vegetation, climate (e.g., intensity and duration of precipitation), and drainage basin characteristics (e.g., length and steepness of slopes, drainage density, relief, size of watershed). Transportation corridor construction activities that cause surface disturbance such as clearing vegetation, excavation of ditches, side and through-cuts, diversion and concentration of flow generally cause the rate of erosion to accelerate. Silts and fine sands are most susceptible to erosion after cutting into ice-rich material.

When the ground cover is removed or disturbed, subsidence and entrapment of water often occurs. If water begins to flow, erosion gullies form. Thermal erosion is generally associated with rapid thawing ofice-rich, fine-grained permafrost. Severe accelerated erosion is always observed when drainage is uncontrolled through an area of exposed ice-rich permafrost.

6.2.2 General Erosion Observations

Exposure of ice-rich permafrost during construction of roads and other projects is all too common. Ice- rich permafrost exposed during late spring through early fall has an extremely high potential to thaw during that construction season and to begin degrading immediately. Ice-rich permafrost waste material excavated any time of the year will almost certainly cause problems if not disposed of properly—in the case of winter excavation, disposed of before spring thaw. When thawed, ice- rich permafrost—typicallysilts with segregated ice or massive ice—experiences a substantial (perhaps complete) reduction in strength owing to the exceedingly high-water content and lack of drainage and consolidation during the thawing process. If the exposure is on a cut slope, a slope failure will result (figure 6-3).

Figure 6-3 Advanced thaw degradation of a cut slope shows block failures and runoff of highly fluid silt into a ditch

Serious environmental issues arise when thawed particulate-laden fluids (sometimes dense slurries) must be controlled. R & M Consultants summarized the possible consequences of thermal erosion as follows (R & M Consultants, Inc., 1973):

- Settlement-induced depressions resulting in water ponding.
- Surficial movement or sliding of thawed materials affecting drainage and drainage structures.
- Redeposition of flowing material that covers, damages, or destroys previously installed erosion control structures.
- Headward erosion and severe gully and fissure development, particularly in areas of cross drainage.
- Stream pollution by excessive sediment transport.

Thawing of ice-rich soils has posed problems since the first construction projects in permafrost environments. Complicating the engineering decision process, decades of observations regarding degradation of ice-rich permafrost have taught us an unfortunate lesson.

Conclusions/recommendations regarding a permafrost problem at one location may not be reliably applicable to an apparently similar permafrost problem at another location. A corollary to this lesson is in the form of a warning to the design engineer: Do not casually use a total design workup from previous projects for dealing with ice- rich cuts. The specific location creates a unique design challenge, so base the design on all available information for that location.


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Figure 6-4 Advanced cut slope thaw with silty runoff flowing in a ditch and general slumping of coarse material.

Figure 6-4 shows three major types of damage and the associated environmental problems obviouslycreated during thawing: (1) damage above the cut slope, (2) damage on the cut slope, and (3) ditch damage, all of which are unacceptable today.

6.3 Previously Tested or Proposed Treatments for Ice-Rich Cut Slopes

A special design feature addressing the instability of cut slopes in ice-rich permafrost and massive ground ice was included in the 1969 design guidelines for the 123-km (56-mile) Livengood to Yukon River initial segment of the Trans-Alaska Pipeline System (TAPS) haul road (Rooney, 2007), now known as the Dalton Highway. Basically, the mitigation procedure was intended to allow thermal erosion to occur in a controlled way. It was further intended that thermal equilibrium of the cut slope would be slowly reestablished when the vegetal mat removed during construction would be naturally restored. This method, illustrated in figure 6.5, is like the “controlled ablation” method presented later in this chapter, but without the control of runoff water as now required.

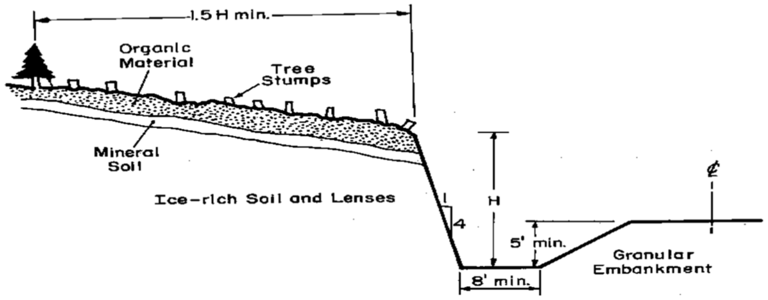
An alternative mitigation strategy is to develop a thermal barrier between the permafrost and the warm ambient air temperatures. In nature, the vegetation overlying the permafrost creates a thermal barrier through a combination of low conductivity and evapotranspiration. Artificial thermal barriers should include the followig (Rooney, 1973):

- Radiation protection in the form of a high reflectivity surface treatment.
- Conduction protection in the form of a low conductivity surface treatment.
- Promotion of heat exchange at the surface through a system that provides shading and high evaporation characteristics.

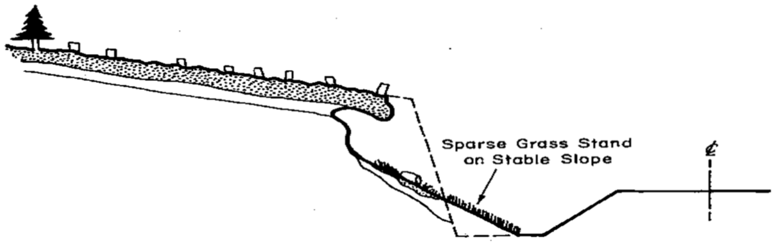
Rooney noted that convective heat transfer induced by the surface characteristics of a thermal erosion treatment is probably of secondary importance. Variations on Rooney’s themes outlined above were developed into experimental features in the fieldand as design features incorporated repeatedly into project plans. Anecdotal and published sources of information have confirmed that these techniques have been employed with varying degrees of success, to mitigate problems related to thawing ice-rich permafrost.

On the basis of observations along the TAPS haul road, Berg and Smith recommended the procedure shown in figure 6-5 (Berg and Smith, 1976). This design concept is shown in its original form because of its importance. It was used successfully in many projects in one modified form or another. A modification to the Rooney/Berg and Smith approach has been presented by the writer and is incorporated as part of the “controlled ablation” design concept presented further in this chapter.

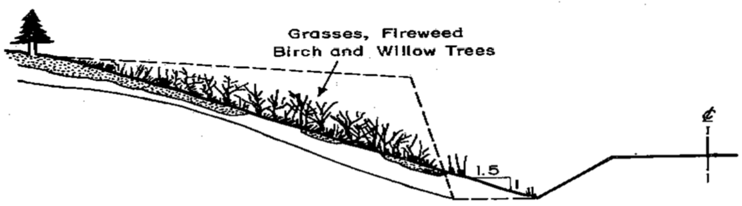
The modified approach is required by environmental concerns. It includes a separation berm to ensure complete containment of thawed material.



a. Initial frozen cut profile.



b. End of first thaw season. Slope is mostly unstable and very unsightly; ditch will require cleaning if massive ice is present.



c. End of fifth or sixth thaw season. Slope stabilizes with reduced thaw and vegetation established. Free water from minimal thawing is used by plants whose root systems develop new organic material.

Figure 6-5 Idealized development of stability in an ice-rich cut (after Berg and Smith, 1976)

The Berg and Smith recommendation was based on the performance of near vertical cuts in ice-rich siltmade on the 90-km (56-mi) Livengood to Yukon River segment of the Dalton Highway (Smith and Berg 1973). The Dalton Highway cuts were made following observations by the project consultants of similar ice-rich, fine-grained soil cut slopes along the Alaska Highway (Rooney, 2007).

Four techniques have been informally discussed within AKDOT&PF and perhaps even tried on a few projects but remain undocumented. These are as follows:

1. Cut the slope very flat (3 to 1 or flatter) with no surface treatment. The presumption is that slow thawing of the lower angled slopes would result primarily in soil settlement with little or no lateral movement. However, fine-grained, very high ice content

materials that experience rapid thawing may flow even if cut at a very low slope (flatter than 6 to 1). An example of thawed material flowing on a very slight grade was observed adjacent to the Glenn Highway about 20 miles west of Glennallen. It is worth noting that these and other materials found within the Copper River Basin were known to exhibit unusual/unexpected stability behavior because of their unique marine origin and geologic history.

2. Cover the cut slope with a vegetation mat (closed netting) to provide minor insulation plus shading.
3. Reduce the slope inclination to 1.5 or 2 to 1, and place topsoil on the slope; seed at two to three times the“normal” application rate (best suited to non-ice-rich permafrost).
4. Cut the ice-rich permafrost slope about 1.5 to 1 and place a gravel buttress (i.e., berm or blanket) adjacent to the slope face (buttress height = cut slope height). The thickness is typically2- to 4-ft. thick with slope heights only limited by the reach of the construction equipment; typically excavators. The inclination must be less than the angle of repose of the gravel. Claridge and Mirza (1981) discussed the successful application of a buttress of crushed rock on a section of Dempster Highway (NWT). The buttress does not need to be thick enough to eliminate thaw entirely. It functions by reducing the rate of thaw and facilitates drainage and thaw consolidation. It protects the slope from both thermal and hydraulic erosion. With proper attention to gradation characteristics, it may also enhance air convective heat transfer in the buttress.

A successful example of large-scale, erosion stabilization of permafrost on a shallow angle cut slope was provided during a runway improvement project at the Kotzebue airport. The top of a hill that extended into aircraft glidepaths was excavated into degradable (though not ice-rich) permafrost soils to improve the approach to the runway, as shown in figure 6-6.

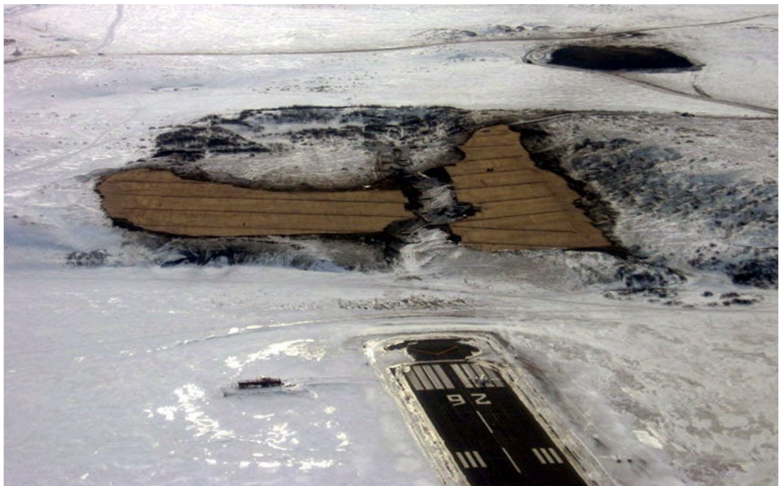


Figure 6-6 Synthetic netting used at Kotzebue Airport protects a large permafrost cut slope

Synthetic matting was placed on a large area of exposed permafrost in spring of 2006 to retard thaw and erosion and promote stabilizing plant growth. Vegetation was established by late summer 2006.

Kinney recently presented the concept of an erosion control soil (ECS) and demonstrated the concept with two projects in the Seattle, Washington, area (Kinney 2008). An ECS is a soil manufactured of natural materials with the correct combination of physical, chemical, and biological properties to provide a sustainable system in the required environment (specific environment at the design site). Mature ECS produces an erosion resistant, free draining vegetation mat in a very efficient manner. The concept of an ECS has not been used in a permafrost environment.

6.4 Recommended Management Practices as of 2020

Select route alignments and use design features that minimize or eliminate thawing of ice-rich permafrost or massive ground ice. This is the preferred way to control thermal erosion. Reconsider and eliminate, if possible, even minimal cuts in ice-rich permafrost areas. For example, perhaps a shallow cut into icy permafrost may be avoided with a small design grade change.

The reader of this section is assumed to have a working engineering familiarity with (1) general materials properties and engineering problems associated with permafrost, (2) standard materials engineering skills needed for roadway/airfield designs, and (3) simple drainage applications of geosynthetics, including geocomposites. The engineer intending to apply information presented in thissection of Chapter 6 must have the knowledge and experience to produce detailed designs from concepts presented here. Furthermore, the engineer must be able to modify each concept as necessary, sothe final design best fits a specific location and construction scheduling.

If the design considers the possibilities for handling ice-rich permafrost on the project, the design should be amenable to simple modifications during construction or even post construction by others. This is according to the general principle of "shared fate," where the success is shared by all.

The construction engineer interpreting plans and specifications at a construction site must realize thatthe design engineer simply may not know what may become evident as construction progresses. The first detailed information about an icy cut face comes after exposure of the face. The ability to maintain a "flexible" interpretation of plans and specifications will be critical to the engineer's success in handling any encounter with ice-rich materials.

Design concepts included in this section should provide useful cut slope treatment options when cuts into ice-rich permafrost materials are unavoidable.

- Design illustrations in this section are conceptual engineering works in progress. Limited experience to date requires that they be presented as tentative recommendations to the degree indicated for each method. While AKDOT&PF has in fact accumulated considerable experience dealing with icy cut slopes, much of the technology used in the past would not fully comply (or comply at all) with the most recent clean water requirements. Each of the designs is intended tominimize runoff rate and/or greatly improve runoff quality.
- Only one design concept presented here (Controlled Ablation) has been repeatedly tested in Alaska, although not through a full range of soil types and thermal conditions. Even this concept has been modified to improve runoff water quality.
- No detailed standards/dimensions have been established except as indicated in the drawings. Design and construction engineers must work with regional geotechnical personnel to address project-specific thermal, stability, and drainage issues, as well as site-specific topographic details.
- Designs based on these drawings and done before construction must be simple and general enough to be modified in the field as construction progresses or to address

post construction problems.

- Constructed features based on concepts presented in this report must remain serviceable long after project construction has been completed. Such features are intended to minimize damage or pollution due to permafrost degradation and must be robust enough to remain functional with little or no maintenance as a permanent part of the project and/or until thermal equilibrium has been reestablished and the feature is no longer required.
- Once constructed, none of the design features illustrated in this section should be removed until issues of thermal equilibrium, stability regarding mass movement, and environmental safety have been completely satisfied for all concerned agencies.
- The possible exception to this could be eventual removal of smaller berms placed to intercept or divert silt-laden runoff during the initial thawing. Removal of some of those berms when they are no longer necessary may aid ditch maintenance. Consult with the Regional Geotechnical Engineer and Environmental Coordinator before any such removal to verify that there will be no stability or pollution issues

6.4.1 Controlled Ablation

Objectives and Applications

Controlled thaw and failure, i.e., controlled ablation, was the method of choice for treating ice-rich cut slopes for about the last 30 years of the 20th century. The process begins when a nearly vertical cut is first made into the icy permafrost. The cut fully exposes the permafrost surface and expedites ablation, i.e., thawing, failure, and drainage of material into an over-wide ditch. The ditch is designed wide enough to provide a catchment area for the thawed material and still allow for normal storm and meltwater drainage.

The rate and extent of thaw and ablation was controlled by the original surface vegetation mat. The mat tends to remain intact while being undercut as the icy material thaws and ablates beneath it. If the process goes as planned, the mat descends downward to cover (i.e., drape over) the thawed material. The mat provides (1) mechanical protection for the newly thawed, unstable material, and (2) an insulation blanket that slows, then eventually stops further thaw.

