Ambio
https://doi.org/10.1007/s13280-023-01866-9

(Un)frozen foundations: A study of permafrost construction practices in Russia, Alaska, and Canada

Katherine Landers, Dmitry Streletskiy

Received: 2 November 2022 / Revised: 17 March 2023 / Accepted: 31 March 2023

Abstract The Arctic is rapidly warming posing a significant threat to underlying permafrost. Permafrost degradation has already resulted in extensive damage to the Arctic's built infrastructure, putting communities and industries at risk. Projected climate warming will further reduce the capacity of permafrost to support infrastructure, thereby requiring a rethinking of construction and development of permafrost regions in the future. This paper focuses on three Arctic regions with a substantial presence of population and infrastructure on permafrost: USA (Alaska), Canada, and Russia. The three regions' permafrost construction practices are examined in order to identify best practices and major gaps. We identify a lack of standardized, codified construction guidelines; an absence of permafrost-geotechnical monitoring in communities; barriers to integrating climate scenarios into future planning; limited data sharing; and low numbers of permafrost professionals as major constraints limiting the region's resilience in the face of climate change. Refining building practices and standards, implementing operational permafrost monitoring systems, developing downscaled climate projections, and integrating local knowledge will minimize the impacts of permafrost degradation under rapidly warming climatic conditions.

Keywords Arctic · Climate change · Infrastructure · Permafrost

INTRODUCTION

The Arctic is experiencing rapid warming—up to nearly four times the global average since the 1980s (Rantanen et al. 2022). Arctic regions are also projected to experience the highest rates of warming in the second half of the century. One of the most prominent terrestrial impacts of this warming is associated with the wide presence of permafrost, or perennially frozen ground. More than 80% of Alaska, 50% of Canada, and 65% of Russia are underlain by permafrost, with diverse people, settlements, and industries dependent on it. Permafrost degradation has been discussed in numerous studies conducted throughout the Arctic (Biskaborn et al. 2019; Vasiliev et al. 2020; Streletskiy 2021; Smith et al. 2022), where it has been shown to manifest itself in the increasingly fragile and vulnerable infrastructures across the region. According to Hjort et al. (2018), 70% of infrastructure in the Northern Hemisphere's permafrost region is vulnerable to near-surface permafrost thaw, with a high likelihood of severe damage to the built environment projected to occur by mid-century.

Arctic communities have struggled to keep up with the rapidly changing climatic conditions that threaten infrastructure stability. A combination of climate and anthropogenic factors have already resulted in significant damage to permafrost infrastructure, including deformations of buildings and linear infrastructure, and an overall reduction in the usable lifespan of important infrastructure across the circumpolar Arctic (Hjort et al. 2022) with a substantial costs projected for Arctic nations by mid-century (Streletskiy et al. 2023; Fig. 1).

Arctic communities have developed context-specific methods of adapting to permafrost degradation through the implementation of specific construction codes and practices, geotechnical monitoring, and municipal infrastructure plans. This paper assesses the development of these

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13280-023-01866-9.

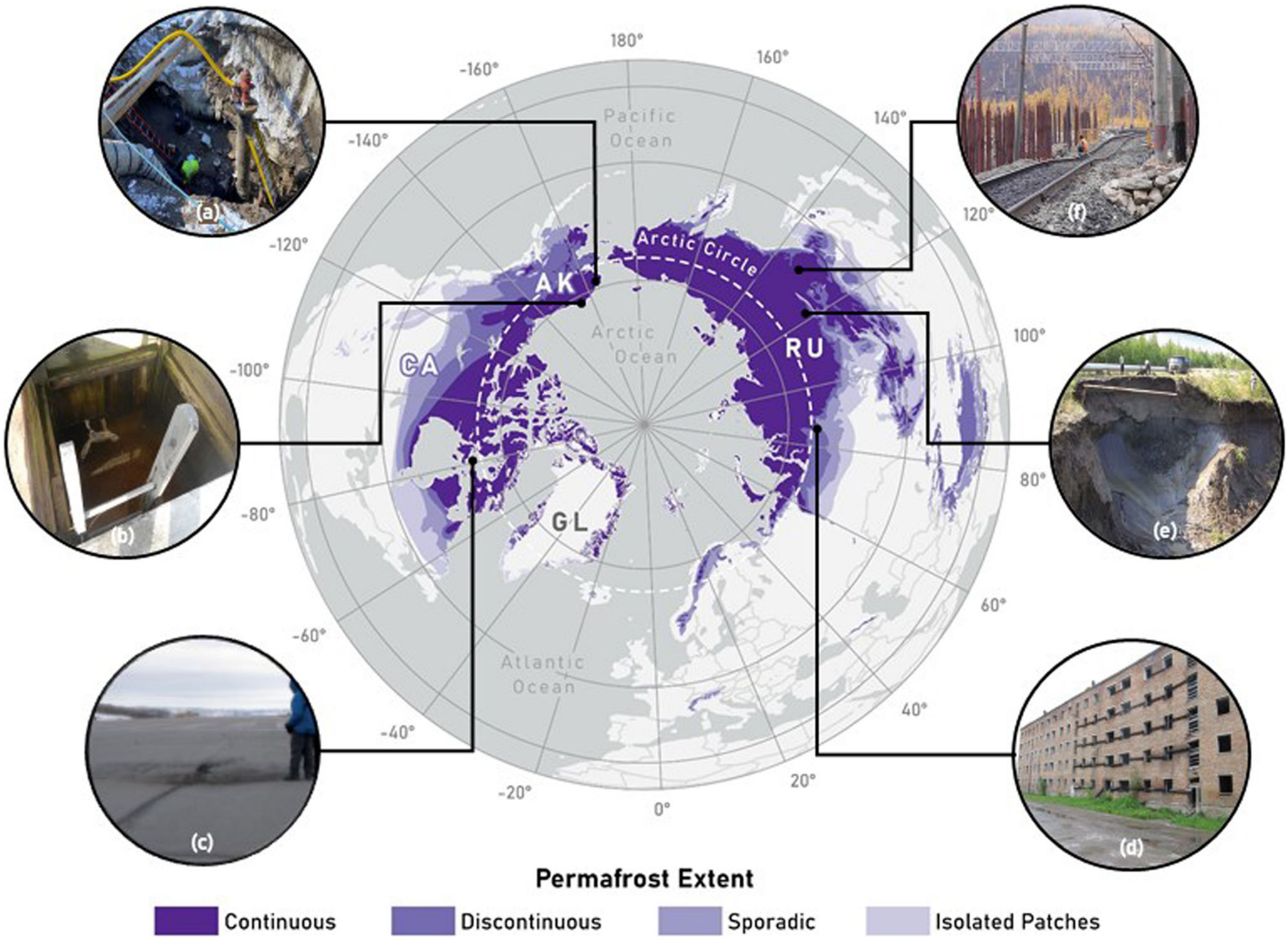


Fig. 1 Permafrost extent and observed impacts of permafrost degradation on infrastructure throughout the circumpolar Arctic: **a** water system sinking in permafrost in Point Lay, Alaska (photo by C. Russell); **b** flooded ice cellar in Utqiaġvik (Barrow), Alaska (photo by K. Nyland); **c** sinkhole in the Iqaluit runway (Nunavut, Canada); **d** deformation of a residential building constructed on permafrost in Igarka (photo by D. Streletskiy); **e** above-ground pipeline in Northern Yakutia crossing an area with ice-rich permafrost (photo by A. Fyodorov), **f** Baikal–Amur railroad deformation (photo by E. Kozyreva)

practices and subsequent steps taken to adapt to or mitigate the impacts of anthropogenic- and climate-induced permafrost degradation in countries with substantial infrastructure on permafrost: USA, Canada, and Russia. In analyzing the pan-Arctic responses to permafrost degradation, we hope to identify any gaps in current strategies and discuss those that may minimize the risks associated with permafrost degradation and improve communities' resilience in the face of rapidly changing conditions.

DATA AND METHODS

Russia, Canada, and Alaska were chosen for this study due to a combination of (1) the sheer abundance of infrastructure on permafrost; (2) the drastic climate-induced changes that are projected to occur in these regions (refer to Figs. 2b, 3b, and 4b); and (3) the extensive literature on their permafrost regimes. We conducted geographic overlay analysis using a geotechnical permafrost model developed by Streletskiy et al. (2012a, b) forced with daily means of temperature and precipitation for present (2015/24) and future (2055/64) periods under the SSP585 scenario, based on the AWI-CM-1–1-MR model. The permafrost-geotechnical model estimates permafrost temperature and active-layer thickness (ALT) to estimate bearing capacity for common types of piling foundations (Fig. 2c, 3c, 4c). Infrastructure data were sourced from Nature's Earth Products, OpenStreetMap, and the State of Alaska Open Data Geoportal.

