



Addressing Environmental Conditions in the Design of Roadways Built on Permafrost

This is one of nine engineering assessments conducted under the Transportation Engineering Approaches to Climate Resiliency (TEACR) Project.¹ This assessment is different from all the others in that it is not a case study focused on exploring climate impacts to a particular asset. Instead, this report is focused on providing general background on the topic of climate change and permafrost thaw, the implications for roadways, how future thawing can be projected, and what can be done to adapt to the impacts.

1. Overview

Permafrost, soil that has remained at or below freezing (32° Fahrenheit [0° Celsius]) for two or more consecutive winter seasons and the intervening summer,² is common throughout the arctic, Antarctic, and high alpine areas. In the United States, approximately 80% of Alaska is currently covered by permafrost³ (although over much of this coverage, it is discontinuous⁴) along with a handful of isolated mountainous areas in the lower 48 States and Hawaii. In Alaska, thawing is ongoing given the well above average temperatures observed over recent decades, and that trend is expected to accelerate with climate change.

Environmental conditions have a significant effect on the performance of roadway infrastructure built on permafrost. Seasonal variations in climate factors affect the soil thermal regime as well as its properties and the integrity of soil layers. Consequently, climate is one factor that has a profound influence on the fundamental performance of the roadway. In permafrost regions, most infrastructure design approaches reflect the particular thermal, mechanical/geotechnical, and hydrogeological⁵ behavior of permafrost and recognize the criticality of climate factors in design objectives, materials selection, construction practices, and structural thickness determination. However, climate-related inputs to these methodologies have traditionally relied on historical weather records. The questions facing transportation

¹ For more information about the project, visit the project website at:

https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/.

² Andersland and Ladanyi 2004.

³ Chapin et al. 2014.

⁴ Discontinuous permafrost areas are characterized by patchy occurrence of permafrost across the landscape with areas of unfrozen soil interspersed in between. This is in contrast to continuous permafrost areas where nearly all the soil is frozen. In Alaska, continuous permafrost is only found in the northernmost part of the State, generally along and north of the Brooks Range.

⁵ Hydrogeology refers to the study of groundwater.

agencies are (1) how and when will climate change influence permafrost’s thermal behavior and (2) what are the implications on roadway performance?

Maintenance due to thawing permafrost already costs the Alaska Department of Transportation and Public Facilities (AKDOT&PF) approximately \$10 million annually.⁶ Figure 1 shows the current and projected (out to 2100) extents of frozen ground (purple areas) at a depth of 3.3 feet below the surface. As can be seen in the maps, regardless of whether a lower or higher greenhouse gas emissions scenario ultimately occurs, a substantial portion of the State is likely to experience thawing which will have significant consequences on the State’s roadway infrastructure and future maintenance costs.

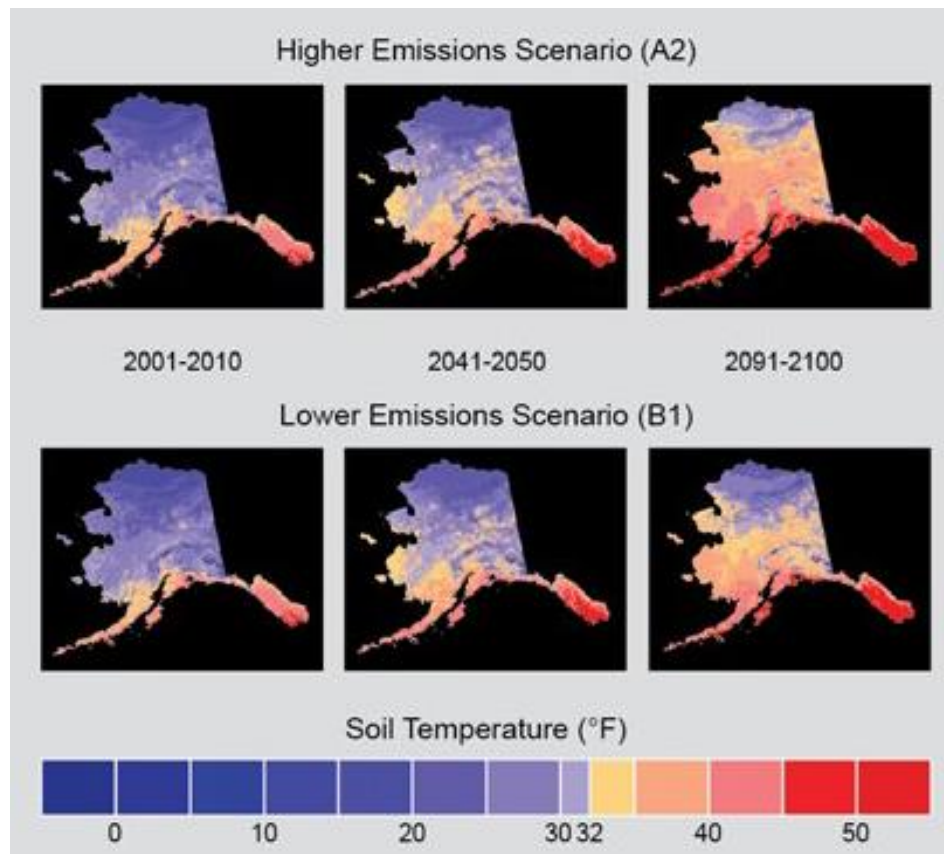


Figure 1: Ground Temperature Projections at a Depth of 3.3 Feet under a Higher (A2) and Lower (B1) Emissions Scenario.⁷

This report begins by examining some of the key characteristics of permafrost and the implications of its thaw on roadways. Following this, various techniques for projecting future permafrost conditions at specific asset locations will be presented. Finally, recommendations are offered on how climate change can be incorporated into the design of roadways built on

⁶ Turchetta 2010. Note that this figure includes costs to maintain AKDOT&PF airports and other facilities underlain by permafrost, not just roads.

⁷ Image source: Chapin et al. 2014.

permafrost. These recommendations include an overarching analysis framework (the Adaptation Decision-Making Assessment Process (ADAP)), techniques for incorporating climate projections into thermal modeling (the most robust technique for projecting future permafrost conditions at a site), and potential adaptation options for mitigating or adjusting to permafrost thaw.

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2. Key Characteristics of Permafrost and its Implications for Roadways

This section provides important background information on the key characteristics of permafrost and the implications of its thawing on roadway infrastructure. Key characteristics include:

- Air temperature considerations.
- The relationship between ground temperatures and permafrost depth.
- Permafrost continuity.
- Permafrost ice content.
- Special features within permafrost like ice wedges, ice lenses, and taliks.

Following this, the implications of permafrost thaw are discussed: specifically, differential longitudinal settlement, shoulder rotation, and slope failures.

2.1. Air Temperature Considerations

For permafrost to occur, freezing conditions must be more prevalent than thawing conditions; this ensures that the depth of thawing is less than the depth of freezing, allowing a portion of the soil to stay frozen all year long. Both the freezing and thawing depths depend in part on the magnitude and duration of the temperature differential above or below freezing at the ground surface.

One way to determine if permafrost may form is to establish the freezing and thawing potential by calculating the annual freezing and thawing indices. The freezing and thawing indices correspond to the summation of the differences between daily temperatures below or above 32° Fahrenheit (0° Celsius), respectively. For example, a mean daily air temperature of 28° Fahrenheit (-2.22° Celsius) during four days corresponds to a freezing index of -16 degree-Fahrenheit days (-8.89 degree-Celsius days).⁸ For permafrost to occur, the absolute value of the freezing index must be larger than the thawing index for a long enough period to maintain the soil temperature below 32° Fahrenheit (0° Celsius) for two or more consecutive years. Figure 2 shows example historical freezing and thawing indices at a site in central Alaska. As can be

⁸ Note that a temperature difference of 1°Celsius is equivalent to a temperature difference of 1.8° Fahrenheit. Thus, Fahrenheit-based degree days are 1.8 times larger in value than their equivalent Celsius-based degree days. The calculation used to arrive at the value shown is as follows:
Freezing point = 32°Fahrenheit (F), air temperature = 28°F so $28^{\circ}\text{F} - 32^{\circ}\text{F} = -4^{\circ}\text{F}$ (difference between the temperature and freezing point) $-4^{\circ}\text{F} \times 4 \text{ Days} = -16^{\circ}\text{F days}$ (temperature difference multiplied by the number of days).

seen, since 1976, the freezing index has been significantly higher than the thawing index, resulting in permafrost.