Common Failures Generally Due to Faulty Installation or Design

The controlled ablation process relies on the existence of a well-developed organic mat and limited massive ice content in the cut. The method relies on the observation that thawed material often assumes a gentle slope that is naturally covered with a descending and readily drapable organic mat. A missing or poor organic mat will not cover the thawed material as expected. If much of the cut slope material is extremely ice-rich or (worse yet) massive ice, the organic mat will tear apart over the open void, thereby failing to control further thaw.

Experience has shown that the use of interceptor ditches or any other feature that damages the thermal stability above cut slopes near the face of the slope leads to thermal erosion of the top of the cut. This renders the drapable organic mat ineffective. Consequently, it is recommended that ditches or any other feature that leads to thermal erosion near the top of slope be avoided. This includes machine clearing that damages the vegetative mat.

Other Considerations

This method was used successfully many times in Alaska in the past as a standard BMP. The problem now is that it would be considered environmentally unacceptable in its original form. The original design could and did produce and release uncontrolled runoff of silt-laden water. Use of the separation berm inthe improved design requires consideration of an overflow drainage feature in an extreme rain event or heavy snow runoff. Standpipes and/or slot bypass drains may be added if appropriate.

Design

Alaska experience suggests that this method will be successful if the height of the back slope is ≤ 3 m (10 ft).Consult with the Regional Geotechnical Engineer for approval of final design details.

Materials

As required by specific design details and location, materials forming the separation berm should be freedraining. The drainage process may be expedited by using combinations of geocomposites and drainpipes as suggested in the berm illustration shown in figure 6-7. The drainage "plumbing" also may be needed if the berm is not constructed using free draining material.

Installation (refer to figures 6-7 and 6-8)

- Initial control of thermal erosion will consist of cutting the slope at a ratio of 1/4 to 1 (nearlyvertical).
- Provide a wide ditch at the base of the cut to allow removal of material, if necessary, and allow deposition of some overlying material during the stabilization process. A

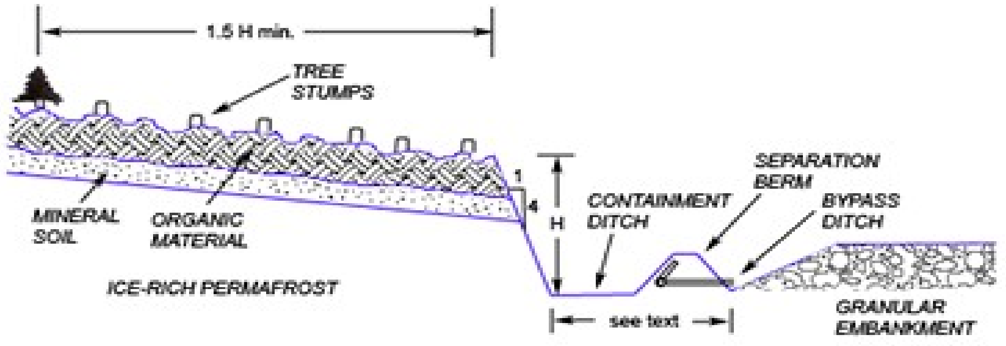
separation/retention berm, with or without internal drainage depending on the availability of a free draining material for the berm, may be required to ensure control and containment of particulate-laden runoff and thaw-weakened material with a sufficiently high-water content that it may flow. The minimum width of the ditch *without* a separation berm is 2.4 m (8 ft)—probably not environmentally allowed at present. The minimum width of the ditch *with* a separation berm is 4.2 m (14 ft), including the width of the separation berm. The minimum height of the separation berm is 0.8 m (2.5 ft) with 1½ to 1 sideslopes. Use of steeper berm sideslopes to a maximum of 1 to 1 may be possible with some gravel materials. The berm may or may not have a flat crown.

- Hand clear the area beyond the slope stake limit to allow controlled ablation of the slope, typically a distance equal to 1½ times the height of the slope. Any tree over 10 cm (4 in.) in diameter and vegetation taller than 1.5 m (5 ft) shall be removed. The clearing activities must be conducted in a manner that ensures that the organic mat is not damaged.
- All slash and timber will be removed from the cleared area to minimize tearing the organic mat. Stumps should be cut as close to the soil surface as possible (i.e., less than 0.3 m (1 ft)). The application of a stranded wire fastened to the stumps may be considered to provide additional tensile strength to the organic mat and reduce tearing of the mat. All tree cutting should be accomplished with hand tools; heavy equipment should not be used outside the limits of the excavated area.
- The organic mat will drape over the face of the slope as the cut degrades, which will shade and insulate the face. The mat will be reinforced with biodegradable netting, if necessary, to prevent tearing of the mat.
- Do not cut an interceptor or crown ditch through the organic mat above the cut slope. If drainage interception is absolutely needed, build a berm rather than cutting through the drapable organic mat**.**
- Vegetation seeding should be attempted only on stable potions of the slope at selected times.
- Diversion levees may be designed above ablating slopes on a site-specific basis.
- See the design concept illustration for the construction sequence. The separation berm

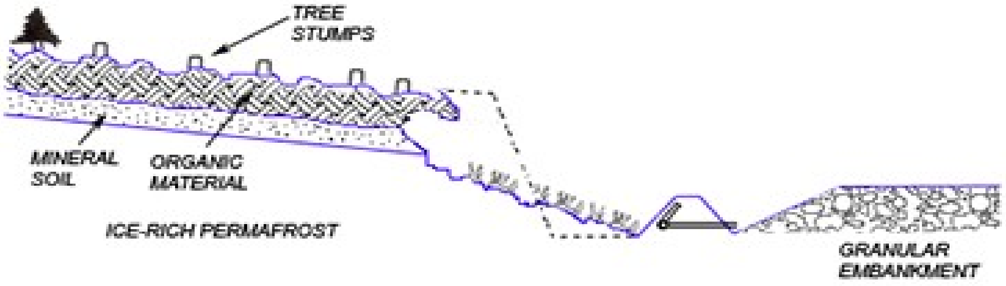
with internal drainage features and additional site drainage measures may require consultation with the Regional Geotechnical Engineer. Construction placement of a geocomposite layer within the berm, as indicated in the illustration, may at first appear impossible. However, the geocomposite can be easily placed against the sloped side of the nearly completed berm and then covered with a blanket of gravel after connections with the drainpipes have been completed.

Maintenance

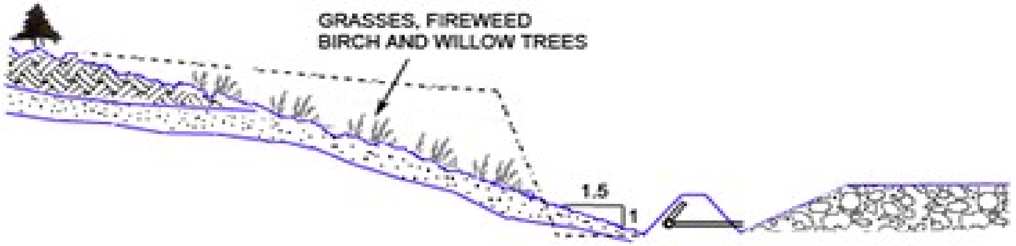
Design so that maintenance is minimal or, preferably, none is required. Maintenance to eliminate localized ponding must be performed. The thawed material retained by the berm should not be removed as it serves to buttress the thawing slope.



INITIAL CUT AND TREE REMOVAL

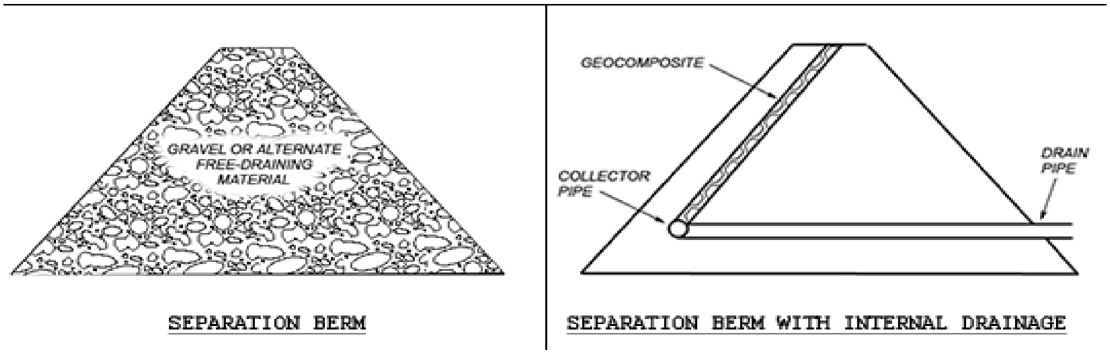


END OF FIRST THAW SEASON



END OF FIFTH OR SIXTH THAW SEASON

Figure 6-7 Progression of controlled ablation process with time.



SEPARATION BERM

SEPARATION BERM WITH INTERNAL DRAINAGE

Figure 6-8 Separation berm used to intercept runoff from controlled ablation.

6.4.2 Gravel Buttress

Objectives and Applications

The gravel buttress concept serves a purpose functionally like the result of controlled ablation. It can be used in place of the controlled ablation for cut heights of up to 3 m (10 ft). It is a recommended alternative when the cut slope height exceeds 3 m (10 ft).

Common Failures Generally Due to Faulty Installation or Design

This feature has not been used enough to have accumulated any history of common failures. The authors consider it to be a reliable method for dealing with ice-rich cut slopes if the designer carefully considers and successfully abides by the following warning. When installing this kind of feature, it is critical to make sure that the buttress is free draining as installed and will remain free-draining. The designer's inadvertent creation of a dam that blocks water flow from exiting the thawing permafrost can cause buttress failure or even catastrophic failure. A good geotechnical rule-of-thumb is to never create a damunless a dam is intended, and that always includes blocking groundwater flow.

Other Considerations

Covering the exposed icy cut slope material with a gravel buttress is a simple and robust technology.Considerations other than those expressed above and below are not warranted, given only limited application of berms for protecting ice-rich cut slopes to date.

Design

Limited (but successful) Alaska experience suggests that this method can be used as a treatment for cut slopes of any height. For cut slopes significantly higher than 3 m (10 ft), perform a slope stability analysis using conservative estimates for properties of materials retained by the buttress. Part of the justification for requiring a 2.7-m (8-ft) minimum buttress width at any stage of construction, regardless of cut height, is the assumed method of placing the berm material. The top of the buttress provides a driving surface for the end-dumps that will haul and place the berm material. While it is likely that material for high berms will be placed with end-dumps, lower berms needed to protect minimal cut heights can be placed with a backhoe.

Consult with the Regional Geotechnical Engineer regarding any slope analysis requirements and for approval of final design details.

Materials

As required by specific design details and location, free-draining materials must be used in constructing the gravel buttress. Geosynthetics placed between the cut face and buttress must be one of those types least likely to plug, blind, or in other ways significantly restrict water flow from the thawing permafrost or from any other groundwater source.

Installation (refer to figure 6-9)

A gravel or rockfill buttress may be used to control thawing of cut slopes in fine-grained permafrost thatwill not self-stabilize. The buttress may be placed with minimum compaction if the angle of repose of the material is greater than the inclination of the finished slope. For a finished slope inclination of 1½ to1, the angle of repose must be greater than 35 degrees.

The cut slope will generally be no steeper than ½ to 1 and consistent with the global slope stability and thermal requirements to achieve the cut. A geotextile, typically needle punched and stretched tight, may be placed on top of the cut slope to facilitate placement of the buttress provided that uniform thaw consolidation is expected. In areas of non-uniform thaw consolidation, such as areas known to have ice wedges or basil ice, it is best to place the rock directly on the frozen soil. By doing so, the rock will conform to the differential settlement, providing stability. The use of geotextiles in these areas will resultin the initial spanning of the void, which will accelerate thawing. As the voids grow, the geotextile will rip, allowing the rock to fall into the void.

The top of the buttress should generally be a minimum of 8 ft wide to facilitate construction. The gradation characteristics of the buttress *may* be specified to ensure that convective heat transfer will occur in the buttress.

Specific site conditions (especially topography) and equipment availability will dictate the extent to which standard construction techniques and design features must be modified to accommodate placement of the buttress. Construction of a free-draining buttress may require temporary equipment access to expedite material placement. For example, if the blanket is constructed with scrapers or end-dumps, then temporary ramps must be provided both up-station and down-station from the blanket to allow ingress and egress of construction during placement of the blanket fill. Additional cutting of the natural slope may be required to provide for the additional width of the blanket.

Maintenance

Expect no special long-term maintenance if this design concept is used. However, keep in mind that when massive ice or very icy soils thaw, a void is created, which can become a problem. If large amounts of massive ice or extremely ice-rich permafrost are encountered in the construction cut, then designers can expect that eventually it may be necessary to add more gravel or rock to the buttress face to replace buttress material lost into voids created by thawing. Limited experience with such buttresses in Alaska suggests that additional materials are usually not needed.

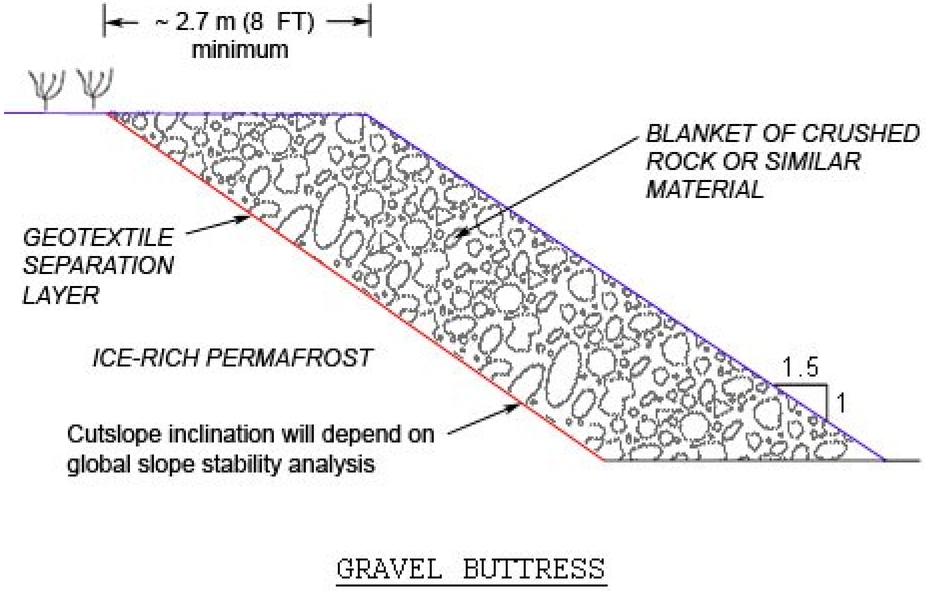


Figure 6-9 Gravel blanket concept showing geotextile placement (geotextile to be used only when uniform settlement is expected).

6.4.3 Insulated Thermal Blanket

Objectives and Applications

As with a gravel buttress, the insulated thermal blanket serves a purpose functionally like the result of controlled ablation. It can be used in place of the controlled ablation for cut heights of up to 3 m (10 ft). It is a recommended alternative when the cut slope height exceeds 3 m (10 ft). Insulated thermal blankets may be used on cut slopes in fine-grained permafrost soils that will not self-stabilize. This method may also be used for cuts in ice-rich permafrost soils where slope height and gravel availability make gravel buttresses impractical.

Common Failures Generally Due to Faulty Installation or Design

This feature has not yet been used in Alaska. Discussion of failure modes are therefore based on assumptions. The thermal blanket is not a buttress, although the illustration (figure 6-10) mayappear to be one.

