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ANALYSIS

All Fall Down? Urban Infrastructure and Permafrost in the Russian Arctic

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Abstract
Soviet policy for settling the Russian North led to extensive in-migration in the 1960s–1980s, resulting in massive population growth and a staggering pace of urbanization in the Soviet Arctic. Multistory houses, road networks, and other infrastructure were built, transforming pristine tundra into anthropogenic and urban landscapes. The Soviet emphasis on developing Russia's Arctic regions, despite the cost and difficulty of doing so, has left a problematic legacy for modern Russia. One of the common problems shared by many Soviet-era urban communities is the debilitated state of infrastructure built on permafrost. This article provides a brief overview of the challenges associated with urban development in permafrost regions in an attempt to identify major causes of present-day infrastructure problems in the communities of the Russian North.

Introduction
Planned socio-economic development during the Soviet period promoted migration into the Arctic and workforce consolidation in urbanized settlements to support the mineral extraction and transportation industries. These policies resulted in a high rate of urbanization in the Soviet Arctic. The harsh environmental conditions presented significant and rather unique challenges to urban development. Specifically, the presence of permafrost, which underlies approximately 66% of Russian territory, limited the applicability of standard construction practices and demanded innovative engineering solutions. Despite significant advances in permafrost engineering, pronounced permafrost degradation was evident in many northern communities by the 1980s and accelerated rapidly starting in the 1990s, resulting in the widespread deformation of buildings. As such, the Soviet emphasis on developing Russia's Arctic regions, despite the cost and difficulty of doing so, has left a problematic legacy for modern Russia. This paper provides a brief overview of the challenges associated with urban development in permafrost regions in an attempt to explain the debilitated state of infrastructure in many Russian Arctic cities.

Permafrost
Permafrost is defined as ground that remains at a temperature below 0° C for at least two consecutive years. The term permafrost is applied without regard to material composition and is based exclusively on the thermal regime of the ground. Despite this simple definition, the processes involved in the formation, maintenance, and degradation of permafrost are rather complex. Although ground temperature is ultimately determined by climatic conditions, the presence or absence of permafrost is strongly influenced by many local factors that influence the heat exchange between the atmosphere and the ground. For example, natural covers such as snow and vegetation tend to serve as insulators, preventing the ground from warming during the summer and/or from cooling during the winter. The ability of the ground to retain moisture and to conduct heat influences the thickness and temperature of permafrost. Depending on climatic, surface, and subsurface conditions, the permafrost layer can be as thin as a few centimeters and as thick as 1.5 kilometers and persist for anywhere from a few years to millennia.

Although the presence of ice is not a criterion in the definition of permafrost, ground ice is responsible for many of the distinctive features and problems in permafrost regions. If their thermal stability is preserved, frozen ice-bonded sediments have the capacity to carry a substantial load imposed by human structures. However, the melting of ground ice due to an increase in heat propagation into subsurface ice-reach permafrost layers results in soil consolidations and significant surface deformations. This can happen in response to climatic warming and/or any surface disturbance associated with human activity. The stability of all types of human infrastructure built on permafrost relies on maintaining the thermal regime of the ice-rich frozen sediments. All in all, permafrost presents a distinctive, highly challenging suite of engineering problems even under stable climatic conditions.

Development in Russian Permafrost Regions
The first written accounts of perennially frozen ground appeared in the seventeenth century, when Russian traders began exploring remote areas of Siberia and

established several outposts in regions underlain by permafrost. However, significant economic development in Russian permafrost regions began at the turn of the twentieth century, with the construction of the Trans-Siberian Railroad. During the construction of the "Great Siberia Railroad," which was completed in 1916, Russian engineers were faced with significant permafrost-related problems. For example, almost immediately after construction, structures and railroad beds were subjected to significant deformations due to changes in the thermal regime of the underlying ice-rich permafrost. Over the subsequent century, several sections of the Trans-Siberian Railroad would require continuous rebuilding and stabilization to ensure normal operation.