The bulk of this paper's analysis is based largely on a review of literature regarding historic, present, and future interactions between permafrost and the infrastructure built atop it. In order to capture the trends of permafrost development throughout recent history which ostensibly still have implications for present and future conditions, the analysis covered a temporal scale of up to approximately 100 years, from the turn of the twentieth century to present day. The

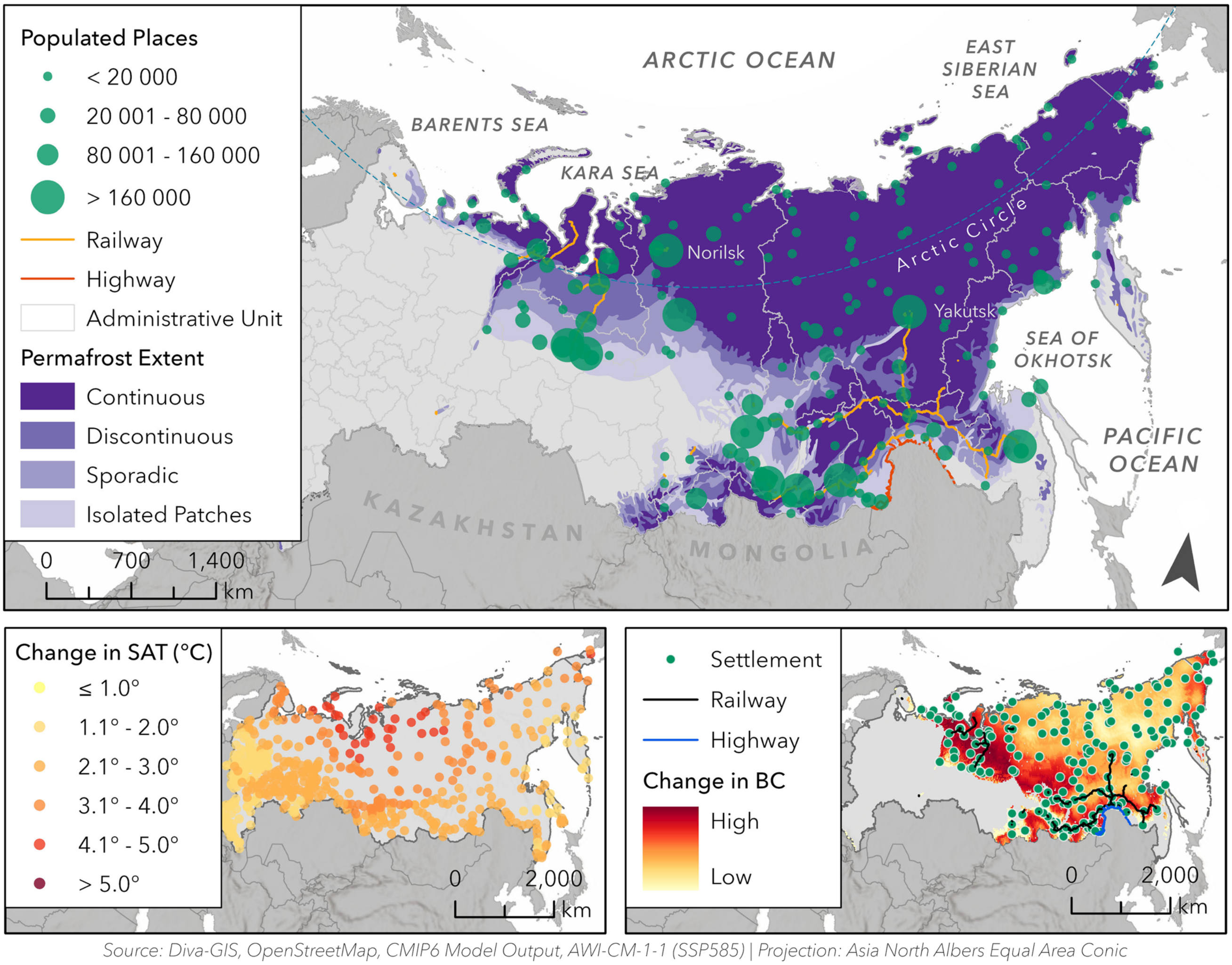


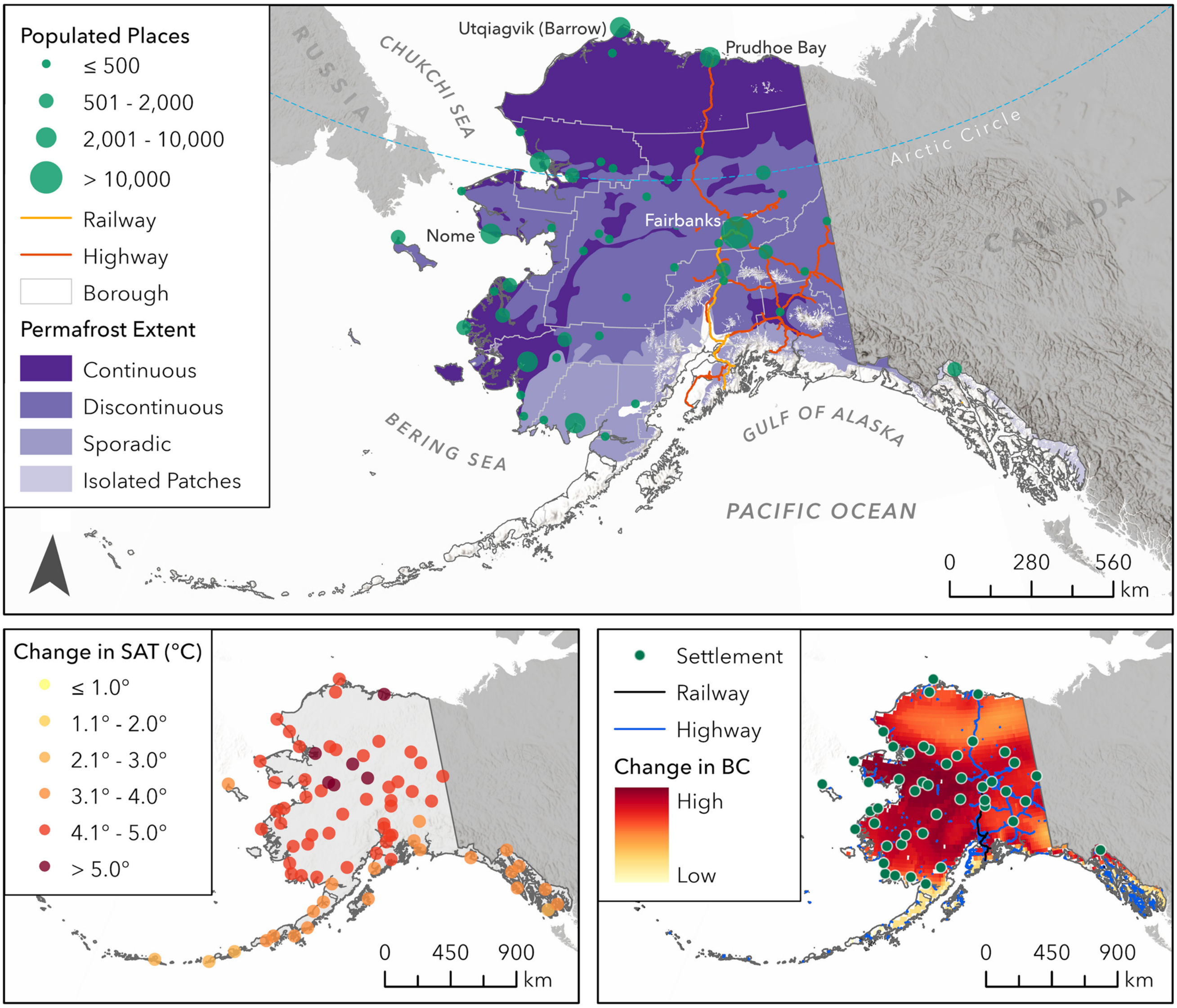
Fig. 2 **a** Permafrost extent of Russia with significant infrastructure and settlements within the permafrost zone. **b** Projected surface air temperature change by mid-century per the SSP585 climate scenario based on the AWI-CM-1–1 model. The highest projected temperature change is expected in Nenets Autonomous Okrug (NAO), Yamalo-Nenets Autonomous Okrug (YNAO), north of Krasnoyarsk Kray. **c** Projected bearing capacity losses by mid-century per the SSP585 climate scenario

primary types of data sources that were assessed in this review are academic case studies, regional engineering and construction codes and standards, local municipal plans, and governmental publications and reports. This analysis was supplemented by correspondence with various practitioners and experts in the field in Russia, USA, and Canada, primarily as a means of confirming findings and recommendations, and locating additional data sources. Table S1 provides a summary of the referenced codes and standards.