When installing this kind of feature, it is critical to make sure that the blanket will be free-draining as installed and will remain free-draining. The designer's inadvertent creation of a dam that blocks water flow from exiting the thawing permafrost can cause buttress failure or even catastrophic failure. A good geotechnical rule-of-thumb is to never create a dam unless a dam is intended, and that always includes blocking groundwater flow.

Other Considerations

Covering the exposed icy cut slope material with an insulated blanket represents new technology. It appears to have good potential for protecting certain icy cut slopes and for doing so in an environmentally acceptable way. It should be less costly than a massive gravel buttress in locations where the limitations of a thin blanket are acceptable and the cut slope is high. It will not, for example, be an acceptable treatment for cut slopes exposing permafrost with a high ice content. In such cases, the large mass of the gravel buttress can serve to cover voids of fairly large size and retain thawed material in place.

Real evaluation of this design concept will follow observations of trial installations in Alaska. Consult with the Regional Geotechnical Engineer for recommendations regarding using this type of design at a specific location.

Design

This method may be appropriate as a treatment for cut slopes of any height. For cut slopes significantly higher than 3 m (10 ft), a slope stability analysis may be warranted. This can help determine whether the proposed thinly blanketed cut slope does not instead require the mass of a full-size gravel buttress for acceptable stability. For minimal cuts, an insulated blanket design will provide a buttress effect that can be verified by stability analysis.

Consult with the Regional Geotechnical Engineer regarding slope analysis requirements and for approval of final design details.

Materials

As required by specific design details and location, free draining materials must be used in constructing the bottom layer of this design feature. Geosynthetics placed between the cut face and the buttress must be one of those types least likely to plug, blind, or in other ways significantly restrict water flow from the thawing permafrost or from any other groundwater source. The insulation type and thickness will be determined by thermal analysis. The topsoil layer should be a material capable of supporting luxuriant plant growth. This layer should be double- or triple-seeded after placement because a heavy growth of vegetation will benefit the thermal properties of the blanket through shading and evapotranspiration.

Installation (refer to figure 6-10)

The select material beneath the insulation should be a sand and/or gravel or a similar non-frost susceptible material, free draining. The minimum thickness of this layer (measured perpendicular to the slope face) is 0.9 m (3 ft). The sand and/or gravel layer may be placed with minimum compaction if the angle of repose of the material is greater than the inclination of the finished slope. For a finished slope inclination of 2 to 1 (as shown in figure 6-10), the angle of repose should be greater than 27 degrees.

The minimum thickness of the topsoil layer (measured perpendicular to the slope face) is 0.6 m (2 ft). Installations for higher cuts may be done with a 1.5 to 1 slope if the frictional properties of the blanket materials, including insulation, will allow stable placement.

Maintenance

There will likely be no special long-term maintenance concerns if this type of blanket is placed on permafrost soils containing only a moderate amount of frozen moisture and few or no massive ice features. When massive ice or very icy soils thaw, a void is created. Any large void may become a problem if the thermal blanket concept is used.

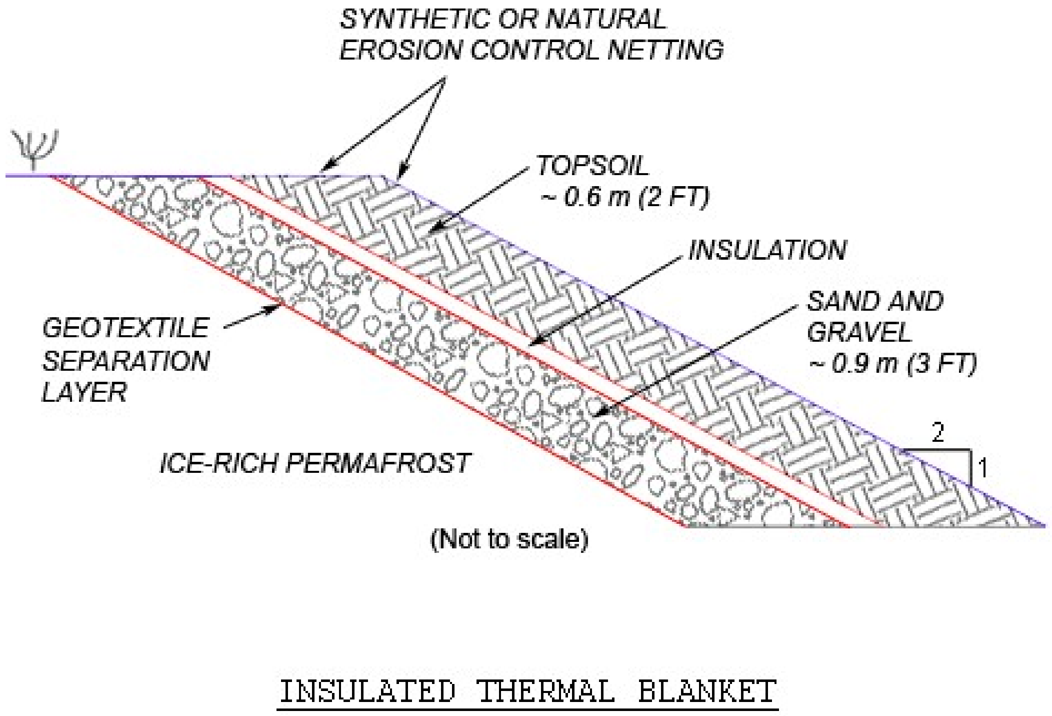


Figure 6-10 Insulated blanket concept showing geotextile and insulation placement.

6.4.4 Retention Berm

Objectives and Applications

Disposal of excavated material is one of the most common problems associated with exposing ice-rich permafrost. Contractors cannot simply stockpile excavated permafrost at a convenient location without regard to the environmental consequences of slope failures, blow outs, or even sediment-contaminated seepage from the eventually thawed material. One solution for the disposal of excavated permafrost is to construct retention berms and place the permafrost inside the berms. When the ice-rich permafrost eventually thaws, it is restricted to the area inside the berms. The retention berms shown herein allow the thaw water to escape.

It is also possible to use excavated permafrost materials—including ice-rich materials—to construct useful transportation-related structures such as runway embankments. This application is discussed briefly elsewhere in this chapter.

Future retainment schemes or civil construction applications for permafrost, like runways, may be complicated by another issue. Runoff water generated during thawing may need treatment before final release to the general environment from the storage or construction site. There are now engineering resources as well as equipment builders/suppliers located within Alaska that specialize in portable systems for processing wastewater at remote sites.

Common Failures Generally Due to Faulty Installation or Design

When a retainment berm for wet, perhaps even slurry, materials is installed, it is critical to make sure that the retaining structure will be free-draining as installed and remain free-draining. Inadvertent creation of a dam that completely blocks water flow from the retained material may cause a failure of the retaining structure.

Other Considerations

At <u>many</u> locations in Alaska, free-draining gravels, shot rock, etc. will not be available. Therefore, berm designs that incorporate a drainage system may be needed often. Reliable designs for constructing such a berm and its “plumbing system” (even from ice-rich materials if necessary) should be developed as AKDOT&PF standards. The Regional Geotechnical Engineer will be a valuable resource for developing such a standard.

Design

Two types of retention berms are illustrated in figure 6-11. Ideally the retention berm will be constructed with gravel or a similar free-draining material. If a free-draining material is not available, the internal drainage features will be required. An overflow drainage feature may be required to accommodate an extreme rain event or heavy snow runoff. Standpipes and/or slot bypass drains may be added if appropriate. The retention berm should be approximately 1/3 the height of the excavated permafrost stockpile. The berm may or may not have a flat crown.

Materials

Select materials as required by specific design details and location.

Installation

Construction placement of a geocomposite layer within the berm, as indicated in the illustration, may atfirst appear impossible. However, the geocomposite can be easily placed against the sloped side of the nearly completed berm and then covered with a blanket of gravel after connections with the drainpipes have been completed.

Maintenance

Design so that maintenance is minimal or, preferably, none is required.

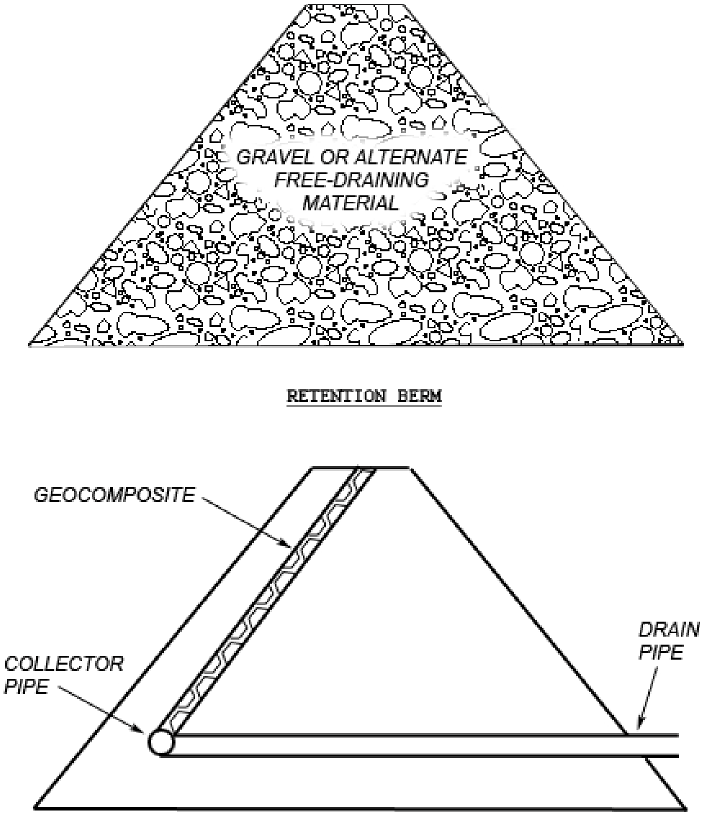


Figure 6-11 Retention berm without drain (top) and with drain (bottom)

6.5 Excavating Ice-Rich Permafrost

This will become a pressing problem immediately after a cut has been made into an ice-rich material. The best time to first consider the problem is never during construction. Plans and specifications for projects where icy permafrost cuts are expected (or even likely) should provide a back-up plan for such contingencies.

6.5.1 Retention of Excavated Permafrost as Waste

Disposal of excavated material is one of the most common problems associated with exposing ice-rich permafrost. It is not acceptable to simply dispose of excavated permafrost at a convenient location without regard to the environmental consequences of failure or runoff from the eventually thawed material. One solution to the disposal of excavated permafrost is to construct retention berms and place the permafrost inside the berms (see section 6.4.4. for berm design). When the ice-rich permafrost eventually thaws, it is restricted to the area inside the berms. If excess water generated during thawing needs treatment before release from the containment area, portable treatment systems obtained fromAlaskan suppliers can be leased or purchased and brought into play.

6.5.2 Using Excavated Permafrost to Build an Embankment

A problem in western Alaska, also related to permafrost degradation, is the use of excavated permafrost to construct a road or airfield embankment. This unusual practice is necessary owing to the scarcity of suitable embankment fill at some locations. Permafrost is excavated in the winter and placed in the location of the required embankment. Over a period of several years the permafrost fill progressively thaws and becomes increasingly stable and viable as a runway embankment. If the thawed material is restrained from lateral spreading and flow, it eventually settles and drains and can be shaped and compacted to form the final load supporting embankment. Snow berms can be placed adjacent to the embankment sideslopes to retain the thawing permafrost or, if necessary, berms of the kind indicated in Section 4.4.4. Given ideal conditions, thawed soil, initially retained by the snow berm, drains and forms its own soil berm that continues to contain the spread of additional thawed material after the snow disappears.

If compaction of frozen soil is attempted, it must be done with heavy rollers to break down the frozen chunks (GeoEngineers, Inc, 2004). Frozen soil compaction will result in an open void structure, and springtime snow meltwater infiltration will occur. An embankment placed with material from a permafrost pit source will likely take years to consolidate and stabilize. In Western Alaska, frozen (or once frozen) silt is the only available material, AKDOT&PF personnel were unanimous in preferring previously thawed borrow pit sources; frozen pits are often preferred by contractors. Use of thawed material ensures that volume changes associated with ice melting in frozen material will occur before placement of the material in the embankment—otherwise the contractor gets paid for hauling and placing a large quantity of water. If the contractor is using frozen material from a freshly made icy cut, the previous issue would be automatically settled. Consult the Geotechnical staff when designing for the use of frozen material.

6.6 The Regulatory Environment

It is not an overstatement to say that any uncontrolled water released from a cut in ice-rich permafrost will quickly become an environmental problem. As covered throughout much of this synthesis, construction activities in permafrost soils often result in the release of water and water-borne fines ontosome observable (and monitored) surface of the construction project. Cut slopes constructed in ice-rich permafrost are visually obvious, or become obvious, and grab the attention of environmental monitors/agencies unless special design and construction care is taken. In fact, such cuts will likely violate clean water regulations without special attention. This section describes the general legal environment regarding this problem.

Realize that this description of the regulatory environment will have a short "shelf life." Environmental regulations change frequently. This version of the regulatory environment represents merely the state of regulation as of mid-2020. Also, be aware that the Internet URLs now providing wonderfully useful information with a mouse click will change. General advice: when you see interesting/useful information on the Internet, save it. It may not be there tomorrow. Better yet, consult the environmental staff whenever runoff from thawing permafrost is anticipated.

The AKDOT&PF prepared a Guide (2005) that explains the requirements of the Alaska Pollutant Discharge Elimination System (APDES), presently administered by the Alaska Department of Environmental Conservation (DEC), "Storm Water Construction General Permit (CGP)" for construction sites. The guide focuses on development and implementation of a Storm Water Pollution Prevention Plan (SWPPP) required for coverage under the CGP.

A SWPPP is a document that describes the nature and extent of a construction activity and the measures that are used to ensure that sediment and other pollutants are not carried into the storm water discharges from the construction site. To control these pollutants, the contractor can use a variety of measures, referred to as best management practices (BMPs). The BMPs form the basis of the SWPPP, and the contractor must select a BMP based on the conditions at the construction site. For a SWPPP to be effective, the contractor must properly design, construct, and maintain the BMPs during the life of the project.

The Guide presents several BMPs, along with application, design, construction, inspection, maintenance, and removal guidelines. Additional BMPs are given on the AKDOT&PF environmental website: http://dot.alaska.gov/stwddes/desenviron/resources/stormwater.shtml

The BMPs must be carefully analyzed before they are recommended for use in a permafrost environment. The Guide makes no reference to permafrost, frozen, freezing, thawing, thermal, or other terms or concepts specifically relevant to handling ice-rich materials.

6.6.1 Summary of Applicable Water Quality Laws and Regulations.

Federal and state governments have passed numerous laws to minimize environmental harm from storm water discharge at construction sites. Some of these laws and subsequent regulations require the implementation of erosion and sediment control measures, while others mandate that construction activities maintain water quality. The two most important water quality related laws and regulations are the Federal Clean Water Act and the State of Alaska Water Quality Standards, as defined in the Alaska Administrative Code (18 AAC 70).

