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Stability of Critical Infrastructure in Permafrost Environments: A Proactive Approach

A proactive approach is about doing the right things at the right time to preemptively address issues and increase the overall success of the project.

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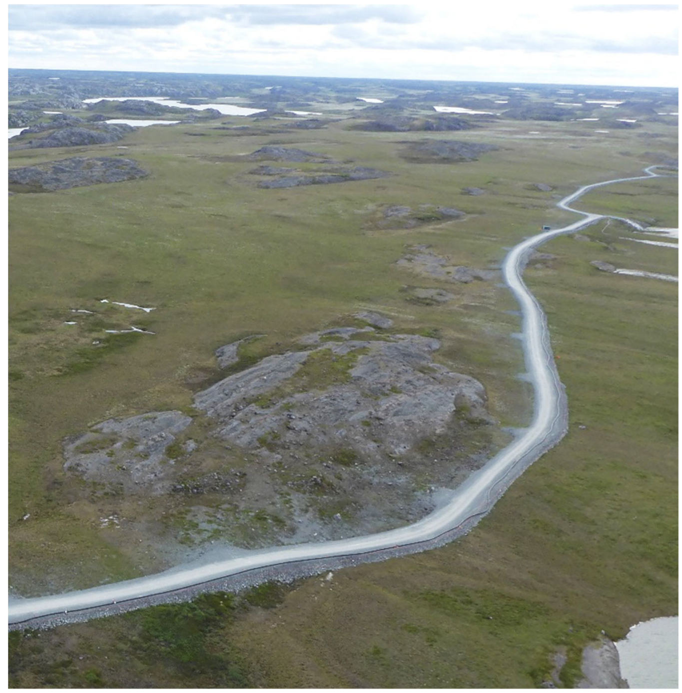
Christopher is a senior geocryologist at SRK Consulting. With over 10 years of experience working on terrestrial and subsea permafrost in the Arctic and Subarctic regions, he specializes in permafrost and ground ice characterization, periglacial geomorphology, thermal analysis, numerical thermal modelling, and thermal design of infrastructure founded on permafrost. He has worked on mining, transportation, and oil and gas projects located in the United States, Canada, Russia, and Greenland.

Prior to joining SRK in 2012, Christopher held a National Sciences and Engineering Research Council (NSERC) position with the Geological Survey of Canada. He has authored over 50 peer-reviewed journal articles and conference proceedings related to his area of expertise.



Run-of-quarry rock road embankment constructed on ice-rich permafrost soils in Nunavut, Canada

Critical Infrastructure and Permafrost

The stability of critical infrastructure constructed on ice-rich permafrost is an important aspect of responsible economic development of natural resources in arctic and subarctic regions. In these regions, surface infrastructure, such as roads, dams, pipelines, and buildings often rely on the frozen state of permafrost for stability and are essential to daily operations.

Permafrost refers to earth materials that are at or below 0°C (32°F) for at least two consecutive years. Surface infrastructure alters the surface energy balance and amount of heat transferred to and from the underlying permafrost, potentially warming it and causing perpetual thaw, which can lead to ground settlement and other processes such as soil creep. Climate change adds an additional level of uncertainty due to the unknown role future conditions may have on the ground thermal regime at each site.

Permafrost degradation may lead to poor infrastructure performance and may pose significant financial and environmental risks to a project.

This article demonstrates how working with permafrost through a planned proactive approach (instead of a reactive one) improves the resiliency of infrastructure and reduces the risks to a project.

Proactive Approach

A proactive approach can benefit nearly all aspects of resource development projects, which is particularly true when confronted by the unique challenges of permafrost.

Proactive actions should take place throughout the life cycle of an infrastructure. Adequate studies, monitoring, and analysis during infrastructure site characterization, design, construction, operation, and closure lead to informed decision-making that can preempt potential issues before they become problems. In contrast, a reactive approach that does not track evolving conditions and responds only to sudden events can miss the warning signs of issues yet to come.

The following sections briefly discuss the proactive actions and best practices that contribute to more resilient infrastructure in permafrost environments. Owners and operators should be familiar with these.

Importance of Thermal Design

Fundamental, early-stage proactive steps in support of infrastructure design include adequate geotechnical evaluation of the substrate, baseline terrain studies as well as climate characterization. A conceptual understanding of permafrost and its response to infrastructure thermal forcing—in the context of contemporary and future climate—should be evaluated in the early stages of design.