BUILDING ON PERMAFROST

Russia

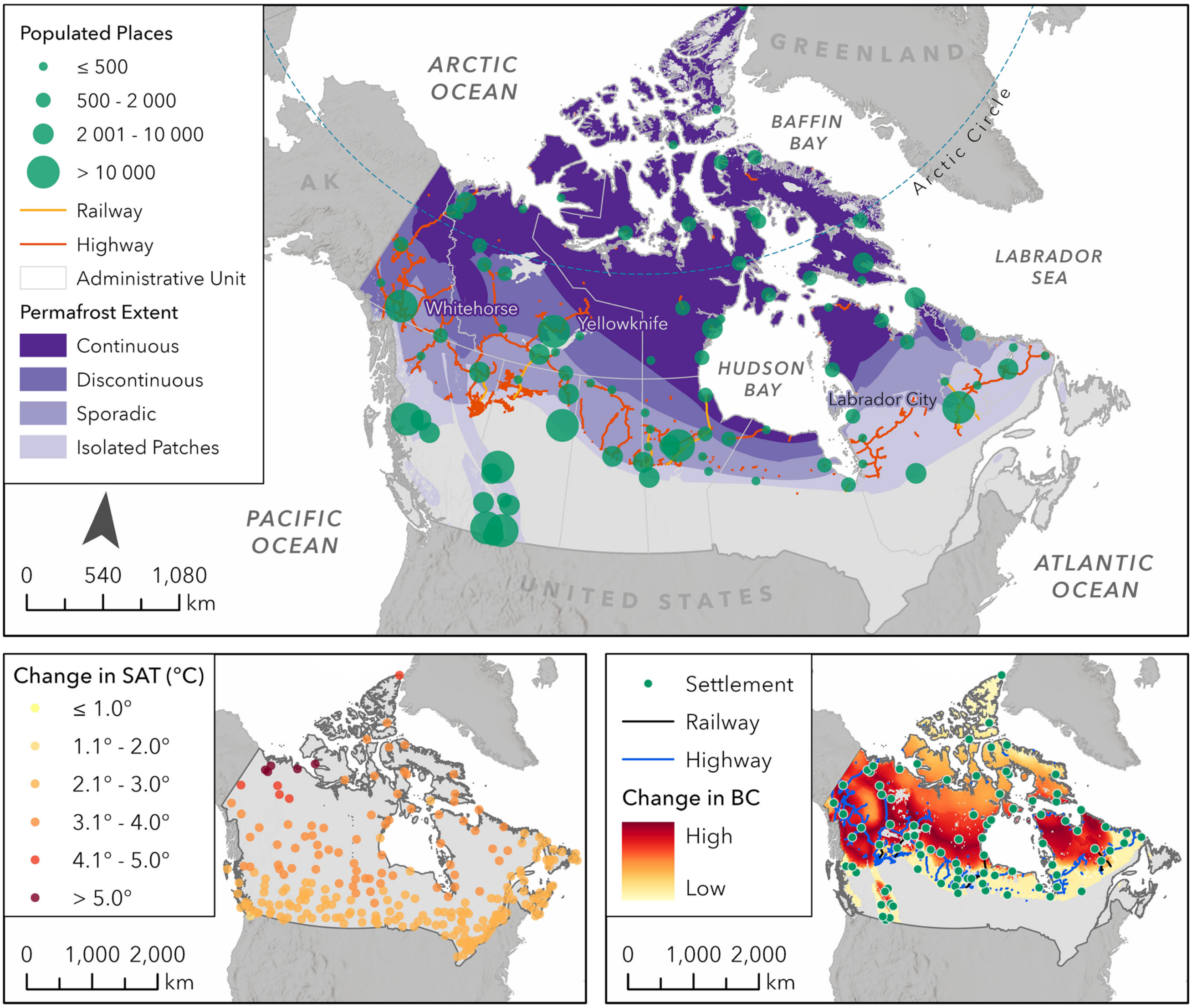
Approximately 65% of Russia's land surface is underlain by permafrost (Fig. 2) (Ershov 1998), and nearly 90% of the global population living on arctic permafrost reside in the country (Ramage et al. 2021). Russian permafrost regions have a long history of permafrost encounters that have resulted in a number of trial-and-error approaches to design and construction on permafrost (Shiklomanov 2005). Years of industrialization, collectivization, extensive resource development, and planned economies by the USSR created a disperse geographic pattern of industrial and urban centers in the Arctic. Cities located on permafrost such as Vorkuta, Norilsk, and Yakutsk experienced rapid growth, transforming from towns with low population density and low-story buildings into cities with concrete and brick multistory buildings connected by networks of paved residential streets and centralized utility networks. These rapidly growing urban and industrial clusters became the focal points of human-induced changes to the permafrost infrastructure system (Grebenets et al. 2012; Streletskiy and Shiklomanov 2016).



Source: Diva-GIS, State of Alaska Open Data Geoportal, OpenStreetMap, CMIP6 Model Output, AWI-CM-1-1 (SSP 585) | Projection: NAD 1983 (2011) Alaska Albers (Meters)

Fig. 3 **a** Permafrost extent of Alaska with significant infrastructure and settlements within the permafrost zone. **b** Projected surface air temperature change by mid-century per the SSP585 climate scenario. The highest projected temperature changes in Alaska are likely to occur in Prudhoe Bay and several settlements in interior Alaska. **c** Projected bearing capacity losses by mid-century per the SSP585 climate scenario based on the AWI-CM-1–1 model

Rapid industrialization and urbanization of the Soviet Arctic required the development of permafrost-specific methods of construction to maintain a growing population and industrial output. Two major methods, one focused on permafrost preservation (Principle I or the Passive Method) and the other based on permafrost thawing prior to building (Principle II or the Active Method), became the main construction principles that were formalized in early Russian standards (Table S1). One of the major advances in permafrost construction occurred with the development and widespread implementation of piling foundations by Mikhail Kim in Norilsk in 1957 (Kim 1959). These foundations minimized heat transfer from buildings and structures in order to preserve the permafrost underneath and were less labor intensive and relatively inexpensive. This allowed for construction in areas where bedrock material was not accessible (Khrustalev 2005; Shiklomanov et al. 2017). Combined with other types of slab foundations and ventilated basements or crawl spaces in areas with ice-rich permafrost, these design techniques supported the development and construction in areas of cold continuous permafrost. Methods of permafrost thawing were also developed for locations where permafrost was shallow (Shiklomanov et al. 2020; Kotov & Khilimonyuk 2021).



Source: Diva-GIS, OpenStreetMap, CMIP6 Model Output, AWI-CM-1-1 (SSP585) | Projection: Canada Albers Equal Area Conic

Fig. 4 **a** Permafrost extent of Canada with significant infrastructure and settlements within the permafrost zone. **b** Projected surface air temperature change by mid-century per the SSP585 scenario. Northwest Territories are expected to have the most drastic warming by mid-century. **c** Projected bearing capacity losses by mid-century per the SSP585 climate scenario based on the AWI-CM-1-1 model

The SNiPs (Stroitelnie Normi i Prvila or the Russian Construction Norms and Regulations) were significant in the anthology of permafrost construction standards, as they warranted comprehensive geotechnical investigations of soil properties and provided a set of step-by-step instructions on how to estimate the structural loads depending on permafrost characteristics. Simultaneously, the "Building Climatology" SNiPs provided various climatological data required to estimate permafrost temperature based on information gathered by an array of government-operated weather stations. However, the rate of revision—about once every ten years—meant that for the better part of each decade, engineers and contractors-based designs on outdated climatology to estimate permafrost temperature and its associated mechanical characteristics. Under a warming climate, this may have resulted in an overestimation in the ability of foundations to support structures.

The collapse of the USSR followed by years of decentralization and transformation to a market economy had a strong negative impact on the state of development and maintenance in the country's permafrost region. Numerous large institutions dealing with permafrost were privatized, and many small engineering and geotechnical companies emerged. The tender system was set for bidding, and commonly resulted in the lowest bidder having no experience with permafrost-geotechnical investigations or construction on permafrost. While large state companies and private enterprises were able to retain permafrost-geotechnical labs and continued permafrost monitoring, many smaller companies and settlements lagged behind with shrinking municipal budgets, often resulting in the outsourcing of permafrost research to small contractors or the abandonment of permafrost investigations altogether. On top of the limited resources to account for the upfront costs of construction, low factors of safety commonly used in Russian engineering and design (Shur and Goering 2009), the lack of proper maintenance and little governmental oversight, and rapidly changing climatic conditions resulted in a deteriorated state of infrastructure. A survey conducted by Kronic (2001) revealed a substantial number of buildings with deformations in the Russian cities on permafrost, and more recent studies have confirmed that permafrost degradation has continued underneath 60% of buildings and structures (Kronic 2001; Shiklomanov et al. 2017; Kotov & Khilimonyuk 2021; Grebenets et al. 2022).

