Guide for Foundations on Changing Permafrost

November 2023

NREL

COLD CLIMATE HOUSING RESEARCH CENTER

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Guide for Foundations on Changing Permafrost

November 2023

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Acknowledgments

The authors would like to thank the following individuals for their assistance:

Dr. Ronald Daanen, State of Alaska Department of Natural Resources
Dr. Billy Connor, University of Alaska Fairbanks
Jana Peirce, University of Alaska Fairbanks
Dr. Yuri Shur, University of Alaska Fairbanks
Dr. Skip Walker, University of Alaska Fairbanks

as well as many others from University of Alaska Fairbanks who have reviewed the document or shared their knowledge with us.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Contents

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Contents (cont.)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

List of Figures

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

List of Acronyms

°C	Degrees Celsius
CCHRC Inc.	Cold Climate Housing Research Center Inc.
CH_4	Methane
CO_2	Carbon Dioxide
°F	Degrees Fahrenheit
Gt	Gigatonne
kpsi	Thousands of pound-force per square inch
NREL	National Renewable Energy Laboratory
mm	Millimeter
UAF	University of Alaska Fairbanks

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Chapter 1: Introduction to Permafrost

Introduction

Permafrost is soil that has remained below 32°F for two or more years. It underlies much of the land in the Arctic, encompassing approximately 21% of the land mass (about eight million square miles) of the Northern Hemisphere (Figure 1). Permafrost generally occurs in areas with long winters, short, cool summers, and an average annual temperature below freezing. Permafrost can primarily be found in Canada, Russia, Greenland, and the northern latitudes of Alaska. In the Southern hemisphere, permafrost is confined to high altitudes in the South American Andes, New Zealand's Southern Alps, and the few ice-free areas of Antarctica. The active layer is a thinner layer of soil that rests on top of the permafrost and freezes and thaws seasonally; its name comes from its ability to support biological activity. Below the active layer, permafrost can extend downward a few inches to a few thousand feet. Permafrost along the Alaska Arctic Coast reaches depths close to 2,000 feet.

Figure 1: Arctic permafrost zone. (Obu 2019)

The areas along the Arctic Ocean are predominantly underlain by continuous permafrost. Continuous permafrost describes areas where permafrost underlies approximately 90%-100% of the landscape. Continuous permafrost accounts for approximately half of all permafrost areas in the Northern Hemisphere. Discontinuous permafrost (50%-90% coverage), sporadic permafrost (10%-50% coverage), and isolated patches (0%-10% coverage) account for the rest.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Generally, the northernmost regions of Alaska are continuous permafrost zones. Interior Alaska is primarily discontinuous permafrost, and south-central coastal and south-eastern Alaska have sporadic and isolated permafrost (Permafrost in Alaska, n.d.). Figure 2 shows the profile of permafrost across Alaska.

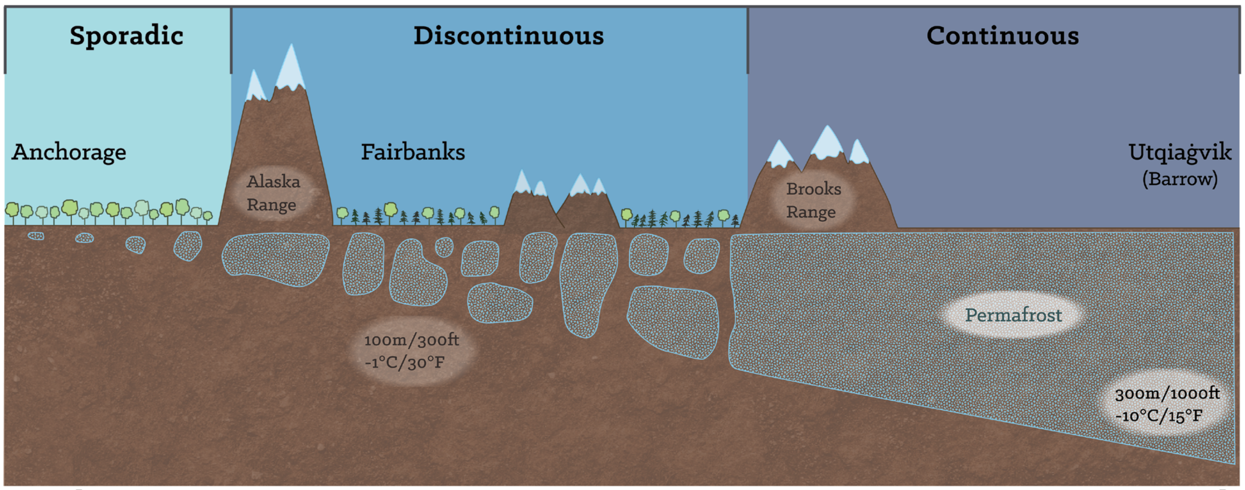

Figure 2: Profile of permafrost from south to north of Alaska. (Hannah Foss, UAF. Shared with permission.)

The extent of permafrost coverage significantly affects construction and thaw mitigation techniques. For example, removing the permafrost layer in some discontinuous, sporadic, and isolated permafrost regions might be worthwhile. Digging out small pockets of permafrost and replacing them with gravel, which is less susceptible to frost, allows for a more traditional foundation, and could be cost-effective in the long run. Construction in the discontinuous area is complicated because it is hard to determine if a location has permafrost, and a single borehole test may miss problematic permafrost formations just a few feet away. Foundations in the discontinuous zone vary depending on the best understanding of the local subsurface; however, permafrost foundations will come into contact with soils near the thawing point, which requires careful engineering. Infrastructure in the continuous zone must always account for permafrost and be developed in a way that keeps it frozen.

Permafrost Concerns

The rule of thumb when building on permafrost is to preserve it in its frozen state or to build so that the construction will not be affected by permafrost thaw. Since water changes phases at typical cold climate temperatures, permafrost's most challenging characteristics arise from water. Water has a relatively high surface tension, allowing it to seep and climb into crevices. Pure water can expand up to 10% of its volume from thawed to frozen states, exerting tremendous forces (up to 25 kpsi) when frozen within a confined space. The more water in the soil, the more complex a construction challenge permafrost will be. Ice-rich permafrost—permafrost high in ice content—can lose significant volume when it thaws as the ice melts. This loss of the ice structure can lead to subsidence of the soil and loss of structural integrity of the foundation.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Ground Movement

As water in the ground freezes and expands, it moves upward along the path of least resistance. This movement results in ground heave, which can damage built infrastructure. Frost jacking can occur when ground ice builds up at the base and sides of infrastructure buried within the active layer. Water seeps in along the solid surfaces through gravity and capillary action, then freezes and pushes the element up a relatively small amount. The ice beneath never completely thaws, and the cycle repeats, leading to further buildup that eventually causes the element to be slowly jacked out of the soil (Figure 3).

Figure 3: Example of frost jacking. (CCHRC Inc.)

Frost jacking is rare in cold permafrost areas like the Northern Arctic where there is continuous permafrost and a thin active layer. Permafrost thaw in the Northern Arctic tends to involve subsidence and ice wedge thaw. Subsidence is when the land sinks as the active layer thaws and the water flows away, the next thaw season the active layer thaws deeper causing the land to sink further (Figure 4). Ice wedge thaw creates differential settlement at the surface, creating thermokarst or holes where the ice used to be.

