

How Vulnerable Is Alaska's Transportation to Climate Change?

Managing an Infrastructure Built on Permafrost

BILLY CONNOR AND JAMES HARPER

Climate change is affecting transportation systems across the country, and scientists and policymakers are working to clarify the trends. Alaska's transportation community, however, has direct experience to verify the impacts of climate change. Geography and extreme climate have made the state a kind of climate-change classroom for the rest of the nation in predicting the effects on transportation infrastructure.

The wear and tear of climate change on Alaska's transportation systems is evident. The state has more than 6,600 miles of coastline, and approximately 80 percent of the land mass has an underlayer of ice-rich permafrost. Alaska has 17 of the nation's 20 largest mountain ranges and experiences extremes in precipitation, snowfall, and temperature swings that are unique to the arctic and northern latitudes.

With warming permafrost, coastal erosion, and increasingly dramatic storms and flood events, Alaska's highways, runways, and other infrastructure are frequently icing, cracking, and washing away. Although these adversities challenge all of the state's major transportation systems—maritime, aviation, and surface—the most acute and costly damage occurs within the road system.

Climate change in Alaska is forcing engineers and planners to adapt both to warming and to cooling trends. Engineers and planners are addressing knowledge gaps in thermal and hydrological dynamics and are translating the findings into new and more robust designs.

(Right:) Differential settlement on an abandoned section of the Richardson Highway, south of Fairbanks, one year after maintenance ceased.

Connor is Director, and Harper is Communication Specialist, Alaska University Transportation Research Center, University of Alaska, Fairbanks.



PHOTO: B. CONNOR, ALASKA UNIVERSITY TRANSPORTATION CENTER

Alaska's Climate Change History

Approximately 50,000 years ago, tropical plants dominated Alaska's more than 660,000 square miles. The ice age changed that landscape—glaciers grew and permafrost formed. Humans appeared in Alaska 11,000 years ago, evidenced by the mummified remains of a child on the northwestern coast (1). Glaciers began retreating approximately 10,000 years ago, leaving behind a scarred landscape, permafrost, and remnant ice buried in moraines that are regularly encountered today.

Permafrost

Permafrost—generally defined as soil continuously frozen for two or more years—has been a source of frustration for Alaska's engineers and plays a key part in today's surface transportation challenges. Most permafrost was not formed by glaciers; in some areas, a dry climate prevented glacial formation, so that much of Alaska—the North Slope, western areas, and the low-lying central region known as the Tanana Valley—has never experienced a glacier.

Even without glaciers, however, these regions present some of the most problematic permafrost formations. For example, a great portion of the permafrost in the Tanana Valley was formed by airborne silt; glaciers to the south deposited the material throughout the valley and into the hills to the north in thin layers that later froze to form syngenetic permafrost, which is characterized by small, horizontal, lenticular ice lenses and large ice wedges.

These dynamics stem from the interplay between thermal and hydrologic forces. Climate change, with its associated impacts on heating and thawing trends, has intensified the engineering challenges of permafrost from season to season.

Thawing permafrost along the Dalton Highway, showing the ice layer just below the vegetation layer. Engineers classify permafrost by performance, temperature, and frequency.



PHOTO: MIKHAIL KANEVSKY, INSTITUTE OF NORTHERN ENGINEERING



PHOTO: B. CONNOR, ALASKA UNIVERSITY TRANSPORTATION CENTER

Breakup on the Yukon River; ice thickness usually exceeds 3 feet.

North Slope

On Alaska's North Slope, seasonal stream flows and ice melt are among the variable hydrologic features affecting transportation. The region is home to the famed Dalton Highway, Prudhoe Bay, and the Arctic National Wildlife Refuge. Planners need a variety of hydrologic data to evaluate, design, and eventually manage roads and other infrastructure. The task involves designing and protecting infrastructure on or near ice- and snow-fed streams and rivers. Each spring brings a phenomenon known as breakup, when snowpack and snow melt create a peak flow of discharge that can descend over the North Slope.

Designing bridge pilings to cross a river that has unknown water and sediment flows is a difficult task; then add 3-foot-thick ice chunks the length of a house. Researchers, engineers, and planners are addressing these issues as they work to extend the state's road system across the invariably inhospitable terrain.

A new transportation corridor will run west from the Dalton Highway across the slope toward the community of Umiat—crossing several ice and snow-fed rivers that flow north out of the Brooks Range. The Alaska University Transportation Center, the Water and Environmental Research Center, and the State of Alaska are conducting a major research project to characterize water flow volumes, sediment transfer, and ice flow patterns in these rivers and streams.