The 1972 amendments to the Federal Water Pollution Control Act (known as the Clean Water Act or CWA) form the primary legal framework meant for controlling construction site discharges and settingwater quality standards. The CWA, implemented by the Environmental Protection Agency (EPA), requires site operators to comply with a General Permit or an individual National Pollutant Discharge Elimination System (NPDES) permit. The nature of handling the EPA rules has changed such that now primary administration and adjudication of the EPArequirements has passed from federal to state hands—to the Alaska Department of Environmental Conservation (DEC). The DEC now handles water quality issues that will be pertinent to construction handling of ice-rich cut slopes through its Construction General Permit (CGP). The following few paragraphs are summarized from the DEC website. https://dec.alaska.gov/water/wastewater/stormwater/construction

The 2016 CGP says that storm water discharges from large and small construction-related activities that result in a total land disturbance equal to or greater than one acre and that enter waters of the U.S. (directly or through a storm water conveyance system) or enter a municipal separate storm sewer system (MS4) leading to waters of the U.S. are subject to the conditions set forth in the permit. The permit also authorizes storm water discharges from certain construction support activities and some non-storm water discharges commonly associated with construction sites.

The goal of the 2016 CGP is to minimize erosion and reduce or eliminate the discharge of pollutants, such as sediment carried in storm water runoff from construction sites through implementation of appropriate control measures. Polluted storm water runoff can adversely affect fish, animals, plants, and humans. To ensure protection of water quality and human health, the permit describes control measures that must be used to manage storm water runoff during construction activities. On December29, 2015, DEC reissued the Construction General Permit for Storm Water Discharges for Large and Small Construction Activities (2016 CGP, AKR100000). The 2016 CGP became effective on February 1, 2016.

The primary requirement of the EPA Storm Water General Permit for Large and Small Construction Activities is development and implementation of a SWPPP. TheSWPPP is a written storm water management plan to protect water quality by minimizing or eliminatingthe pollutants (including sediment) in the storm water discharges reaching waters of the U.S. from construction activities. The DEC requires the preparation of a SWPPP before the start of any construction activities that disturb 1 acre or more of land. For all projects disturbing one acre or more, the contractor must minimize potentially harmful water quality impacts by using BMPs to control erosion and sedimentation.

The Alaska DEC sets water quality standards for Alaska waters and regulates discharges into these waters. All discharges of storm water from construction projects disturbing five acres or more that are authorized under the EPA Storm Water General Permit for Large and Small Construction Activities must be reviewed by DEC and require a plan review fee.

Other federal and state laws and regulations applicable to storm water discharges from construction activities are listed below. There are thresholds for jurisdictional applicability for many permits/authorizations. The ADF&G Fish Habitat Permits (fish acts below) are for work below ordinary high water (OHW), and obviously would not apply to many, perhaps any, projects or areas where cut slopes in ice-rich soils would be an issue.

Section 404 Permit of the Clean Water Act. The U.S. Army Corps of Engineers (USACE) administers this requirement. A permit is required for dredging, grubbing, excavating, or filling in rivers, streams, lakes, ponds, tidelands, and wetlands. The section 404 permit usually requires erosion and sediment controls to ensure minimal harm to jurisdictional areas and is related to the USACE 404 permit – Alaska DEC 401 Water Quality Certification.

Alaska Statute 16.05.871, Anadromous Fish Act. The Alaska Department of Natural Resources (ADNR) regulates construction activities that will affect freshwater anadromous fish habitat. Any activity that will pollute or change the natural flow or bed of a stream important for the spawning, rearing, or migration of anadromous fish must be approved by ADNR to ensure that the construction plans and specifications will protect fish and game. Often, the ADNR permit requires an erosion and sediment control plan.

Alaska Statue 16.05.841, Fish Passage Act. like above, but for resident fish species.

6.7 References

AK&DOT 2005

Berg, R., and N. Smith. Observations along the pipeline haul road between Livengood and the Yukon River. Special Report 76-11, Hanover, NH: US Army CRREL, October, 1976.

Claridge, F.B., and A.M. Mirza. "Erosion control along transportation routes in northern climates." Arctic, Volume 34, No. (June 1981), June, 1981: 147-157.

GeoEngineers, Inc, 2004

Kinney, T. personal communication (October 2008).

R & M Consultants, Inc. Case studies of hydraulic and thermal erosion. Report Number HD-003, Fairbanks, AK: R & M Consultants, November 1973.

Rooney, J.W. A study of thermal erosion control techniques. Proposal submitted to Alyeska Pipeline Service Company, R & M Consultants, Inc., 1973.

Rooney, J.W., R & M Consultants, Inc., personal communication. (November, 2007).

Smith, N., and R. Berg. "Encountering massive ground ice during road construction in central Alaska." Proceedings, Second International Conference on Permafrost. Yakutsk, USSR, 1973. 730-736.

Vinson, T.S., and R.L. McHattie. Documenting best management practices for cut slopes in ice-rich permafrost. FHWA-AK-RD-09-01 final report, Juneau, AK: Alaska Department of Transportation and Public Facilities (DOT&PF), May, 2009.

7. DRAINAGE IN PERMAFROST TERRAIN

7.1 Overview

Every highway engineer understands the importance of drainage. Poor drainage not only affects the impoundment of water, but it also impacts the moisture content in the embankment itself. Water generally weakens the soil layers, reducing the life of the pavement structure.

Drainage in permafrost adds the dimension of thawing the permafrost itself, perhaps the most challenging aspect of embankment design. Water is more destructive in permafrost than air temperature and is perhaps the most difficult to manage (figure 7-1). While the principles of drainage common to temperate climates generally apply, the principles of thermal erosion and potential mass transport of thawed permafrost must also be applied. In areas of ice-rich permafrost, thawing permafrost can generate considerable water.

Larger drainage patterns can be characterized by using topographic maps, aerial and satellite photographs, or surficial observation. As noted by the Alaska Road Commission, drainage in permafrost requires careful inspection of the terrain, including water movement in the active layer.

Figure 7-1 shows the water in the active layer and at the top ofthe permafrost, often called a perched groundwater. In most cases construction will either channelize water, resulting in permanent changes in drainage patterns, or block water movement in this layer, resulting in thermokarsts and impoundment.

Even minor activities may cause destructive changes in drainage patterns. Figure 7-2 and figure 7-3 show the alteration of drainage and subsequent thawing of permafrost from the installation of a fiber optic cable along the northern portion of the Dalton Highway. The construction method used a mechanical shallow burial technique. Both thermal and sediment erosion are expected to continue.

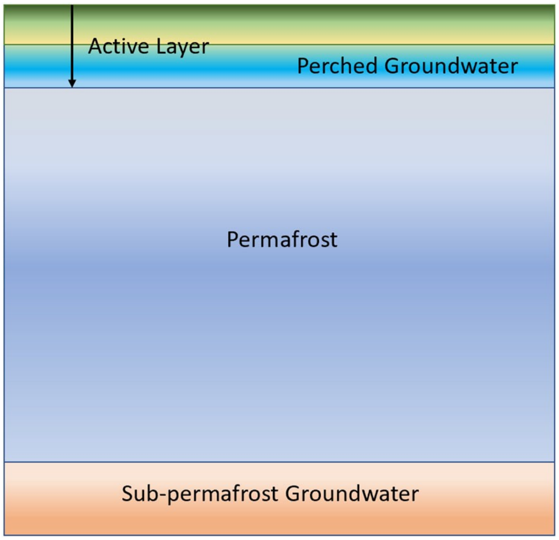


Figure 7-1 Depiction of water in permafrost regions

Figure 7-2 An example of advection along the Dalton Highway from the installation of fiber optic cable. Photo by Mikhail Kanevskiy

Figure 7-3 Erosion due to advection resulting from installation of fiber optic cable along the Dalton Highway. Photo by Mikhail Kanevskiy

It is critical that drainage and erosion control account for the thermal impacts in addition to thermal considerations. These are inseparably coupled such that if either is ignored, the consequences may be severe.

7.2 Advection

Advection is the transport of a substance, energy, or extensive quantity by bulk motion, often a fluid such as water or air. Advection in permafrost generally relates to the thermal energy transported by bulk water flow and the transport of sediments freed during the thaw process. Moving water will causethe thaw of permafrost faster than any other natural system. Consequently, the design engineer must be keenly aware of the movement of water along, across, and beneath the embankment. Failure to address advection will invariably result in poor roadway performance and high maintenance costs.

7.3 Understanding How Permafrost Affects Surface Drainage

Surface drainage in permafrost regions is a complex interaction between topography, ice-rich soil, and polygons. In general, the goal of highway designers is to move water from one side of the roadway to the other with minimal disruption. This is straightforward where drainage patterns are defined by the topology. However, in permafrost regions, drainage patterns are further determined by thawing ice wedges, thermokarsts, thaw consolidation, and sheet flow through the vegetation on top of the permafrost layer.

Shoulder warming due to build-up of snow from plowing on the side slopes of the embankment results in thermokarsts (figure 7-4). Esch (Esch, 1977) showed that these thermokarsts begin to form during the first year after construction. Figure 7-5 shows water ponding at the toe of the slope resulting from the formation of the talik. Thawing accelerates as warm water moves into low-lying areas.

As the talik grows, longitudinal cracks move up the slopes and into the roadway, as shown in figure 7-6. Once started, it is nearly impossible to stop degradation until equilibrium has been reached. Unfortunately, the only method of eliminating the ponded water is to fill the depressions. Backfilling with fine grained material works better than usinggranular material beause coarse grained material will still allow water to move through the system.

As shown in figure 7-1, there is often water on top of the permafrost. This perched groundwater may be flowing, even on what appears to be flat terrain. The weight of a constructed embankment will compact the vegetation in the active layer, cutting off the flow of water. Unless measures aretaken to allow the water to pass, the resulting ponding may result in thawing of the permafrost on the upstream side of the embankment while potentially preserving the downstream permafrost. Figure 7-7 shows the progression of wetting at the bottom of the photos and drying at the top of the photos due to the roadway embankment.

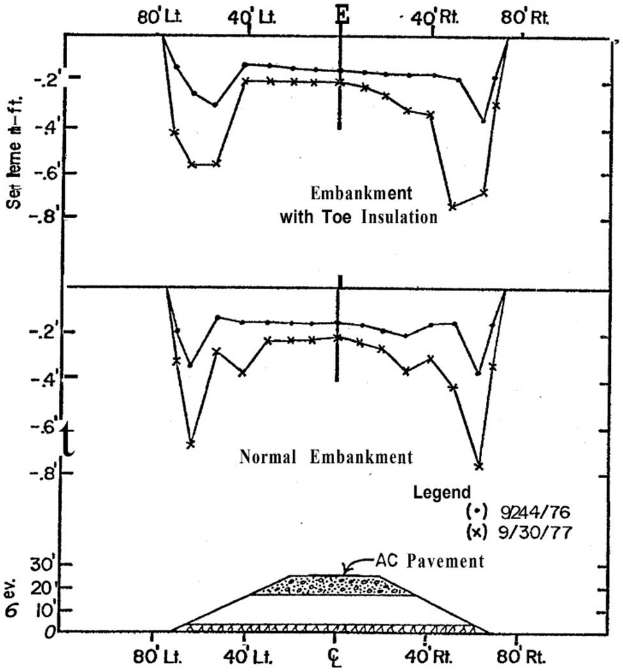


Figure 7-4 Thaw consolidation due the formation of thermokarsts along the roadway embankment. (Esch, 1977)

Figure 7-5 Water ponding in a talik formed at the toe of the slope.

Figure 7-6 Longitudinal cracking due to thawing permafrost (photo DOT&PF)

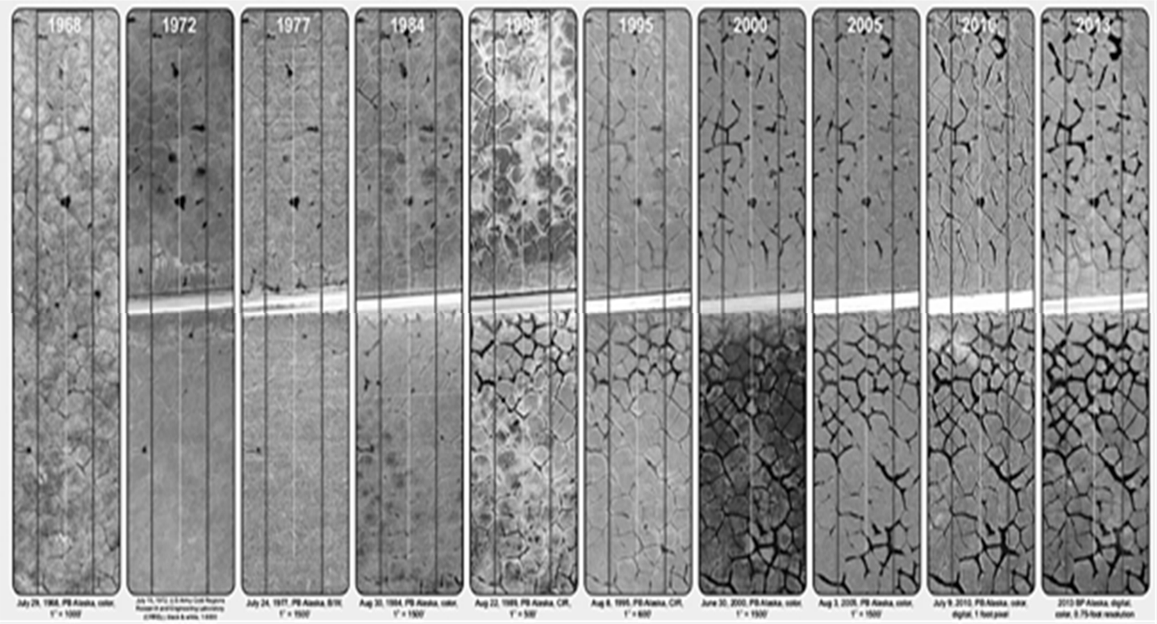


Figure 7-7 Time series (1968 – 2013) of changes to water flow through ice-wedge polygons due to the construction of Spine Road near Lake Coleen, Prudhoe Bay. Aerial photographs courtesy of BP Alaska Exploration.

7.3.1 Drainage Resulting from Thawing Ice Wedges

Thawing ice wedges have the greatest potential to alter drainage patterns. Where there is polygonal ground, the locations of ice wedges are readily seen. However, in many areas, the surface has thawed and refrozen, masking the wedges. As a result, there may or may not be any surface evidence of the existence of those wedges. Figure 7-8 shows the impact of thawing ice wedges on the roadway even though they cannot be seen in the surrounding terrain. In these cases, the designer must rely on the geotechnical engineer to identify those areas that have ice wedges at depth.

Where low-centered polygons exist, melting ice wedges will drain the polygonal ponds, transforming the low-centered polygons into high-centered polygons. Figure 7-9 shows polygonal ground during the transformation.

If the roadway or airport embankment has been in place for an extended time, the location of the wedges will likely become evident, and appropriate action may be taken to ensure proper drainage. This has been discussed in chapters 2 and 3.

Figure 7-8 Thawing of deep ice wedges on the abandoned section of the Richardson Highway east of Fairbanks

Figure 7-9 Drainage of low-centered polygons on the North Slope of Alaska, Photo by Mikhail Kanvskiy

7.4 Drainage Structures in Permafrost

7.4.1 Culverts

The most common method of allowing the water to pass is to use regularly spaced culverts. There are few guidelines on the appropriate space. As a result, the designer is left to the use of regional experience and judgment. The minimum cross-culvert size is 36 inches, if cover permits, to ensure capacity as the culvert settles. In flat terrain, the slope on the culvert should be between 1 and 3 percent, with a maximum camber of half the crossfall applied parabolically along the length of the culvert. If the terrain requires more than a 2 percent gradient, the camber should equal 0.5 percent applied parabolically over the length of the culvert (American Iron and Steel Institute, 2007). This allows for settlement of the culvert caused by the weight of the embankment.