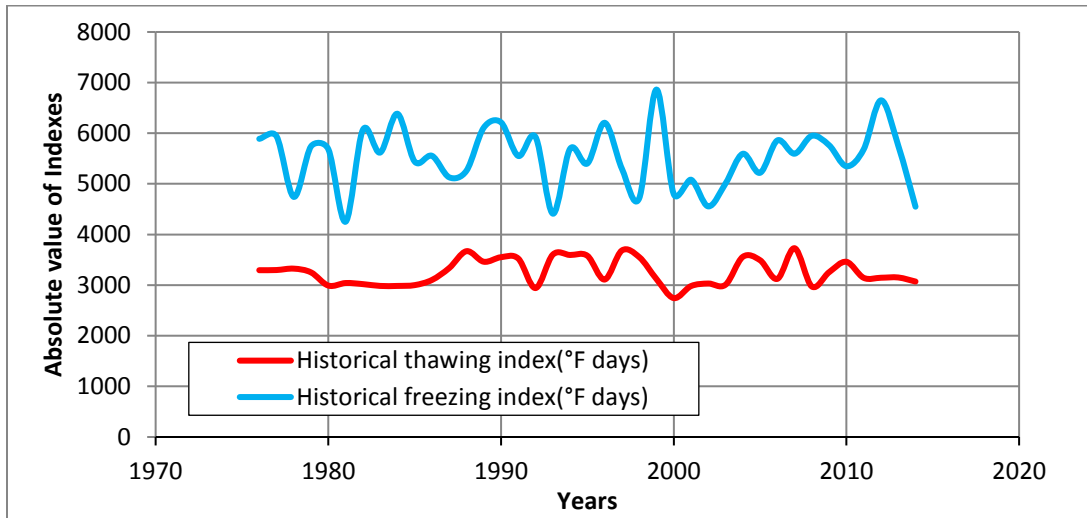


Figure 2: Sample Observed Air Freezing and Thawing Indices in Central Alaska.⁹

2.2. Ground Temperature and Permafrost Depth

Although all permafrost is, by definition, at a temperature below freezing, how much below freezing varies from region to region. Permafrost temperature also varies with depth. The following discussion provides an overview of a typical ground temperature profile in permafrost regions.

First, even in regions with permafrost, the uppermost part of the soil is subject to an annual thaw cycle from late spring to early fall. This seasonally thawed layer of soil at the surface is called the active layer. The active layer thickness varies year-to-year based on weather conditions and geographic location. Soil subsurface conditions, soil ice and water content, snow cover thickness, presence of water ponding at the surface, and vegetation, amongst other things, all affect the active layer thickness.

Below the active layer lies perennially frozen ground (i.e. the permafrost). Although it always remains below freezing, immediately below the active layer the permafrost temperature increases and decreases throughout the year in line with air temperatures. The warmer the permafrost is (i.e., the closer its temperature is to 32° Fahrenheit [0° Celsius]), the more prone it will be to seasonal thawing and an increase in the active layer depth as air temperatures warm.

⁹ Underlying temperature data are from the Livengood, AK weather station.

In some locations where there is permafrost, prevailing air and ground temperatures are too warm to maintain permafrost without additional factors protecting it. In these locations, a thick layer of organic material on the surface insulates the ground from summertime heat, preserving the permafrost below it. Removing this protective organic layer can lead to the nearly immediate thawing of the permafrost.

Continuing deeper into the soil profile, at a certain depth, the permafrost becomes immune to fluctuations in air temperature and its temperature *increases* with greater depth due to geothermal heat emanating from the center of the Earth. At some depth, the ground temperature exceeds 32° Fahrenheit (0° Celsius) and permafrost ceases to exist.

2.3. Permafrost Continuity

In areas where permafrost occurs, a classification is made with respect to its prevalence both in the vertical and horizontal dimensions. This classification system divides permafrost regions into two types: those with continuous permafrost and those with discontinuous permafrost. The continuous permafrost zone is characterized by wide-ranging blocks of frozen soil (permafrost) whereas the discontinuous zone is characterized by frozen soil blocks surrounded by an unfrozen ground matrix both horizontally and vertically (see Figure 3). In the discontinuous zone, the permafrost blocks exist in a wide range of sizes, from dozens of square feet to a few acres.¹⁰

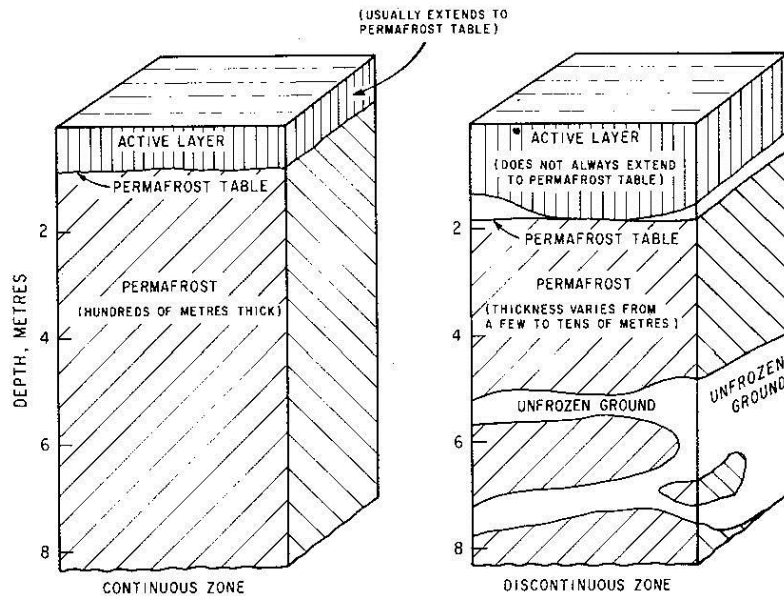


Figure 3: Continuous versus Discontinuous Permafrost.¹¹

¹⁰ Andersland and Ladanyi 2004.

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Horizontally, continuity can vary based on several factors, especially slope aspect with respect to the sun. Areas with slopes facing towards the sun generally have little to no permafrost while lowlands and slopes facing other directions have more permafrost with greater thickness.¹²

2.4. Permafrost Ice Content

In permafrost, the ice binds the soil particles into a strong, stable, low-permeability soil; an ideal foundation for infrastructure facilities. When permafrost thaws, the ground typically settles because the areas formerly occupied by the ice crystals collapse causing voids that lead the overall soil profile to compress. Accordingly, it is critical to know the ice content of permafrost when considering the potential for ground settlement when the ice thaws. The ice content in permafrost varies and depends on the permafrost formation process and soil type.

Two types of permafrost exist, epigenetic and syngenetic. These permafrost types are differentiated by their formation processes. Epigenetic permafrost is formed in soils that were not frozen when they were deposited and were later subjected to a colder climate condition that caused the permafrost to form. By contrast, syngenetic permafrost is formed in soils that were already frozen *during* the soil deposition/formation process. Because freezing occurs throughout the formation process, syngenetic permafrost generally has a higher ice content than epigenetic permafrost. Thus, thawing syngenetic permafrost is typically more impactful with respect to thaw settlement. Ice content is also generally higher in fine-grained soils and organic material. Thawing occurring in areas with these types of soils will also generally entail greater settlement.

2.5. Special Features: Ice Wedges, Ice Lenses, and Taliks

In addition to the prevailing permafrost soil conditions discussed above, various special features exist within the permafrost matrix that can present extreme challenges to the design of roadway infrastructure. These special features include ice wedges, ice lenses, and taliks, each of which is described below.

2.5.1. Ice Wedges

Ice wedges, vertically elongated masses of nearly pure ice, can be found near the surface just below the active layer in some permafrost regions. Ice wedges are formed gradually in vertically oriented weakness zones formed by the shrinkage of the ground in winter under extreme cold conditions. As the ground shrinks, small wedges open up that are filled with melting water from snow and rain during the spring and summer. During the next winter, the water freezes and expands, enlarging the wedge. This process repeats in a positive feedback loop and widens the wedge year after year as illustrated in Figure 4.

¹² Bjella 2014.

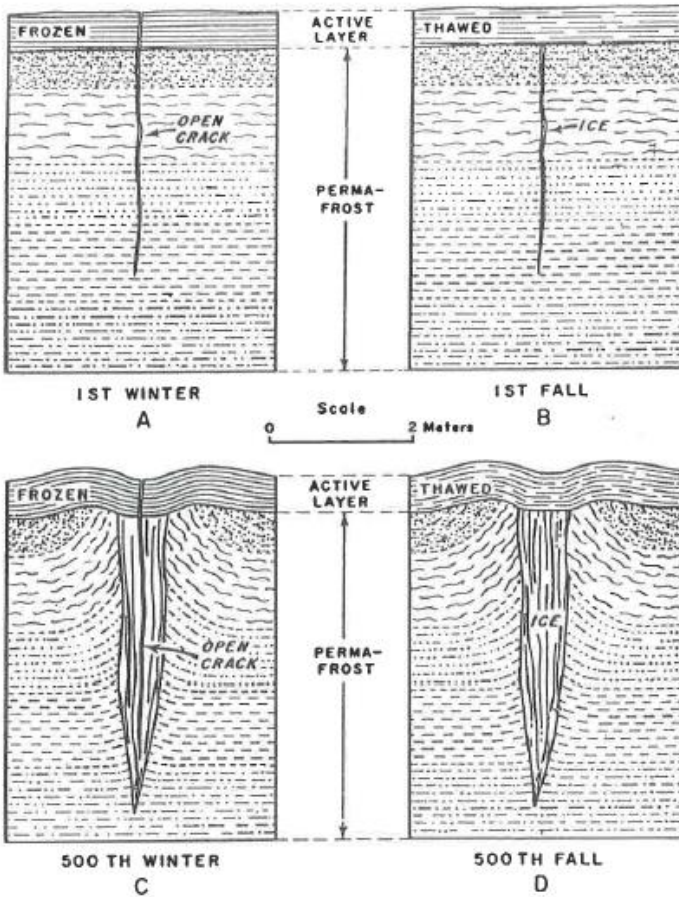


Figure 4: Schematic Representation of Ice Wedge Formation.¹³

Ice wedges typically form in geometric patterns on the landscape. Under proper conditions, this can be visible on the surface in the form of patterned ground, which is characterized by geometric shapes (e.g., circles, polygons, nets, strips) as shown in Figure 5. Regardless if they are visible on the surface, ice wedges present a serious challenge to roadway design once exposed: since they are nearly pure ice, they have extreme deformation potential if thawed.

