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Robinson, P., & McIlwaine, S. (2020). Losing ground: Adapting construction management approaches to permafrost retreat. In *Proceedings of the 37th Annual Conference of Researchers in Construction Management (ARCOM): Proceedings of the 36th Annual Conference of Researchers in Construction Management (ARCOM)* (pp. 605-614). Association of Researchers in Construction Management. https://www.arcom.ac.uk/-docs/archive/2020-Indexed-Papers.pdf

Published in:
Proceedings of the 37th Annual Conference of Researchers in Construction Management (ARCOM): Proceedings of the 36th Annual Conference of Researchers in Construction Management (ARCOM)

Document Version:
Publisher's PDF, also known as Version of record

LOSING GROUND: ADAPTING CONSTRUCTION MANAGEMENT APPROACHES TO PERMAFROST RETREAT

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A significant amount of critical energy and resource infrastructure rests on permafrost. As the global climate changes, more areas of permafrost are becoming affected by seasonal thawing, leading to changing ground conditions which were unforeseen during design and construction. As the untapped energy and resource potential of the northern icefields becomes more accessible, construction in these environments is only set to increase. In this paper, recent literature on design and construction in areas of retreating permafrost is examined, and a mixed-methods approach is described which includes a survey of experienced construction managers, and interviews with industry experts whose primary work is in geo-technical research and development of structures in Arctic regions. It seeks to identify the construction challenges faced by the changing ground conditions, and to establish how existing approaches and practices to construction in permafrost need to be adapted for the future. The study confirms that existing practices generally work well, and the challenges are well defined. But it identifies several interlocked areas which must be further understood for the success of both existing and future projects in permafrost and Arctic regions. These include expanding survey ranges, improved risk tracking and management, milestone mapping, adaptive design, and intensive logistics management. The research makes it clear that for a successful project, the ground conditions and their interaction with the project design must be fully understood, and stakeholders must be brought on board with improved approaches and convinced of the criticality of complete understanding before proceeding with construction.

Keywords: Permafrost, construction methods, infrastructure, climate change

INTRODUCTION

This paper reviews the current practices for establishing infrastructure on areas of permanently frozen ground - permafrost - and examines how these will need to adapt to account for climate-change-induced instability of the permafrost ground. Permafrost is ground which remains completely frozen. Found mainly in the Arctic, Antarctic and high alpine zones, permafrost represents one of the most challenging yet critical construction environments on earth (Oswell 2011). Continuous permafrost is a sheet of frozen material which lies under the sub-surface of an area and maintains a maximum surface temperature of 0°C. It is often present in layers around 100m thick,

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Robinson, P and McIlwaine, S (2020) Losing Ground: Adapting Construction Management Approaches to Permafrost Retreat *In:* Scott, L and Neilson, C J (Eds) *Proceedings of the 36th Annual ARCOM Conference,* 7-8 September 2020, UK, Association of Researchers in Construction Management, 605-614

and may reach over 1,500 m in thickness, (Vincent *et al.,* 2017). The main zones of interest in this paper are located across Alaska, Siberia, and the Tibetan Plateau.

In the last half century, significant infrastructure has been established in permafrost regions. Major projects include the China-Russia Crude Oil Pipeline (CRCOP), the Baikal-Amal Mainline (BAM) in northern Siberia, and the Trans-Alaska Pipeline System (Hjort *et al.,* 2018). The Chinese Qinghai-Tibet Corridor (QTC) contains several projects under construction or repair including 470 km of railway and the Qinghai-Tibet Highway, (Lin *et al.,* 2011; Sun *et al.,* 2018). This infrastructure represents an enormous investment with Streletskiy *et al. (*2014) estimating the potential cost of hard-standing structures in Russia alone at $80 billion.

Permafrost is sensitive to climatic changes. Projections for the next fifty years show a retreating permafrost layer as the arctic zones contract in response to global warming (IPCC 2014). In a hallmark study, Hjort *et al. (*2018) found that approximately 3.6 million people and 70% of the current infrastructure on permafrost is located in areas with a high potential for thaw by 2050.

This represents one third of all pan-Arctic construction and an estimated 45% of the hydrocarbon extraction fields in the Russian, American, Canadian and Norwegian Arctic (Yumashev *et al.,* 2019). Risks are mostly due to thaw-related ground instability, (Wu and Niu 2013), and estimates for addressing this are placed at upwards of $15 billion (USD) in direct impacts, excluding knock-on effects on transport, trade and the global energy supply.