Despite growing research on impacts of climate change on permafrost infrastructure (Khrustalev and Davidova 2007; Khrustalev et al. 2011; Streletskiy et al. 2012a, 2012b; Shiklomanov et al. 2017), changing climatic conditions were not taken fully into consideration. An extremely warm year in 2020 and oil spill in Norilsk (Sokratov et al. 2020; Rajendran et al. 2021; Zhang et al. 2022) exposed the deficiencies at local, state, and federal levels including a lack of (1) adequate permafrost and geotechnical monitoring; (2) reliable data records due to inadequate data exchange and storage by numerous companies who perform permafrost-geotechnical monitoring; (3) governmental oversight and regulations regarding the permafrost regions under changing climatic conditions; and (4) legislative acts regarding planning and construction on permafrost. In addition, the federal construction standards SNiPs were demoted to Construction Rules (Stroitelnie Pravila) a set of suggested "principles," thereby destroying important enforcement mechanisms associated with codification.

Overall, the impacts of permafrost degradation in Russia are unparalleled due to the vast scale of infrastructure. While official statistics likely underestimate the scale of the problem, recent assessments confirm the dismal state of permafrost infrastructure (Grebenets et al. 2022). Factors such as aging infrastructure, restricted access to financing, low enforcement of construction standards and maintenance, lack of transparency, and limited data availability all contribute to a negative outlook for this rapidly warming region. However, there is substantial variability among regions within the Russian Federation. For example, NAO, YNAO, and Sakha are likely to have a better outlook than the Komi, Magadan, and Chukotka where a high likelihood of permafrost degradation is compounded by a low capacity to address these risks (Streletskiy et al. 2019).

Despite some promising attempts to reinstate permafrost monitoring in municipalities on local and federal levels (Melnikov et al. 2022) and the growing recognition of permafrost's strategic importance, the Russian Arctic is still ill-equipped to face the challenges associated with climate warming and permafrost degradation. Almost 60% of Russia's permafrost zone is expected to experience high levels of bearing capacity loss by mid-century (Fig. 2c), which will in turn impact the ability of foundations to support buildings and structures, especially considering the low factors of safety commonly used in Russian engineering and design. While large oil, gas, metal, and mining enterprises incorporate permafrost-geotechnical monitoring into operational activities, settlements and communities on permafrost have limited municipal budgets and are likely to see an increasing number of deformations in the absence of information regarding changing permafrost conditions. Further, there is no legislation protecting those affected by permafrost degradation under rapidly changing climatic conditions. The wide use of artificial freezing systems such as thermosiphons allows the preservation of strategically important and economically viable infrastructure in the future but can come at considerable cost to already expensive operations.

Alaska

With upwards of 80% of its land mass underlain by permafrost (Fig. 3a), the impacts of climatic warming on Alaska have been increasingly apparent in recent years (Hjort et al. 2022). The state is highly dependent on its terrestrial transportation system, which includes seasonal and all-season roads like such as the Dalton and Alaska highways, railways, inter- and intra-village trails, and pipelines, for the movement and connectivity of its people and natural resources (Moffatt & Nichol 2021; Hjort et al. 2022). Its sparse and isolated settlements are connected via this expansive system of roads and railways, though notably, 82% of Alaska's communities do not have access to the contiguous road system and are accessible only by air. The state boasts the largest aviation system in North America (Alaska DOT&PF Division of Statewide Aviation 2021), with 394 rural and international airports, and an additional 362 recorded landing areas (Alaska Region FAA & ADOT&PF 2019). Though the state's permafrost settlements are relatively small compared to those in Russia, Alaska's linear transportation network spans the entire range of permafrost zones (Figs. 3a), making it susceptible to any degradation that may occur. This is especially concerning considering that under current projections, more than 90% of Alaska's permafrost zone is expected to experience high levels of bearing capacity loss by mid-century (Fig. 3c).

Alaska's infrastructure came into being through a combination of publicly and privately sponsored projects, resulting in a nonlinear, sometimes disjointed development process. The rapid and haphazard development associated with the gold rushes of the 1890s and early 1900s went largely unregulated and without government intervention. Any lessons learned from this period were not immediately implemented in the region's building practices and were largely ignored in federally sponsored projects throughout the first half of the twentieth century. After the attack on Pearl Harbor in 1941, concerns regarding Alaska's vulnerability were heightened, and construction of the AlCan (now Alaska) highway followed shortly thereafter. Intended as a pioneer road to provide a terrestrial communication and supply line between the continental U.S. and Alaska (Cysewski 2013), the 2545 km highway was completed at an unprecedented pace, taking just eight months from start to finish (Nelson 2011). Unfortunately, contrary to Russia's generally "systematic & holistic" approach to permafrost science at the time (Nelson 2011, p. 652), Alaska's vague curiosity in "perpetually frozen ground" and even the decades of experience constructing roads and trails on permafrost for mining practices (Connor et al. 2020; Cysewski 2013) had not translated into systematized engineering applications at this point. Explicit warnings of the region's permafrost vulnerability by experienced practitioners and locals were ignored. This, combined with a rushed timeline, "brute force" engineering and construction methods based in mid-latitude practices, and the abundance of ice-rich permafrost along the route resulted in a disastrous final product: just months after completion, thaw-related issues necessitated a rerouting of nearly a third of the roadway (Nelson 2011). In response to this high-stakes failure, Siberian-born geologist Dr. Siemon Muller published "Permafrost or permanently frozen ground and related engineering problems," a review of Russian-based permafrost literature available at the time. This would become the first English-language publication of its kind (Cysewski 2013) and would serve as a touchstone in permafrost construction practices throughout North America.

During the period immediately following the failed AlCan project, permafrost research in the United States expanded rapidly, producing new methods and understandings of permafrost science and engineering that are still used today. Within ten years of the AlCan highway construction, the first permafrost engineering research site in the United States was established in Fairbanks in1945, and the Alaska Road Commission published its first report on how to construct roads on permafrost in 1952. This occurred in conjunction with the strides being made by the US Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL), which included the development of the n-factor method, predictions of thermal conductivity of soils, applications of aerial photograph interpretations of permafrost environments, and systematized studies of various foundation and embankment designs (Cysewski 2013). In the 1970s, construction of the Trans-Alaska Pipeline System (TAPS)—an 800-mile (1288 km) long, 4-ft (1.22 m) diameter crude oil pipeline resulted in major advances in permafrost engineering and construction that still hold incredible value today. These include the incorporation of new cooling technologies such as air ducts, thermosyphons, and air convection embankments in roadway and foundation design, and—perhaps most notably—the inclusion of soil scientists and geologists in engineering and design stages of large infrastructure projects (Connor et al. 2020; Mathieson & Croft 2022). In 1975 the current paradigm of permafrost construction was established, stating that there are four options to choose from when building on permafrost: keep it frozen, thaw it, remove and replace it, or accept the consequences of thaw beneath the structure (Connor et al. 2020).

Even despite the increased understanding of permafrost properties and innovations in design practices that were made throughout the mid-twentieth century, a combination of rapid development, narrow construction windows, and varying public and private interests resulted in countless instances of poor practice and bad outcomes in the design and construction of permafrost infrastructure. According to Connor and Harper (2013), the most acute and costly impacts have been observed in roadways, with US$11 million spent annually on permafrost-related roadway issues (Rettig 2011). Additionally, in a survey of North Slope Borough inhabitants conducted by Liew et al. (2022), 66% of respondents reported permafrost-related damages to residential buildings, 41% of reported road damages, and 26% reported damages to buried pipelines and utilidors. On top of the residual issues associated with historic practices, the dearth of up-to-date, standardized, and codified guidelines have resulted in a tendency for over-design in some instances, and entirely inappropriate design in others. Even now, very little is officially codified in U.S. construction standards. Most codes are out of date, preventing the standardization of construction methods. The repercussions of poor design practices of the past are also holding the state in a cycle of constant maintenance—a large portion of work done by Alaska's Department of Transportation is dedicated to maintenance, siphoning budget away from much-needed development efforts. Additionally, according to Melvin et al. (2016) and Streletskiy et al. (2023), the largest permafrost-related damages are projected to occur in the interior and south-central regions of the state, which are primarily underlain by discontinuous permafrost.