If conditions require and where possible, alternative infrastructure sites with more favourable ground conditions may need to be considered to reduce long-term maintenance costs and risks. The conventional geotechnical and thermal design approaches to permafrost and infrastructure should also be challenged to develop a site-specific solution. Thermal design of the infrastructure must dovetail with the physical design to achieve the criteria and intended function over the design life.

The thermal design calculations should include reasonable assumptions, parameterization of inputs, and capture the underlying physics of the problem, while realistically depicting the infrastructure to be constructed and operated.

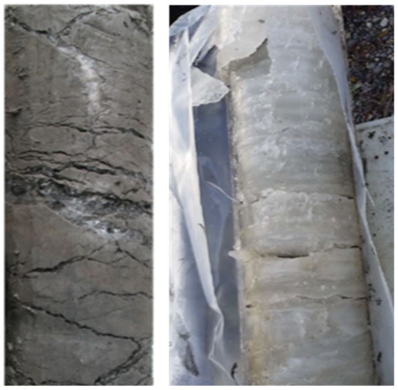
Thermal designs are not directly transferable from one site to another and the rules-of-thumb used for the last 40 years no longer apply in midst of the current changing climate. Practitioners must carefully consider future changes in climate while applying the best available information and demonstrating good engineering judgment.

In some cases, poor infrastructure performance is due to inadequate design, construction, maintenance, and irrespective of climate change.

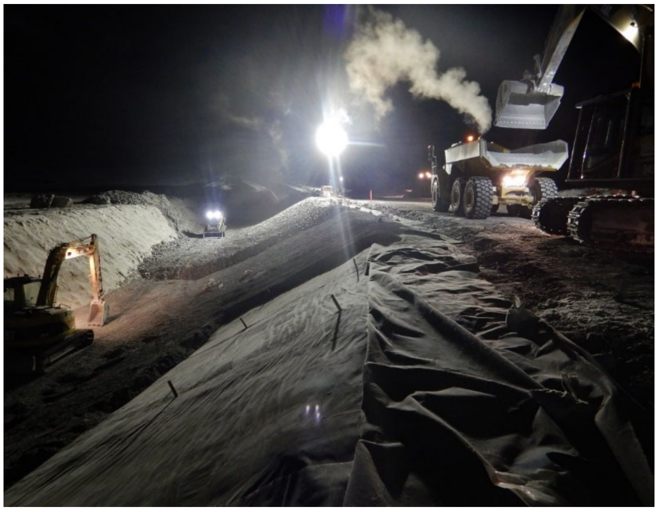
Experience gained from past successes and failures should be integrated in the development of creative design solutions. In some jurisdictions, the need exists for more rigorous standards and review to ensure adequate thermal design and construction. More rigorous thermal designs and third-party reviews are proactive steps that owners can take to protect their investment.

Construction and Intended Design

A next step in the proactive approach is ensuring construction is overseen by the design engineer or other qualified professionals. The direct involvement during construction of professionals who understand the design, the permafrost foundation, and the impact of seemingly minor changes ensures the design is constructed according to the specifications and the predicted thermal performance is achieved.



Permafrost cores with ice-rich silty clay (left) and massive ground ice (right)



Winter excavation of a key trench during construction of a frozen foundation tailings dam in Nunavut, Canada

The poor performance of infrastructure at numerous sites can be directly ascribed to the lack of engineering oversight during construction, incorrect implementation of design specifications and quality checks, or inadequate consideration of site-specific ground conditions.

A design report that includes thermal design should accompany the issued-for-construction drawings. As-built surveys and reporting for the constructed infrastructure should also be developed to provide documentation following completion. As-built information is essential for future reviews of infrastructure performance and for understanding the permafrost response over time.

A proactive step during construction is to require as-built surveys and reporting; this helps ensure adequate construction, provides documentation of deviations from the design, and supports the future evaluation of infrastructure founded on permafrost.

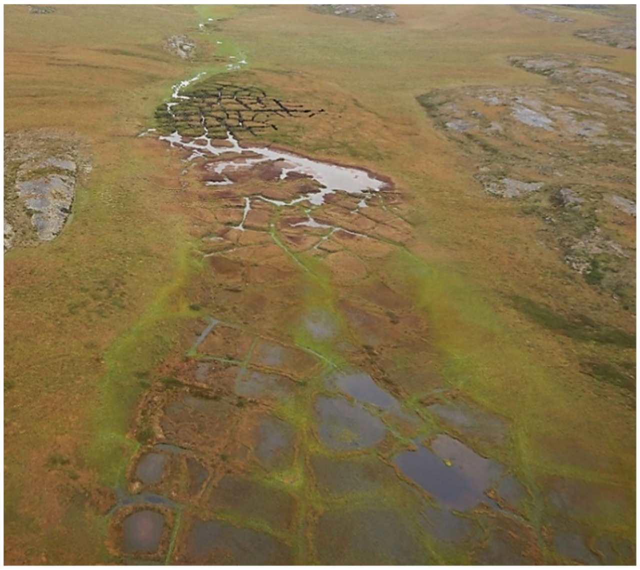
Thermal Monitoring and Informed Decision-making