Figure 4: Ground subsidence. The stairs used to touch the ground. (M. Rettig, NREL)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

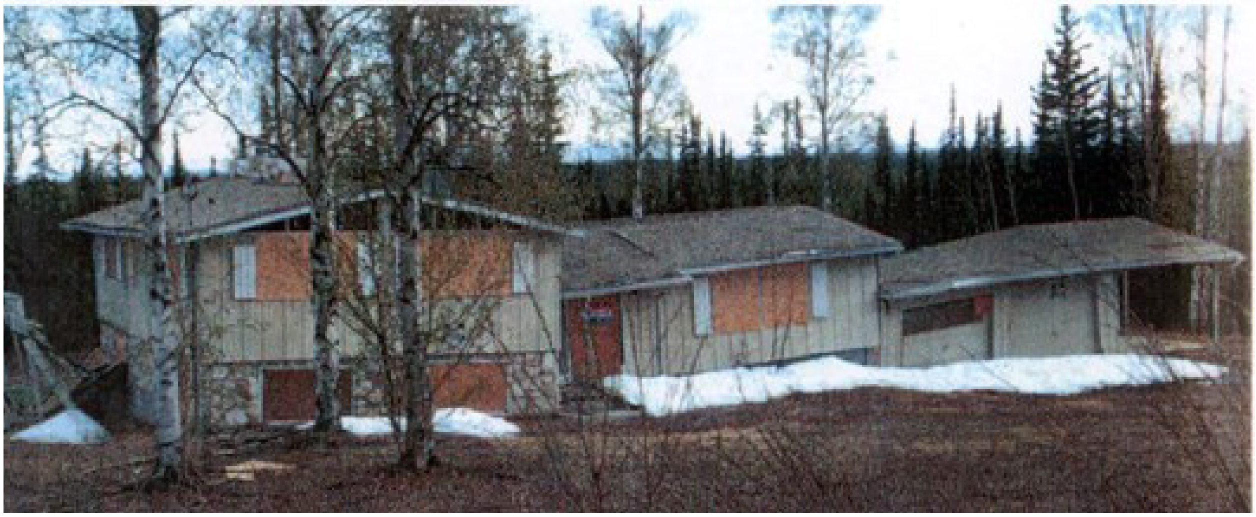

Figure 5: Ice wedge thaw creates differential settlement at the surface, creating thermokarst boreholes where the ice used to be. (D. Holmgren, Thotpro)

Flowing Water

Groundwater flow within permafrost areas is complex because of forces exerted by confinement and pressure. The permafrost layer prevents uphill water infiltration in areas with relatively steep or rolling topography. In valleys and lower hillside elevations, this can cause a positive hydrostatic pressure at the surface, a common source of artesian wells, particularly in areas of discontinuous permafrost. Buildings thaw the permafrost below them and are particularly susceptible to this upwelling groundwater. In Northern Alaska, surface runoff peaks in spring, around late April to mid-May. The permafrost below the active zone prevents infiltration, resulting in increased surface water and flooding of low areas during early thaw periods. Because soil subsidence is characteristic of typical permafrost thaw areas, further accumulation of surface runoff occurs. Standing water is then warmed by the sun and stays warm for a long time, creating more thaw and compounding the problem.

Massive glaciation occurs when groundwater surfaces through ground fissures or wells during freezing temperatures. Large water bodies that do not freeze completely in the winter are significant heat sources that have a warming effect on permafrost. In areas where surface water flow is relatively shallow, the flow channel becomes restricted during freezing periods, forcing water to the surface through cracks and fissures in the frozen surface in a process called overflow (also naled or aufeis). Once at the surface, the overflow freezes in a relatively thin sheet that grows throughout the winter (Figure 6).

Figure 6: *Aufeis* at an arctic river, Northwest Territories, Canada. (Peter Schmidt, Wikimedia Commons)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

This effect is prevalent in sections of the channel where flow is usually constricted, such as natural dams or critical-flow areas and man-made structures such as bridges and culverts. In Northern Alaska, ice buildup upstream of some structures can range from 10-20 feet above the surface (US Army Corps of Engineers, St. Paul District, n.d.). During thawing periods, the downstream flow of the ice can cause damage by introducing tremendous pressure on structures.

Topography

Topographical conditions such as shading, drainage, and ground cover also affect the rate of permafrost degradation. In Interior Alaska, extensive boreal forests aid in shading the ground during the summer. Above the Arctic Circle, the tundra carpets a landscape with a thick mat of annual and perennial species of shrubs, grass, and a layer of peat moss. Both forest and tundra are ecosystems in a natural balance with the environment, insulating the permafrost layer and keeping the active layer at a minimum . Damage to either, be it from environmental change, clearing, or repeated physical trampling, can eventually kill the overgrowth in that area, stripping the ground of insulation, speeding up thaw and subsidence, and transforming the landscape in a way that may not be easily reversed (Luhn 2016; Figure 7).

Figure 7: Tundra damage caused by human traffic. (G. Davis, NREL)

Carbon Dioxide Release and Carbon Feedback

Permafrost comprises nearly a quarter of the land surface in the Northern Hemisphere (~12.6 million square miles). It holds between 1,100-1,500 gigatonnes (Gt) of carbon in its frozen state. As it degrades, permafrost releases several greenhouse gases, including carbon dioxide (CO_2) and methane (CH_4), into the atmosphere. Some of the CO_2 is reincorporated into organic compounds through photosynthesis (marine and terrestrial). Some dissolves into the oceans, where it becomes carbonic acid (contributing to ocean acidification) or is sequestered as biotic calcium carbonate. Methane released from thawing permafrost is not readily recaptured or removed, and once in the atmosphere, it traps radiation nearly 30 times more effectively than CO_2. Over time, increasing amounts of greenhouse gases accumulate in the atmosphere, trapping solar radiation. The resulting global temperature increase leads to additional permafrost degradation, a cycle known as permafrost carbon feedback. This effect is enhanced when the process occurs quickly (i.e., days to years; Miner et al. 2022). Models suggest that permafrost currently contributes around 0.4 Gt of CO_2, but this could increase to 56-102 Gt by the end of this century (MacDougall & Knutti, 2016). By comparison, deforestation and burning fossil fuels produce around 35 Gt of CO_2 and CH_4 annually (IEA, 2022; Saunois et al., 2020). Measuring these gases on a global scale (particularly methane) is challenging, and modeling this process is an ongoing effort for climate scientists.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Permafrost Terms

Thaw-stable permafrost occurs in soils that are not frost susceptible, meaning they do not change physical dimensions between frozen and thawed states, such as coarse-grained sand and well-drained gravel soils. These soil types are common in old riverbeds or areas where water-borne erosion has filtered and placed the coarser-grained materials.

Ice-rich permafrost is permafrost that contains excess ice. This type of permafrost is prevalent in Northern Alaska, where ground conditions typically include fine, poorly drained soils. In areas of discontinuous permafrost, ice-rich zones may be found in locations with poorly drained soil or areas prone to accumulated surface runoff. Areas prone to significant ice deposits, such as the base of avalanche falls or beneath glaciers, often contain ice-rich permafrost.