Efforts are being made to enhance both the state's and country's codes and standards to more explicitly address permafrost construction and design practices, as Alaska's rural infrastructure continues to expand. For example, the North Slope Borough recently began publishing long-term comprehensive development plans for each of its eight communities. Notably, each plan cites the lack of and subsequent need for permafrost-specific engineering and construction standards to aid in a more robust and resilient approach to its development. The groundwork has been laid for significant progress, perhaps most notably the Arctic Strategic Transportation and Resources (ASTAR) project, a collaboration between the Department of Natural Resources and the North Slope Borough. Alaska's Department of Transportation is also making strides in the advancement of permafrost science and engineering practices through multiple research and development projects.

Alaska's resilience to withstand permafrost-related hazards is heavily dependent on its ability to adapt its systems to not only manage risks to existing infrastructure, but to plan for increasingly severe consequences associated with the impacts of climate change. Though high safety coefficients are likely to offset some of the negative impacts in this region, the combination of permafrost degradation with the high rates of coastal erosion, not directly considered in this study, makes many communities vulnerable. Recent years have proven promising for Alaska, as state officials, planners, and community leaders have taken tangible steps to address its weaknesses with respect to permafrost including multiple regional and statewide initiatives, which has been further bolstered by a recent influx of funding intended to specifically address arctic infrastructure (*Infrastructure Investment and Jobs Act for Alaska* n.d.). Many of the most vulnerable communities are primarily indigenous, and so it is essential that the needs and priorities of the communities continue to be prioritized and directly addressed. In all, future success for Alaska's permafrost resiliency, though promising, is not guaranteed.

Canada

Approximately 50% of Canada is underlain by permafrost, a majority of which is located within Yukon, Northwest Territories, and Nunavut (Fig. 4). Like Alaska, Canada's settlements on permafrost are relatively small and isolated, reflecting settlement patterns of First Nations people and the history of resource development by European settlers (Pressman 1986; Couture et al. 2003), connected by an array of permanent and seasonal linear infrastructure networks (Hjort et al. 2022). The primary forms of infrastructure within Canada's permafrost region fall into three general categories: municipal (buildings, utilidors, water reservoirs), transportation (roads, airfields, railways), and resources (dykes, dams, pipelines, mines) (Couture et al. 2003). The development of this infrastructure came about through a mixture of private developers building access roads, and federal projects to construct road and air access to isolated communities [Transportation Association of Canada (TAC) 2010].

Many of the remote regions throughout Canada's north hold incredible economic importance and have undergone extensive growth in the last few decades, particularly in the hydroelectric, oil and gas, mining, marine and freshwater transportation, and infrastructure sectors (Couture et al. 2003). However, warming permafrost is expected to pose significant challenges to these sectors as the region's economy and population continue to grow (Prowse et al. 2009). One major consideration will be the usability of seasonal ice roads, which play a crucial role in transporting resources to and from remote settlements in the north. The windows of usability have steadily decreased over time due to warming conditions—from 1996 to 2009, the average opening time to light traffic was delayed by about three weeks (Prowse et al. 2009). It may soon, therefore, be necessary to incorporate all-season road networks in order to maintain these services, even despite their vulnerability to and influence on permafrost degradation. Similar situations will arise as Canada's north contends with the Catch-22 of development in the face of climate change, as needs relating to mining and hydroelectric power, accessibility for northern residents to southern road networks, and national defense continue to drive the country's development (Transportation Association of Canada (TAC) 2010).

Canada's north has a fraught history with development of infrastructure on permafrost. Though records of the presence of permafrost date back to the sixteenth century, consistent interest in and references to its presence were scarce through the beginning of the twentieth century (Brown 1970). Up until the establishment of the Standards Council of Canada (SCC) in the 1970s, standardized building codes did not exist in the country, let alone those which discussed construction atop permafrost. The Klondike Gold Rush in the 1890s did see some advancements in trail design specific to permafrost regions (Cysewski 2013), but for the most part, throughout the mid-twentieth century the presence of permafrost was often not considered during the construction process (Prowse et al. 2009). For example, in the 1980s, construction in Dawson, Yukon was conducted without consideration for the subsurface conditions, resulting in an immediate loss of functionality for many of the newly constructed structures due to thawing ground ice (Prowse et al. 2009). Another example is the Norman Wells pipeline: built in 1985, it experienced upwards of 3.5 m of settlement in a span of 17 years of operation (Couture et al. 2003). Even now as the understanding of permafrost has improved, the legacy of this oversight must be contended with. Most structures built before the late 1990s are especially vulnerable to the impacts of climate change (Prowse et al. 2009), and a significant number of existing structures have shallow foundations (Couture et al. 2003), which are hyper-sensitive to the surface and subsurface variability associated with increasing active-layer thickness.

In response to the explicit impacts of climate change on Canada's northern infrastructure, the SCC established the Northern Infrastructure Standardization Initiative (NISI), intended to develop infrastructure standards specific to the needs of its northern territories and to fill in the existing gaps in permafrost construction guidelines. In conjunction with the NISI, in 2012 the SCC created the Northern Advisory Committee on Adaptation Codes and Standards (NAC), composed of representatives from the Northwest Territories, Nunavut, Yukon, and Nunavik (Moore 2012). The standards that have since been created under the NISI cover topics such as geotechnical site investigations, mitigating permafrost degradation, and extreme weather challenges—all specifically tailored to the unique conditions of Canada's north (Northern Infrastructure Standardization Initiative | Infrastructure, n.d.). Additional research has been conducted in the region to consider high-resolution climate modeling and simulations to explore the potential impacts of climate change on permafrost engineering technologies (Faki et al. 2022). Overall, Canada is facing permafrost-related challenges to infrastructure which has the potential to severely impact many communities and industrial centers located in areas with ice-rich permafrost. The development of permafrost construction standards, on-going permafrost monitoring, and relatively easy access to low-cost financing suggests a positive outlook for this region.

DISCUSSION AND MANAGEMENT OF FUTURE RISKS

The varying contexts within which these three regions have developed resulted in an assortment of strengths and weaknesses in contending with the impacts of climate change. Russia has a robust history of permafrost research and construction practices, but also much older infrastructure. Alaska and Canada, though closely linked in both history and geography and with similar characteristics in their northern developments, are at different stages in their permafrost management regimes, with Alaska far behind Canada in the relative availability of northern engineering codes and guidelines. Looking forward, all three regions must simultaneously grapple with the legacies of historical construction practices, while integrating rapidly changing conditions into development plans in order to minimize permafrost-related hazards. The following sections outline major issues related to permafrost degradation in order to minimize the risks and improve resilience of communities on permafrost.

Codification of building standards

Codification of permafrost design and construction standards could potentially play the most important role in stabilizing Arctic infrastructure. Russia has a seemingly robust system of codified recommendations and guidelines, though without the enforcement apparati necessary to make them effective. The demotion of SNiPs to guidelines as opposed to enforceable standards negates their potential efficacy altogether. In combination with a lack of municipal funding, Russia's capacity to handle climate- and anthropogenic-based permafrost degradation has severely declined in recent years. On the other hand, Alaska and the United States can have relatively robust enforcement structures, though no standards to enforce. The state still lags significantly behind as it is largely dependent on a combination of outdated Arctic construction guidelines and federal standards based primarily on mid-latitude engineering practices. Canada has made the most tangible strides in this realm, as the recent establishment of NISI is explicitly intended to standardize permafrost construction techniques with the input of the communities for whom it matters most.

Permafrost and geotechnical monitoring and early warning systems

Permafrost monitoring systems will assist in real-time assessments of permafrost conditions which can be more effectively incorporated into building practices. Currently, most of permafrost monitoring is conducted based on research projects under the umbrella of the Global Terrestrial Network for Permafrost (GTN-P) and have no dedicated long-term funding. In Alaska, monitoring efforts are led by the University of Alaska Fairbanks and the U.S. Geological Survey (USGS) (Urban and Clow 2018), while Geological Survey of Canada (GSC) collects data in Canada (Smith et al. 2005). Numerous academic institutions are involved in permafrost monitoring in Russia (Drozdov et al. 2015; Vasiliev et al. 2020), while many Russian weather stations monitor near-surface permafrost temperature (Zhang et al. 2005; Chudinova et al. 2006; Streletskiy et al 2015; Kamnev et al. 2021). A majority of private enterprises operating in permafrost regions already have relatively robust permafrost monitoring systems, however, data are commonly restricted or proprietary. Reducing barriers to access geotechnical monitoring data collected by commercial or consulting companies can be valuable to provide independent evaluations of permafrost stability and increase transparency for stakeholders and investors not familiar with permafrost.

