Protecting Arctic Infrastructure as the Permafrost Degrades

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Scientia

PROTECTING ARCTIC INFRASTRUCTURE AS THE PERMAFROST DEGRADES

Roads, bridges, and airports are now being built all across the Arctic. However, as this happens, the future of the sturdy permafrost these structures are built upon is looking increasingly uncertain. In his research, **Dr Marolo Alfaro** at the University of Manitoba uses both computer modelling and real-world sensing to assess the impact that the Arctic's warming climate is having on this infrastructure. Starting from analysis of a newly-constructed highway in Canada's Northwest Territories, his team's efforts could soon provide local communities with vital guidance as to how their infrastructure should be maintained and protected.

Building on Permafrost

Covering roughly 15% of the entire surface of the Northern Hemisphere, permafrost can be found extensively within Arctic regions, where temperatures rarely rise above freezing. Within this ground, materials including soil and rock are held together by solid ice, making it incredibly hard and incompressible.

Although regions containing permafrost are some of the most sparsely populated places on Earth, there are still many thousands of people who call them home. As a result, engineers have needed to overcome enormous challenges to design, build and maintain the infrastructures required to connect these communities with the rest of the world.

Dr Marolo Alfaro and his colleagues at the University of Manitoba play an important role in these efforts. 'Our research involves evaluating the performance of a variety of infrastructure projects that include highway embankments, riverbanks, hydroelectric facilities, and underground nuclear waste repositories,' he explains.

In many cases, highway embankments – raised areas that allow roads to smoothly pass across rough terrains – are built using compacted, locally-sourced permafrost as a fill material. In recent years, however, this frozen fill material has come under increasing and unprecedented threat. As the climate warms due to human activity, nowhere on Earth is experiencing a faster rise in temperature than the Arctic. Increasingly, local communities are finding that the near-constant freezing temperatures required to sustain frozen fill material can no longer be relied upon.

Providing Smart Recommendations

When temperatures rise above 0°C, structures built from frozen fill material, as well as the permafrost they are built upon, can be far more easily distorted under their own weight. Such deformations lead to cracks in the fill material, which remain when the

temperature drops back down below zero, threatening the stability of entire structures.

Already, many Arctic communities are suffering from these damages, and must spend increasing amounts of time and money to maintain and repair vital infrastructures. To assess this impact, Dr Alfaro and his team use cutting-edge computer simulations to predict how real-life structures will deform and crack as temperatures rise. 'These studies are providing important guidance for advanced design and

The Inuvik to Tuktoyaktuk Highway

construction practices, by providing engineers with modelling and analysis recommendations,' says Dr Alfaro. 'This helps them to predict and mitigate excessive deformations and instabilities of earth structures and foundations.'

The quality of predictions made using these models can be improved by incorporating real climate data, gathered by both satellites and ground-based weather stations. Crucially, this enables researchers to compare their results with measurements of deformations in real structures – allowing them to fine-tune the predictions of their simulations. Ideally, these models could one day allow Arctic communities to monitor their infrastructures in real time – informing them when and where maintenance needs to take place. Yet before this can happen, several key challenges must first be addressed.

Studying Structural Stability

To ensure the best possible accuracy in their models, it is crucial for researchers to characterise the mechanical properties of particular structures. So far, Dr Alfaro and his colleagues have largely focused on highway embankments. In the Arctic, embankments are often constructed using frozen fill material, sourced from nearby permafrost.

Prior to their latest research, Dr Alfaro's team remained uncertain of the mechanical behaviours exhibited by embankments as they experience natural thawing. This created the goal of accurately describing the strength and deformation of their constituent fill materials as they thawed over summer, and froze over winter. In particular, the researchers would focus on three key aspects of embankment deformation.

Firstly, to comply with road construction standards, embankments can often reach several metres in height. As permafrost degrades, these embankments are particularly vulnerable – causing material to slough away from their sides. The problem can be further exacerbated as permafrost thaws beneath embankments, compressing under the weight of the structures. Finally, variations in the material structures of fill and permafrost can create weak points in embankments, further threatening their stability.

Together, these factors threaten to render vital roads undriveable. For Dr Alfaro and his colleagues, this made it incredibly important to investigate how embankment deformation mechanisms are triggered, and to recreate the behaviour as accurately as possible in their models. In 2017, the team was presented with an ideal opportunity to address these issues.

The Inuvik to Tuktoyaktuk Highway

That year, a new highway opened in Canada's Northwest Territories, linking the Arctic communities of Inuvik (which was already connected to the outside world via a highway) and Tuktoyaktuk – a previously isolated village on the coast of the Arctic Ocean. As the first road to Canada's Arctic coast that can be driven on year-round, the project was an enormous feat of engineering, costing $2.2 million per kilometre to construct, and another $12,000 to $15,000 per kilometre to maintain each year.