Ice-poor permafrost has a low moisture content and enough ice to bind the soil particles together. This condition is common in soils that drain relatively well. Ice-poor permafrost can also occur within ice-rich permafrost, where ground ice formation has drawn moisture out of the surrounding permafrost soil. Ice-poor permafrost has a relatively low heat conductivity and can act as a stabilizing buffer for underlying ice-rich permafrost against thermal changes. The ice-poor layer above ice-rich permafrost helps improve the resilience of ecosystems in changing environments.

Cold permafrost is permafrost that remains at or below 30°F year-round.

Warm permafrost exists between 30° and 32°F during portions of the year. Since warm permafrost soils are nearer the thawing point of water, they are more susceptible to environmental changes.

Thermokarst landscapes occur when ice-rich permafrost thaws. Examples in the Arctic include thermokarst lakes, collapsed pingos, sinkholes, and pits.

Ground ice is relatively pure ice surrounded by permafrost soil. The combination of permafrost soils, annual freeze/thaw conditions, and surface and/or groundwater can cause water to concentrate within a freezing zone and result in the formation/growth of ground ice.

Ice wedges are structures that form perpendicular to the ground surface. During the thaw season, surface runoff can penetrate the upper permafrost layer through cracks or fissures. This water freezes during the cold season and expands, forming a wedge within the upper permafrost layer. This action repeats annually, expanding the ice wedge's width, depth, and length.

Ice lenses are ice structures that form parallel to the ground surface and form through a process called cryosuction . This condition can occur at any layer in the soil and is most prevalent in fine-grained soils with smaller pore spaces. They can cause permafrost ground to expand up to 50% of its volume.

Pingos are mounds that are formed when large ice lenses cause ground upheaval. Pingos in Northern Alaska can rise as much as 200 ft above the surrounding tundra.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Chapter 2: Site Survey

Is There Permafrost?

Permafrost is found throughout northern latitudes, but generally, the farther north you go, the more likely you are to build on thicker, continuous permafrost. The presence of permafrost affects many ecological processes; ground ice supports the soil layers above it and influences topography. Permafrost is vulnerable to warming temperatures and can be unstable if thawed, depending on the complex interaction of its characteristics, local water movement, local temperatures and climate conditions, surface boundary conditions, seasonal freeze and thaw cycles, and increased human traffic (Street and Melnikov, 1990). With these dynamic factors, it is challenging to forecast permafrost degradation.

Failure to address the presence of permafrost could lead to costly structural settlement issues later. A building's foundation should reflect the type of permafrost on the site and the building's construction method. Determining the best mitigation strategies for your location means surveying the site conditions and understanding the challenges before construction begins. On continuous, ice-rich permafrost, the best mitigation is to keep the ground under the building frozen.

Soil Composition

Soil particles range from the size of gravel (20mm to 4.75mm) and sand (4.75mm to 0.0075mm) to silt (0.0075mm to 0.002mm) and down to clay-sized particles (less than 0.002mm). Gravel and sand particles are rounded, whereas clays and silts are rodlike or platelike.

Soil properties influence how water and heat energy are transferred in the ground. Therefore, the soil composition of an area affects its susceptibility for thawing. Thaw-stable permafrost is permafrost in bedrock, in soils that are well-drained with larger particle sizes; both gravel-sized and sand-sized and includes coarse-grained sediments. When this type of soil is thawed, the expected movement is minor, and foundations remain sound.

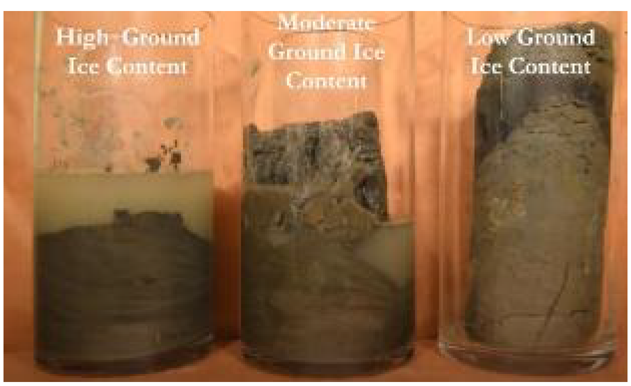

Figure 8: Visualization of high, moderate, and low ground ice content. (Photo still from video by Ben Jones, UAF)

Fine grained soils with high ice content create high risk for foundation if the ice thaws (Figure 8). In areas of permafrost, fine-grained soils and those that drain poorly (e.g., silts and clays) are considered "thaw unstable." These ice-rich areas contain 20% to 50% excess ice, more ice than the volume required to fill the pore space in the unfrozen state. Thawing can result in loss of bearing strength and excessive settlement. Ice-rich sediments that are unstable thaw more extensively once site modifications occur (Lawson, 1986).

Ice-rich permafrost has a high load-bearing capacity in its frozen state. Once thawed, it loses this capacity. Any disturbances to the natural vegetation can accelerate the thawing process on these sites. Studies examining ways to re-vegetate ice-rich permafrost did not focus on ice-rich mineral soils. The best mitigation solution for this soil type is minimizing or eliminating disturbances (Zhang et al., 2018).

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Determining Presence and Depth of Permafrost

Surface and Ground Features -- What Can You See?

When features are visible, a detailed inspection of the site during the summertime can help indicate whether there is permafrost and any ecological damage before construction. Almost all sites north of the Brooks Range are in areas of continuous permafrost. In areas of discontinuous permafrost, it can be difficult to find where the pockets of permafrost exist and to what extent.

Any variation in elevation and drainage in the landforms profoundly influences the vegetation and water composition in Alaska; plains in Northwest Alaska are mainly wet, the hills are moist, and the mountains are dry (Walker, 2000). In Interior Alaska, terrains that are untouched and have wet, swampy ground, black spruce, and pooling of water are good indicators of permafrost. While permafrost can be found in just about any biome, black spruce and tamarack often grow on wet, cold sites on top of permafrost, and drainage or pooling can indicate frozen ground (ADF&G, 2018) . Tussock tundra (Figure 9) is the most common biome across lowlands, terraces, and other shallow slopes for Northern regions and are usually found on continuous permafrost (Walker, 2000). The vegetation for the tundra consists of cottongrass and dwarf shrubs, frequently growing on fine-grained, acidic soils.

Figure 9. Tussocks near Point Lay, Alaska. (J. Herbert, CCHRC, Inc.)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Features in the landscape, as well as existing nearby structures, can indicate the presence of ice-rich permafrost and if the area is experiencing ground ice aggregation or degradation. Ice-wedge polygons are an indication that the permafrost is unstable. The edges of each polygon are formed by ice wedges; ice wedges thaws into water and have no structural stability. (Figure 10 and 11). They are frequently found along the Arctic coast and other permafrost areas worldwide.

Figure 10. Ice wedge polygons. (G. Davis, NREL)

Figure 11. Exposed ice wedge. (J. Peirce, UAF)

Pingos are low mounds or cone-shaped formations of soil with massive ice cores. Pingos are usually covered with vegetation and develop when hydrostatic water pressure pushes up a layer of frozen ground. Larger pingos often develop craters that fill with water during the summer. Polygons and pingos both indicate ground ice.

Sub-surface

While surface and ground features can indicate the presence of permafrost—especially ice-rich permafrost—they do not tell the whole story. A sub-surface study can provide a complete picture of the extent of permafrost in the area, showing the depth, distribution, and amount of ground ice.