Notably, none of the three regions have a dedicated centralized monitoring network. Government-operated permafrost monitoring networks are critical in order to establish the baseline of permafrost changes in natural conditions and to provide high-quality data products that can be readily available for land use planners and engineers operating in permafrost regions. While monitoring of permafrost in natural conditions is limited with a few exceptions, operational permafrost-geotechnical monitoring in population centers is practically absent in all three regions. The establishment of permafrost-geotechnical monitoring and incorporation of this monitoring into early warning systems will allow municipalities to track and prevent permafrost-related infrastructure failures and enable extra time to prevent costly and dangerous damage to surrounding infrastructure.

Participatory inventory and monitoring networks

Incorporating community input in monitoring efforts can make inventory datasets more robust and ensure that a community's needs are appropriately acknowledged (Liew et al. 2022). Participatory monitoring can be a powerful tool in collecting data that would otherwise be overlooked, due to scope, money, and other variables which often get in the way of obtaining such granular data. Boike et al.'s (2022) app-based permafrost thaw monitoring system could be adapted to provide residents of permafrost zones a user-friendly means of documenting the locations, severity, and frequency of permafrost-related degradation to buildings, roadways, and other infrastructure they interact with on a regular basis. This information could then be used by public facilities offices to more accurately contend with and allocate resources for maintenance needs, while also compiling valuable data that can be used to better refine building practices and standards.

Utilization and further development of climate modeling for infrastructure planning

Construction and planning in permafrost regions require good understanding of changing climatic conditions, applications of permafrost-geotechnical models, knowledge of spatial footprint of exiting or planned infrastructure, and optimal construction costs and designs. The use of climate modeling has already become a standard practice for the U.S. and Canada, whose agencies both reference IPCC RCP climate models (RCP 4.5 and 8.5) by the Standards Council of Canada (CSA Group 2019), and RCP 8.5 with a 30-year design life for the Alaska Department of Transportation (Fresco et al. 2021) for research and planning endeavors. In Russia's SP for Building and Structures on Permafrost, it is recommended to forecast the permafrost temperature for critical infrastructure buildings with lifespan of more than 20 years, but there is a general lack of recommendations of what types of climate scenarios to use. Moreover, there is a disconnect between low resolution of climate models and high-resolution requirements for geotechnical models (Schneider von Deimling et al. 2021). However, use of climate scenarios, especially as resolution and accuracy continue to improve, is important tool for planning the lifespan of newly constructed infrastructure, so agencies can avoid the tendency for needless over-engineering brought about by largely arbitrary lifespan designations.

The lack of reliable infrastructure databases and publicly available construction costs for Arctic countries are limiting the ability to estimate which types of infrastructure are affected by permafrost degradation, identify optimal planning designs, and calculate the costs to local communities and states. Panarctic studies on the impacts of climate change on permafrost infrastructure indicate that the absence of high-resolution publicly available infrastructure databases has resulted in a significant underestimation of infrastructure affected by permafrost degradation (Suter et al. 2019). Presently, there are no products available that provide consistent geospatial coverage of Arctic infrastructure that can be used for future planning and development. For example, the GHS-BUILT product (Pesaresi et al. 2019), while having reasonable spatial coverage, lacks specific attributes of infrastructure types. Bartsch et al.'s (2021) infrastructure product looks promising but only is limited to a 100 km buffer from the Arctic coast. The Federal Emergency Management Agency (FEMA) in the United States has been in the process of compiling a comprehensive national database of infrastructure, though it has yet to be made publicly available. With improved automated detection of built infrastructure (Manos et al. 2022), there is potential to develop high-quality infrastructure geospatial data to assist in construction and panning on permafrost under rapidly changing climate. Local knowledge is critical in validation of these databases.

Additional cross-regional information sharing

The development of permafrost science and engineering, as illustrated in this paper, benefits greatly from the sharing of information across the Arctic regions; however, rarely was this collaboration done on a systemic scale. Presently, permafrost data remain largely segregated, rarely crossing over political, or even institutional, boundaries. This lack of collaboration leaves everybody worse off, as "a lack of shared research—especially data—significantly reduces effectiveness of understanding permafrost overall" (Bouffard et al. 2021, p. 1). Continued international cooperation, collaboration, and data exchange in the study of permafrost is essential for Arctic countries. Establishing a robust knowledge exchange that can aid in the accuracy of permafrost models and efficacy of construction techniques, while reducing the amount of time and money inevitably spent on redundant studies and costly mistakes is needed to minimize risks of permafrost degradation in the future.

Systematization of maintenance activities

Due to the abundance of permafrost throughout these regions, often the only option for construction is to accept the future consequences that come with it; therefore, planned maintenance and mitigation is part and parcel of development activities. This approach often results in reduced levels of service and shorter lifespans of infrastructure, as well as reduced comfort and safety for users (Stephani et al. 2022). In order to adapt existing infrastructure to account for degrading permafrost, Stephani et al. recommend the following four methods: (1) limit heat intake in the summer; (2) enhance heat extraction in the winter; (3) reinforce embankments and improve ground stability; and (4) manage water via limiting advection and thermal erosion. Similarly, Grebenets (1989) and Grebenets and Tolmanov (2021) focus on maintaining a proper thermal regime, mitigating dangerous cryogenic processes, and protecting foundations located in the active layer from corrosion as effective methods in maintaining infrastructure on permafrost. They recommended using ventilation of crawl spaces, timely snow removal, and use of drainage systems as effective means of maintaining the permafrost thermal regime, and the use of thermopiles and other active cooling methods to decrease permafrost temperature and increase bearing capacity of foundations.

In addition to these technical solutions, a set of more explicit guidelines for maintenance activities can also remove the often-arbitrary methods of determining which infrastructure is in the most need of service: standardized deformation thresholds do not yet exist in most regions, which not only curtails lifespan forecasting and planning, but places the onus of assessments solely on individual judgment calls and sometimes even political mandates.

Education and professional certifications

Engineering design is highly contextual in and of itself and must be hyper-specific to the conditions of the site in question. As important as it is to have a comprehensive set of codes and guidelines, a substantial portion of the process must still be based on the discretion of the practitioner and based on the site's unique combination of characteristics. In this sense, no matter how robust the standardization system is, engineering and construction will always be based at least partially on the expertise and perspectives of the designer. While various studies and building codes have acknowledged the highly specific nature of permafrost construction activities, it is essential that engineers and contractors have a basic understanding of the potential issues; otherwise, they may not know the questions to ask or the potential problems to account for. This applies in particular to the tender-based bidding processes which allow firms with no experience in northern engineering practices to take on highly complex projects. Perhaps the most direct way to address this is to require professional certification in Arctic engineering, akin to Alaska, which requires professional engineers in the state to complete a standardized course in Arctic Engineering (State of Alaska Department of Commerce, Community, and Economic Development 2019). Certifications of the like are currently lacking in Canada and Russia.

CONCLUSIONS AND PERSPECTIVES

The impacts of climate change are especially pronounced in the Arctic and have already resulted in infrastructure deformations across Russia, Alaska, and Canada permafrost regions. Projected changes are likely to further exacerbate permafrost degradation, limiting the ability of permafrost to support infrastructure due to a loss of bearing capacity and thaw subsidence in regions with ice-rich permafrost. The capacity to address the challenges associated with permafrost degradation varies among the three countries due to their history of development, population size, and settlement patterns. Russia is characterized by much larger, older, and permanent infrastructure, while Alaskan and Canadian Arctic has lighter and smaller infrastructure in indigenous communities and industrial shift-worker camps.

More professionally trained and certified engineers are needed to address the future challenges with infrastructure on permafrost. Improved codification of building standards on permafrost can ensure proper design, improve transparency, and ensure liability in case of inadequate engineering. However, this cannot guarantee that rapidly changing climatic conditions and/or improper maintenance will not result in infrastructure failure. Only proper permafrost monitoring in undisturbed environments as well as in populated and industrial centers can allow for the detection and prevention of infrastructure failure. In urban and industrial areas, this geotechnical monitoring can be supplemented by early warning systems, while in smaller communities, community monitoring may be the best solution. More attention should be given to everyday activities that help to protect permafrost such as snow removal in winter, avoiding water ponding along roads and under houses, and limiting vegetation disturbance before implementing expensive engineering solutions such as thermosyphons. Reducing barriers in data collection and knowledge exchange among all stakeholders, including indigenous groups, industries, municipalities, and government and research organizations operating in permafrost regions will help to ensure adequate planning, construction, and proper maintenance of built infrastructure on permafrost.

Acknowledgements This research was supported by U.S. National Science Foundation (NSF) grants RISE-2019691, 2020404, 2022504, and 2127364 to the George Washington University. Opinions, findings, conclusions, and recommendations expressed in this paper are those of the authors, and do not necessarily reflect the views of NSF. We thank two anonymous reviewers for constructive and insightful comments on the manuscript.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest in relation to this article.