Thermal monitoring of infrastructure and its underlying permafrost foundation is often necessary for performance evaluation, regulatory compliance, and development mitigation strategies for the future.

At its most basic level, monitoring provides information on the thermal behaviour of the infrastructure and resulting heat transfer with the underlying permafrost foundation. This information is compared with the values predicted during the design stage; it is used to monitor the trajectory and rate of change that may warrant action.

Monitoring data should be used proactively to identify exceedance of thresholds and to identify rapidly changing conditions, such as the advection of heat from water seepage leading to thermal erosion of ice-rich permafrost soils. Monitoring may also allow for timely mitigation, which can minimize the cost of infrastructure repair.

Conversely, inadequate monitoring can lead to regrettable, but avoidable results. Cases are documented where instrumentation, such as ground temperature cables and inclinometers, was installed but never used in a meaningful way until after extensive ground thaw and damage to the infrastructure had occurred.



Poorly drained terrain with ice wedge polygons in Nunavut, Canada

Proactive monitoring includes data collection, analysis, and review by a qualified professional. The cost of proactive monitoring is minor in comparison to costly repairs resulting from permafrost degradation that can lead to infrastructure failure and disruption of production with significant impacts to the surrounding environment.

A Changing Climate

Earth's climate has been changing ever since its beginning, with notable periods in the geological record where permafrost has caused dramatic changes to the landscape. Most arctic regions have experienced recent periods of warming that are expected to continue into the foreseeable future. The dynamic nature of permafrost continues to respond to these changing conditions.

It is therefore important to address future needs by actively considering climate change in new and legacy infrastructure founded on permafrost. Our work has shown the most technically defensible approach in considering climate change should be based on transparent and reproducible procedures that use all IPCC-accepted climate change model results in order to not bias the outcome toward one or two preferred climate change models. None of the climate change models are inherently right or wrong; they must be used with engineering judgment and the best available information at the time.

The observed distress of infrastructure is in some cases unrelated to climate change and is instead caused by poor design, inadequate construction, changes in operation, or site-specific conditions.

The current impact of climate on challenged infrastructures needs to be assessed honestly. For example, failure of a road culvert to convey water due to poor maintenance (which leads to surface water ponding and permafrost degradation impacting a road embankment) is not necessarily caused by climate change but is often represented as such.

Adapting existing infrastructures to meet current and future needs is a critical part of the proactive approach. The development of appropriate adaptation measures and the justification of related costs first start with identifying the risks posed by climate change to permafrost and to the infrastructure and evaluating the inadequacies of the infrastructure under current conditions. These investigations may result in a reduction of the risk profile of the infrastructure.

Independent Review

An independent, third-party review actively ensures critical aspects have not been overlooked. Engaging a technical expert may include review of the infrastructure design prior to submission for regulatory approval, investment by banks and other financial institutions, and undertaking of construction. A third party may also offer review of the overall integrity of the infrastructure in permafrost environments, leading to new questions and perspectives that were not addressed by the design engineer.

Site-wide review of infrastructure integrity and permafrost conditions can add value and minimize future costs and disruption to production.

Ongoing review of infrastructure integrity and changes in permafrost is an integral step of the proactive approach; it ensures that timely corrective action can be implemented when needed to mitigate permafrost degradation.

Adopting a Proactive Approach

Permafrost poses a formidable challenge due to its unique properties and dynamic nature. Natural and human-induced changes to permafrost are occurring and will continue to occur. A more proactive approach to the design and construction of critical infrastructure founded on permafrost is needed to address current and future needs. Seemingly minor steps taken by owners and operators can improve the resiliency of infrastructures, thereby minimizing the long-term costs, potential environmental impacts, and overall risk to the project.

Adopting a more proactive approach starts with engaging qualified experts that are willing to look beyond the obvious and challenge conventional thought, while using the latest technology and best available information. Such an approach results in recommendations that add significant value to the project.