One sub-surface investigative method is rodding, also called frost probing, in which a half-inch or quarter-inch steel rod is pushed into the soil using body weight or a heavy hammer. The presence of permafrost is inferred once the rod ceases to advance as it reaches frozen soil. (Frozen soil makes a dull thud, whereas rock makes a distinctive clicking sound.) The resulting core drilling survey can indicate the depth of the active layer, the soil characteristics and water content in the soil (Figure 12).

Scale (ft)	Depth (ft)	Froz.	Sample #	Moist. g/g %	Recov. %	Drill Method
						MC
1						
	1.5					
2	2.3					
	2.5					
3	3.0					
4	4.0					
	4.5		1	31.4		
5	5.0				100	
6						
7	7.0		2	38.5		
8						
9	9.0					
	9.5		3	38		
10	10.0				100	
11	11.0					
12						
13	13.0		4	59.6		
14						
15	15.0		5	35.1	100	
16	16.0					
17	17.0		6	39.8		
18						
19						
	19.5		7	53.1		
20	20.0				100	

Figure 12. Example of a borehole subsurface drill log. (CCHRC Inc.)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Core drilling with a machine is a more comprehensive method and will give more information on the soil content and permafrost (Figure 13). It is necessary to sample from several site locations, as one or two samples will not be indicative of the entire area.

Figure 13. Using an auger to bring up a soil sample. (CCHRC, Inc.)

Resistivity logging uses electrical resistivity and leverages the electrical resistivity properties of the subsurface materials. It can provide deeper subsurface information than drilling alone. It is used primarily in the oil industry in open-hole wells and is generally expensive. Resistivity logs measure fluid saturations in the formation's rock and can advise whether the soil is saturated and ice rich as well as other rock properties such as porosity and permeability.

Degradation of Ice-Rich Permafrost

At a Building Level

Signs of permafrost degradation around a building can be subtle. Cracks in walls or doors that do not shut properly in different seasons can signal thawing and settling issues. While it does not necessarily confirm permafrost problems, these are visible signs often from thawing and settling. Other signs indicating permafrost and settlement issues include crooked front steps, unlevel floors and roof lines, and cracks in the drywall (Figure 14).

Figure 14. Cracks in drywall caused by ground movement. (G. Davis, NREL)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Permafrost Degradation in the Area

The types of degradation are governed mainly by the amount of ice within the soil and how it is being disturbed. While disturbances can be natural, such as changes in air temperatures, fire, and snow cover, sites stripped of natural vegetation have been recorded to have twice the rate of thawing compared to natural thawing (Osterkamp, 2007). The disturbance in permafrost results in several distinct landforms. Changes in the ground surface, such as surface water ponding, can result in sinkholes and ground collapse also call thermokarsts. Infrastructure can be affected from ground settlement along roads and gravel pads due to surface disturbance. Permafrost degradation can cause cosmetic damage, movement in structures, and loss of service. Major permafrost degradation can result in major repairs to restore service and frequent maintenance to ensure service. The condition of surrounding buildings and other infrastructure is another visible clue. Nearby buildings on piles are signs the area is susceptible to permafrost degradation. If the building is on the ground, signs of permafrost degradation include settlement around the building.

Permafrost Degradation in the Landscape

Any increase in fire, flooding, stripping, or compacting of vegetation can start retrogressive thaw slumps. Once that occurs, the permafrost can rapidly deteriorate. Active layer detachments are small failures between the permafrost and the active layer, and they can deepen the active layer and thaw the ice-rich zone at the top. This can be caused by air temperature increases and excess snow cover.

New thermokarst terrains (Figure 15) indicate ice-rich permafrost degradation. While thermokarst depressions, pits, mounds, and lakes result from thawing ice-rich permafrost, the annual thawing of the active layer itself does not produce thermokarst terrain. These characteristic landforms indicate other disturbances, such as climatic change, stripped vegetation, and disturbances in the established ground thermal regime, such as flowing water. In Interior Alaska and other boreal regions with permafrost, “drunken forests,” or trees (Figure 16) leaning in random directions are good indicators that the ground is ice-rich as the trees’ roots tend to be shallow above the permafrost.

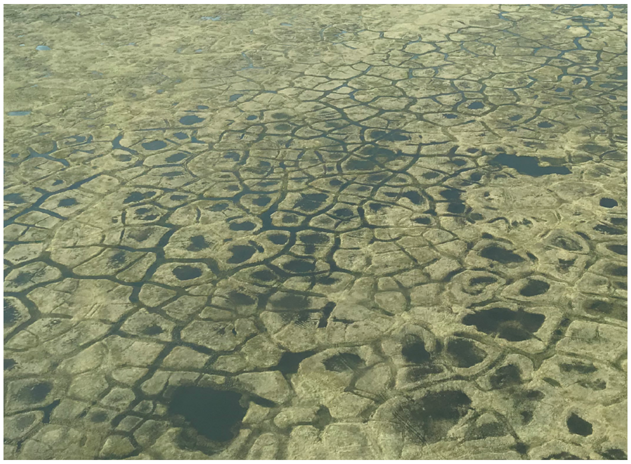

Figure 15. Example of thermokarst terrain. (M. Kavevskiy, UAF)

Figure 16. Example of “drunken” trees losing their foundation due to permafrost thaw. (R. Garber-Slaght, NREL)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Remote Sensing

The need to monitor and record the significant changes to permafrost regions from the amplification of global climate change in the Arctic and remote sensing methods use has expanded in the last decade. Satellite imagery and radar, spectroradiometers, aerial photos and photogrammetry are some of the expanding sensor capabilities used to capture the changing topography and comparing the erosion or surface accumulation during the period. Combined with ground observations, the enhanced methods have managed to capture the landscape changes which includes surface temperature, snow characteristics, topography, surface water, shrub and forest expansion and human activity. There can be indicators of degrading permafrost that has been discussed such as thermokarst lakes, depressions, pits, and mounds. Other visible signs of degrading permafrost that can be captured include active-layer detachments, coastal erosion, and flooding.

Survey Checklist

Choosing the best foundation for a building on permafrost depends on the construction method and the type of permafrost present. The following steps will help to determine which mitigation strategies will work best for your location:

1. Survey the area and site.
    a. Is there permafrost?
        i. The farther north you go, the more likely that there is thicker permafrost.
    b. Is it continuous or discontinuous permafrost?
        i. Is the site on, below or above the continuous permafrost line?
            1. If above, you have permafrost!
            2. If below, you can be in discontinuous or sporadic zones.
                a. Signs in the area:
                    i. Drunken forests, black spruce, pooling of water even when dry.
                    ii. Can the frozen soil be avoided or removed?
    c. How deep is the permafrost? Can the frozen soil be dug out? What will be left behind?
    d. Is the permafrost thaw stable? Is there gravel?
        i. Soil composition
            1. Fine grained, rock with ground ice are thaw unstable.
    e. What do the surrounding buildings look like? Are they directly on the ground or on piles? Are they level?
        i. Floors tilting
        ii. Doors and windows jamming
        iii. Cracks in floors, walls, ceilings
        iv. Window glass breaking
        v. Structural failures
    f. Are the area roads flat or wavy?
    g. Are there pools of water in the area even though it hasn't rained recently?