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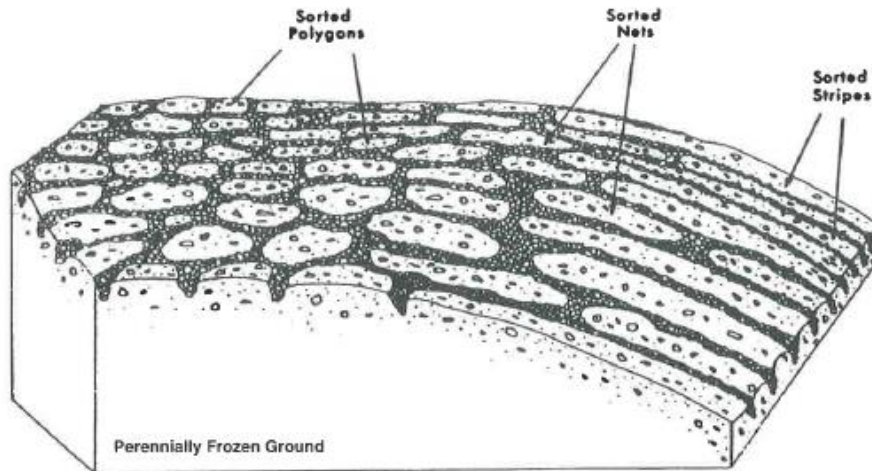


Figure 5: Schematic Representation of Patterned Ground due to the Presence of Ice Wedges.¹⁴

2.5.2. Ice Lenses

Another structure, one of the most common and problematic manifestations of the effects of ground freezing, is the formation of horizontal ice lenses near the freezing plane of the permafrost. This occurs when snowmelt water drains down through the active layer (aided by fine-grained soils, when present, acting as a wick) and encounters the top of the permafrost. Since the permafrost is impenetrable to the water, it accumulates at the top of the permafrost. When water in soil pores freezes to ice, the original volume of water expands by approximately nine percent to exert an upward pressure on soil layers above, a phenomenon known as frost heave. The moisture movement is more pronounced in soils containing silt as they have high capillarity potential to attract more water.

Frost heave and the subsequent thawing can induce surface movements up to several inches in a single season. During both the expansion and settlement phases, it is rare to see the surface settle back to its initial position. Movements repeated year after year lead to notable instability of the surface and can cause significant damages to roads. Furthermore, the amount of heaving is often variable across the landscape causing significant impacts to roadway infrastructure.

2.5.3. Taliks

A talik is a layer of year-round unfrozen soil that lies *within* the permafrost. Three different types of naturally formed taliks exist: open taliks, through taliks, and closed taliks. Open and through taliks often form under lakes due to the heat retention properties of water bodies which keeps the nearby soils warm and unfrozen. Closed taliks, surrounded by permafrost on all sides, can form naturally after a lake silts up to form a bog or because of groundwater flows.

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Taliks can also form due to human activities that thaw the permafrost, a process that will lead to settlement.

2.6. Permafrost Thaw and Roadway Infrastructure

In permafrost areas, soil particles are tied together by the ice in the soil structure, giving the frozen ground high strength and stability and low permeability.¹⁵ This leads to beneficial properties that can be used for efficient construction of infrastructure in northern regions, such as road foundations or impermeable barriers for a contaminated site. However, as noted above, major problems can occur when these ice-rich materials melt (i.e., when the active layer penetrates deeper and the ice contained within starts to thaw). In this case, the properties inherent to permafrost are no longer valid and the stability and effectiveness of the infrastructure can be compromised. It is important to note that once the soil has been thawed, it is much more difficult to refreeze due to the free water trapped within pores, which takes more energy to cool. The impacts of permafrost thawing on roadways can be severe. The most prominent ones include differential longitudinal settlement, shoulder rotation, and slope failures; each of these are discussed in turn below.

2.6.1. Differential Longitudinal Settlement

During winter, when soil water freezes to ice, the resilient modulus¹⁶ of frozen soil could rise as high as 1 to 3 million pounds per square inch (70,307 to 210,921 kilograms per square centimeter), which can be 20 to 120 times higher than the value of the modulus before freezing. During spring thaw, as the frost begins to disappear from the top-down, the subgrade is soaked with excess free water from the melting ice. The soil subgrade rapidly loses its load-bearing capacity under wet conditions (by about 50 to 60 percent of its resilient modulus under normal conditions), thereby significantly weakening the infrastructure system. Allowing heavy vehicles on such weakened roads will contribute to significant structural damage or even failure.

To make matters worse, the settlement from melting permafrost is not uniform longitudinally along the length of the roadway. This is because the characteristics of the underlying permafrost and soils can vary significantly over short horizontal distances. Furthermore, when ice wedges, taliks, and ice lenses are encountered, the road overlying these areas can settle at significantly greater rates than elsewhere. All of this results in some parts of the roadway settling at much greater rates than other parts over short distances resulting in a wavy pattern

¹⁵ Andersland and Ladanyi 2004.

¹⁶ Resilient modulus is the standardized measurement of resistance of roadbed soil or other pavement material to being temporarily deformed (i.e. its stiffness or, more technically, a standardized modulus of elasticity) based on the recoverable strain under repeated loads. Among other factors, the resilient modulus proportionately decreases with increasing moisture. Typical values for natural soil may range from 5,000 to 40,000 pounds per square inch (352 to 2,812 kilograms per square centimeter).

of differential settlement that requires intensive maintenance to maintain serviceability safety, and prevent vehicle damage. In addition, such settlement often occurs quickly and, given the great depths of permafrost in many areas, can continue for a long time until the permafrost is completely thawed and foundation soils are drained or stabilized.

2.6.2. Shoulder Rotation

In addition to differential settlement running longitudinally along a roadway, thawing permafrost can also cause differential settlement issues laterally across the roadway cross-section. Often, the permafrost under the shoulders of the roadway thaws before the permafrost under the center of the roadway embankment. This is partly attributable to snowplowing practices. When snow is plowed, it piles up on the edge of the embankment. The snow piles can actually act as insulation from the extreme cold air temperatures, keeping the ground underneath the shoulders relatively warmer than the ground underneath the center of the embankment (which, since it has been plowed, is able to cool more since it is exposed directly to the cold air). Standing water trapped in ditches along the shoulder can exacerbate the effect as the water retains heat, further warming the ground under the shoulders. If the warming is great enough, the result is a rotation of the shoulders as the permafrost on the shoulders thaws and the ground subsides. Figure 7 provides a conceptual illustration of this phenomenon. On the surface of the road, long longitudinal cracks form that get progressively larger over time if left unaddressed (see Figure 6). Intensive maintenance is needed in these situations to prevent further roadway failure.