PHOTO: MARGARET DARROW, UNIVERSITY OF ALASKA FAIRBANKS

Researcher Margaret Darrow of the Alaska University Transportation Center checks a thermal modeling data collection station along the Dalton Highway. Thermal and hydrological research enables transportation engineers to gain a better understanding of the effects of permafrost on road embankment stability.

Thermal Trends

Thermal trends at and below the surface are another area of interest. Studying trends in soil temperatures, ice content, soil strength, and slope stability clarifies the failure mechanisms of unstable soil slopes in permafrost regions. Subsurface conditions are a typically complex mixture of frozen and unfrozen areas, affecting groundwater flow and slope stability. The areas also vary in depth and may have only one active layer or may be more deep-seated.

Warming trends exacerbate these dynamics. Heat changes affect permafrost, in turn increasing subsurface water flow, which affects roads. Many research projects are focusing on the impact of Alaska's temperature changes on groundwater flow, permafrost degradation, and the resulting instability in road surfaces and slopes.

Costly Impacts

Alaska's recent climate variations are significantly different from those in the rest of the nation. Alaska has warmed at more than twice the rate of the continental United States in the past half-century, and the annual average temperature has risen by 3.4°F (2). The impacts on infrastructure include the following:

- ◆ Damage to roadways, airports, and bridges from melting permafrost;
- ◆ Culvert movement and damage from melting permafrost or flooding;
- ◆ Road and infrastructure loss from flooding; and
- ◆ Loss of roadways from slides caused by melting permafrost.

Permafrost appears to be the cause of the most severe and costly of these issues. In a newspaper interview, Mike Coffey, Chief of Statewide Maintenance and Operations for the Alaska Department of Transportation and Public Facilities, estimated that the state spends \$11 million annually on permafrost-related issues with roads (3)—the estimate did not include airport runways, railways, and municipal infrastructure.

The remoteness of Alaska's infrastructure increases the maintenance and operations costs. In Anchorage or Fairbanks, gravel and crushed aggregate may cost approximately \$20 per yard, but in the more damaged and remote areas, such as Savoonga, the costs can soar up to \$1,000 per yard with increased transport, fuel, materials placement, and labor expenses (3). The costs of permafrost damage to Alaska's publicly owned infrastructure are expected to grow by an estimated 10 to 20 percent, or \$3.6 billion to \$6.1 billion, by 2030. By 2080, these costs could grow by \$5.6 billion to \$7.6 billion (3).

Types of Permafrost

Alaska's engineers encounter two types of permafrost: syngenetic and epigenetic. One type of syngenetic permafrost, yedoma, has a high frozen moisture content, often exceeding 300 percent. In other words, yedoma is soil suspended in ice and turns mostly into water when it thaws. To the untrained eye, yedoma looks like frozen silt. Syngenetic permafrost typically is found north of the Alaska Range.

Epigenetic permafrost is often found on Alaska's North Slope, above the Brooks Range and south of the Alaska Range. This permafrost was formed simply by freezing in place. The properties and moisture content vary with the soil type and moisture content.

Yedoma, a type of syngenetic permafrost, has a frozen moisture content often exceeding 300 percent; photo shows lenticular ice formations of yedoma with ice-rich silt layers between the visible ice.



PHOTO: MIKHAIL KANEVSKY, INSTITUTE OF NORTHERN ENGINEERING



PHOTO: MIKHAIL KAMENSKY, INSTITUTE OF NORTHERN ENGINEERING

Ice wedge in permafrost on the North Slope; permafrost often contains ice wedges formed by repeated cracking in the earth; the thawed wedges leave large voids, which can be disastrous below structures.

The ice structure is distinct, with the ice features concentrated near the surface of each soil layer as it freezes.

Both epigenetic and syngenetic permafrost may contain ice wedges, formed by repeated cracking in the earth. The thawed wedges leave large voids in the earth, which become disastrous for any structures built above.

Although these two types of permafrost are fairly easy to identify, classification is a more complex process.

Classifying Permafrost

Engineers classify permafrost by three attributes—performance, temperature, and frequency—and define permafrost by how it performs when it thaws:

- ◆ *Thaw-stable permafrost* retains most of its strength as it thaws and generally is not a problem for engineers. Thaw-stable permafrost typically is found in granular soils or in silts and sands with low moisture content.