REFERENCES

Alaska DOT&PF Division of Statewide Aviation. 2021. *Airports and Aviation Annual Report*. Alaska Department of Transportation and Public Facilities. https://dot.alaska.gov/documents/aviation/2021-Annual-Report.pdf

Alaska Region FAA & ADOT&PF. 2019. *Alaska Aviation System Plan: The Economic Contribution of the Aviation Industry to Alaska's Economy*. Alaska Department of Transportation and Public Facilities.

Bartsch, A., G. Pointner, I. Nitze, A. Efimova, D. Jakober, S. Ley, E. Högström, G. Grosse, et al. 2021. Expanding infrastructure and growing anthropogenic impacts along Arctic coasts. *Environmental Research Letters* 16: 115013. doi:https://doi.org/10.1088/1748-9326/ac3176

Biskaborn, B.K., S.L. Smith, J. Noetzli, H. Matthes, G. Vieira, D.A. Streletskiy, P. Schoeneich, V.E. Romanovsky, et al. 2019. Permafrost is warming at a global scale. *Nature Communications* 10: 1–11.

Boike, J., S. Chadburn, J. Martin, S. Zwieback, I.H.J. Althuizen, N. Anselm, L. Cai, S. Coulombe, et al. 2022. Standardized monitoring of permafrost thaw: A user-friendly, multiparameter protocol. *Arctic Science* 8: 153–182. https://doi.org/10.1139/as-2021-0007.

Bouffard, T.J., E. Uryupova, K. Dodds, V.E. Romanovsky, A.P. Bennett, and D. Streletskiy. 2021. Scientific cooperation: Supporting circumpolar permafrost monitoring and data sharing. *Land* 10: 590. https://doi.org/10.3390/land10060590.

Brown, R. 1970.*Permafrost in Canada: Its influence on Northern development*. https://doi.org/10.3138/9781442632615

Chudinova, S. M., O. W. Frauenfeld, R. G. Barry, T. Zhang, and V. A. Sorokovikov. 2006. Relationship between air and soil temperature trends and periodicities in the permafrost regions of Russia. Journal of Geophysical Research: Earth Surface. Doi: https://doi.org/10.1029/2005JF000342

Connor, B., and J. Harper. 2013. How vulnerable is Alaska's transportation to climate change?: Managing an infrastructure built on permafrost. *TR News* 284: 23–29.

Connor, B., D.J. Goering, M. Kanevskiy, E. Trochim, K.L. Bjella, and R.L. McHattie. 2020. Roads and Airfields Constructed on Permafrost: A Synthesis of Practice. Edited by University of Alaska Fairbanks. Institute of Northern Engineering, Alaska University Transportation Center, and Alaska. Department of Transportation and Public Facilities. Dot:59181

Couture, R., S. Smith, S.D. Robinson, M.M. Burgess, and S. Solomon. 2003. On the hazards to infrastructure in the Canadian North associated with thawing of permafrost. In *Proceedings of Geohazards 2003, 3rd CanadianConference on Geotechnique and Natural Hazards*, 97–104. Richmond, British Columbia: Canadian Geotechnical Society, Bitech Publishers Ltd.

CSA Group. 2019. *Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation* (CSA Plus 4011:19). Canadian Standards Association (CSA Group). https://climatechange.toolkitnwtac.com/wp-content/uploads/sites/21/2019/08/Technical-Guide-Infrastructure-CSA.pdf (Standard)

Cysewski, M.H. 2013. Initial permafrost engineering research in Alaska. ProQuest Dissertations Publishing.

Drozdov D., Y. Rumyantseva, G. Malkova, V. Romanovsky, A. Abramov, P. Konstantinov, D. Sergeev, N. Shiklomanov, and A. Kholodov, et al. 2015. Monitoring of permafrost in Russia and the international GTN-P project. 68th Canadian Geotechnical Conference - GEOQuébec 2015, Québec, Canada, September 20–23, 2015. Paper 617, 7 p.

Ershov, E. 1998. *Foundations of geocryology*, 1–575. Moscow: Moscow State University.

Faki, A., L. Sushama, and G. Doré. 2022. Regional-scale investigation of pile bearing capacity for Canadian permafrost regions in a warmer climate. *Cold Regions Science and Technology* 201: 103624.

Fresco, Nancy, Cameron Tauxe, Michael Lindgren, Peter Bieniek, John Walsh, Kyle Redilla, Bob Togerson, et al. 2021. Future Projections of Precipitation for Alaska Infrastructure. HFHWY00132 / FWHA 4000(188). Research and Technology Transfer. Alaska Department of Transportation & Public Facilities.

Grebenets, V.I. 1989. Management of the thermal regime of permafrost in the built-up area. PhD Dissertation, Moscow State University.

Grebenets, V.I., and V.A. Tolmanov. 2021. The influence of the specific regime of snow deposits on permafrost in the cities of the permafrost zone (on the example of the Norilsk region). *Ice and Snow* 61: 457–470. https://doi.org/10.31857/S2076673421030101.

Grebenets, V.I., D. Streletskiy, and N. Shiklomanov. 2012. Geotechnical safety issues in the cities of Polar Regions. *Geography, Environment, Sustainability* 5: 104–119.

Grebenets, V.I., A. Kizyakov, A. Maslakov, S. Sokratov, I. Streletskaya, V. Tolmanov, and F. Yurov. 2022. Impact of hazardous cryogenic processes on urban infrastructure in the Arctic. *Vestnik Moskovskogo Universiteta. Seriya* 5: 25–36.

Hjort, J., O. Karjalainen, J. Aalto, S. Westermann, V.E. Romanovsky, F.E. Nelson, B. Etzelmüller, and M. Luoto. 2018. Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications* 9: 5147. https://doi.org/10.1038/s41467-018-07557-4.

Hjort, J., D. Streletskiy, G. Doré, Q. Wu, K. Bjella, and M. Luoto. 2022. Impacts of permafrost degradation on infrastructure. *Nature Reviews Earth & Environment* 3: 24–38.

Infrastructure Investment and Jobs Act for Alaska. (n.d.). Alaska Department of Transportation and Public Facilities. https://dot.alaska.gov/infrastructureact/. Accessed 3 October 2022

Kamnev, Y.K., M.Y. Filimonov, A.N. Shein, and N.A. Vaganova. 2021. Automated monitoring the temperature under buildings with pile foundations in Salekhard (preliminary results). *Geography, Environment, Sustainability* 14: 75–82.

Khrustalev, L. 2005. *Geotechnical fundamentals for permafrost regions*. Moscow: Moscow State University Press.

Khrustalev, L.N., and I.V. Davidova. 2007. Forecast of climate warming and account of it at estimation of foundation reliability for buildings in permafrost zone. *Earth Cryosphere* 11: 68–75.

Khrustalev, L., S. Parmuzin, and L. Emelyanova. 2011. *Reliability of northern infrastructure in conditions of changing climate*. Moscow: University Book Press.