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Chapter 3: Permafrost Foundations

Mitigation Strategies

The basic rule of building on permafrost is: if it's frozen, keep it frozen. This idea translates into foundation designs that allow cold air to keep the soil frozen in winter and protect the soil from the summer sun. The foundation should help redirect the heat leaking from the building so it does not thaw the ground below; this is usually achieved by keeping the building out of contact with the ground. The warmer the permafrost, the harder it is to keep frozen. Sometimes it may even need to be cooled actively. Water is also a significant driver of permafrost thaw; protecting the ground under a building from runoff is very important. Maintaining the vegetative layer under the structure will also help insulate the permafrost.

New Construction

The first and easiest mitigation strategy for new constructions is to avoid building on permafrost at the building or community level. Avoidance is not always possible, but it is the simplest solution to the issue of thawing permafrost. In areas of discontinuous permafrost, one mitigation strategy is to remove the permafrost completely on the desired site and replace them with non-frost-susceptible soils (US Army and Air Force, 2004). The design and construction can then follow conventional standards for a non-permafrost zone. This strategy can be costly if the layer of permafrost runs deep.

Another option in discontinuous permafrost is to pre-thaw and pre-consolidate the ground where the foundation will go. This mitigation tactic requires enough heat to escape the building to ensure that the soils stay thawed. Several issues can arise with this strategy. It can be challenging to anticipate the area of thaw the building would cause. A miscalculation could lead to thaw outside the pre-thawed, consolidated area, resulting in settlement and refreezing at the boundaries lead to ground heaving. It is also problematic if the structure is not used and is left unheated for a freezing season, which would allow the ground to refreeze (US Army and Air Force, 2004).

Protect It First, Then Build on It

Leave the Ground Cover Undisturbed

Tundra vegetation acts as an insulative layer for the permafrost beneath it, keeping the temperature relatively stable. In the winter, it recaptures water evaporating from the ground, releasing it as oxygen into the atmosphere and simultaneously dissipating heat from the ground (Rice, 1996). Tundra is easily disturbed and damaged; when this happens, the insulative qualities are lost, and the permafrost warms and thaws in the summer. Protecting and maintaining the natural ground cover provides thermal protection for the frozen permafrost layer.

Ensure Water Drains Away From the Foundation

Many issues with thawing permafrost originate where water and permafrost converge. Keeping water runoff away from the foundation will help mitigate permafrost thaw. Avoid building in low-lying areas where water pools. Also, install a gutter system that diverts water from the building and associated infrastructure.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Permafrost Foundations for New Buildings

Pile Foundations

Pile foundations are drilled deep into the ground, preferably down to bedrock. They are typically steel or treated wood. The piles elevate the building above the ground allowing cold air to circulate in the winter, which helps keep the permafrost frozen. Adjustable screw jacks should be installed on top of all the piles to allow for leveling of the structure as soil conditions change (Figure 17). This foundation technique is the most recommended by permafrost experts.

Figure 17. Adjusting foundation screw jacks in Atmutluak, Alaska. (CCHRC Inc.)

Where bedrock is too deep to reach practically, one alternative is adfreeze steel pipe piles (Figure 18). The process of adfreezing occurs when ice causes two objects to stick to one another. Adfreeze piles are placed deep enough into the permafrost that the ground will remain reliably frozen, and then the hole is backfilled with slurry, which will freeze to the pile and the frozen ground. An engineer should oversee this process.

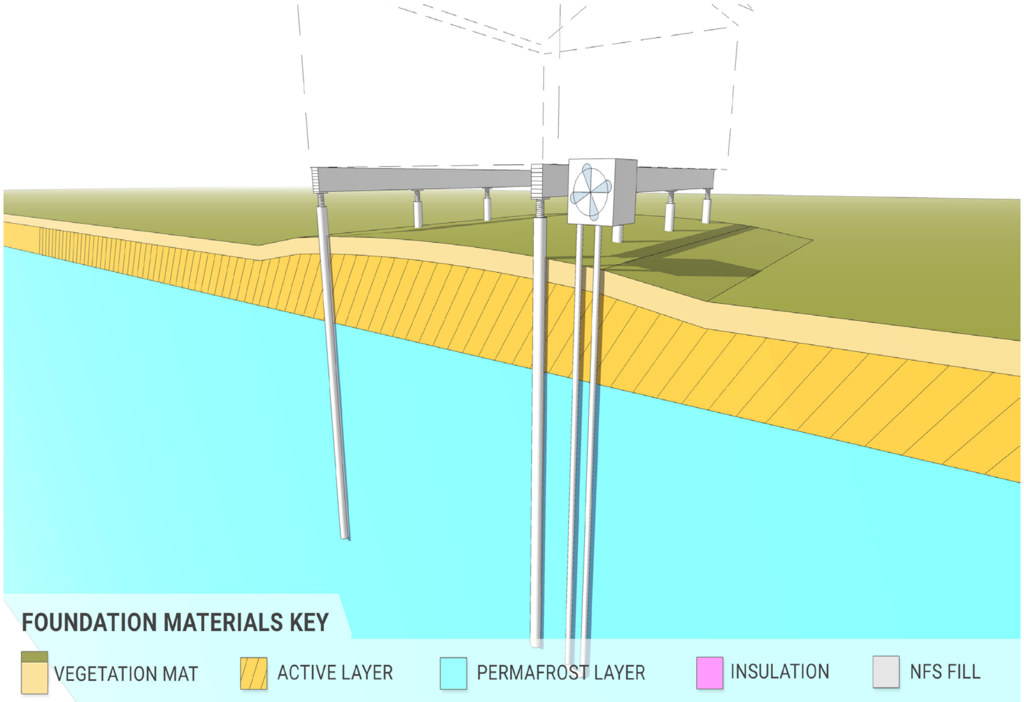

Figure 18. Adfreeze pile foundation. (C. DiRutigliano, CCHRC Inc.)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Because piles are inserted into the ground, they affect—and are affected by—the permafrost. Without mitigation, piles can transfer enough heat to significantly change the ground's thermal profile. Depending on the water content of the permafrost, this can lead to settling or heaving. Frost heave can cause tensile stresses in the piles, which can lead to cracks in the foundation. Understanding the soil and planning the piles correctly for the soil type can alleviate these concerns. A structural engineer can design piles specific to the soil properties.

Post and Pad

Post-and-pad-foundations refer to posts that rest on individual footings. The posts are usually steel, treated wood, or wooden cribbing, while the pads are treated wood or cement. The pads should be coupled with a large gravel pad that insulates the permafrost below (Figure 19). One of the benefits of the post-and-pad approach is that adjustment is possible. As with pile foundations, the post-and-pad foundation can be adjusted with a screw jack at each post. For a post-and-pad foundation to perform well amidst permafrost conditions they must be executed well and maintained.