- ◆ *Thaw-unstable permafrost* loses almost all of its strength with thawing; yedoma is an example, as are ice-rich silts and sands, ice wedges, and frozen peat. Epigenetic permafrost may or may not be thaw unstable, depending on the content—gravels or silts. Syngenetic permafrost is almost always thaw unstable, because the layers consist of silts.

Permafrost also is classified by temperature—warm permafrost is between 30°F and 32°F, and cold permafrost is below 30°F. Warm permafrost typically is found south of the Yukon River, the locations of the Elliott, Richardson, and Parks Highways that connect Fairbanks, Anchorage, and Canada's Yukon Territory. The average permafrost temperature in the Fairbanks area in central Alaska is approximately 31°F. In southern Alaska's Copper River Basin, much of the permafrost is 31.5°F. In these areas, any warming will melt the permafrost. Both epigenetic and syngenetic permafrost can be warm or cold, depending on the location.

Construction almost always leads to warming.

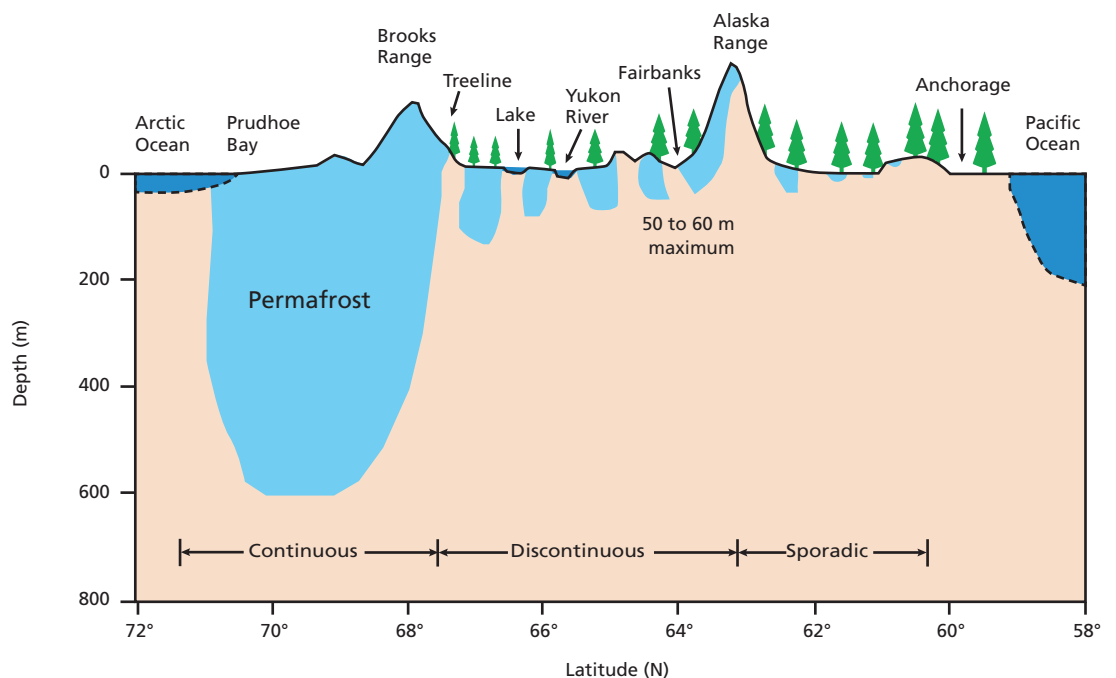


FIGURE 1 Transect of Alaska, showing the frequency and depth of permafrost. (Source: Larry Hinzman, International Arctic Research Center)



Alaska's western shoreline in 2008, near Newtok, showing the quick erosion that led to relocation of the village.

Building a roadway over the permafrost, for example, often raises the temperature enough to cause melting. An increase in air temperature also accelerates thawing.

In contrast, cold permafrost, like that typically found on the North Slope, is around 27°F. Although only slightly colder than permafrost found to the south, the few degrees of difference dramatically increase the strength of the ice and provide a buffer against a warming climate.

Finally, engineers classify permafrost by its frequency at a given location—sporadic, discontinuous, or continuous:

- ◆ *Sporadic* permafrost is found in isolated areas. Glacier National Park in Montana, for example, has many examples of sporadic, warm permafrost.

- ◆ *Discontinuous* permafrost contains areas with and without permafrost.

- ◆ *Continuous* permafrost appears in areas that are completely frozen year-round. The graphic in Figure 1 (page 26) indicates the distribution of permafrost in Alaska. Sporadic and discontinuous permafrost—whether epigenetic or syngenetic—are almost always warm permafrost.