For Dr Alfaro's team, the highway was the perfect testbed for assessing the capabilities of their models. In their experiment, they fitted several embankment sections along the road with sensors to monitor their temperatures, and to detect any mechanical deformations.

In addition to these efforts, they also assessed the performance of a technique commonly used to protect embankments against thawing – based on hardy, permeable fabrics named 'geotextiles'. When placed in the embankment side slopes, this material can reinforce the weakened slopes during thawing, while also improving the drainage of meltwater during the thawing season.

Assessing Year-round Changes

Over the six years following the highway's construction, Dr Alfaro's team closely monitored any changes in the highway's embankments. In the test sections, they found that the central and lower portions of embankment remained frozen over the summer, even as air temperatures occasionally rose above 0°C. Compared with uncovered embankments, thawing rates were higher at the very bottom, where the slopes reached the ground.

Altogether, these results confirmed a critical need for researchers and engineers to consider both the near- and long-term impacts of climate change as they design and construct embankments, and draw out plans for their maintenance. In addition, they provide important recommendations for the team's modelling techniques.

By adapting simulations to recreate their field observations more closely, the researchers hope that highway operators could use them to accurately assess the impact of thawing on embankment deformation. Furthermore, this could be done without relying entirely on real-time sensing techniques – which can't realistically be applied along the entire length of a highway.

Improving Infrastructure Designs

The team now plans to expand on these efforts even further. 'Our recent research improves the design and performance of Arctic transportation infrastructure, related to the effects of climate change,' Dr Alfaro describes. 'It provides recommendations for modelling and analysis that help engineers predict and mitigate excessive deformations and instabilities.'

Alongside the use of geotextiles, the researchers also plan to test out a wide variety of other methods to mitigate against excessive embankment deformations and instabilities. Among these is the use of 'geogrid-geofoam composite'. Geogrid is a type of geosynthetic used as reinforcement, while geofoam is a form of polystyrene that is often used as an insulator

and lightweight embankment fill material. When placed over roughly-textured ice on the ground, it can prevent the permafrost underneath from thawing over the summer. If it does thaw, the geogrid-geofoam composite will bridge any empty gaps that form beneath the embankment.

Another proposed method suggests that thawing could be accelerated before embankments are built. Once the road is constructed, the structures won't deform as readily as the permafrost and fill material thaws naturally. Alternatively, some researchers suggest that heat exchange devices could be incorporated into embankments, which continuously cool the permafrost and fill material, after the road has been constructed.

As each of these methods are considered, a combination of field experiments and precise computer models will be vital, as researchers, engineers and highway operators determine the future of Arctic infrastructure.

Securing the Arctic's Future

In the coming years, local authorities predict that the usage of the Inuvik-Tuktoyaktuk highway will steadily increase, especially due to tourism and mining. Furthermore, a recent uptick in economic activity across the Arctic has led to unprecedented rates of road construction. As this happens, rapid warming in the Arctic is widely expected to accelerate, making it ever more important to monitor highway embankments, and to provide adequate resilience against future degradation of fill material, and the permafrost underneath.

Dr Alfaro's team also hopes that the scope of their research could soon expand to consider many other types of infrastructure – each vital to sustaining remote Arctic communities. 'The outcomes of this research project are also applicable to other northern transportation infrastructure including airports, railways, river crossings, pipelines, and electric transmission lines,' Dr Alfaro summarises.

With increasingly large swathes of the Arctic experiencing above-zero temperatures for a significant portion of the year, the experimental results and modelling techniques produced by Dr Alfaro and his colleagues come at a crucial time. Through the profound changes to come, the team's efforts could provide communities with the vital tools they need to survive in a rapidly changing world.

Meet the researcher

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Dr Marolo Alfaro is a Professor in the Department of Civil Engineering at the University of Manitoba. He has worked as a geotechnical engineering consultant for a wide range of infrastructure projects. His research focuses on structures built using earth fill materials and reinforced soil – including hydroelectric dams, pile foundations, stabilised artificial slopes, and underground disposal sites for nuclear waste. He is now a member of the Canadian Geotechnical Society's Research Board, where he will serve as Chair after 2023. In 2019, Dr Alfaro received the Society's Geosynthetics Award, recognising his outstanding contributions to the applications of geosynthetics in civil, geotechnical and geo-environmental engineering, both in Canada and internationally.

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FURTHER READING

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