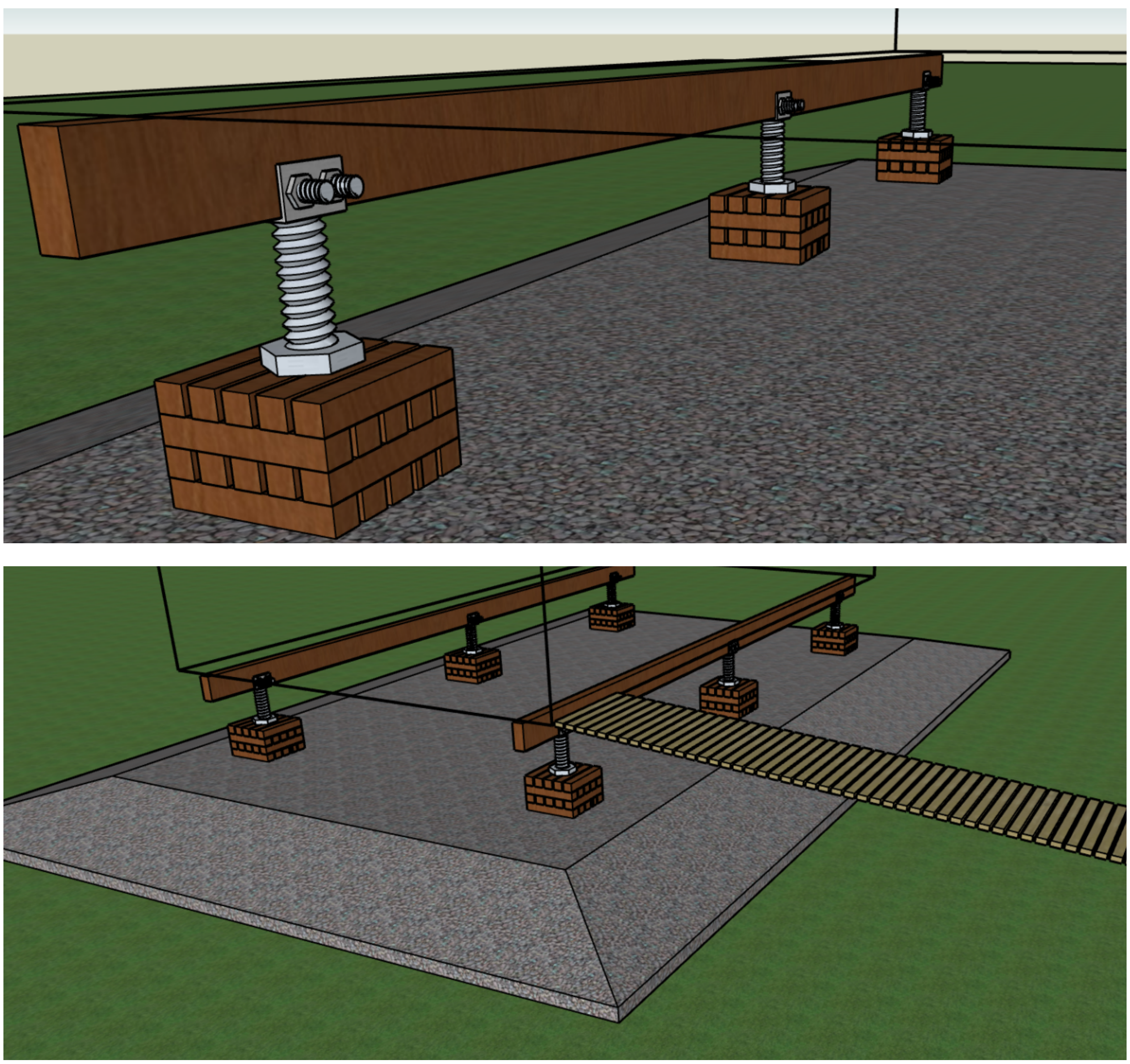

Figure 19. Post and pad foundations shown on a gravel pad. (J. Biddle, NREL)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Slab on Grade

Slab-on-grade foundations are concrete slabs that rest directly on the ground or a gravel pad. They are uncommon in permafrost areas as they can be expensive to maintain. Slab-on-grade foundations on permafrost generally have active cooling systems installed to help keep the permafrost from thawing. Removal of permafrost to install a gravel pad is expensive and difficult to maintain. Rigid foam insulation can be placed under the floor to limit heat transfer; however, it does not stop heat transfer to the ground.

Foam Raft

The foam raft foundation is a thick layer (12-18 inches) of polyurethane foam sprayed onto an undisturbed site (Figure 20). First, a builder lays a geotextile material on the ground, followed by premade foam blocks to support the edges of the steel floor joists and separate them from the ground. Next, they spray polyurethane foam into the space under and between the metal joists. Once this is set, they can install wooden flooring onto the sprayed raft. Foam raft foundations are more energy efficient than conventional, raised foundations, but their long-term performance is under investigation.

Figure 20. (Top and right) Anaktuvuk floating raft foundation; (left) Quinhagak raft foundation under construction. (CCHRC Inc.)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Space Frame and Other Prefabricated Foundations

Space frame foundations consist of an interconnected three-dimensional tubular framework designed for the structure and its support conditions. These foundations sit on top of insulation (usually a gravel pad), preventing the steel or aluminum material from sinking into the ground. Space frame foundations minimize material usage through their geometry, resulting in optimal designs that lower the weight. Space frames are adjustable and can be restabilized after ground shifting. The many support points can be useful in small adjustments to keep the structure level; however, this can cause maintenance to become more difficult with so many points to adjust.

Figure 21. Space frame foundation with thermosiphons in Atmautluak. (CCHRC Inc.)

Modular Tubular Foundation is a term often used interchangeably with space frame and Triodetic since all function similarly (Figure 21). Modular foundation systems have been used in permafrost regions for the last 30 years for domes and space frames, and they have recently been applied and studied in residential buildings.

Since each system is prefabricated, it can be dismantled and moved to another location if necessary. As few as 10% of the support points are weight-bearing, and the systems can direct loads away from areas where the soil capacity has been an issue. Less reliance on optimal soil conditions allows for minimum site preparation and geotechnical input (Vangool, 2018).

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Moveable or Skidded Foundations

Moving a home is helpful in areas of particularly unstable permafrost. Space frame, post-on-pad, and foam raft foundations can be built on skids, i.e., metal skis with attachment points (Figure 22). If the ground below becomes unstable, the homes can be moved to a better location. Ideally, the new location will have a gravel pad or matting to protect the vegetation from the skids.

Figure 22. Mertarvik skidded space frame. (CCHRC Inc.)

Cooling

Passive Cooling Systems

Passive cooling methods reduce heat gain and dissipate heat without active mechanical assistance. In a foundation, one way of achieving this is to dissipate heat through an air barrier between the building and the ground; another is to use geothermal energy transfer (Dennison 2017; Humlum et al. 2003). The air barrier method allows cold winter air to flow naturally through a building's unobstructed crawlspaces, keeping the frozen soil from warming (Kanevskiy 2019). Passive geothermal energy transfer is often achieved using thermosiphons embedded in the ground under and beside the foundation. Thermosyphons are large, sealed pipes that contain a fluid under a vacuum that evaporates near ground temperature and thus pulls heat out of the soil and releases it to the air via condensation at the top of the pipe. They require careful design and are not helpful on site where there is a presence of standing water or ice wedges. Both approaches require conditions where the air temperature is significantly below the soil temperature. Passive cooling systems are recommended for locations with permafrost temperatures below –26.6°F (Johnston 1981 as cited by Wagner 2014; CSA Group 2019; Kanevskiy 2019).

Active Cooling Systems

Active cooling systems are often necessary to maintain building stability in areas with rapidly changing permafrost. Cooling coils are placed underneath the foundation to help prevent heat from moving to frozen soils (Figure 23). An active cooling system is installed just like any other mechanical component of a building. The cooling coils connect to an electrically driven chiller unit, which removes heat from the soil and channels it elsewhere. This mechanism allows the active cooling system to be used year-round, especially in summer. These systems are often used in larger commercial structures and buildings that require foundations on the ground, like vehicle storage buildings.