Culverts encourage thermal erosion along the toe of slope on the uphill side of the embankment as the water moves along the embankment to the culvert. To minimize the impact on the traveled way, the designer may want to consider flattening the slopes to keep the water farther away from the trafficked surface (figure 7-10).

One means of reducing thermokarst damage is to increase the length of the culvert at the outlet to release the water farther from the embankment (figure 7-11). It is critical that the exposed section be embedded well into to the embankment to guard against potential for band failures. This technique should only be used for culverts with intermittent low flows with little or no ponding expected.

Figure 7-10 Erosion at the toe of slope due to advection

Figure 7-11 A culvert with an extended outlet

The inlet tends to be more problematic, especially if the culvert is an inlet control. A talik is often formed at the inlet because of advection (figure 7-12). Notice that the end of the culvert is depressed because of thaw settlement. Extending the inlet will not help and in some cases will cause a buoyant failure. Advection can be reduced by ensuring that the culvert is of sufficient size to ensure no water ponds at the inlet. It may be helpful to use a headwall or riprap to stabilize the slopes (figure 7-13).

Figure 7-12 Settlement of an inlet due to advection

Settlement through the barrel of the culvert is perhaps the most difficult to address. As the water flows through the barrel, heat is transferred to the permafrost, resulting in thaw settlement. As the culvert settles, buckling generally occurs. If bands are used to connect culvert sections, the bands often separate fromthe culvert, allowing material from above to fall. Spiral culverts use J-seams in their construction. These seams are weak and will separate as the culvert settles. Consequently, it is recommended that J-seams be welded on any spiral culverts that are installed in permafrost terrain.

7.4.2 Permeable Embankments

Permeable embankments constructed of a layer of rock at the bottom of the embankment with a separation geotextile above and below the rock minimize the disruption of the flow of water. In doingso, altering of the thermal regime is minimized. If coarse rock is readily available, this can be an effective solution. Otherwise, the cost becomes prohibitive.

7.5 References

American Iron and Steel Institute, 2007

Esch, 1977

8. CONSTRUCTION

8.1 Overview

"A design is only as good as those who build it" could not be more true than for roadways and airports constructed on permafrost. Construction staff should understand the impacts of construction on thepermafrost. As discussed in Chapter 1, early roadbuilders in the north recognized that even minor disturbances in the vegetation results in the thawing of permafrost. Consequently, it is important to minimize disturbance of the terrain during construction.

Communication with everyone on the project, including equipment operators, inspectors, etc., to ensure that they know the importance of adherence to specifications, permits, and best practices is key. In many cases, once the thermal regime has been disturbed, it cannot be undone. The intent of this chapter is to ensure that construction staff understand the importance of specifications, permits, and ways to avoid unintended consequences in permafrost terrain.

8.2 Importance of Minimizing Disturbance

The design of roadways and airports in temperate climates focuses on economics and safety, which dictate alignment. Stripping of vegetation along with cut/fill activities are common practices. In permafrost regions, such practices have proved costly. In areas of discontinuous permafrost, simply clearing the trees over ice-rich permafrost can increase the thaw depth by 5.9 ft. in the first five years. Linell (Linell, 1973) found that removing vegetation caused 8.8 feet of thaw after five years. Linell reported the depth of thaw increased to 15 ft when trees were removed and 22 feet when vegetation was removed, indicating that the impact cannot be reversed.

While it is tempting to remove brush and trees to provide visibility to the right of way, doing so when permafrost is present may affect the roadway by causing thaw consolidation and ponding water adjacent to the roadway. These thermokarsts often accelerate thaw along the toe of slopes, which result in longitudinal cracking in the traveled way. Consequently, clearing should be performed only when required. If vegetation must be removed to ensure sight distances, do so without damaging the underlying mosses.

8.3 Small Mistakes; Big Consequences

Even small construction mistakes during construction may have large consequences in permafrost terrain. The simple act of parking equipment on the tundra outside the construction zone can trigger thawing of the underlying permafrost, resulting in a talik. This talik may result in a maintenance problem for many years.

In another case, a contractor may choose the wrong equipment to subcut beneath a park road, requiring the use of thaw and cut. As a result, the rate of thawing may exceed the contractor's ability to remove the thawing material and the meltwater. Consequently, the cost of the project may rapidly increase, and the completion of the project may be delayed.

As construction proceeds, project personnel must remain vigilant, especially when permafrost is involved. The repair of construction damage to the permafrost is rarely effective.

8.4 Enforcement of Permits

Enforcement of permits is always important. Failure to follow the requirements of permits in areas underlain by ice-rich permafrost may result in irreparable damage. In many cases, areas of ice-rich permafrost are considered wetlands. As such, wetland regulations apply. The Corps of Engineers and other regulatory agencies are keenly aware the impacts of construction over permafrost.

While it is always prudent to discuss permits with the contractor before commencement of construction, the presence of permafrost increases the need for everyone to ensure that equipment operators and inspectors know and understand the terms of the permit.

8.5 Managing Unforeseen Ice

Unfortunately, geotechnical investigations do not always identify high ice content permafrost. In discontinuous permafrost zones, it is not uncommon to encounter ice in roadway cuts. The ice may be an ice wedge or basil ice (glacial ice). In either case, the construction staff should immediately contact the regional Materials Engineer for instructions concerning how to proceed. In general, work in the area should be stopped until the extent of the ice can be determined. If the ice mass is small, it will likely be removed. If the mass is extensive, then other actions may be taken to minimize the impact of thawing. The appropriate action depends upon several factors, including the extent of the ice, the probability and rate of anticipated thaw, and the impact of thaw. Actions may include full or partial removal, some method of insulation, or some means of passive cooling. In any case, rapid action may be required.

There have been several cases in which rapid thaw has resulted in rapid movement of the soil as the ice has melted. In some cases, damage to adjacent land has occurred.

8.6 Winter Construction

Summer construction over permafrost terrain will invariably result in thaw of the underlying permafrost. Depending on the temperature of the permafrost, the ice content, and the depth of the active layer, the resulting thaw may not be recoverable. In these cases, the designer may choose to construct the embankment during the winter months.

Winter construction can be considerably more expensive than summer construction because of the difficultyof mining, transporting, and placing material. The daylight hours are short, requiring the work area be lit.The workforce and equipment must endure cold temperatures.

The design may vary considerably. In some cases, the design may call for placement of thawed material in lifts, with each lift being allowed to freeze before subsequent layers are placed. In this case, it is generally best to construct the embankment early in the year to avoid removing the frozen overburden. However, the contractor may choose to construct the embankment in late winter so that the soil freezes more quickly. If so, take care to remove the frozen overburden in the material source so that only thawed material is placed.

In other cases, the contractor can place frozen material. Experience has shown that compacting frozen material is essentially impossible. Consequently, this approach is generally reserved for the lower portions of high embankments. The intent is that the material will remain frozen, which will minimize settlement. If possible, use dry material or, better yet, rock to minimize settlement. Avoid ice-rich material, which can result in settlement caused by creep of the ice.

Geosynthetics are often used to separate layers of materials. In the case of winter construction, the geosynthetic may separate material that is placed in a frozen state from material that is placed in a thawed state.

Obtaining density when frozen material is placed is difficult and of limited value because normal density specifications cannot be achieved. Consequently, the construction engineer is often instructed to use judgment concerning the level of compaction that can be reasonably achieved.

While winter construction is difficult, in some instances, it can improve the long-term performance of the embankment. The construction engineer should check with the designer to understand the objectives and limitations of winter construction.

8.7 References

Linell, 1973

9 BEST PRACTICES IN MAINTENANCE

9.1 Overview

Maintenance forces are rarely trained in techniques to minimize the impact of maintenance activities on permafrost. Consequently, irreparable damage can be done by improper maintenance out of a lack of understanding. The purpose of this chapter is to provide maintenance forces with the knowledge to make the proper decisions.

9.2 Minimizing Damage Outside the Roadway Prism

In general, maintenance personnel should avoid work outside the roadway prism or other engineered structures in permafrost terrain. If work is required, consider consulting with the geotechnical engineers and others trained in permafrost engineering. Damage to vegetation, alteration of drainage patterns, or other disturbances that alter the thermal balance may result in unintended consequences for both the roadway and adjacent properties. If work on undisturbed adjacent permafrost cannot be avoided, conduct work during frozen and preferably snow-covered conditions. Active layer measurements on the same project have indicated that operating a track-mounted drill in summer and winter has left comparable appearing "scars" in vegetation, but summer drilling has increased the depth of seasonal thaw far deeper than winter drilling.

9.3 Impacts on Drainage Patterns

Before altering drainage patterns, check with the Hydraulic Engineer and Environmental Coordinator. When in permafrost terrain, also ask the geotechnical engineers to review the proposed change to ensure the change will not have unacceptable consequences such as thermal and physical erosion or thermokarst. Even routine ditch cleaning can result in unanticipated consequences.

Drainage patterns should be monitored along the roadway. If drainage patterns change in a way that adversely impacts the roadway, the regional hydrologists and the materials section should be consulted before any action is taken. They can also advise as to whether action may be beneficial.

Culverts are important in moving water across the roadway. As such they should be inspected every three to five years to determine their condition and function. If any culvert is damaged or not functioning properly, appropriate action should be taken. If the culvert is no longer required, it may be abandoned in place in many circumstances. Larger culverts, especially those in deep fills, may be lined by using one of several lining techniques. Contact the hydraulic engineer for guidance.

9.4 Selection of Materials to Fill in Longitudinal Cracks and Thermokarsts

Longitudinal cracks in the roadway surface are commonplace in permafrost regions. Little guidance has been provided concerning how best to repair them. The most common method is to simply fill them with a flowable aggregate such as sand, pea-gravel, or basecourse. Another method is to compact hot asphalt mix into them. Neither of these methods has proved satisfactory because repairs have a short life.

Because the material tends to settle into these voids rapidly, it appears as if the cracks and thermokarsts are opening rapidly. In fact, they are moving only a few inches. As they open, the entire mass of the patching material slides down into the void, giving the illusion of rapid movement.

While low fines content material flows readily into the void, it also allows water to flow readily into the voids. If there is ice-rich permafrost at depth, the water will rapidly thaw the permafrost, resulting in an acceleration of the damage. Experience has shown that it is better to fill the void with a material with high fines content, i.e., low permeability, to reduce the water flow through the system. Pavement can then be placed over the surface if appropriate. While this will not eliminate the movement, it should slow the rate of movement.

9.5 Surface Levelling Techniques

Cracking and differential settlement require leveling to keep traffic flowing. Over the years, the process has varied, but in general material is added and graded to a smooth surface. If appropriate, hot mix asphalt, cold mix, or high float is used as a wearing course. In most cases, there is little effort to restore the surface to its original elevation.

Typically, there is little effort to fill any deep-seated voids. As a result, these voids may reappear within weeks of the levelling. It is suggested that these voids be filled as described in Section 9.4 before the levelling process. While properly filling the voids will not prevent voids from reforming, it will improve the performance of the roadway and may increase the time between repairs.

10 CLIMATE CHANGE

10.1 Overview

The focus of this chapter is on available tools and contacts to help designers navigate the climate maze. Researchers and engineers at the University of Alaska Fairbanks create tools that that are useful to the practicing engineer. These tools are highlighted in this chapter, as are approaches that may be incorporated into the design. Unfortunately, there are no firm policies or procedures related to how to incorporate climate change into the design process. However, AKDOT&PF recognizes that the climate is changing and that it is having a significant impact on the performance of its roadways and airports. These impacts often increase the costs of construction and maintenance of these facilities.

Our knowledge of the earth's changing climate continues to evolve. Consequently, this chapter provides a simplified snapshot of our understanding. It is suggested that engineers consult climatologists to obtain the latest trends and forecasts. The Scenario Network for Alaska and Arctic Planning (SNAP) provides current and future climate data for Alaska, as well as tools to evaluate those data. It also provides tailored climate data upon demand. For more information visit the SNAP website at https://uaf-snap.org.

The Alaska Climate Research Center (ACRC) at the University of Alaska Fairbanks provides digital meteorological and climate data and performs climate research. ACRC products provide a wealth of local information for use in engineering designs. Visit the ACRC website at climate.gi.alaska.edu.

The Alaska Center for Climate Assessment and Policy (ACCAP), also located at UAF, focuses on community needs assessments, resource studies, climate modeling, and the development of products and tools. ACCAP provides a service of webinars aimed at increasing public understanding of Alaska's climate. See the ACCAP website at uaf-accap.org.

The National Weather Service Alaska (NWS Alaska) provides weather forecasting, anticipated weather patterns and historical weather data. NWS Alaska works with the centers listed above. NWS Alaska can be found at https://www.weather.gov/arh.

All of these organizations have proved to be willing to help state agencies and the public at large understand Alaska's climate. Do not hesitate to contact them for information related to any project requiring those data.

10.2 Difference between Climate and Weather

Weather and climate reflect two different ways to aggregate a system in terms of time, space, and complexity. Weather represents atmospheric conditions at a specific time and place. The weather is typically quantified by variables such as temperature, moisture, wind speed and direction, and barometric pressure. Climate refers to atmospheric conditions over an area and a long period of time.Climate is a much broader phenomenon than weather and encompasses different periods of time and interactions with earth systems (e.g., atmospheric composition, volcanic eruptions, changes in the earth's orbit around the sun, changes in the energy from the sun itself).

Weather and climate can both be predicted by using existing measured conditions and numerical models to project what is likely to occur. Weather predictions are driven by knowledge of meteorology, the study of atmospheric events. Typical timescales of prediction can range from now-casting of up to the next 6 hours, short forecasts (0 to 48 hours), medium forecasts (3 to 6 days and 8 to 14 days), and long outlooks (monthly and seasonal). Data from ground stations, planes, boats, satellites, and models are combined to produce the range of estimates. Note that weather predictions are typically presented as the likelihood of an event happening. For example, the weather forecast may indicate a 10 percent chance of rainfall between 1:00 and 2:00 pm.

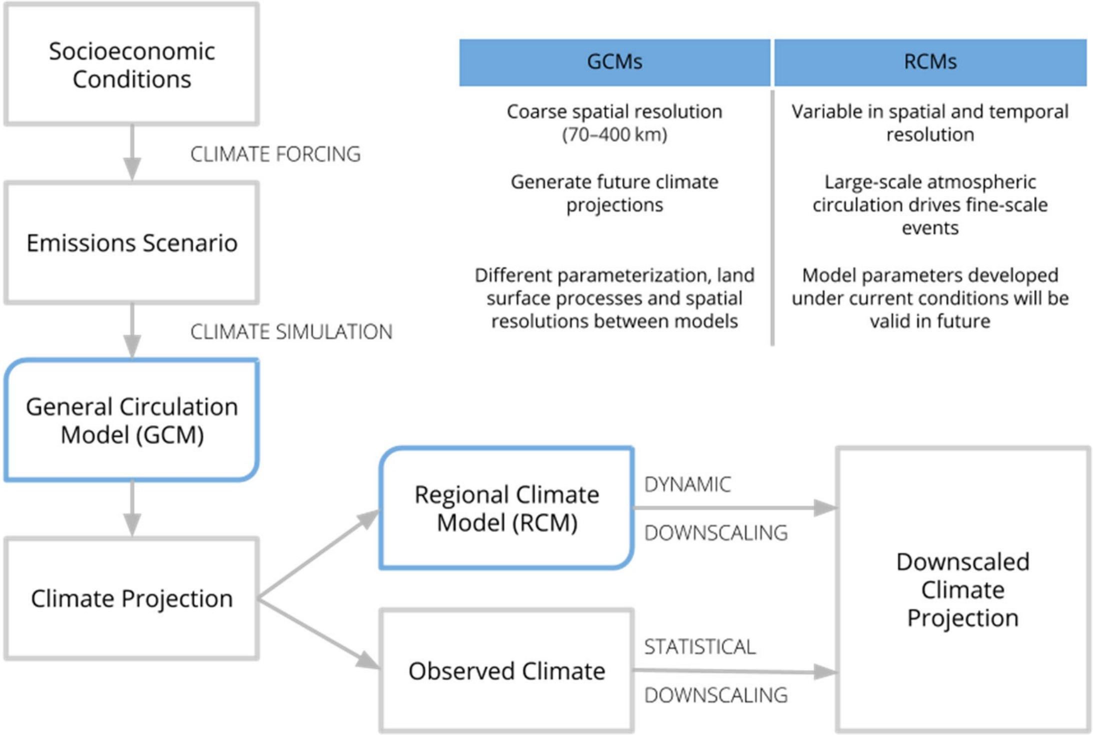
Climate is predicted with models that include atmospheric and oceanic characteristics, including interannual and interdecadal variability, such as the tropical climate variability in the Pacific associated with the El Niño–Southern Oscillation (ENSO), which has a strong impact on the global climate system. These models are used to create future climate scenarios, which do not represent established probabilities but physically plausible relationships between different climate variables and the spatial patterns in relation to future pathways of greenhouse gas emissions.