Existing infrastructure built on permafrost must be assessed and safeguarded to prevent damage in the wake of rapid thawing of the continuous permafrost layer (Yumashev *et al.,* 2019). Many projects in permafrost areas are undergoing testing and remedial work in an attempt to future proof them. Serious changes have been found in the ground regime and bearing capacity in Central Asian and Eurasian mountainous regions, possibly from the effect of seismic activity on ground stability (Sun *et al.,* 2018; and Liu *et al.,* 2019). The cost to existing infrastructure in the coming three decades in Alaska from remedial works is estimated at $5.6 - $7.6 billion (USD), under the Regional Climate Projection, (Larsen *et al.,* 2008), and $570 million (USD) has been set aside for research and mitigation of the damage retreating permafrost will cause in Canadian permafrost regions over the next decade (Anthony 2019).

Howard (2009) notes that the Arctic and Antarctic regions house around 25% of the world's untapped energy and resource reserves. These areas will become more accessible as the ice retreats, implying that the operational tempo of construction projects will only increase (Shur and Goering 2009). As existing Arctic permafrost zones contract and new avenues open for energy and trade, demand for supporting infrastructure and utilities will increase (Sun *et al.,* 2018). This will include communication, energy conduits, supply depots and emergency provision (Farré *et al.,* 2014). The renewed interest in this 'untapped economic potential' emphasises the importance of understanding the changing conditions, (Farré *et al.,* 2014).

Aims of the study

The main concern for construction is the impact of retreating permafrost on the load-bearing capacity of the ground. Although the engineering methods for establishing projects on permafrost are extensively documented, construction management techniques have been given little direct focus in literature.

The aim of this study is to review the existing construction management practices for building on permafrost and establish a preliminary view on how these needs adapted for the projected changes in climate. The hypothesis is that while existing procedures and practices are effective, they no longer fully address the changing risks. Three questions were set for the study:

- What are the existing approaches to construction on permafrost?
- What challenges do these practices face and what shortcomings do they cause for projects?
- How can these existing approaches be adapted for the future?

METHODOLOGY

Literature on permafrost construction was reviewed, including accounts of specific projects in permafrost regions. Very little literature was found dealing specifically with construction management for projects on permafrost, suggesting that more input from experts and practitioners in the field is needed.

To supplement the literature review with up to date opinion and analysis, a mixed methods approach was adopted. Quantitative data was collected via an on-line questionnaire sent to a range of project managers, site engineers, designers and subcontractors, in order to construct a picture of how projects are presently conducted in permafrost regions. 73 responses were received mostly from practitioners working in permafrost regions. Given the limitation of this relatively niche field, 73 is considered a reasonably significant sample, and acceptable for a preliminary survey, (Sue and Ritter 2012). The survey was analysed using several statistical tools, but the detailed statistical analysis is not relevant to this paper and is not described here.

Qualitative data was collected from interviews conducted on-line with three industry experts whose primary area of work is in geo-technical research and development of structures on permafrost. One is based in Alaska, the other in St Petersburg and the third in Vancouver, and together they bring a wide geographic scope to the study.

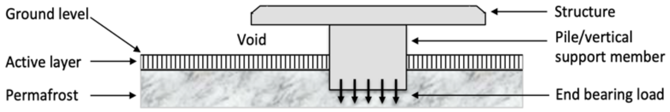
The interviews were carried out in a semi-structured format, centered around a set of key questions but allowing for follow-up to elucidate particular points. The responses were transcribed for coding and analysis using NVivo. Nodal cluster analysis was conducted (Edwards-Jones 2014). Nine nodes and eight clusters were identified. The qualitative and quantitative data were assessed separately which allowed some of the shortfalls of each data collection method to be assessed, improving its reliability.

LITERATURE REVIEW

Several techniques are used for construction on permafrost, (Li *et al.,* 2016). A general rule is that what is frozen should be kept frozen and vice versa (Charles 1959). This means avoiding deepening the active layer - the thin surface layer which thaws and re-freezes seasonally. For structures on permafrost, the goal is to prevent direct contact with this layer, both to reduce thermal transference and avoid putting direct pressure on the ground, therefore overcoming the problem of differential thaw settlement (Doré *et al.,* 2016). A common method is to use space frames to help distribute the load and leave a self-regulating airgap (Oswell and Nixon 2015), see Figure 1. Piles may be installed at unstable areas to bypass the sub-surface and anchor directly to bedrock.