Figure 23. Active cooling loops laid under a slab on grade commercial foundation. (CCHRC Inc.)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Retrofitting Existing Buildings

Environmental

Some site conditions can be managed around existing buildings, such as leaving the ground cover undisturbed and providing adequate water drainage away from the structure. Mitigation strategies associated with building location are less applicable to existing buildings. If the structure is built in a low-lying area where it is difficult to direct water, it may help to add fine grain soils, silts, and clays to cut off any water from flowing into the area.

Cooling

Cooling refers to techniques that keep the permafrost frozen through the warmer months. Although cooling systems are most efficient when installed in new construction, there are ways to apply cooling techniques to existing structures. Removing everything--debris, storage, snow--from under the structure that obstructs wind flow will help keep the ground cool. Skirting can be fine but needs a gap to keep airflow. If there is skirting it is important to discourage and/or remove any snow that it collects. Both snow and water collection will speed up permafrost thaw, so proper airflow around the structure will keep snow from accumulating and later melting into pools of water. Active and passive cooling techniques can be retrofitted into a structure, but the process will be more complicated and expensive than environmental cooling retrofits. Similarly, steps can be taken to encourage evaporation around areas where water pooling is known to occur. Encouraging airflow near the foundation can also allow moisture to evaporate in the summer (Government of Nunavut 2013).

Control Water Runoff

As discussed in Chapter 1, water exerts forces that affect the permafrost in multiple ways. Water management is essential to mitigate flooding and runoff in the spring, thaw in the summer, and frost heave in the winter. Both still and moving water increase the rate of thaw of the permafrost. Gutters and downspouts that move rain and runoff from the roof away from the foundation are essential in most locations (Figure 24). Depending on the site, using ditches to guide meltwater away from the foundation of a building can be a relatively easy solution for water pooling near the foundation. In some locations, this solution is more difficult or not practical. If a ditch redirecting the excess water is not an option, adding gravel to pooled water can help. Making the pool shallower will lower the amount of water that absorbs heat.

Figure 24: (left) Gutters and a downspout help direct rain and snow-melt. (right) Drain spouts and flexible drain channels direct water away from the building and into a ditch that feeds a retention pond (in the distance). (G. Davis, NREL)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Insulation

Because snow is mostly air, it is an excellent insulator. A layer of snow over permafrost will keep it warmer than the ambient air temperature. The result is a thicker active layer of permafrost in areas with significant snow accumulation than in areas with little or no snow accumulation. Building foundations should be kept clear of snow so that the permafrost under and around the building can cool during winter. Installing snow fences on the windward side of buildings can help prevent snow accumulation next to and beneath the building. If snow is plowed, it should be moved to an area with good drainage, not in low-lying areas, as this can create puddles when the snow melts and increase permafrost thaw. At the community level, a snow dump allows for snow to be collected from multiple locations and placed in an area where it would be unlikely to further permafrost thaw once it melts.

Figure 25. Examples of tundra vegetation. (J. Peirce, UAF)

Seasonal thermal insulation can be used with buildings with open crawlspaces and those with ventilated crawlspaces. However, data showing the benefits of ventilated crawlspaces need to be better documented. Seasonal thermal insulation involves placing insulation on the permafrost in April and removing it in October, allowing it to refreeze during the winter. Failure to remove the insulation can result in a temperature difference of 2-3°F, enough to keep the permafrost from refreezing (Perreault, 2016). In winter, insulation removed from the permafrost can be transferred to the underside of the house flooring to keep it warm. As previously discussed, native vegetation works as natural insulation (Figure 25). A thick moss or vegetative layer can be a cooling system for permafrost, much like an evaporative cooler works. Once native vegetation has been removed, it is nearly impossible to replicate. Moss is a native vegetation that can help control water flow and insulate the permafrost.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Structural Engineering

Along with the environmental adjustments that can be made to stabilize the foundation, there are structural retrofits that could help. Although these retrofits can be more complicated and expensive, this can vary depending on the approach.

Adjustable Foundations

An adjustable foundation is a structural approach where screws or jacks are applied to the piles or pads (Figure 26) allowing the foundation to be manually adjusted—the resting height raised or lowered at various points. If subsidence or rising happens with the ground underneath the foundation, the building can be re-leveled to avoid structural damage. Adjustable screws or jacks are easiest to install in a new home; however, retrofitting them into existing piles or post-on-pad is possible. Space frame foundations are also adjustable.

Figure 26. Adjustable foundation example. (B. Tracey, Point Lay)

Reinforce and Restore Existing Foundations

Instead of changing the type of foundation, it is possible to reinforce and restore the existing foundation. There are multiple ways that this can be approached. Piles can be made under or around the house using materials found locally. Adding piles outside the current footprint of the house and then extending the joists to rest on the new piles is an option. Heavy items like sand-filled 55-gallon drums could help prevent building collapse (personal communication Dr. Paul Perreault, September 20, 2020). If a pile foundation is shifting, shims or spacers can be used to adjust to different heights (personal communication Dan Holmgren, April 11, 2020). However, in most cases, trying to restabilize the existing foundation permanently is usually too expensive compared with other retrofit options (Bommer et al., 2009).

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Other Considerations

Any changes on the surface can have detrimental effects on the permafrost. Even if a building foundation is well designed, if the driveway is not well planned it can cause problems to the adjacent structure. Driveways should divert water away from buildings. Wooden walkways from the driveway to the house help protect the tundra around buildings from destruction by vehicles or regular foot traffic. Another solution to supplement more direct mitigation techniques is modeling and forecasting. Knowing the current soil profile and temperature and predicting how the capacity will change are important when trying to keep the foundation stable. Data obtained from weather stations, soil maps, and snow depth measurements can be used to simulate various scenarios. These models can help to identify areas at different levels of risk and predict potential damage and adverse effects of changes in permafrost conditions (Nelson et al. 2001; Oelke & Zhang 2007; Streletskiy et al. 2012).

Utilities and Utility Connections

Buried utilities may be less unsightly and more protected from freezing but are challenging to reach for maintenance or servicing. Above-ground utilities make this more manageable, but even when they are not buried in unstable permafrost, they are still susceptible to the movement of the ground below. Joints are often the weak point, particularly rigid joints that cannot adjust to changing ground conditions. Flexible joints and pylons that allow movement are possible solutions (although not widely available). The warmer water in the pipes can cause severe problems if a leak goes unchecked, so even small leaks must be prevented or stopped quickly. All water pipes above or below ground should be well insulated, and above-ground insulation needs to be protected from UV light and rodents (Figure 27).

Figure 27. Insulated water and fuel pipes in Antarctica, further protected by a pedestrian bridge crossing. (Photo by G. Davis)

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

Community Scale Mitigation Strategies

After exploring all feasible options, a community may decide it is in its best interest to relocate. Keeping the community in its ideal location is the goal of retrofitting and mitigating any potential foundation issues.

Planners must consider the effect of an entire community concurrently with individual home design. Community mitigation strategies are similar to those for individual buildings but are applied at a larger scale. Community layout—both streets and houses—can affect snow drifting patterns, although this can be difficult to predict. During the winter, large snow fences solve the immediate problem of snow drifting around neighborhoods, but they can cause long-term damage to permafrost by creating massive drifts on the windward side. Active snow plowing around buildings—in streets and public areas—and snow dumps are two straightforward but labor-intensive methods of sequestering snow in an area where melting would not further permafrost thaw.