As shown in figure 10-1, developing climate projections starts with prescribing the socioeconomic conditions that drive emissions scenarios or representative concentration pathways (RCPs). These are divided into different assumptions of climate forcing, clustered around terms of low (4.5 RCP / B1 scenario), medium (6 RCP / A1B scenario), and high (8.5 RCP / A2 scenario). These conditions are then fed into global circulation models (GCM), which are run globally at relatively coarse spatial resolutions.

Models vary in terms of parameterization, land surface processes, and spatial resolutions.

It is important that models represent a range of conditions so they can evaluate a variety of potential scenarios.

Downscaled climate data are typically used in Alaska because of strong regional processes and because Arctic locations amplify changes in climate. Below, these processes and how they relate to the downscaling process are discussed. One issue to be aware of is that in climate and weather data there are typically a temporal and spatial resolution trade-off. Typically, data with high temporal resolution (i.e., hourly) represent either a point or a relatively large area (> 25 km^2). Finer spatial resolution data (i.e., ~1 km^2) are often available monthly. Climate data are created by models, while weather data can either be modeled, collected via satellite or created with a mix of the two techniques. Many weather and climate products available for the continental United States do not extend to Alaska. As GCMs improve and regional climate models (RCMs) run more easily, it is important to connect general theory about climate in Alaska with specifics about the models and data.



GCMs	RCMs
Coarse spatial resolution (70–400 km)	Variable in spatial and temporal resolution
Generate future climate projections	Large-scale atmospheric circulation drives fine-scale events
Different parameterization, land surface processes and spatial resolutions between models	Model parameters developed under current conditions will be valid in future

Figure 10-1 Conceptual model detailing the process of creating downscaled climate projections that canbe analyzed and used for decision making.

10.2.1 Orographic Effects Affect Regional Weather and Cclimate

Orographic refers to relating to mountains, in particular their position and form.

Precipitation and temperature are strongly influenced by orographic effects in Alaska, which can cause strong regional variations that are important in relation to localized permafrost conditions.

Mountains serve as natural topographic barriers that cause large changes in precipitation (figure 10-2). On the windward slope, typically adjacent to an ocean, ample moist air is available. As it rises over the mountains, the air cools, causing the water vapor to condense, which leads to increased precipitation. A well-known version of this phenomenon occurs on the south side of the Chugach range, which is covered by temperate rain forest. Permafrost is generally only found in isolated pockets in this area or of higher elevations. As the air and moisture continue up and over the range, the air warms as it descends the leeward slope, resulting in decreased precipitation, known as a rain shadow.

Orographic precipitation effects are found throughout the state and have not been explicitly studied with respect to permafrost distribution. However, because they strongly influence both rain and snow, there is likely a much stronger relationship than currently recognized. This is especially true as it relates to snow distribution because snow has an important insulation effect on the ground and can strongly control permafrost distribution. This process can occur on a variety of scales, making it important to consider when data for modeling permafrost conditions are collected and extrapolated.

Winter temperature inversions are important in relation to permafrost distribution in discontinuous and isolated permafrost areas (figure 10-3). In Fairbanks, inversions play a major role in controlling the distribution of permafrost. Permafrost is present in low-lying areas and on hill slopes in some areas. Moving toward higher elevations in the hills, permafrost is absent.

Wind redistribution is critical to understanding snow variability, especially in areas with orographic effects. Snow plays a major role in controlling ground temperature, as a lack of snow and exposure to air and wind allow the ground to rapidly cool. Wind redistribution of snow can occur at three main scales: A) mountain range scale; B) ridge scale, and C) slope scale (Mott et al. 2018). Snow depths increase over the mountain range scale with elevation and decrease caused by the rain shadow effect as it traverses over the range.

At the ridge scale, low-level clouds form as air descends ridges within the mountains as higher-level clouds seed them. Advective processes dominate in this area. As air masses move up small intermediate ridges, updrafts cause divergent patterns. Air continues to flow over the ridges, and eddies and downdrafts form, creating convergence on the leeside. Snow deposition intensifies in these areas. Accounting for these processes within data requires model resolutions of 50 m or less (Gerber et al., 2018), but this is not currently available in Alaska. However, recognizing where these processes occur can help account for them in terms of understanding their effects on permafrost.

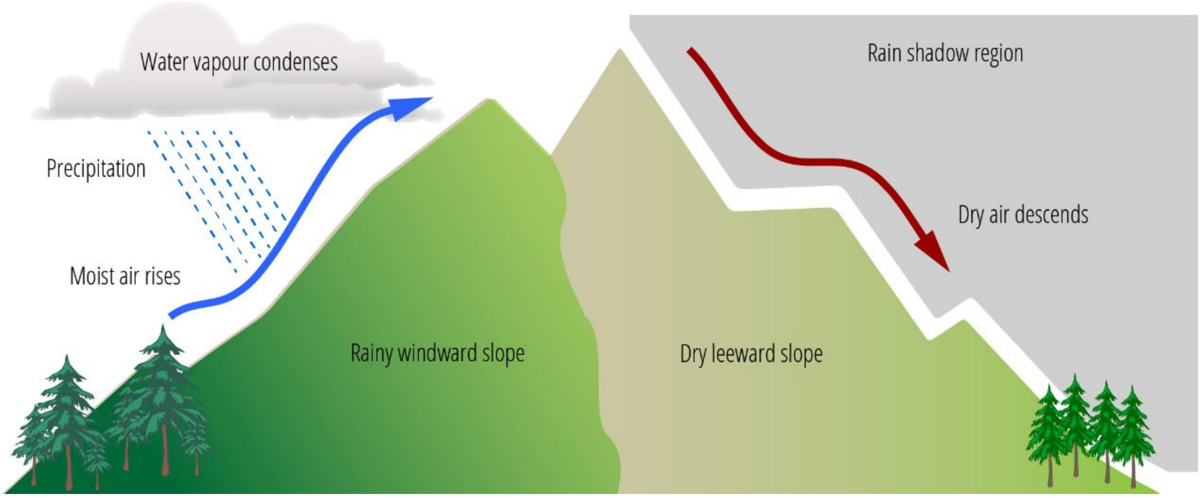


Figure 10-2 Example of the orographic precipitation effect in which there are rainy windward and dry leeward slopes, which create a rain shadow region.

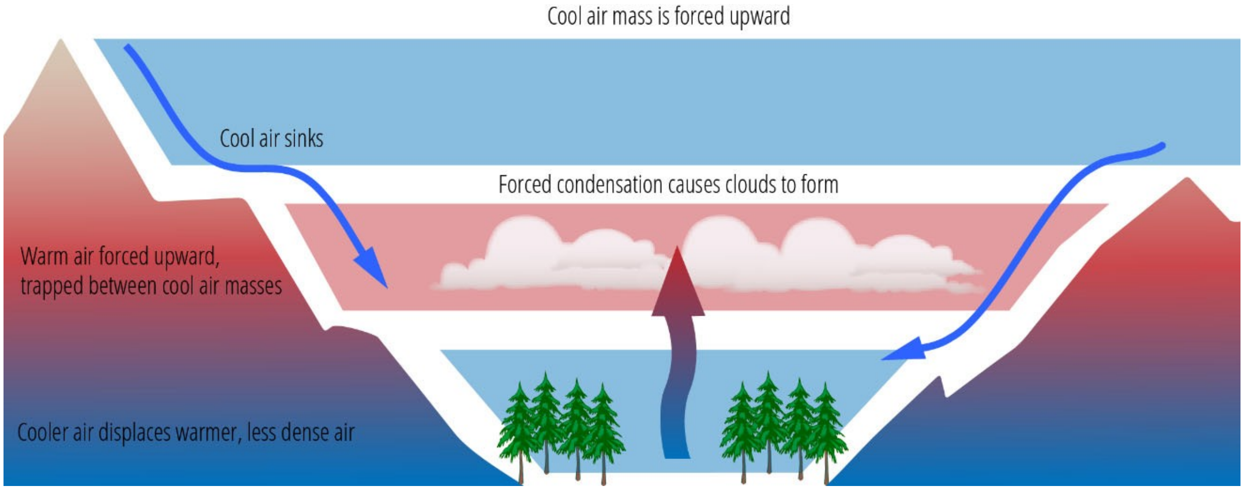


Figure 10-3 Example of the orographic precipitation effect in which there are rainy windward and dry leeward slopes, which create a rain shadow region.

10.2.2 Main Drivers of Climate

Two major indices provide insight into Alaska climate: The Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). The PDO is the main annual pattern in the North Pacific of monthly sea surface temperature (SST) anomalies (Mantua and Hare 2002) (figure 10-4). These anomalies are generated by subtracting the global mean SST anomaly and the climatological cycle. The PDO is associated with changes in precipitation, temperature, snowpack, and drought. It generally operates on a decadal scale and is often associated with winter temperature anomalies (Papineau 2001). The positive phase in Alaska is often related to higher temperatures and more precipitation, versus the negative phase, which exhibits the opposite pattern (Wendler et al. 2017). The PDO is complex; recent research suggests that there is a linear connection between the impact of the PDO and the ENSO (Jian et al.2019). Up-to-date information on the PDO is available from the NOAA Teleconnections site.

The ENSO is composed of two periodic warming and cooling sea surface temperature cycles known as El Niño and La Niña. They occur in the Equatorial Pacific region, as shown in figure 10-4. Typically, the cycles occur every 2 to 7 years and reach their peak intensity from December through April. El Niño occurs more frequently and brings unusually warm temperatures that can last 9 to 12 months. This creates a low-pressure system in the Pacific that brings warmer temperatures to Alaska and extends the Pacific Jet Stream into the continental United States. La Niña typically has a duration of 1 to 3 years, with the same peak intensity timing, but it is associated with colder temperatures. It creates a blocking high pressure system that creates variability in the Polar Jet Stream from Alaska through the Midwest and leads to wetter conditions on the West Coast. Information about current and past events of the ENSO is available from the NOAA Physical Sciences Laboratory site.

Climate research has shown strong links between greenhouse gases and changes in the Earth's climate.While it is important for the design engineer to recognize the link between the production of greenhouse gases and climate, that research is best left to the climate scientist. Public policy related to greenhouse gases is outside the scope of this synthesis. For the task at hand, it is more important that the engineer recognize and understand that the climate is changing and that the design of the engineered system must account for those changes. This in no way undermines the importance of the prediction of future climate or its impact on the Earth's environment. The engineering community relies on those predictions to adapt the buit environment.

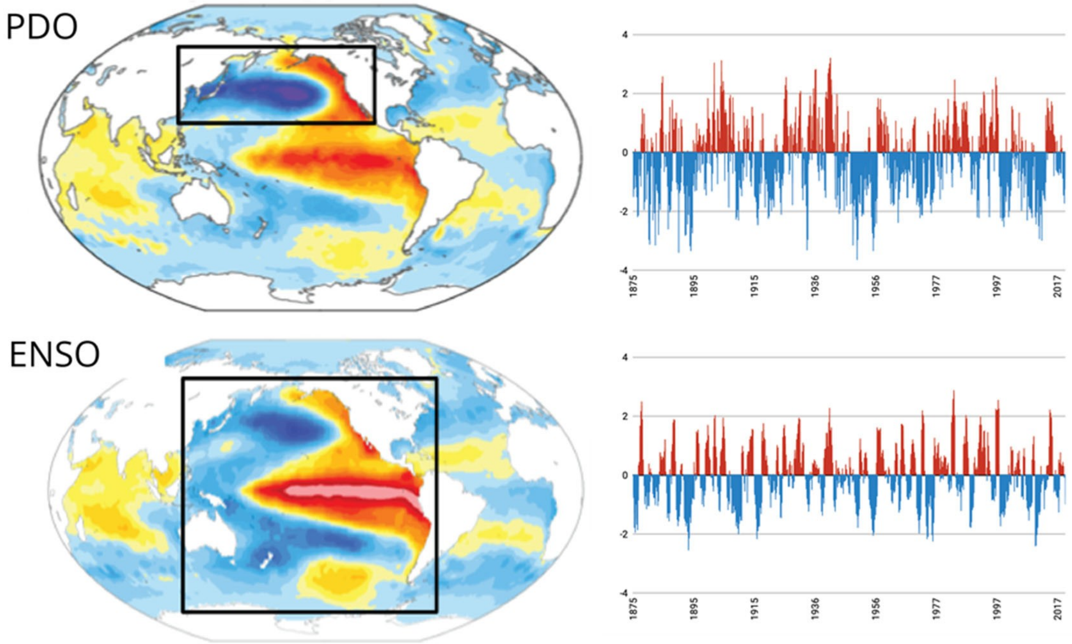


Figure 10-4 The PDO and ENSO (top and bottom left) global expressions, obtained by linearly regressing monthly SST* anomalies by the leading Principal Component (PC) time series within the indicated domains. They can also be visualized as time series, based on the PDO HadISST data and the Multivariate ENSO Index for the period 1875-2020. Adapted from Deser et al. (2010) from the NCAR Climate Data Guide

Alaska's climate is influenced by four main drivers: latitude, altitude, continentality (the degree to which the area is subject to the influence of a landmass), and the seasonal distribution of sea ice (Shulski and Wendler, 2007).

Latitude varies widely within the state and results in large differences in seasonal variation of daylight and incoming solar radiation. In the winter, areas north of the Arctic Circle will have continuous periods in which the sun does not rise above the horizon, whereas in other regions such as the Interior there is little solar radiation, as the sun is restricted to rising only a few degrees. In the summer, even though the hours of daylight are long, the solar elevation angles remain low, creating a long path for energy through the atmosphere and resulting in increased absorption and reflection.

Altitude and topography strongly influence weather patterns. Alaska has several mountain ranges, including the Brooks Range to the north, the Alaska Range in the Interior of the state, and the Chugach, St. Elias, and Coast Mountains on the southern coast.

Alaska has 13 climate zones, as updated in 2015. Figure 10-6 is based on averages from 1971 to 2000 PRISM (the Parameter-Elevation Regressions on Independent Slopes Model) outputs. These climate zones were developed in collaboration with scientists from the University of Alaska-Fairbanks, National Weather Service - Alaska Region, NCDC Regional Climate Services, Oregon State University, and University of Nebraska-Lincoln (Bieniek et al. 2012). These zones are used for both climate and hydrological analysis. The current climatic zones that interact with permafrost conditions may be quite different than those that existed when the permafrost originally formed.