Figure 6: Example of Shoulder Rotation along an Alaskan Highway.¹⁷

¹⁷ Image source: Chris Dorney, WSP

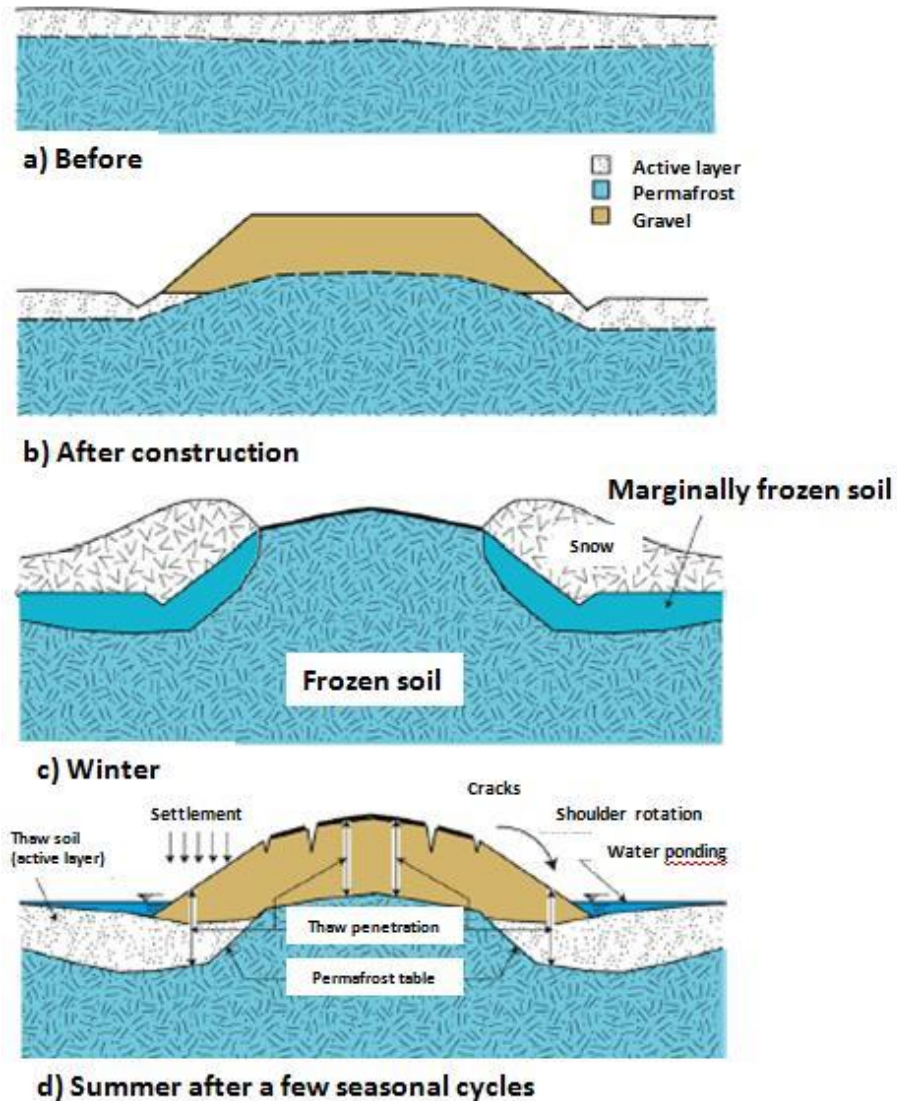


Figure 7: Conceptual Illustration of Permafrost Thawing causing Shoulder Rotation.¹⁸

2.6.3. Slope Failures

Thawing permafrost can cause instability and slumping in both natural and engineered slopes along roadways resulting in slides that can obstruct the roadway drainage or the roadway itself, in some cases presenting a threat to the safety of the traveling public. Slopes facing the sun are the most prone to issues due to their greater absorption of solar energy. Slopes *cut* into the permafrost are particularly vulnerable to slumping because the protective organic soil layer cap has been removed.

¹⁸ Image source: McGregor et al. 2010.

3. Techniques for Analyzing Permafrost Thaw

Accurately determining the depth of permafrost thaw likely to occur at various points along a roadway as climate warms requires a sophisticated and computationally intensive modeling effort. This type of modeling, a form of finite element analysis,¹⁹ is called thermal modeling. Thermal modeling uses generally recognized equations for thermal transfer to calculate the temperatures at various ground depths given ambient air temperatures and soil properties. Various alternative techniques to thermal modeling exist (for example, the Stefan Equation or the Modified Berggren Equation) but none are as robust as a modeling based approach. Previously, these simpler techniques were in more widespread use due to difficulty in obtaining thermal modeling software and limitations in computing power; thermal modeling was something primarily undertaken by academics on research projects. Fortunately, recent advances in computers and the development of commercial software applications that perform thermal modeling have allowed such modeling to become regularly used in the design of real-world projects.

Although advances in computing have made thermal modeling practicable on actual projects, building and running a thermal model is still a significant undertaking. The models, for example, require detailed site-specific data on soil types, soil properties, ice/moisture content, and ground temperatures in order to accurately capture the thermal dynamics at work. Furthermore, some of these data, such as the ground temperatures, will have ideally been collected over a period of years so that one can have confidence that the results were not biased by the sample being inadvertently chosen from one abnormal year. Thus, extensive fieldwork is required to collect, process, and analyze these data well in advance of a project's planned construction date. Once the data have been assessed and verified for accuracy, they can be input into the model.

After the data have been entered into the thermal model, the model must be calibrated to ensure that it can accurately estimate current ground temperatures (i.e., permafrost conditions) given the existing ground cover and observed air temperatures. This is accomplished by running the model with past observed air temperatures and seeing how close the model's ground temperature outputs match the actual observed values collected in the field. The specific air temperature metric required by the thermal model is the average daily temperature (the average of each day's maximum and minimum temperature). This metric is

¹⁹ Finite element analysis is a generalized methodology for solving complex mathematical problems that involves breaking the larger domain of a project (e.g., in the case of a road on permafrost, one cross-section of the roadway) into smaller, more manageable sub-domains (in the case of thermal modeling, small grid cells covering the roadway embankment and surrounding ground). Mathematical equations are solved for the smaller domains then reconstituted into a global system of equations to develop a global solution for the whole project domain (i.e., the single roadway cross-section).

required for each and every day of the calibration period which, ideally, will extend back several decades, depending on the availability of local weather data. The observed and modeled ground temperatures at different depths are then compared and, if significant differences exist, professional judgment is used to adjust the model to better align with actual observed conditions.

Once the thermal modeller is satisfied with the degree of convergence between his/her model and the observed ground temperature profile, the next step is to incorporate the project design (e.g., a new road's embankment in lieu of the natural ground conditions) and temperature projections into the model. Traditionally, the temperature projections are simply an extrapolation of historical daily average temperatures into the future assuming static conditions over time. To incorporate climate change, however, projections from climate models can be used (more details on this are provided in Section 4.2 below). The outputs of the model will indicate the change in depth of the active layer/permafrost table over time as a result of constructing the project and/or projected climate changes.

How much settlement/deformation of the roadway can be expected as a result of the thawing permafrost? This is a difficult question to answer fully as it involves a number of complex interacting factors. The primary factor is the initial ice content of the underlying permafrost soil; as discussed above, the more ice present, the larger the void left when it melts (recall that liquid water has less volume than an equivalent amount of ice) and the more the ground settles. This factor can be used to calculate, using the outputs from the thermal model, a *minimum* amount of deformation (self-weight settlement) that can be expected given the projected thawing.

In addition to settlement from the thawing itself, the weight of vehicles on the road above and the weight of the embankment itself can further contribute to settlement of the roadway. The water from the thawed permafrost may even get squeezed out laterally from underneath the roadway if nearby frozen ground remains causing further geotechnical issues. There may also be a tendency for the embankment to be pushed outwards as well as downwards because of all these forces. Fully accounting for these additional factors, collectively referred to as mechanical deformations, is difficult because it requires a dynamic consideration of thawing in the thermal model; essentially, the model must be re-run with a new soil profile (reflective of past thawing and settlement) each year or even each day, depending on the accuracy required. This is a resource intensive and time-consuming process even under static climate conditions.

4. Incorporating Climate Change

Incorporating climate change into the design of roadways on permafrost requires a team that has knowledge of climate science, expertise in permafrost modeling, and a mastery of cold

region engineering and maintenance techniques. This section provides an introduction to some important considerations when working through how climate change might impact the design of a roadway project on permafrost. It begins by introducing the Adaptation Decision-making Assessment Process (ADAP), an overarching framework that guides one through a climate change assessment for a specific asset or project. Next, two key elements of the framework are called out and given extended discussion with respect to roadways built on permafrost: (1) how to incorporate climate projections into thermal modeling (Step 4 in ADAP) and (2) how to adapt roadway infrastructure (and maintenance practices) to deal with the issues of permafrost thaw (Step 6).

4.1. The ADAP Approach

ADAP is a step-by-step process for conducting engineering-level adaptation assessments of individual transportation facilities. Figure 8 provides a flow chart showing the various steps and decision-points in ADAP. The methodology was developed for the TEACR project and applied on a number of case studies across the country involving all types of transportation assets and climate stressors. The process consists of the following eleven steps:

1. Understand the site context.
2. Document the existing or future base case facility.
3. Identify climate stressors.
4. Develop climate scenarios.
5. Assess performance of the facility.
6. Develop adaptation options.
7. Assess performance of the adaptation options.
8. Conduct an economic analysis.
9. Evaluate additional considerations.
10. Select a course of action.
11. Develop a facility management plan.

Each of these steps is discussed in detail on the ADAP portion of the FHWA's TEACR website²⁰ so a full description of the process will not be repeated here. Nonetheless, a broad overview of the approach is provided below.