Kim, M. 1959. Experience with construction and operation of buildings in Norilsk. *Osnovanija, Fundamentu i Mehanika Gruntov* 3: 14–16 (in Russian).
Kotov, P.I., and V.Z. Khilimonyuk. 2021. Building stability on permafrost in Vorkuta, Russia. *Geography, Environment, Sustainability* 14: 67–74.
Kronic, Y. 2001. *Accident rate and safety of natural-technogenic systems in cryolithozone*.(In Russian)
Liew, M., M. Xiao, L. Farquharson, D. Nicolsky, A. Jensen, V. Romanovsky, J. Peirce, L. Alessa, et al. 2022. Understanding effects of permafrost degradation and coastal erosion on civil infrastructure in Arctic Coastal Villages: A community survey and knowledge co-production. *Journal of Marine Science and Engineering* 10: 422. https://doi.org/10.3390/jmse10030422.
Manos, E., C. Witharana, M.R. Udawalpola, A. Hasan, and A.K. Liljedahl. 2022. Convolutional neural networks for automated built infrastructure detection in the arctic using sub-meter spatial resolution satellite imagery. *Remote Sensing* 14: 2719. https://doi.org/10.3390/rs14112719.
Mathieson, W., and P. Croft. 2022. Permafrost degradation impacts on the Trans-Alaska pipeline. *GEOSTRATA Magazine* 26: 34–41. https://doi.org/10.1061/geosek.0000420.
Melnikov, V. P., V. I. Osipov, A. V. Brouchkov, S. V. Badina, M. R. Sadurtdinov, D. S. Drozdov, G. V. Malkova, M. N. Zheleznyak, et al. 2022. Past and Future of Permafrost Monitoring: Stability of Russian Energetic Infrastructure. Energies 15. Multidisciplinary Digital Publishing Institute: 3190. (Journal article)
Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, et al. 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1611056113.
Moffatt and Nichol. 2021. *Long Range Development Plan*. North Slope Borough Port Authority Department.
Moore, C. 2012. SCC forms Northern Advisory Committee on Adaptation Codes and Standards. *Standards Council of Canada*. (Blog post)
Nelson, F. E. 2011. "America's Glory Road" … On Ice: Permafrost and the Development of the Alcan Highway, 1942–1943. In *Engineering Earth: The Impacts of Megaengineering Projects*, ed. S. D. Brunn, 643–661. Dordrecht: Springer Netherlands. doi:https://doi.org/10.1007/978-90-481-9920-4_37.
Northern Infrastructure Standardization Initiative | Infrastructure. (n.d.). Retrieved 4 October 2022, from https://www.inf.gov.nt.ca/en/services/facilities-and-properties/northern-infrastructure-standardization-initiative
Pesaresi, M., and S. Freire. 2019. GHS settlement grid, updated and refined region model 2014 in application to ghs-built r2018a and ghs-pop r2019a, multitemporal (1975-1990-2000-2015) r2019a. European Commission, Joint Research Centre (JRC), 2019. 10
Pressman, N., and X. Zepic. 1986. Planning in cold climates: a critical overview of Canadian settlement patterns and policies. Institute of Urban Studies.
Prowse, T.D., C. Furgal, H. Melling, and S.L. Smith. 2009. Implications of climate change for Northern Canada: The physical environment. *Ambio* 38: 266–271. https://doi.org/10.1579/0044-7447-38.5.266.
Rajendran, S., F.N. Sadooni, H.A.-S. Al-Kuwari, A. Oleg, H. Govil, S. Nasir, and P. Vethamony. 2021. Monitoring oil spill in Norilsk, Russia using satellite data. *Scientific Reports* 11: 3817–3817. https://doi.org/10.1038/s41598-021-83260-7.
Ramage, J., L. Jungsberg, S. Wang, S. Westermann, H. Lantuit, and T. Heleniak. 2021. Population living on permafrost in the Arctic. *Population and Environment* 43: 22–38.
Rantanen, M., A.Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment* 3: 1–10.
Rettig, M. 2011. Alaska seeing impact of climate change in its infrastructure, villages. *Daily News-Miner*, January 30.
Shiklomanov, N.I. 2005. From exploration to systematic investigation: Development of geocryology in 19th-and Early—20th-Century Russia. *Physical Geography* 26: 249–263.
Shiklomanov, N.I., D.A. Streletskiy, V.I. Grebenets, and L. Suter. 2017. Conquering the permafrost: Urban infrastructure development in Norilsk, Russia. *Polar Geography* 40: 273–290.
Shiklomanov, N., D. Streletskiy, L. Suter, R. Orttung, and N. Zamyatina. 2020. Dealing with the bust in Vorkuta, Russia. *Land Use Policy* 93: 103908.
Schneider von Deimling, T., H. Lee, T. Ingeman-Nielsen, S. Westermann, V. Romanovsky, and S. Lamoureux. 2021. Consequences of permafrost degradation for Arctic infrastructure–bridging the model gap between regional and engineering scales. *The Cryosphere* 15: 2451–2471.
Shur, Y., and D.J. Goering. 2009. Climate change and foundations of buildings in Permafrost Regions. In *Permafrost Soils*, ed. R. Margesin, 16:251–260. Soil Biology. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-69371-0_17
Smith, Sharon L., M.M. Burgess, D. Riseborough, and F. Mark Nixon. 2005. Recent trends from Canadian permafrost thermal monitoring network sites. *Permafrost and Periglacial Processes* 16: 19–30. https://doi.org/10.1002/ppp.511.
Smith, S.L., H.B. O'Neill, K. Isaksen, J. Noetzli, and V.E. Romanovsky. 2022. The changing thermal state of permafrost. *Nature Reviews Earth & Environment* 3: 10–23.
Sokratov, S. A., V. I. Grebenets, and D. A. Streletskiy. 2020. Impact of permafrost factor in ecological disasters due to spills of fuel and lubricants in the cryolithozone (with Norilsk region as an example). In, 2020:GC070–0012
State of Alaska Department of Commerce, Community, and Economic Development. 2019. *Statues and regulations: Architects, engineers, land surveyors, and landscape architects*.
Stephani, E., G. Doré, and Julie Malenfant Lepage. 2022. An overview of major engineering challenges for developing transportation infrastructure in Northern Canada. *The School of Public Policy Publications (SPPP)* 15. Calgary: University of Calgary, The School of Public Policy. 2667318736. Coronavirus Research Database; ProQuest Central; Social Science Premium Collection. https://doi.org/10.11575/sppp.v15i1.73187
Streletskiy, D. 2021. Permafrost degradation. In *Snow and ice-related hazards, risks, and disasters*, ed. W. Haeberli and C. Whiteman. Oxford: Elsevier.
Streletskiy, D., and N. Shiklomanov. 2016. *Russian arctic cities through the prism of permafrost*, vol. 201. New York: Berghahn Press.
Streletskiy, D., N. Shiklomanov, and E. Hatleberg. 2012a. Infrastructure and a changing climate in the Russian Arctic: a geographic impact assessment. In In *Proceedings of the 10th International Conference on Permafrost*, vol. 1, pp. 407–412. The Northern Publisher, Salekhard, Russia
Streletskiy, D.A., N. Shiklomanov, and F.E. Nelson. 2012b. Permafrost, infrastructure, and climate change: A GIS-based landscape approach to geotechnical modeling. *Arctic, Antarctic, and Alpine Research* 44: 368–380. https://doi.org/10.1657/1938-4246-44.3.368.
Streletskiy, D.A., A.B. Sherstukov, F.E. Nelson, and O.W. Frauenfeld. 2015. Changes in the 1963–2013 shallow ground thermal regime in Russian permafrost regions. *Environmental Research Letters* 10: 125005. https://doi.org/10.1088/1748-9326/10/12/125005.

Streletskiy, D.A., L.J. Suter, N.I. Shiklomanov, B.N. Porfiriev, and D.O. Eliseev. 2019. Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environmental Research Letters* 14: 025003. https://doi.org/10.1088/1748-9326/aaf5e6.

Streletskiy, D.A., S. Clemens, J.P. Lanckman, and N.I. Shiklomanov. 2023. The costs of Arctic infrastructure damages due to permafrost degradation. *Environmental Research Letters* 18: 015006. https://doi.org/10.1088/1748-9326/acab18.

Suter, L., D. Streletskiy, and N. Shiklomanov. 2019. Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. *Polar Geography* 42: 267–286. https://doi.org/10.1080/1088937X.2019.1686082.(Journalarticle).

Transportation Association of Canada (TAC). 2010. *Primer on Developing and Managing Transportation Infrastructure in Permafrost Regions*. https://tac-atc.ca/sites/tac-atc.ca/files/site/doc/resources/primer-permafrost2010.pdf

Urban, F.E., and G.D. Clow. 2018. *DOI/GTN-P climate and active-layer data acquired in the National Petroleum Reserve-Alaska and the Arctic National Wildlife Refuge, 1998–2019*. Report 1092. Version 1.2: June 2021: Version 1.1: June 2020; Version 1.0: August 2018. Data Series. Reston, VA. USGS Publications Warehouse. doi:https://doi.org/10.3133/ds1092. (Report)

Vasiliev, A.A., D.S. Drozdov, A.G. Gravis, G.V. Malkova, K.E. Nyland, and D.A. Streletskiy. 2020. Permafrost degradation in the western Russian arctic. *Environmental Research Letters* 15: 045001.

Zhang, P., Yan Chen, Y. Ran, and Yunping Chen. 2022. Permafrost early deformation signals before the Norilsk oil tank collapse in Russia. *Remote Sensing* 14: 5036. https://doi.org/10.3390/rs14195036.

Zhang, T., O.W. Frauenfeld, M.C. Serreze, A. Etringer, C. Oelke, J. McCreight, R.G. Barry, D. Gilichinsky, et al. 2005. Spatial and temporal variability in active layer thickness over the Russian Arctic drainage basin. *Journal of Geophysical Research: Atmospheres* 110.

AUTHOR BIOGRAPHIES

Katherine Landers is a MS Candidate in Geography and GIS at the George Washington University. Her research interests include sustainable development and resilience building, contextual engineering, and the impacts of climate change on human and natural environments.
Address: Department of Geography, The George Washington University, 2036 H St., NW, Washington, DC 20052, USA.
e-mail: klanders@gwu.edu

Dmitry Streletskiy (✉) is an Associate Professor of Geography and International Affairs at the George Washington University. His research is focused on understanding diverse impacts of climate change on ecosystems, population, and overall sustainability of the Arctic regions.
Address: Department of Geography, The George Washington University, 2036 H St., NW, Washington, DC 20052, USA.
e-mail: strelets@gwu.edu