Structures may be elevated above the ground to prevent degradation of the active layer by the combined effects of reduced ablation, thermal insulation and increased moisture retention (Van der Sluijs *et al.,* 2018). One example of this is seen in the Qinghai-Tibet Railway (QTR), (Wu *et al.,* 2007), which uses raised bridges over the permafrost to prevent rail operations affecting the sub-base. This method prevents damage from passive thermal transmission from the rails but does not address the impact of climate change-induced permafrost retreat, (Lv *et al.,* 2019). For metaled surfaces, a common method is to lay soil under the gravel sub-base and geotextile to allow better water drainage and reduce the load-signature (Ma *et al.,* 2016). However, Hjort *et al.* (2018) reports that this method has proven inadequate, as the active layer often continues to deepen or else the permafrost has receded outright.

Figure 1: Avoiding load on the active layer



Approaches to construction in permafrost can be categorised as active or passive. Passive measures include elevating the structures sufficiently to prevent a heat-bloom affecting the active layer. Tundra vegetation can be used as a passive biological insulator, for example on the original embankment of the QTR, where a raised embankment was used to reduce the thermal transmission from the rail-lines (Wu and Niu 2013). Passive methods were originally deemed sufficient to safeguard the infrastructure from ground instability while mitigating the risk of thaw. Hjort *et al.* (2018) conclude that these traditional methods will not be adequate to counteract the shift ground stability due to rapid permafrost retreat.

Active measures are less commonly used on permafrost projects, as it is costly and difficult to seat a structure in excess of 100 km long into bedrock (Hauck and Geistauts 1982). Active measures can include the use of thermosyphons to redirect unwanted heat from the active layer, the instalment of temporary embankments, artificial freezing of the soils via liquid nitrogen, or the construction of frozen geo-cylinders - i.e., cylinders composed of bored frozen soils - to act as an insulating layer, primarily for oil pipelines, Ma *et al.* (2016). Vermiculite powder may also be injected into the asphalt mix to increase its ablation and decrease the quantity of insolation it retains (Oswell 2011; Li *et al.,* 2016).

Piling is also common (Doré *et al.,* 2016). Some authors have begun investigating the utility of quicklime energy piles, an approach which accepts that the ground will thaw so its purpose is not to serve as structural support but to accelerate the thawing, allowing the design and construction to progress as if building on swampland. This may be more economic than boring through the ice. However, this approach is only truly effective in shallow permafrost and can create other problems in terms of increased local instability or releasing previously trapped gasses (Liu *et al.,* 2019). While it may be an option for static structures on the Tibetan Plateau, it is not a long-term solution for regions such as Siberia and Alaska and would be unlikely to pass the feasibility stage due to rapid cost escalation (Van der Sluijs *et al.,* 2018; Liu *et al.,* 2019). Active methods require intensive engineering works and tend to be used where the risk of permafrost degradation is too high for passive methods to be an acceptable form of mitigation (Hjort *et al.,* 2018).

Adapting Construction Management Practices

A wide-ranging review of the literature has revealed several critical areas which will require more intensive management in areas of potential permafrost retreat.

1. Defining the project scope and requirements with stakeholder engagement

Project feasibility must be more thoroughly assessed and will likely occur over a more protracted period (Greenslade and Nixon 2000; Oswell and Nixon 2014). This is because factors such as the total ice-content, ground and surface temperature, confining pressure and strain rate, frost-heave and slope stability must be more carefully considered before groundworks can commence (Lv *et al.,* 2019). These factors were neglected in the Norman Wells Canol Pipeline. Although constructed between 1943 and 1944 (Oswell 2011), it nevertheless serves as a useful example of where ground conditions were poorly understood, the construction methods untested and the pipeline was insufficient to meet the demand. Its throughput only ever reached 25m^3 of oil per day before the project was abandoned early (MacNaughton *et al.,* 2007).

2. Long-term project-planning

Kokelj *et al. (*2010) suggest that long-term management plans should be established for the monitoring, mitigation and reclamation of the permafrost ps. Greenslade and Nixon (2000) take this further in their evaluation of the TAPS. They consider that its success was largely due to proactive project management and high levels of innovation in the design. The TAPS cost a total of $8 billion USD in 1977, making it the most expensive privately developed construction project at that time (Van der Sluijs 2018).