First, Steps 1 and 2 focus on gaining a thorough understanding of the asset and its context; necessary first steps on any project. Either existing or newly proposed assets can be evaluated under ADAP. After this, Steps 3 and 4 dive into the specific climate stressors of relevance to the asset and how their values may change in the future with climate change. If the stressors are

²⁰ For more information about the ADAP process, visit the project website at: https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/.

not found to change in a way that would risk harm to the asset, then the analysis can be stopped at this point. The following section in this report will expand on Step 4 providing some basic background on climate projections and discussing how they can be incorporated into thermal modeling for purposes of roadway design on permafrost. Worth noting is that ADAP calls for a scenarios-based approach to future climate change, meaning that, since the exact amount of change in future climate stressors is impossible to precisely predict, multiple future climate scenarios should be evaluated to test the sensitivity of the asset to the range of possibilities. This scenarios approach is foundational and has bearing on the rest of the steps in the process. More on what the scenarios approach involves and why it is needed is provided in the next section on climate change projections.

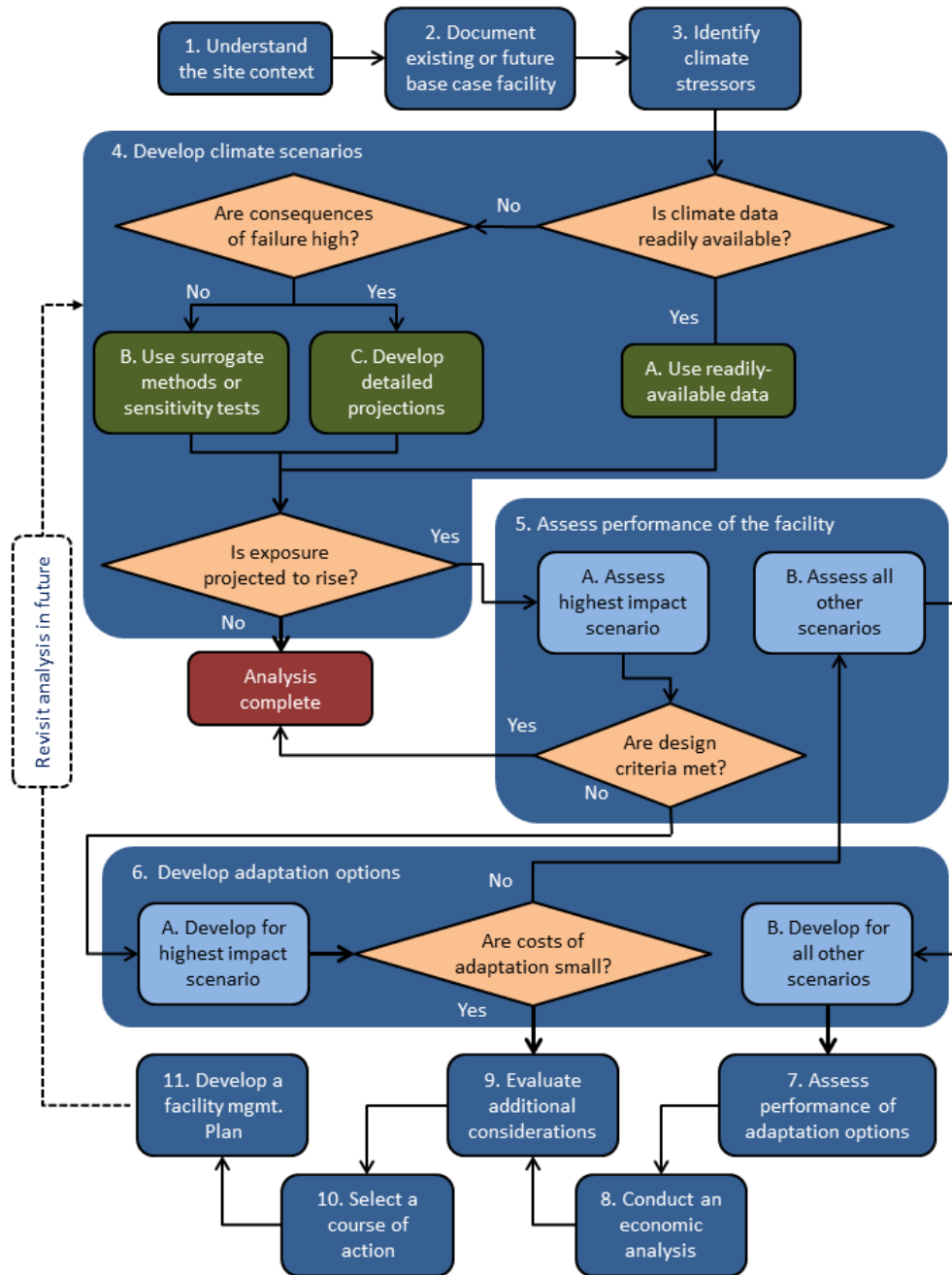


Figure 8: The Adaptation Decision-Making Assessment Process (ADAP).

In Step 5, the possible future values of the climate stressor are evaluated for their effects (if any) on the asset. With respect to permafrost thaw evaluations, this is the step where the thermal model would be run to determine the degree of thawing under the existing or proposed asset. Ground settlement calculations would also be completed at this stage of the process. If the projected climate conditions are not great enough to induce thawing or other

problems with the asset, then the analysis can be concluded at this step. However, if problems are found, then the analysis proceeds to Step 6.

Step 6 involves formulating an adaptation option(s) for each climate scenario that was found to create problems for the asset. Adaptation options can be alternative designs, alternative maintenance regimes, operational alternatives, or some combination thereof. Regardless, cost estimates of each adaptation option should be developed. There are a variety of adaptation options available to deal with roadways in areas of thawing permafrost. A sampling of possible options are provided in the Section 4.3 below.

Step 7 involves evaluating the performance of each adaptation option under each possible climate change scenario. The purpose of this step is to develop an understanding of how effective each adaptation option is under the range of climate scenarios being tested. This information is useful for decision-making and a critical input to the economic analysis. For purposes of evaluating roadways built on (or to be built on) permafrost, this step would involve re-running the thermal models but this time with the design(s) (or operation/maintenance actions) of the adaptation option(s) included instead of the initial standard design concept (or existing design). The thaw settlement would also be calculated for each scenario and adaptation option.

In Step 8, an economic analysis of the various adaptation options is conducted to determine if their added costs are outweighed by the benefits they provide (in terms of reduced maintenance/damage costs). This determination may very well change depending on the climate scenario being tested. Thus, a full accounting of benefits versus costs needs to be made across the adaptation options and across all climate scenarios, the output typically being in the form of a table of benefit-cost ratios and/or net present values.

Step 9 considers other important factors to decision-making that can be difficult to monetize for use in the benefit-cost analysis, such as community or political concerns. In Step 10, all information is evaluated and a decision is made. This is to be followed up by, in Step 11, the development of a facility management plan that involves periodic re-evaluation of observed climate changes (and their effects on the asset) along with consideration of any updated climate projections that may have come out subsequent to the initial analysis. Through following the eleven-step ADAP process, an agency can be assured they have done their due diligence to evaluate their asset against future climate changes and are making the most informed decision possible to minimize long-term costs, given available information.

4.2. Climate Change Projections and Thermal Modeling

Step 4 of ADAP involves the development of climate projections that can be used in the thermal modeling of the asset being evaluated. Since the use of climate projections is likely to be

something new for many thermal modelers and cold region highway designers, this section provides a brief background on how climate projections are developed. Following this, some specific considerations regarding their application to thermal modeling are discussed.

4.2.1. Climate Projections

Climate change science is a rapidly evolving field of study. New insights are gained on a regular basis that help scientists better project how the climate may evolve due to the increase in atmospheric greenhouse gasses from human activity. This section of the report will provide users with a high level overview of how climate projections are currently developed. A more detailed explanation of current practice can be found in FHWA's *Synthesis of Approaches for Incorporating Climate Change into Project Development*.²¹ Practitioners reading this document more than a few years beyond its original publication date are encouraged to also consult newer texts that will better reflect the latest scientific thinking in this constantly developing field.

Developing projections of future climate requires an understanding of how the world's climate system functions. While much of the basics of the system are known and dependent on the fundamentals of chemistry and physics, there are many patterns and feedbacks in the system that require additional research to be fully understood. Nonetheless, enough is known that climate scientists have been able to develop fairly accurate models of the Earth's climate system. These models, known as global climate models (GCMs), have been run with information on historical greenhouse gas concentrations and are able to simulate observed historical conditions relatively faithfully. The process of running GCMs with historical greenhouse gas emissions data to replicate previous time periods is known as backcasting. Accurate backcasting results have given scientists confidence that the models can make reasonable projections of future climate conditions under assumptions of increased greenhouse gas concentrations.

GCMs are capable of providing projections for a variety of different climate metrics. Temperature and precipitation metrics are the most commonly utilized but others, such as wind speed and direction, are also available (although are generally regarded as being less reliable). In most cases, the metrics are available for each day through the year 2100.²² For example, one can obtain the maximum and minimum temperature for each day along with the amount of precipitation projected. A plethora of secondary metrics can be developed from this information through statistical analysis of the daily data. One simple metric, used in thermal modeling, is the daily average temperature, which can be obtained by averaging each day's

²¹ For more information about the current practice, visit the project website at:

https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/.