After classifying the permafrost at a location, engineers derive any number of combinations to describe it. The descriptions help engineers make categorical distinctions to facilitate adaptive designs.

Permafrost Design Challenges

Permafrost design typically encounters difficulties with changes in temperatures or moisture, and the costs are long term. Engineers must decide whether to keep the permafrost cold or to adopt another strategy. Often, the choice is to move forward and accept the increased maintenance costs.

The greatest and most costly impacts of warming appear in the transition zones between warm and cold permafrost and in coastal areas prone to erosion. In these areas, Alaska's transportation infrastructure is most fragile; because the transition zone is predominately yedoma, the impacts of thawing are severe.

As climate warms, permafrost degradation becomes a challenge for embankment designers and maintenance crews. The transition areas show how permafrost may transform from cold to warm between rehabilitation or reconstruction periods. Groundwater and advective heat transfer have increasingly affected permafrost degradation below embankments. In addition, research shows that groundwater flow along the permafrost tables accelerates permafrost degradation. To monitor the subtleties of the subsurface dynamics requires thermal imaging and modeling technology.

Thermal modeling of Alaska's problematic road embankment configurations has led to more thermally stable embankment designs. The design strategies seek to reduce the thawing of ice-rich permafrost. Modeling also assists researchers and engineers in exploring how surface temperatures affect the stability of permafrost below roadway embankments. The improved embankment designs have reduced maintenance and mitigation costs dramatically.

In coastal regions, climate-related erosion is a primary threat. The U.S. Army Corps of Engineers identified erosion threats in 180 Alaska communities. In the Yupik village of Newtok on Alaska's western shore, shoreline erosion swallowed the dump site, the barge landing, and other infrastructure. The village is being relocated to higher ground on an island 8 miles away, at an estimated cost of \$130 million, which includes a new barge facility, a new roadway,



Researchers record glacial measurements at a remote location; findings on snowmelt, river flow, precipitation, and other hydrologic forces help planners charting new transportation corridors on Alaska’s North Slope and in other regions adapt designs to a changing climate.

and a new airport. The cost of relocating or protecting all 180 threatened communities could exceed \$23 billion.

Uncertain Predictions

As research explores these issues, many questions remain. Decade-to-decade warming and cooling trends, for example, complicate the forecasting to address these issues.

Despite rising temperatures, climate models predict that parts of the globe will experience both long- and short-term cooling trends. The Pacific Decadal Oscillation (PDO) indicates that changes in Pacific and Atlantic Ocean currents will cause warming and cooling trends in Alaska on a 30-year cycle (4). The last change occurred in the mid-1970s, with high temperatures, and the next cycle in the PDO has begun a drop in temperatures.

Some climatologists maintain that the upcoming PDO will be shorter but will lower the depth of the cooling trend beyond past cycles (4). Others predict a deeper and perhaps longer PDO, similar to the beginnings of the last ice age.

This uncertainty causes a dilemma, as the planning and decisions made in the past 30 years may not be appropriate for the next 30. For example, if per-

mafrost thawing reverses, what new and unseen design challenges will arise? Nevertheless, many of the associated transportation infrastructure challenges will stem from permafrost—what it is and how it behaves.

Permafrost Design Strategies

Specific cases illustrate that the formation of the permafrost will determine its engineering properties and the possible design strategies. Because thaw-stable permafrost typically does not produce the most problematic design challenges, and cold permafrost does not pose a threat until extreme warming, solutions can focus on the remaining classes of permafrost. An engineer has several design options:

- ◆ Keep the permafrost frozen;
- ◆ Thaw the permafrost;
- ◆ Design the structure for anticipated thermal variation—that is, for freezing and thawing; or
- ◆ Remove and replace the frozen soil.

All of these options are expensive. The choice is compounded by permafrost’s ambiguity and complexity; classification helps to clarify. Table 1 (below left) illustrates the kinds of designs that can be useful, depending on the class of permafrost.

Many considerations influence design choices. Thaw-unstable permafrost loses strength with thawing—leading to structural damage, whether to a roadway, bridge, building, or embankment. In areas of sporadic permafrost, keeping the permafrost frozen is not a good option, because the structure is likely to warm the ground enough to melt the permafrost. Research has shown that the side slopes of these roadways stay at approximately 6°F, because the snow insulates against the cold winter air (5). In this case, a warming climate may help in the long term by eliminating the sporadic permafrost and the impacts of thawing permafrost on infrastructure.