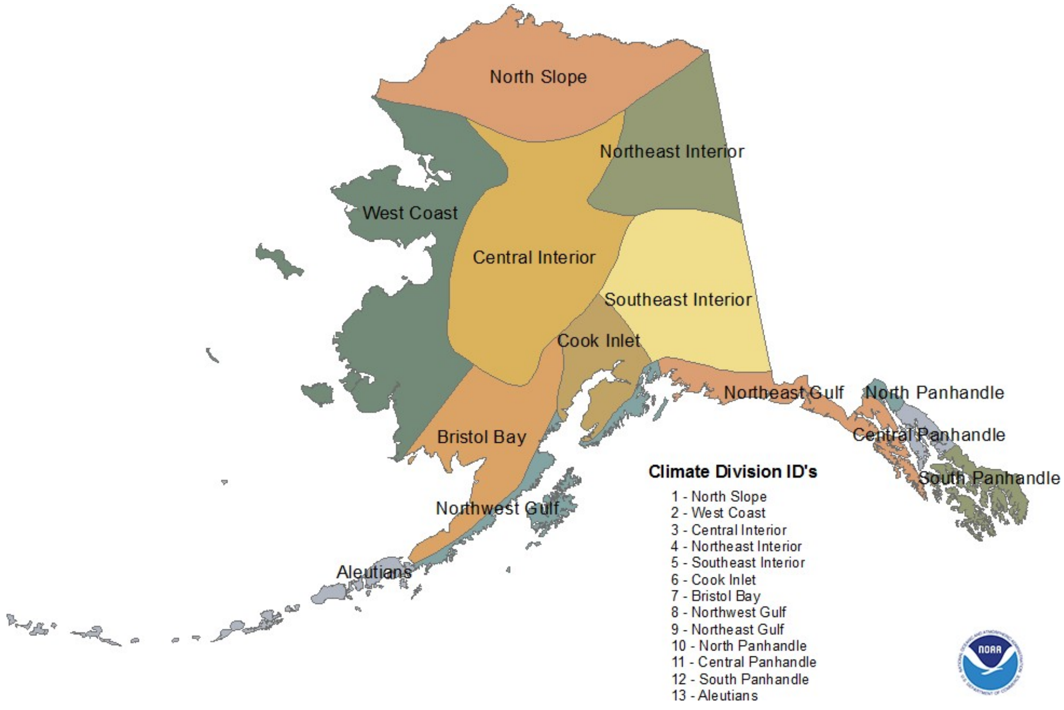


Figure 10-5 Current Alaska climate divisions. More information is available on the NOAA Alaska Climate Division FAQ page.

Linking current conditions to the past climatic record is easily accomplished by using automatically generated monthly summaries. These are available for the climate zones and can be found by using NOAA’sNational Temperature and Precipitation Maps (figure 10-6).

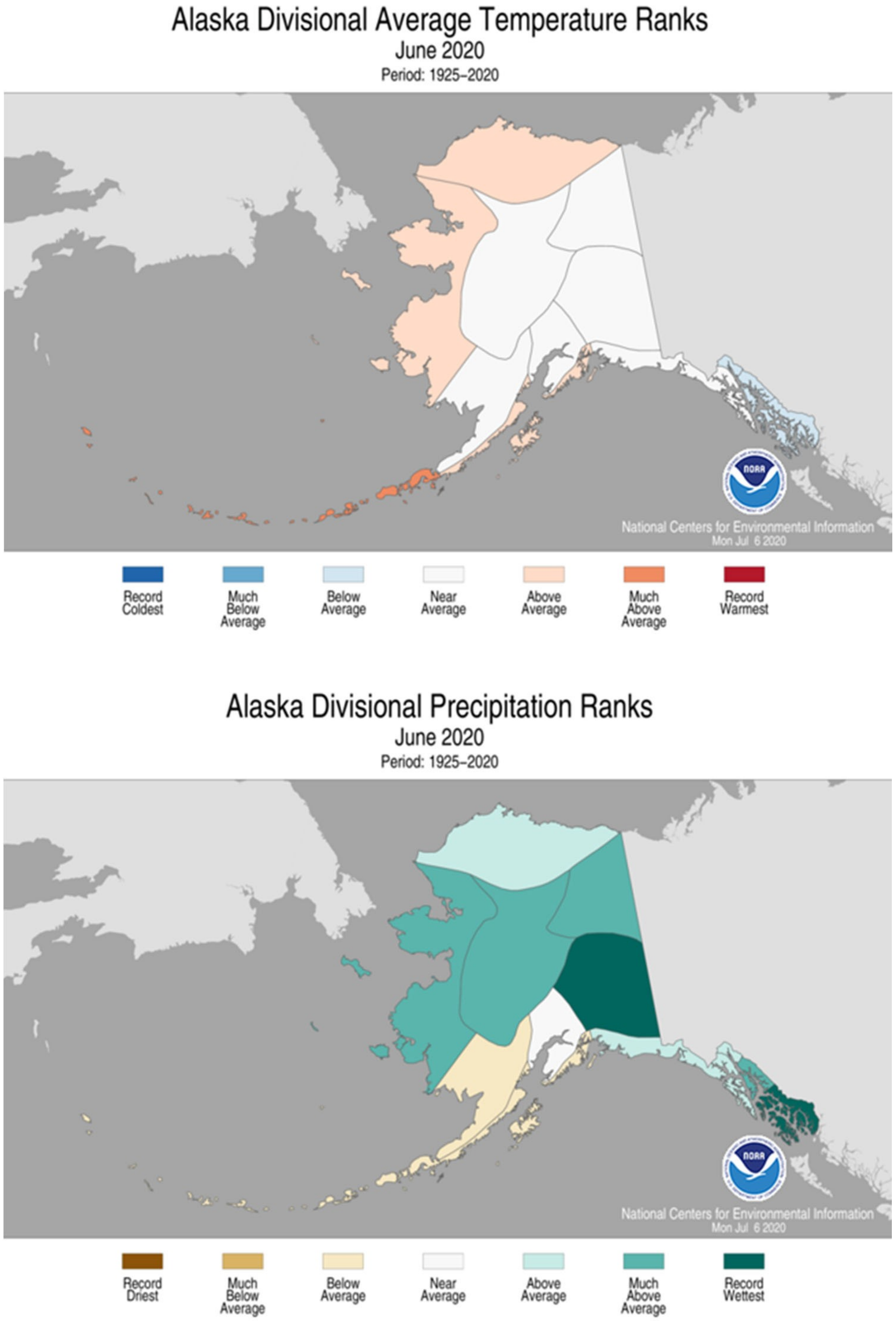


Figure 10-6 Example of monthly climate zone summaries for temperature and precipitation available from NOAA's [National Temperature and Precipitation Maps](#).

10.3 Critical Climate Variables

Design considerations for permafrost can include several factors, including air temperature, precipitation types and amounts by season, prevailing wind speed and direction, freezing/thawing degree days, sunshine and cloudiness, and various other factors such as topography, geography, and proximity to surface water and wetlands.

This section provides a regional overview of climate data for temperature, precipitation and wind speed that provide input into design considerations for permafrost.

10.3.1 Temperature

Temperature variability is summarized in figure 10-7 for Alaska climate divisions. Mean temperature was calculated for each 30-year multi-decadal period, for which the mean from 1980 to 2009 was subtracted from the other periods to produce anomalies. Only areas with permafrost, delineated from the 2008 map of Alaska, were summarized for each climate division. Comparing each period to the 1980 to 2009 baseline provides a clear picture of temperature in each of the other periods in each of the climate zones.

As expected, the North Slope had the lowest mean average temperature during the 1980 to 2009 era. The Northwest Gulf, which only contains a few assets on permafrost, had the highest mean temperature, more than 0 °C. In comparison to the 1930 to 1959 period, all climate zones were colder. In the 2020 to 2049 period, all areas are predicted to warm by 1 to 2 °C on average. By 2070 to 2099, this is predicted to increase 3.8 to 5.8 °C above the 1980 to 2009 period. Much of this warming occurs during the winter months (Walsh et al. 2018).

This pattern of warming is already reflected in the land-based station data. As shown in table 10-1, Barrow on the North Slope, McGrath in the Central Interior, and Kotzebue on the West Coast show warming in the winter, spring, and autumn over the period of 1976 to 2018. Warming during the summer generally leads to an increased thickness of the active layer and an increase in subsidence of the intermediate layer, the ice-rich layer at the base of the active layer. The same pattern in the spring can be more variable, as warmer temperatures can lead to a faster break-up and jump-start on the deepening of the active layer. This warming may also occur while snow is still present and may have less of an effect. During the autumn, increased temperatures can delay freezing of the active layer and increase the number of freeze-thaw cycles.

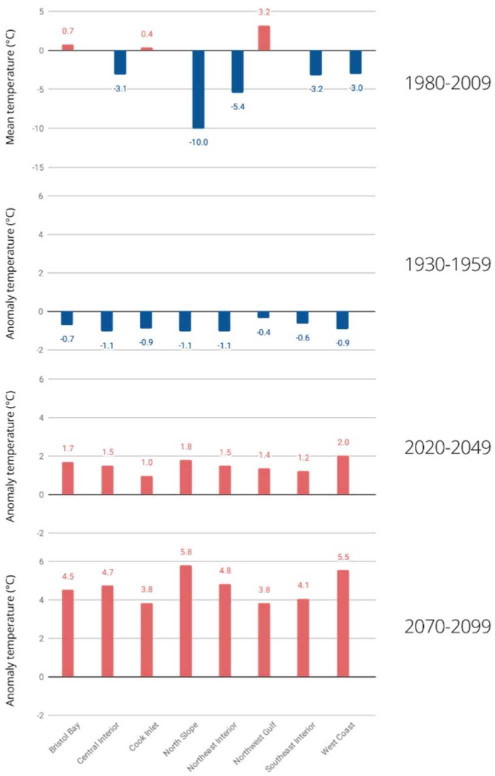


Figure 10-7 Temperature (°C) over four -0-year multi-decadal periods showing mean (top) and anomaly values for Alaska climate divisions.

Temperature variations can also be examined over a longer, 70-year time (table 10-2). The first thing to note is that warming for the three communities with the greatest magnitude of temperature increase has stayed the same (McGrath) or decreased (Barrow and Kotzebue). This does not mean that the increase is not occurring. It points to the complexities of the change and the difficulties in ascribing a linear increase to processes that are temporally variable. Second, unlike the 1976 to 2018 period, none of the communities shows cooling in the winter or spring. Instead, most show substantial warming, especially in the winter. Comparing the differences between these two time periods indicates that landscapes may be experiencing more complex shifts than indicated by shorter-term data.

As a comparison of tables 10-1 and 10-2 show, exploring trends over multiple time frames provides insight into the variability of climate over time. In doing so, it becomes clear that changes are not constant. Nor are these changes consistent between seasons. Much of this variability can be explained by the PDO and ENSO, as discussed in Section 10.2.2.

Table 10.1: Total change in mean seasonal and annual temperature (°F), 1976-2018 matched to the climate divisions of Alaska, data produced by the Alaska Climate Research Center.

Division	Location	Winter	Spring	Summer	Autumn	Annual
North Slope	Barrow	11.2	11.3	4.3	18	11.4
Central Interior	Bettles	2	0.4	-0.8	3.6	1.8
Southeast Interior	Fairbanks	-1.4	-1.5	1.6	2.2	0.7
Southeast Interior	Delta Junction	3.3	-0.4	0.4	1	2.4
Central Interior	McGrath	5.6	4.1	3.7	7.1	5.4
West Coast	Kotzebue	4	5.3	3.5	7.3	5.3
West Coast	Nome	-0.5	1.4	0.3	3.7	1.7
West Coast	Bethel	2.9	3.1	3.5	4.8	3.9
Bristol Bay	King Salmon	2.3	0.4	3	5.6	3.2
West Coast	St. Paul Island	-1.2	0.5	1.6	2.8	1.3
Cook Inlet	Talkeetna	4.5	3.5	3.3	5.8	4.6
Southeast Interior	Gulkana	0.5	0.1	1.8	-1.2	1
Cook Inlet	Anchorage	1.2	0.1	2.3	3.6	2.1
Cook Inlet	Homer	1.3	1.4	3.2	2.9	2.4
Northwest Gulf	Kodiak	-1.7	-1.6	0.9	0	-0.4

Table 10-2: Total change in mean seasonal and annual temperature (°F), 1949-2018 matched to the climate divisions of Alaska, data produced by the Alaska Climate Research Center.

Division	Location	Winter	Spring	Summer	Autumn	Annual
North Slope	Barrow	9.8	6.7	3.7	7.3	6.8
Central Interior	Bettles	8.7	5	1.7	2.8	4.9
Southeast Interior	Fairbanks	8.1	3.8	2.4	1.5	3.9
Southeast Interior	Delta Junction	9.9	3.4	1.4	1.4	4.9
Central Interior	McGrath	9.7	5.3	3	3.2	5.3
West Coast	Kotzebue	9	3.2	3.8	4	4.9
West Coast	Nome	6.1	3.7	2.8	2	3.6
West Coast	Bethel	8.5	5.1	2.4	1.8	4.4
Bristol Bay	King Salmon	10.2	4.6	2.1	2.6	4.8
West Coast	St. Paul Island	1.7	2.2	3.1	2.2	2.3
Cook Inlet	Talkeetna	9.7	5.6	3.1	3.7	5.6
Southeast Interior	Gulkana	8.4	2.6	1.3	0.6	3.3
Cook Inlet	Anchorage	8	3.9	2.4	3.7	4.2
Cook Inlet	Homer	7.4	4.4	3.8	3	4.7
Northwest Gulf	Kodiak	2	2.5	1.9	0.7	1.8

10.3.2 Precipitation

Precipitation variability was summarized as shown in figure 10-8 by using the same techniques as those used for temperature. It should be noted again that these mean values combine both solid and liquid precipitation. Overall, most areas are predicted to experience an approximately 25 percent increase by 2070 to 2099 over 1980 to 2009 values. In the 1930 to 1959 period, only the Southeast and Northeast Interior zones showed notable increases in precipitation. By 2020 to 2049, all areas are predicted to begin to show increases, except for the West Coast,which is predicted to show a slight decrease, like the 1930 to 1959 period. These increases, especially by the 2070 to 2099 era, will likely affect the thickness of the active layer and permafrost base thickness.

However, this analysis does not include changes in intensity or duration of precipitation, especially in the summer. As discussed earlier, this can drastically increase advective processes and lead to preferential thawing of permafrost where water is draining. This is currently not routinely incorporated into the numerical model being used to examine the permafrost characteristics.

10.3.3 Wind

Wind plays a key role in convective processes that affect climate conditions. Monthly community data are available for both historical and projected periods from the Alaska Community Wind Data tool. This looks at changes in both wind speed and direction over time. The intersection between temperature and windspeed can also be useful to understand snow drifting, especially for considering increases in blowing snow, which may also thaw the permafrost.