²² In some cases, sub-daily data can also be obtained although it is generally not as readily available.

maximum and minimum temperatures. It is important to realize that the metrics are not meant to represent a weather forecast for exactly what conditions will be on a specific day. Instead, they are meant to be analyzed together over the course of many years (e.g., a 20 to 30 year period over which climate is defined) and, over this longer time horizon, can be used to discern patterns and trends in the data brought on by climate change.

GCMs are highly sophisticated specialized software tools that often require substantial computing power to operate. They are developed and run by prominent research institutions throughout the world and are generally not directly accessible to the general public, however, their outputs (i.e., the climate projections) are made publicly available. There are dozens of different climate models currently in existence, each with its own slightly different view of how the Earth’s climate system operates. What this means for the practitioner is that there are many different opinions of what the Earth’s future climate will be; one for each model. Each of these projections can be thought of as a different possible scenario for future conditions. A variety of techniques have been developed to help practitioners make sense of all the different projections available amongst the different models. One approach is to average together the outputs from each separate model together into an ensemble average value. This can be problematic, though, in that it can mask distinctive patterns captured by one model and not another. An alternative is to select the median model output or, if resources allow, the median output and the output of models towards the higher and lower ends of the range so as to better capture the perspectives of individual models.

GCMs display significant variation in their projections of changes in climate in Arctic regions where permafrost is prevalent, like Alaska. For this reason, the Scenarios Network for Alaska and Arctic Planning (SNAP) at the University of Alaska Fairbanks undertook a project to determine which GCMs best simulate Alaska’s climate. This was accomplished by calculating the degree to which backcasted GCM outputs aligned with historical climate data. Three models were determined to perform well for the State and have daily data available: these are summarized in Table 1 below.

Table 1: Available Well-Validated GCMs with Daily Temperature Projections for Alaska.

Center	Model	Acronym
Geophysical Fluid Dynamics Laboratory (NOAA)	Coupled Model 3.0	GFDL-CM3
Institut Pierre-Simon Laplace	IPSL Coupled Model v5A	IPSL-CM5A-LR
Meteorological Research Institute (Japan Meteorological Agency)	Coupled General Circulation Model v3.0	MRI-CGCM3

When modeling future climate, some assumptions are required regarding the amount of

greenhouse gases that will be released into the atmosphere in the coming decades. The actual value is an unknown, dependent on advances in technology, the global economic trajectory, the personal decisions of the world's people and businesses, and the policy decisions of governments. To help put some bounds on the possibilities, scientists have developed plausible future greenhouse gas emissions scenarios. Each scenario encompasses assumptions about the rate of greenhouse gas emissions, the composition of those emissions, and where they are emitted from. To make climate modeling more efficient and to facilitate comparison of model outputs, the global climate modeling community has agreed to run their models with a common set of emissions scenarios. These scenarios are updated periodically based on emissions trends and the needs of the research community and adaptation practitioners.

The latest round of emissions scenarios was developed as part of the Coupled Model Intercomparison Project Phase Five (CMIP5). In CMIP5, these emissions scenarios are called representative concentration pathways (RCPs). There are four primary emissions scenarios used in analyses. These include, in the order of increasing concentration of greenhouse gases: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Of these, RCP2.6 is often not analyzed in adaptation studies as it is viewed as being unrealistically optimistic regarding the extent to which greenhouse gas emissions can be reduced in the future. This leaves, for any given climate model, three plausible projections of future climate variables, one for each (realistic) emissions scenario. Combine these three emissions scenarios with the dozens of different climate models and there can be over a hundred different projections of what future climate conditions will be for any given location. The amount of data available can be daunting. Clearly, not every set of projections can be run separately through the thermal model as this would be a huge effort. How should the practitioner sort through this sea of projections to determine which set of scenarios to use for the thermal modeling (and, ultimately, for project design)?

One solution is to deal jointly with the problem of selecting climate models and emissions scenarios. An out-year can be selected (typically, at the end of the design life of the project so as to most likely capture the maximum climate effects) and the various climate models/emission scenario combinations can be ranked from highest to lowest for the metric of interest (e.g., average temperature). From this list, the maximum, median, and minimum projections can be selected (or some other combination like the 90th percentile, median, and 5th percentile). The climate model/emissions scenario combinations responsible for those three values could then serve as the scenarios to be used for analysis in the thermal model. With this approach, it would not matter if some of the three combinations chosen included the same emissions scenario or model (e.g., two of the three scenarios using RCP6.0 or two of the three using the same climate model), as one would be confident that the full range of possible futures has been considered. More sophisticated index-based variants of this approach exist as well. These techniques also consider intermediate out-years (not just the end of the design life) in

order to capture any differences in the relative positions of the climate model/emission scenario combinations over time.

One other key item to be aware of with respect to climate projections is the concept of downscaling; i.e. the process of creating more location-specific projections. GCMs, as their names imply, are global in scope: their projections cover the entire planet. To accomplish this, given the volume of the mathematical calculations involved, GCMs divide the planet up into a relatively coarse resolution grid (each cell typically being over 50 miles across, depending on the model). The climate projections are the same for any location within each of these large cells. However, in reality, there can be significant variation in climate within these areas, particularly in mountainous regions and in areas near large waterbodies. To address this issue, climate scientists have developed downscaling techniques to provide more spatially refined projections. While downscaling adds its own uncertainties to the process of developing climate projections, it can add value in many situations.

There are two main techniques for downscaling in use today: statistical downscaling and dynamic downscaling. Statistical downscaling uses historical observed weather data to add spatial variation to the projections within a GCM grid cell. For example, if recorded temperatures have consistently been cooler on a mountaintop within a GCM cell that is showing warming, the temperature projections for the mountain may be assumed to remain cooler than the surrounding land by the same margin they had been historically. In the statistically downscaled output, both the mountaintop and surrounding land would both show warming, but the mountaintop would remain cooler relative to the surrounding land by the same degree as with historical observations. Statistical downscaling therefore assumes that climate change will not alter the relative differences in conditions between locations within a cell. However, this assumption may not always be true; there may be cases where climate change alters local climate dynamics and changes these relative differences. To address this concern, dynamic downscaling was developed.

Dynamic downscaling essentially involves creating a small-scale GCM for the area of interest (typically, a region). These small-scale GCMs are referred to as regional climate models (RCMs). RCMs take the outputs of GCMs and, using a finer grid mesh and more details on local topography, waterbodies, and other important features, develop higher resolution outputs that still comport with the larger scale GCMs. These data can be very useful for permafrost analyses but, unfortunately, RCMs take a lot of resources to develop and maintain and are not available in all locations. Practitioners are encouraged to carefully investigate the full range of climate models available for their project area as part of Step 4 in ADAP and to select the set of projections that best suits their needs. Local academic institutions and climate change consultants may be able to assist in this effort.

4.2.2. Climate Projections and Thermal Models

Incorporating climate projections into thermal modeling is a necessary step for assessing climate change impacts to roadways constructed on permafrost and for evaluating the effectiveness of adaptation options. Fortunately, climate projections, whether downscaled or directly from GCMs, can be easily incorporated into thermal models; climate models readily provide the metrics that thermal models need as inputs. As previously discussed, thermal models typically require average daily temperature data. This information is easily derived from the daily maximum and minimum temperature outputs from climate models. More sophisticated thermal modeling efforts can also make use of precipitation projections so that hydrogeological effects on the thermal regime can also be considered. The projections of daily precipitation from climate models can be helpful in this effort.

Perhaps the greatest challenge with using climate model projections in thermal modeling is in making the transition between the historical observed climate data needed to calibrate the thermal model²³ and the modeled climate projections of the future. There can often be an abrupt transition between the conditions shown in the historical data and the conditions projected in the climate model. For example, modeled conditions may be much warmer than recent observations are showing (or vice-a-versa). If an abrupt transition between observed and modeled conditions is ignored, the thermal model projections of the future can become biased and the results questionable.

This possibility of an abrupt transition in climate metrics is to be expected because, as previously noted, the climate model outputs are not meant to be weather forecasts for a specific day or even a specific season or year. Local climate patterns can be cyclical over years or even decades and the model may be representing a different point in the climate cycle than the actual climate system. Over the long 20 to 30-year timeframes used in interpreting climate model outputs, this does not necessarily present an issue, but for thermal modeling, where a continuous temperature record is required, this mismatch in the cycles can be a cause for concern. Furthermore, there may also be a permanent bias in the climate model projections for the specific location of interest. While the climate modelers go to great lengths to remove the bias in their models by comparing their model's outputs, when run to represent past conditions, with observed data and calibrating accordingly, they may not be successful at eliminating all bias in their model at every location. Bias may be minimized globally across the climate model but may persist to a certain degree at specific locations. For thermal modeling,

²³ Historical observed temperature data are required to accurately calibrate thermal models. The actual observed air temperature data are needed so that observed ground temperatures and the resulting permafrost patterns can be replicated. It is not possible to accurately calibrate thermal models using backcasted outputs from climate models because the air temperatures from the climate models will differ from what actually occurred leading to inaccurate ground temperatures and an inability to replicate the permafrost pattern currently observed (the goal of the thermal model calibration efforts).

such bias, even if only fractions of a degree or so, can represent a significant issue, especially when transitioning from the observed data to the climate model projections. How can these issues be addressed so that a smooth transition between observed and modeled climate information can be made?