3. EFMI and ECI for Operability and Buildability

The TAPS pipeline project is managed from the operations control centre in Anchorage and has three separate leakage monitoring stations to provide effective early warning of breakages (Streletskiy *et al.,* 2012). This project helps demonstrate the need for early contractor involvement (ECI) and the early facilities managers involvement (EFMI) (Oswell and Nixon 2014;). With such projects, considerable thought is required on how to adapt the system to a changing environment and increasing demand over its lifetime (Hauck and Geistauts 1982). Likewise, the project complexity and the specialised construction techniques required involving the contractor(s) early in the project design to ensure buildability.

In the long term, EFMI is critical for infrastructure on permafrost (Greenslade and Nixon 2000). Wu *et al. (*2007) and Lin *et al. (*2011) cite poor integration of facilities management in the early stages of highway and railway engineering in the Qinghai-Tibet permafrost region as causing otherwise avoidable issues down the line. For example, Lin *et al. (*2011), point out that the poor provision of monitoring stations across the Qinghai-Tibet Highway meant that lateral and transverse stress fractures caused by frost heaving near the road embankment and metaled surface were undetected until inspection units found the tears weeks after they occurred. Likewise, Kin (2015) points out how poor monitoring provision and a de-centralised maintenance network across the Soviet boundaries of the old Baikal pipeline network led to its eventual failure and breakdown. In this instance, there was no early involvement of the facilities management team.

4. Increased scientific research

Large scale infrastructure projects in permafrost regions require the extensive involvement of scientific research teams, both for determining ground suitability and monitoring of the permafrost conditions (Oswell and Nixon 2014). The initial BAM project was considered a failure, and poor survey work and a weak knowledge base was touted as a key factor (Kin 2015). Projects such as CRCOP and the TAPS demonstrate scientific involvement on a level not seen in any other construction sector (Oswell 2011 and Sun *et al.,* 2018). Conversely, where this is absent, projects have been riddled with issues correlating to poor design, poor long-term management and inadequate maintenance provision, Kin (2015). From the perspective of managing a project in permafrost conditions, the implication may be drawn that there is no 'gold-plated' design approach with each project needing its own data-driven, bespoke approach, (Dore *et al.,* 2016).

5. Recognising the Logistical Challenge

Any infrastructure project spread over hundreds of miles of varying terrain is a logistical challenge and can require establishment of temporary roads, supply depots, workforce accommodation, helicopter landing sites and temporary airstrips, (Hjort *et al.,* 2018). In permafrost, these challenges are redoubled, as construction will be seasonal depending upon the climatic conditions, with a restricted window for operations, meaning there is often a longer lead-time for the manufacturing and delivery of materials. Permafrost regions are remote, with little supporting facilities and infrastructure for the physical workforce, (Hauck and Geistauts, 1982), and for a project to be successful, extensive enabling works may be needed, often months prior to the main construction phase (Hjort *et al.,* 2018), with temporary works subject to the same design issues as the permanent facilities (Kin 2015).

RESULTS

From an analysis of the literature, surveys and interviews, several elements have emerged relating to the further efforts needed to adapt existing construction management approaches to future needs.

1. Improve the Setting of Project Milestones

The responses suggested a strong need to improve milestone planning. This is surprising, as planning is considered a well-managed facet of construction. However, older approaches have been unable to protect both the infrastructure and the permafrost, and as the end-state of projects becomes less clear, milestones have become harder to map, (Hjort *et al.,* 2018).

Assigning milestones involves looking at operational windows and against the need move materials (McFadden and Barnnett 1991). Efforts are ongoing to establish new shipping lanes and oil-extraction fields in the Arctic as the ice retreats and accessibility increases (Farre *et al.,* 2014). As the working season lengthens, increased movement should be possible via sea lanes (Ma *et al.,* 2016). This combination of factors may revive the role of logistics managers and replace the ad hoc approach often taken in such projects (Streletskiy *et al.,* 2012).

2. Design Flexibility and Improving Survey Procedures

Until the 1990s, survey data was reviewed in 1km sections to establish construction methods appropriate to the geology (Farre *et al.,* 2014). This led to the application of one or two 'catchall' designs applied to the different ground conditions (Liu *et al.,* 2011; Doré *et al.,* 2016), but this ased that ground conditions were contiguous and would respond consistently to one or two design approaches. To address this, modular designs may be used, which can be adjusted to the conditions (Van der Sluijs 2018), although non-modular designs which can be relatively easily adjusted to the conditions, may also be used. This is being tested in the QTR where two designs are employed, which both vent excess thermal energy away from the permafrost but do so in two different ways and across different ground conditions.