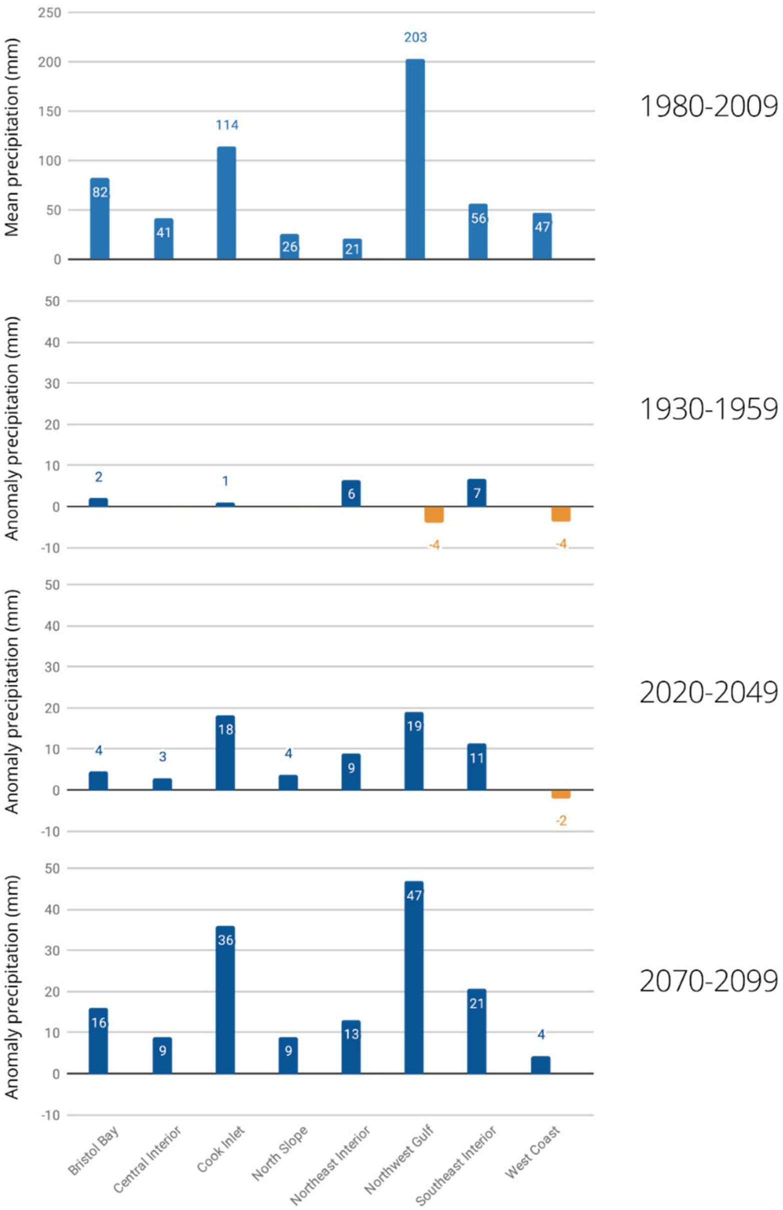


Figure 10-8 Precipitation (mm) over four 30-year multidecadal periods showing mean (top) and anomaly values for Alaska climate divisions containing permafrost and DOT assets as shown in Figure 10-6. The anomalies were derived by subtracting the associated means from the 1980 to 2009 mean. These were derived by using downscaled projections from the original SNAP downscaled temperature product at 2x2-kilometer spatial scale to a 1x1-kilometer spatial scale using a bilinear interpolation for the Integrated Ecosystem Model (IEM) project. These included 1) CRU TS 3.1 data (1900-2009); 2) 2 AR4/CMIP3 climate model projections (2010-2100) (cccma_cgcm3_1 and mpi_echam5) and one projected emissionscenario (A1B); and 3) 1 AR5/CMIP5 climate model projection (2010-2100) (ncar_ccsm4) and one projected emission scenario (RCP 8.5).

10.4 Climate Data Availability

Selecting climate data for examining permafrost conditions is a process. In recent years, the data cycle for generating new and updated climate products has compressed. It is important to understand the various types of data available and to develop consistent workflows for when, where, and how they get used. Because of this compressed production cycle, incorporating processes for updating data and maintaining continuity with past analysis is useful. This is a larger issue within the engineering community in general. In Alaska, there is an effort to modernize, streamline, and standardize access to climate data. This includes updating the Environmental Atlas of Alaska, which currently exists in hard copy form, into an online system known as the Arctic Environmental and Engineering Data and Design Support System (Arctic-EDS), which will be active by 2023. The Arctic-EDS will be a hybrid approach consisting of an online graphical user interface, programmatic data access via an application programming interface (API), and Jupyter notebooks demonstrating the API use and engineering applications.

It is common to work with climate data by downloading land-based station data from a variety of sources. Where they do not exist, an individual project will sometimes install a temporary station to collect data for short-term periods, typically the project duration of three years. Alaska remains data-poor in comparison to the continental United States. When a source for climate data is selected, it is important to be aware of what processes are represented in the data.

The University of Alaska Fairbanks supports several climate research and data centers including SNAP, ACCAP, and ACRC. The missions and websites are provided in Section 10.1. Each of these centers have public outreach funding. Don’t hesitate to contact them to help with climate related questions, data and trends.

10.4.1 Land-Based Station Data

Land-based stations remain the gold standard for recording climate data since they represent the conditions of the surrounding area. The data sets include air temperature, precipitation, and wind speed and direction, which are critical for calculating permafrost characteristics such as active layer depth and mean annual ground temperature. The longest records available for Alaska extend over a century but are available for only a few locations within each climate zone. Many of these make up first order stations, where observations are collected by National Weather Service personnel. The distribution of stations and the length of monitoring are shown in figure 10-9. Most stations have been monitored for fewer than 50 years. Land-based station data are assimilated from a variety of national, state, and local surface meteorological networks. A variety of websites are available for accessing data. Three of the best places to conduct initial queries include NOAA Climate Data Online, the Alaska Climate Research Center (ACRC) and the Meteorological Assimilation Data Ingest System (MADIS).

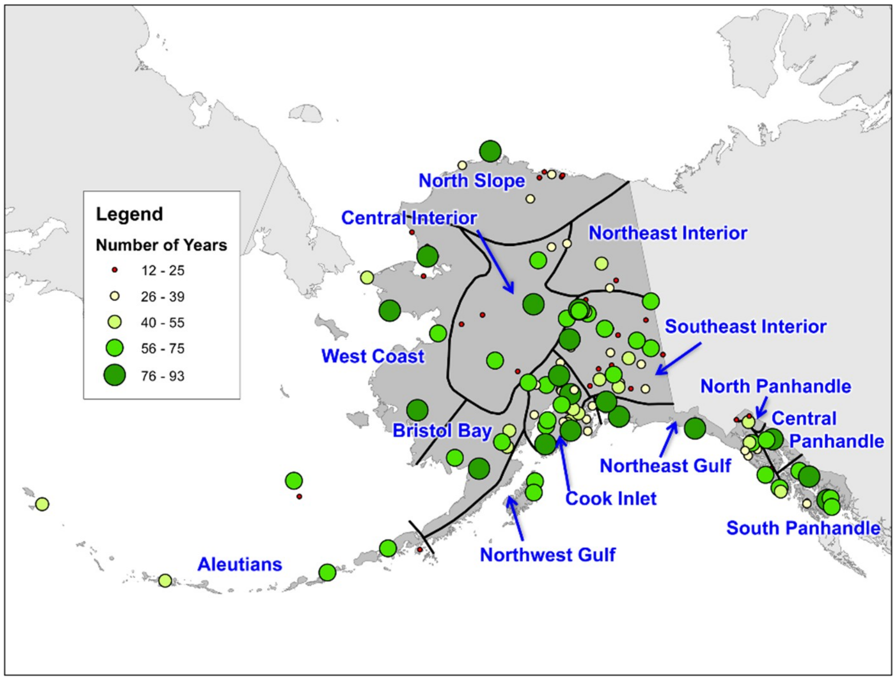


Figure 10-9 Totaled years of temperature observations between 1920 and 2012 at weather stations within the Global Historical Climatology Network database overlaid with the Alaska climate divisions (Bieniek et al. 2014a).

Each of these organizations maintains a variety of products derived from land-based station data. The NOAA NCEI Map Viewer makes it easy to find the hourly, daily, and normal observational data from Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) stations. Once the data set ID is known, NOAA also provides API access to programmatically query and download data sets. The Alaska Climate Research Center provides access to daily, monthly, and yearly summaries with NOAA data acquired from the Applied Climate Information System (ACIS). MADIS is a database and data delivery system that aggregates data from a variety of sources in addition to NOAA, including Remote Automated

Weather Stations maintained by the National Interagency Fire Center and AKDOT&PF stations. The MADIS Surface data tool provides a useful map interface for data discovery but requires a subscription to use the data.

The advantage of using land-based station data for permafrost analysis is that they are the closest reflection of the local environment. This means that it also reflects the any orographic effects present at that location. Given that orographic effects can strongly affect temperature, precipitation, and wind patterns, this is useful for permafrost applications.

For permafrost applications, land-based station data have mainly been used by site-level investigations. Larger regional, national, and international permafrost modeling efforts have transitioned to using gridded historical data to better capture landscape level characteristics.

10.5 References

Bieniek, P. A., and Coauthors, 2012: Climate divisions for Alaska based on objective methods. J. Appl. Meteorol. Climatol., 51, 1276–1289, https://doi.org/10.1175/JAMC-D-11-0168.1.

Bieniek, P.A., J. E. Walsh, R. L. Thoman, and U. S. Bhatt, 2014a: Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. J. Clim., 27, 2800–2818, https://doi.org/10.1175/JCLI-D-13-00342.1.

Deser et al. (2010)

Gerber et al., 2018

Jian, R. A. O., C. I. Garfinkel, and R. E. N. Rongcai, 2019: Modulation of the northern winter stratospheric El Niño–Southern Oscillation teleconnection by the PDO. J. Clim., 32, 5761–5783, https://doi.org/10.1175/JCLI-D-19-0087.1.

Mantua, N. J., and S. R. Hare, 2002: The Pacific Decadal Oscillation. J. Oceanogr., 58, 35–44, https://doi.org/10.1023/A:1015820616384.

Mott et al. 2018

Papineau, J. M., 2001: Wintertime temperature anomalies in Alaska correlated with ENSO and PDO. Int.J. Climatol., 21, 1577–1592, https://doi.org/10.1002/joc.686.

Shulski and Wendler, 2007

Walsh, J. E., and Coauthors, 2018: Downscaling of climate model output for Alaskan stakeholders. Environ. Model. Softw., 110, 38–51, https://doi.org/10.1016/j.envsoft.2018.03.021.

Wendler, G., T. Gordon, M. Stuefer, G. Wendler, T. Gordon, and M. Stuefer, 2017: On the Precipitation and Precipitation Change in Alaska. Atmosphere (Basel)., 8, 253, https://doi.org/10.3390/atmos8120253.

10.6 Bibliography

Behrangi, A., A. Singh, Y. Song, and M. Panahi, 2019: Assessing Gauge Undercatch Correction in Arctic Basins in Light of GRACE Observations. Geophys. Res. Lett., 46, 11358–11366, https://doi.org/10.1029/2019GL084221.

Bourne, S. M., U. S. Bhatt, J. Zhang, and R. Thoman, 2010: Surface-based temperature inversions in Alaska from a climate perspective. Atmos. Res., 95, 353–366, https://doi.org/10.1016/j.atmosres.2009.09.013.

Buytaert, W., M. Vuille, A. Dewulf, R. Urrutia, A. Karmalkar, and R. Célleri, 2010: Uncertainties in climate change projections and regional downscaling: implications for water resources management.

Hydrol. Earth Syst. Sci. Discuss., 7, 1821–1848, https://doi.org/10.5194/hessd-7-1821-2010.

Cao, B., S. Gruber, D. Zheng, and X. Li, 2020: The ERA5-Land soil temperature bias in permafrost regions.

Cryosph., 14, 2581–2595, https://doi.org/10.5194/tc-14-2581-2020.

Chakraborty, T., and X. Lee, 2019: A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability. Int. J. Appl. Earth Obs. Geoinf., 74, 269–280, https://doi.org/10.1016/j.jag.2018.09.015.

Challinor, A. J., T. Osborne, A. Morse, L. Shaffrey, T. Wheeler, H. Weller, and P. L. Vidale, 2009: Methods and resources for climate impacts research. Bull. Am. Meteorol. Soc., 90, 836–848, https://doi.org/10.1175/2008BAMS2403.1.

Christensen, J. H., F. Boberg, O. B. Christensen, and P. Lucas-Picher, 2008: On the need for bias correction of regional climate change projections of temperature and precipitation. Geophys. Res. Lett., 35, https://doi.org/10.1029/2008GL035694.

Douglas, T. A., M. R. Turetsky, and C. D. Koven, 2020: Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. npj Clim. Atmos. Sci., 3, 1–7, https://doi.org/10.1038/s41612-020-0130-4.

Eden, J. M., M. Widmann, D. Grawe, and S. Rast, 2012: Skill, correction, and downscaling of GCM- simulated precipitation. J. Clim., 25, 3970–3984, https://doi.org/10.1175/JCLI-D-11-00254.1.

Ehret, U., E. Zehe, V. Wulfmeyer, K. Warrach-Sagi, and J. Liebert, 2012: Should we apply bias correction to global and regional climate model data? Hydrol. Earth Syst. Sci., 16, 3391–3404, https://doi.org/10.5194/hess-16-3391-2012.

Grosse, G., S. Goetz, A. D. McGuire, V. E. Romanovsky, and E. A. G. Schuur, 2016: Changing permafrost in a warming world and feedbacks to the Earth system. Environ. Res. Lett., 11, https://doi.org/10.1088/1748-9326/11/4/040201.

Liston, G. E., and K. Elder, 2006: A distributed snow-evolution modeling system (snowmodel). J. Hydrometeorol., 7, 1259–1276, https://doi.org/10.1175/JHM548.1.

Navarro-Racines, C., J. Tarapues, P. Thornton, A. Jarvis, and J. Ramirez-Villegas, 2020: High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. Sci. Data, 7, 1–14, https://doi.org/10.1038/s41597-019-0343-8.

Paik, S., S. Min, X. Zhang, M. G. Donat, A. D. King, and Q. Sun, 2020: Determining the Anthropogenic Greenhouse Gas Contribution to the Observed Intensification of Extreme Precipitation. Geophys. Res. Lett., 47, https://doi.org/10.1029/2019GL086875.

Pan, X., and Coauthors, 2016: Bias corrections of precipitation measurements across experimental sites in different ecoclimatic regions of western Canada. Cryosph., 10, 2347–2360, https://doi.org/10.5194/tc-10-2347-2016.

Schuur, E. A. G., and Coauthors, 2015: Climate change and the permafrost carbon feedback. Nature, 520, 171–179, https://doi.org/10.1038/nature14338.

Tao, J., R. D. Koster, R. H. Reichle, B. A. Forman, Y. Xue, R. H. Chen, and M. Moghaddam, 2019: Permafrost variability over the Northern Hemisphere based on the MERRA-2 reanalysis. Cryosphere, 13, 2087–2110, https://doi.org/10.5194/tc-13-2087-2019.

Thornton, P. E., S. W. Running, and M. A. White, 1997: Generating surfaces of daily meteorological variables over large regions of complex terrain. J. Hydrol., 190, 214–251, https://doi.org/10.1016/S0022-1694(96)03128-9.

Yang, D., D. Kane, Z. Zhang, D. Legates, and B. Goodison, 2005: Bias corrections of long-term (1973- 2004) daily precipitation data over the northern regions. Geophys. Res. Lett., 32, 1–5, https://doi.org/10.1029/2005GL024057.