One solution, most applicable to temperature projections, is to compare the local historical weather observations and backcasted climate model outputs to develop an adjustment factor(s) for future projections. This approach entails assembling all the historical observed temperature data for the project site as far back in time as possible, ideally decades (this effort will have been completed already for the thermal model calibration). The backcasted climate model outputs for the asset location from each of the climate models that will be used in the analysis should also be assembled, ideally for as far back as the observed data extend. A minimum of 20-years' worth of data should be used. The difference between the average daily observed and backcast temperature values can be used to determine an adjustment factor that states to what degree (if any) the observed data are warmer or cooler than the backcasted model data at the site of interest. For example, one may conclude that, on average, the modeled data are one degree warmer than the observed data for the asset location. Using this knowledge, the adjustment factor can then be applied to all future climate projections from that model to create an adjusted future simulation that is, theoretically, a closer match to local conditions. Thus, in the example where the model was on average one degree warmer than observed data, this information can be used to reduce the future model average daily temperature projections by a degree. The adjusted temperatures would then be the ones used in the thermal modeling.

It is important to note that each separate climate model used in the analysis would have its own adjustment factor. Thus, if there are three separate models being used to develop future climate scenarios, then there would be three separate adjustment factors, one to apply to each model. Also, the discussion above assumes a relatively simple approach to the adjustments where there is one factor applied to all future values. Alternate, more sophisticated approaches can be utilized as well that create separate adjustment factors for each season or month. Each factor would then be applied to the corresponding season or month in the future projections (e.g., an adjustment factor for May would be applied to all future projections for that month). This approach drills down more precisely to determine where differences in the model outputs and observations lie so as to more fine tune the adjustments. Whatever approach is used, the key to coming up with a reliable adjustment factor is basing it on data over a long time period; as noted above, at least 20 years of data should be used. Worthwhile adjustment factors cannot be created based on only a few years of data.

One final consideration with respect to thermal modeling using climate projections is the additional level of effort involved. As discussed above, because of the uncertainties in future greenhouse gas emissions and how the Earth's climate system will respond, a scenarios approach is recommended for analyses. Using a scenarios approach provides a sensitivity analysis of the asset to various possible future conditions, which allows decision-makers to make an informed decision on the course of action to take. While indispensable to informed decision-making, the scenarios approach entails more thermal modeling and settlement calculation work than was traditionally the case when it was assumed climate would remain static and only one set of future conditions needed testing.

However, some of the most time-consuming aspects of thermal modeling are initial model development and calibration and the level of effort for these fixed costs remains unchanged no matter how many scenarios are tested. The most resource intensive aspect of incorporating additional scenarios into the model will likely be obtaining and prepping the data for those scenarios (e.g., calculating the adjustment factors). It will also add some computational processing time. One element that does add more significant effort is testing adaptation options because these must be "built" in the model: practitioners with resource limitations are encouraged to limit the adaptation options tested to those that have the most promise. Overall, although practitioners should be cognizant of the extra effort needed when budgeting for their work and devising project schedules for thermal modeling and settlement calculations, incorporating climate scenarios is likely to only result in a moderate increase in level of effort and should be practicable to implement on real world projects.

One exception to the observation above is if mechanical deformation (incorporating the effects of the roadway embankment's own weight and the weight of vehicles on it) is to be incorporated into the modeling. Mechanical deformation considerations greatly increase the amount of work because it means that settlement calculations must be made at least annually and then, for each year, the thermal model altered and re-run using the new pattern of settlement/thaw. Even without climate change, incorporation of mechanical deformation adds significant work; repeating the work for multiple climate scenarios will only exacerbate this. Recognizing this, the research team has identified the efficient consideration of mechanical deformation as a gap in understanding that is deserving of further research.

4.3. Adapting to Climate Change Impacts

There are three basic approaches for roadway designers to deal with the possibility of thawing permafrost under warmer climate conditions:

- Avoid permafrost areas (for new construction).
- Delay the thawing process/prevent permafrost thaw from occurring.

- Increase maintenance and accept the thaw.

Each of these options is discussed in the sections below along with other less frequently employed techniques.

4.3.1. Avoid Permafrost Areas

Avoidance may be a viable option for new roadway construction. If the corridor can be located outside of areas with permafrost or in areas where permafrost has already thawed or been “pre-thawed,” the construction procedures would be those typically suitable for the soil types encountered.

4.3.2. Delay or Prevent Thawing

If permafrost cannot be avoided, there are measures that can be taken to eliminate or reduce the effects that thawing permafrost can have on a roadway. Some of the most promising techniques include maintaining the frozen condition through:

- Air convection embankments (ACE).
- Thermosiphons.
- Insulation.

Each of these techniques is discussed in the sub-sections below.

Air Convection Embankments

Air convection embankments (ACE) is a relatively new design strategy for dealing with permafrost, although the principles behind it have been known for quite some time. Through casual observations that have been verified on numerous research projects, it has been found that in cold areas such as Alaska, highly permeable, coarse-graded rock piles promote the cooling of underlying soils. Evidence of such phenomena have been studied and observed within railroad embankments²⁴ and within the face of rock fill embankments.²⁵ This has been referred to through the years as an air convection cooling phenomenon or system. The effect of the phenomenon has stirred great interest amongst those seeking to maintain permafrost in a frozen state (or at least limit thawing) under roadway infrastructure. Some examples of ACE have been implemented in the Fairbanks, Alaska, area such as along Thompson Drive on the University of Alaska Fairbanks campus (see Figure 9). The main advantage of ACE is its simplicity as a passive system without any moving parts or dedicated power needs.²⁶

²⁴ Goering 2003.

²⁵ Lebeau and Konrad 2007.

²⁶ McHattie and Goering 2009.



Figure 9: ACE on Thompson Drive embankment in Fairbanks, AK.²⁷

How does ACE work? During the winter months, the air above the ACE is very cold (well below freezing) while the foundations below the embankment are relatively warm. This temperature gradient results in an unstable air density gradient within the embankment because cold air is denser (heavier) than warm air; the cold air wants to sink while the warm air at the bottom of the embankment wants to rise. This unstable density gradient, created by the thermal gradient within the embankment, can cause circulation of the air between the rocks and convective heat transfer. The convective heat transfer exposes the foundation soil to the cold arctic air and evacuates any remaining heat from the embankment allowing the soil to cool. In summer, the convection typically shuts down because the air within the embankment is colder (and heavier) than the ambient air. Thus, beneficially, the cold air tends to remain trapped low within the embankment.²⁸ Warming of the soils within the embankment gradually does occur over the course of the summer. The coolness gained throughout the winter, however, acts as a hedge against this inevitable warming; the more cooling that is achieved in winter (i.e., the more vigorous the convection), the more capacity the permafrost has to weather the summer without thawing.

ACE can be installed throughout the entire embankment or just on the shoulders to prevent shoulder rotation. Figure 10 shows a schematic of the convection cells that can form within a full ACE embankment and Figure 11 shows the corresponding air temperatures (reds and oranges indicate warmer air, greens and blues indicate cooler air). As one can see, in the

²⁷ Image source: Google Earth Street View.

²⁸ This behavior has been observed most strongly on short flat sections of roadway. Such behavior may be lessened on longer stretches of ACE installed on sleeper slopes.

circulation cells, the colder air is moving downwards while the warmer air is moving upwards out of the embankment. As cold air moves downward, it warms as the heat is extracted from the material and is eventually replaced by colder and heavier air coming from the top part of the embankment. The air movement occurs as long as the thermal gradient within the ACE is significant enough to create an air density gradient. By the summer months, the air trapped between rocks at the top of the embankment is warmer and lighter than the cold air from the previous winter trapped at the base of the embankment, so air circulation does not occur. As temperatures cool the following fall, the air at the top of the embankment again becomes cooler than that below and the circulation cells become active again.