3. Better Communication of Uncertainty and Risk
On permafrost projects, the risk of ground thaw causing shear damage to structures is difficult to predict (Yumashev *et al.,* 2019). To better manage risk, improved communication on permafrost projects is needed, especially as new approaches and unfamiliar designs come into play (Dore *et al.,* 2016). In the interviews, 3D imaging was suggested as one means of doing this, especially for discussions with clients. 3D imaging is used in the energy industry and the evolution of 4D BIM can better help clients and contractors understand and mitigate potential hazards (Zhang *et al.,* 2013). For permafrost, using software along with land survey data could help clients and designers better manage the risks and adapt the design for the conditions.

4. Improved Logistics Management
Logistics planning will change significantly over the coming decades. McFadden and Bennett (1991) explain how during the construction of the TAPS in Alaska's oilfields, all material and personnel had to be transported via air or barge during a narrow seasonal window, with materials sitting in storage months ahead of transport. With the retreat of the underlying ice, logistical planning can be adapted. It may be possible to establish storage facilities closer to construction sites, ahead of the operations window (Oswell and Nixon 2015), as seen in the ongoing effort of the Russian Navy to establish new naval depots in the Arctic, (Staalesen 2019).

For the future of construction in inland regions, the practice of establishing temporary roads may need to continue. However, as Ma *et al. (*2016) have pointed out, the design of the roads themselves will need to adjust to cope with the relatively rapid thaw observed in Permafrost. With the scale of construction on permafrost regions set to increase, there will be more users, larger facilities and more supporting facilities.

5. A New Generation of Research, Operation and Maintenance
The approach taken for the feasibility phase for the Baffin Island Mary River Iron Mines Project demonstrates the level of research required before construction commences, especially over the complex permafrost terrain (Zhang *et al.,* 2013). A survey was conducted across nearly 108 km of track in need of re-alignment (Vladislav *et al.,* 2010), in order to identify the main permafrost-related features in the ground and, rather than find new ways to build on them, bypass them completely. Wu *et al. (*2007) suggests this is the preferred approach, although the option is often not feasible, especially where access is restricted such as on the Tibetan Plateau.

Another key aspect is the question of operation and maintenance of structures placed on permafrost. One of the key environmental lobby's concerns with the proposed Enbridge Pipeline extension was the risk of shearing in the pipeline and the subsequent environmental impact (Yumashey *et al.,* 2019). A similar concern for the new road and rail networks of the QTR, is the need to track damage to the roads due to heave-thaw-related instability (Oswell and Nixon 2015).

Several methods have been proposed for this, including the use of autonomous civil aviation units to track key sections of road, rail and pipeline networks (Mitchell 2019). Another is the establishment of sensor networks in the pipelines (Zhang *et al.,* 2013), although this relies on sensors which may become faulty or inaccurate and only inform the operators of problems after they have occurred.

CONCLUSION

The research findings suggest a strong positive sentiment towards the effectiveness of existing construction management procedures, but an equally strong sentiment supporting the need to adapt these approaches in the near future. One conclusion from the survey responses and interviews is the need for stronger emphasis on adapting construction techniques and methods, rather than adapting the infrastructure itself, implying that at present, the design and suitability of the infrastructure less a concern than the construction techniques.

The challenge of permafrost is well-defined, and the industry's understanding is improving rapidly. Efforts are being made to understand how working in this climatically sensitive environment will change and how the interplay between the air-temperature, seasonality and the frozen ground will affect the infrastructure founded on it. Ongoing ground research will expand the level of detail available to construction managers and their design teams. However, innovation and new approaches are also needed in the planning and management of the construction process. With this, significant up-front investment will be needed, and future investors will need to be well informed of the short-term costs and long-term viability and have a complete understanding of the risks and mitigating measures needed.

Wider Implications for Climate Change Mitigation and Adaptation

Although this topic was not addressed in the research, technical discussions on opening up the Arctic regions cannot be held without reference to the wider political and ethical issues raised. Political economists sometimes criticise the asption that climate-change-inducing economic development for the good of the 'global economy' inevitably requires the measures needed to address the resulting problems to be applied at a local and community level, (see Nightingale *et al.,* 2019)

In this case, the indigenous people of the Arctic region, already vulnerable to climate change effects, will be further impacted by induced effects arising from development of their own region. Behl (2016) points out the ethical dilemma of this and notes that it is 'important to gain a better understanding of the nature of climate vulnerabilities faced by Arctic people, explore options that increase resiliency and help indigenous peoples adapt to climate change'. Since no construction occurs without the acquiescence and participation of local communities, this is an issue that construction professionals will need to be increasingly aware of as these previously frozen regions open up.

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