Figure 28. This meltwater retention pond is used by nearby buildings that channel rainfall and meltwater away from the building and parking area. (NREL)

Once breakup begins, drainage plans and meltwater retention areas fed by multiple buildings and public places can prevent water accumulation around buildings. Moving water into collection sites that do not cause flooding or water contamination issues is critical (Figure 28). Sloped ditches and culverts along roads can move water and may require annual maintenance. Culverts are often used to protect roads from eroding. However, because water patterns in permafrost are complex, the best locations for culverts are not always clear, and these systems can fail even after careful planning.

The blanket of tundra that protects the permafrost is susceptible to damage from repeated heavy loads: conventional vehicles, repeated trampling, and excavation. Restoration is a long and challenging process that is not always successful. Communities can limit site degradation by collectively retrofitting buildings to ensure the ground is protected and well-drained. This process could include improved floor insulation in buildings and the removal of solid skirting from the foundations of all raised buildings. Using a gravel pad as a base for the foundation can protect the permafrost from the influence of the house. While this option strips the vegetation on and around a building site, it is a viable solution that insulates the permafrost below (more so when coupled with boardwalks). Another approach is to create fewer buildings by including more multi-family buildings: duplexes, fourplexes, and housing clusters that use centralized utilizes. This action reduces the amount of disturbed land and the number of utility connections.

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

[This page is intentionally left blank]

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

References

Alaska Department of Fish and Game. (2018). “Elements That Create Forests,” in Alaska Wildlife Curriculum - Tree Basics.

Bommer, C., Phillips, M., Keusen, H.-R., & Teysseire, P. (2009). Bauen im Permafrost—Ein Leitfaden für die Praxis [translated Building in Permafrost—Practical guide]. www.wsl.ch/publikationen/pdf/9819.pdf

Briaud, J.-L. (2013). Soil Classification. In Geotechnical Engineering (pp. 46–62). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118686195.ch4

CSA Group. (2019). Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation (Technical Guide CSA PLUS 4011:19).

Dennison, P. (2017). Understanding and Developing Estimates Based on Practical Foundation Methods for Alaska’s Discontinuous Permafrost Region [Degree of Master of Science in Engineering Management]. Department of the Air Force Air University: Air Force Institute of Technology.

Government of Nunavut. (2013). A Homeowner’s Guide to Permafrost in Nunavut.

Humlum, O., Instanes, A., & Sollid, J. L. (2003). Permafrost in Svalbard: A Review of Research History, Climatic Background and Engineering Challenges. Polar Research, 22(2), Article 2. https://doi.org/10.3402/polar.v22i2.6455

Kanevskiy, M. (2019). Permafrost and Permafrost Related Risks (INE 19.04).

Kanevskiy, M., Shur, Y., Jorgenson, M., Ping, C.-L., Fortier, D., Stephani, E., & Dillon, M. (2011). Permafrost of Northern Alaska. Proceedings, Twenty-First International Offshore and Polar Engineering Conference, 1179–1186.

Lawson, D. (1986). Response of Permafrost Terrain to Disturbance: A Synthesis of Observations from Northern Alaska, U.S.A. Arctic and Alpine Research. https://www.tandfonline.com/doi/pdf/10.1080/00040851.1986.12004058?needAccess=true

Luhn, A. (2016, December 23). Arctic oil rush: Nenets’ livelihood and habitat at risk from oil spills. The Guardian. https://www.theguardian.com/environment/2016/dec/23/arctic-oil-rush-nenets-livelihood-and-habitat-at-risk-from-oil-spills

MacDougall, A. H., & Knutti, R. (2016). Projecting the release of carbon from permafrost soils using a perturbed parameter ensemble modelling approach. Biogeosciences, 13(7), 2123–2136. https://doi.org/10.5194/bg-13-2123-2016

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

References (cont.)

Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., Fix, A., Sweeney, C., Elder, C. D., & Miller, C. E. (2022). Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment, 3(1), Article 1. https://doi.org/10.1038/s43017-021-00230-3 Nelson, F. E., Anisimov, O. A., & Shiklomanov, N. I. (2001). Subsidence risk from thawing permafrost. Nature, 410(6831), 889–890. https://doi.org/10.1038/35073746

Oelke, C., & Zhang, T. (2007). Modeling the Active-Layer Depth over the Tibetan Plateau. Arctic, Antarctic, and Alpine Research, 39(4), 714–722.

Osterkamp, T. E. (2007). Characteristics of the recent warming of permafrost in Alaska. Journal of Geophysical Research, 112(F2), F02S02. https://doi.org/10.1029/2006JF000578

UAF. (n.d.). "Permafrost in Alaska," in Hot Times in Cold Places: Permafrost During Climate Change. University of Alaska Fairbanks (UAF), Oregon Museum of Science and Industry (OMSI), and the Goldstream Group. Retrieved January 21, 2022, from http://www.permafrosttunnel.org/permafrost-in-alaska.html

Perreault, P. V. (2016). Altering the Thermal Regime of Soils Below Heated Buildings in the Continuous and Discontinuous Permafrost Zones of Alaska [Doctoral Dissertation]. University of Alaska Fairbanks.

Rice, E. (1996). Building in the North (4th ed.). University of Alaska Press.

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Zhuang, Q. (2020). The Global Methane Budget 2000–2017. 63.

Street, R. B., & Melnikov, P. I. (1990). Seasonal snow cover, ice and permafrost. Climate change: the IPCC impacts assessment, 1-46.

Streletskiy, D. A., Shiklomanov, N. I., & Nelson, F. E. (2012). Permafrost, Infrastructure, and Climate Change: A GIS-Based Landscape Approach to Geotechnical Modeling. Arctic, Antarctic, and Alpine Research, 44(3), 368–380. https://doi.org/10.1657/1938-4246-44.3.368

US Army and Air Force. (2004). UFC 3-130-04 Foundations for Structures—Arctic and Subarctic Construction. 272.

US Army Corps of Engineers, St. Paul District. (n.d.). Engineering Problems and Construction in Permafrost Regions Encyclopedia Arctica 2a: Permafrost-Engineering (Encyclopedia Arctica 2a: Permafrost-Engineering). Retrieved July 21, 2021, from https://collections.dartmouth.edu/arctica-beta/html/EA02a-07.html

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems

References (cont.)

Vangool, Wi. (2018, June 13). Mechanical foundation system for new and retrofit construction. Building Tomorrow's Society.

Wagner, A. (2014). Review of Thermosyphon Applications (Technical Report TR-141; p. 46).

Walker, D. A. (2000). Hierarchical subdivision of Arctic tundra based on vegetation response to climate, parent material and topography. Global Change Biology, 6(S1), 19–34. https://doi.org/10.1046/j.1365-2486.2000.06010

Zhang, X., Li, L., McHattie, R., & Oswell, J. (2018). Experimental Study of Ice-Rich Permafrost Cut Slope Protection. Journal of Cold Regions Engineering, 32(1), 04017018. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000149

Funding for this publication was provided by the National Science Foundation Navigating the New Arctic Program Award 1928237, Ice-Rich Permafrost Systems