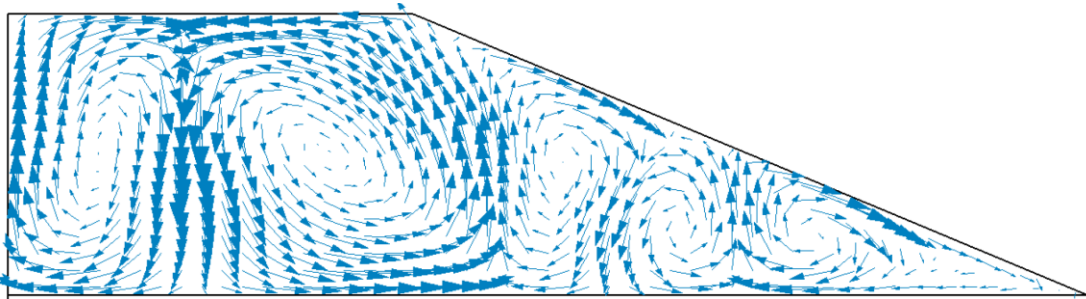


Figure 10: Schematic of Wintertime Circulation Cells in ACE.²⁹

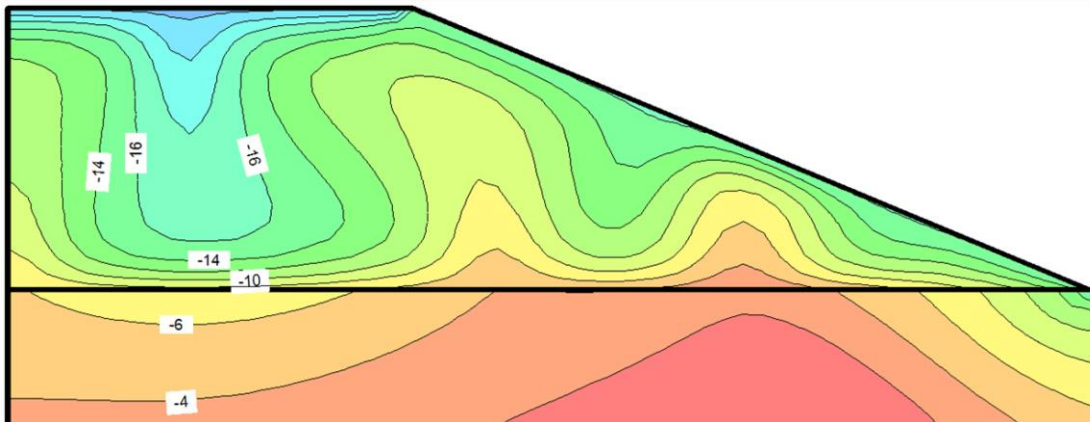


Figure 11: Air Temperature Contours within ACE in Winter.³⁰

To be efficient, an ACE embankment must possess high porosity to allow air convection. High porosity means high hydraulic conductivity as well. In a permafrost environment, liquid water means heat. So, if surface water flows within the ACE, it will bring heat to it and, depending of the duration and intensity of the infiltration, might reduce the cooling effect.

²⁹ Image source: GEO-SLOPE International.

³⁰ Image source: GEO-SLOPE International.

ACE has been proven effective to maintain foundations frozen in specific situations. However, applying ACE in every case is not a recommended approach. As noted above, the roadway corridor should be located where the permafrost degradation will have a lesser effect on the soils supporting the road. Roadways should also be built on granular soils as much as possible. Surface water drainage should eliminate standing water along shoulders and around culverts to minimize soil saturation. Also, one design may not be appropriate for the entire roadway length. Finally, ACE may not be a permanent long-term solution to permafrost melt in locations where future temperatures may get warm enough to render it ineffective or even counterproductive under certain conditions. More research is needed to determine how ACE performs under warming climate conditions and various soils properties.

Thermosiphons

Thermosiphons (also spelled thermosyphons) are passive heat exchange devices that transfer heat from the soil to the air. A thermosiphon is generally a closed tube containing a fluid such as carbon dioxide or propane. The fluid runs in a network of tubes looped horizontally just above the permafrost table to be protected. The horizontal tubes are connected to vertical finned tubes. The fluid within the horizontal tubes evaporates when it captures heat moving towards the permafrost. In a gaseous state, the fluid circulates naturally to the vertical finned pipes where it loses heat through the fins and becomes liquid again before circulating to the horizontal pipes again. Thermosiphons can be effective but are high-cost. Figure 12 shows a typical installation.

Insulation

Insulating the permafrost from thawing temperatures can be achieved with panels of extruded insulation (see Figure 13). This material works well and has low moisture absorbency compared to foam insulation. Insulation works best when installed as high as feasible in a roadway embankment. It is less effective when the mean annual soil surface temperature (MASST) is above freezing. Even so, it is effective for reducing frost heave on the roadway and serves as a lightweight fill material in roadway embankments. That said, it has proven ineffective in insulating roadside slopes.



Figure 12: Thermosiphon Installation in Alaska.³¹



Figure 13: Insulation Installation.³²

Other Techniques

Many other measures can be investigated for suitability to delay or prevent thawing in specific cases. These include:

- Slope shading (see Figure 14).
- Air ducts (see Figure 15).
- Laying back side slopes (making them flatter).

³¹ Image source: Billy Connor, University of Alaska, Fairbanks.

³² Image source: Billy Connor, University of Alaska, Fairbanks.



Figure 14: Slope Shading.³³

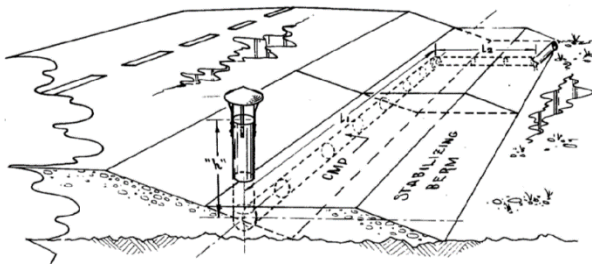


Figure 15: Air Ducts.³⁴

Information on these and other mitigation techniques are discussed in detail and compared in a research paper entitled “Reducing Maintenance Requirements on Permafrost-Affected Highways: Permafrost Test Sections Along the Alaska Highway, Yukon.”³⁵

4.3.3. Enhanced Maintenance

In some cases, the warming associated with climate change may be too great to fully prevent permafrost thaw underneath the roadway. In such situations, the goal of the adaptation strategy should be to delay the thawing (and associated higher maintenance costs) for as long as possible. At the point in time where permafrost thawing cannot be prevented, enhanced maintenance regimes will need to be instituted. At that time, agencies would have to plan for regular, near-constant maintenance and increased funding allocations, equipment positioning, and materials stockpiles; unfortunately, this would likely be a very expensive option.

Maintenance of unpaved roadways is easier and cheaper than maintaining conventional asphalt

³³ Image source: Billy Connor, University of Alaska, Fairbanks.

³⁴ Image source: Billy Connor, University of Alaska, Fairbanks.

³⁵ Reimchen et al. 2010.

or concrete pavements and should be considered during the initial planning of a new roadway. In some cases, reverting problematic stretches of existing paved road to gravel may be worth considering. Any decision to continue to enhance maintenance should be weighed economically against the measures listed in the previous section.

5. Conclusions

This report has introduced the important features of permafrost and the effects of its thawing on roadway infrastructure built on or near it. Climate change and its implications on permafrost have been discussed as well. From this discussion, it is clear that the effects of thawing permafrost on roadway infrastructure in Arctic regions will be substantial in the decades ahead. Techniques are developing for incorporating climate change into thermal modeling and settlement calculations so that impacts to roadways can be studied in detail. However, this area of study is still in its infancy and research is needed to address knowledge gaps in the process and make it more efficient so it can be employed routinely on typical projects. Likewise, knowledge on adaptation options for roadways built on permafrost is developing, but limited. There are adaptation strategies available at this time to mitigate permafrost thaw, but their effectiveness over the long term is still being studied. Additional research on the performance and effectiveness of various known approaches will help provide guidance to practitioners developing strategies to deal with permafrost thaw.

6. References

1. Andersland, O.B. and B. Ladanyi. 2004. "Frozen Ground Engineering," Second Edition.
2. Bjella, K.L. 2014. "Dalton Highway 9 to 11 Mile Expedient Resistivity Permafrost Investigation."
3. Chapin, S.F. III, S.F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, D.A. McGuire, and M. Serreze. 2014. "Ch. 22: Alaska," *Climate Change Impacts in the United States: The Third National Climate Assessment*. J.M. Melillo, T. (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program.
4. Goering, D.J. 2003. "Passively Cooled Railway Embankments for Use in Permafrost Areas," *Journal of Cold Region Engineering*, 17(3).
5. Lebeau, M. and J. Konrad. 2007. "The Effects and Significance of Natural Convection in Rockfill Dams under Cold Climate Conditions."
6. McGregor, V.R., D. Hayley, et al. 2010. "Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions," Ottawa, ON: Transportation Association of Canada.
7. Mchattie, R.L. and D.J. Goering. 2009. "Air Convecting Embankment (ACE) Design Guide."
8. Reimchen, D., B. Stanley, R. Walsh, G. Doré, and D. Fortier. 2010. "Reducing Maintenance Requirements on Permafrost-Affected Highways: Permafrost Test Sections Along the Alaska Highway, Yukon."
9. Turchetta, D. 2010. "Taking Stock: Climate Change and Transportation." *Public Roads*, 73(5).