In areas with permafrost categorized as discontinuous, warm thaw, and unstable, a warming climate generally may not prove as helpful. The temperature of the permafrost ranges between 30°F and 32°F, but in areas of discontinuous permafrost, the temperature of the permafrost is slightly colder. Consequently, the decision to keep the permafrost frozen depends on the predicted temperatures. If the temperatures will remain the same or lower, keeping the permafrost frozen makes sense.

Preserving Permafrost

Keeping permafrost cold, however, is expensive. The warming caused by the construction of a roadway will likely cause thawing, even without climate

TABLE 1 Adapting Designs to Permafrost

Design Option	Consider Using
Keep frozen	When warming is not likely to occur; permafrost temperature is below 30°F; permafrost is thaw stable
Thaw permafrost	When permafrost is warm and sporadic; designers anticipate warming; permafrost is thaw stable
Thermal design	When foundation movement is unacceptable
Remove and replace	When permafrost is shallow, or the thickness layer is low; thin layer of thaw-unstable permafrost sits on top of thaw-stable permafrost; project involves critical infrastructure; permafrost is sporadic



A research team prepares to conduct river gauging for a major hydrologic study for the new North Slope transportation corridor; understanding the effects of flow rates, sediment transfer, annual runoff, and ice floes on potential river crossing sites is a key issue.

change. In most cases, because of the cost, engineers accept the effects of thawing permafrost and use annual maintenance to level and patch these areas. Consequently, climate change accelerates thawing, so that discontinuous permafrost moves northward into areas dominated by cold continuous permafrost.

The most common methods to keep permafrost cold include insulation, air convective embankments, thermosyphons, and air duct systems:

- ◆ Insulation typically is placed 3 feet below the road surface to reduce the heat going into the permafrost (6).

- ◆ Air convective embankments consist of uniformly sized rocks stacked up. Convective cells are created within the rocks during the winter and cool the permafrost below (7).

- ◆ Thermosyphons, like those used on the Trans-Alaska Pipeline, remove ground heat during the winter by turning a liquid into gas inside a pressurized tube. The gas rises to the top of the tube, releasing heat into the cold air above ground; the liquid condensate then falls back to the bottom of the tube (8).

- ◆ Air ducts apply the chimney effect—a horizontal pipe laid in the roadway slopes is equipped with a vertical chimney at the outlet.

Continuous thaw, unstable, cold permafrost is generally not a problem, because it will not melt in the near term or eventually become discontinuous, warm permafrost. Climate warming is not likely to have a significant impact on the performance of roadways and bridges in cold permafrost areas, because the predicted climate changes will not melt the permafrost sufficiently within the life of the roadway

structures. Consequently, the best alternative is to keep this type of permafrost cold.

Adapting to Change

Although the impact of climate change on infrastructure is more severe in Alaska than in other regions, Alaska demonstrates important lessons for engineers and planners in adapting to both warming and cooling trends. This entails addressing the emerging gaps in knowledge through thermal and hydrological research and then integrating the findings into new and more robust designs.

References

1. Grove, C. Remains of Ice-Age Child Discovered in Interior Alaska. *Anchorage Daily News*, February 25, 2011.
2. *Global Climate Change Impacts in the United States*. U.S. Global Change Research Program, 2009.
3. Rettig, M. Alaska Seeing Impact of Climate Change in Its Infrastructure, Villages. *Fairbanks Daily News Miner*, January 30, 2011.
4. Hartmann, B. and G. Wendler. The Significance of the 1976 Pacific Climate Shift in the Climatology of Alaska. *Journal of Climate*, Vol. 18, 2005.
5. Esch, D. C. Evaluation of Experimental Design Features for Roadway Construction over Permafrost. *Permafrost*. Fourth International Conference Proceedings, National Academy Press, Washington, D.C., 1983.
6. Esch, D. C. *Insulation Performance Beneath Roads and Airfields in Alaska*. Final Report, Alaska Department of Transportation and Public Facilities, December 1986.
7. Goering, D., and P. Kumar. *Roadway Stabilization Using Air Convection Embankments*. Final Report, Institute of Northern Engineering, Transportation Research Center, University of Alaska, Fairbanks, September 1994.
8. Forsström, A., E. Long, J. Zarling, and S. Knutsson. *Thermosyphon Cooling of Chena Hot Springs Road*. Final Report, Institute of Northern Engineering, University of Alaska, Fairbanks, February 2003.