As the twentieth century went on, Russians gained valuable experience that resulted in the gradual evolution of permafrost construction methods. A major breakthrough came in the 1950s and is associated with the implementation of another colossal infrastructure project in permafrost regions, namely the development of the Mining and Metallurgy Complex and the city of Norilsk on the Tymur Peninsula in the far north of Central Siberia. There, civil engineer Mikhail Kim perfected a design that required "pile foundations" for permafrost construction. The pile foundation consists of several rows of 8 m–16 m reinforced concrete piles frozen into the permafrost and a set of concrete beams laid on top of the foundation piles at 1.2–1.8 m above the ground. Such a foundation puts a layer of air between the ground and the building, effectively decoupling the heat generated by the structure from the frozen ground and thus preventing the warming of ice-rich permafrost. The ability of pile foundations to support the structural load of the building (bearing capacity) is contingent on the temperature-dependent freezing bond between the piles and the permafrost: the lower the temperature of the permafrost, the higher the bearing capacity of the pile foundation. However, this was believed not to be a problem, since pile foundations can cause a reduction in permafrost temperatures underneath buildings due to the ventilation of the space between the structure and the ground, the absence of snow cover, and the shading of the ground beneath the structure. As a result, this method was considered to be effective even in areas characterized by ice-rich permafrost that was approaching the melting point. But most importantly, Kim's foundation could be built relatively cheaply and very quickly compared to other alternatives. Moreover, Kim's innovation coincided with the development of the manufacture of prefabricated concrete building elements, which could be quickly assembled on a pile foundation to construct large multistory housing, social, cultural, or industrial facilities. As a result, the rate of construction of new residential buildings in Norilsk increased from 5 per year in the 1950s to approximately 18–20 per year from the 1960s to the late 1980s. Construction on piles was considered to be a major engineering achievement, prompting the Soviet media to proclaim that the "Permafrost is Conquered."

Following the Norilsk experiment, pile foundations quickly proliferated throughout the vast Eurasian permafrost regions, contributing greatly to the acceleration of urban and industrial development in the Soviet Arctic. More than 75% of structures in Russian permafrost regions are constructed on pile foundations.

It should be noted that pile foundations are also prevalent in permafrost construction in North America. However, the developments there are dwarfed by those in the Russian Arctic. Northern communities in Alaska and Canada consist predominantly of small wooden or composite structures, whereas in Russia large 5- to 12-story concrete or masonry buildings are the norm even for small, isolated Arctic towns.

Warming and Degradation of Urban Permafrost

Despite the proclaimed victory over permafrost, reports of structural deformations of buildings caused by permafrost warming started to appear within 10–15 years of initial construction—and these have only multiplied with time. As early as 1969 and 1971, collapses of concrete buildings in the large East Siberian city of Yakutsk were attributed to the reduced bearing capacity of pile foundations due to permafrost warming. A detailed analysis of city infrastructure following these accidents revealed that approximately 100 masonry structures erected on pile foundations in Yakutsk had deformations.

In Norilsk, a two-story restaurant collapsed in 1976, killing 12 people and injuring 30. This disaster was attributed to the poor quality of the specific structure. However, in the 1980s more than 30 large residential buildings in different parts of the city developed significant deformations and had to be demolished. According to temperature monitoring under the residential buildings in Norilsk, permafrost degradation affected 39 buildings in 1989, 145 in 1995, and 393 in 2000.

By the mid-1990s it had become apparent that there were widespread problems with the stability of infrastructure built on permafrost. Infrastructure surveys conducted in the late 1990s in several Russian cities built on permafrost found that between 10% and 80% of urban infrastructure was in a potentially dangerous state. The rate of permafrost-related damage to infrastructure has only accelerated over the past two decades: in the 2000s just 10% of Norilsk infrastructure was in a critical state due to permafrost-related deformations, but this figure had increased to more than 30% by the mid-2010s, not counting the large number of structures that were demolished due to their potentially dangerous condition. The problem of infrastructure stability on permafrost received global attention in the summer of 2020 when an oil storage tank in Norilsk collapsed due to its pile foundation's loss of bearing capacity, spilling 21,000 tons of diesel fuel into nearby streams and lakes.

Causes of Permafrost-Related Infrastructure Problems in Russian Arctic Communities

Although there is a tendency to attribute permafrost-related reductions in infrastructure stability solely to climate-induced environmental changes, the problem appears to be more complex. The unprecedented rate of air temperature increases throughout the circumpolar Arctic over the last decades is responsible for permafrost warming and degradation. This explains the broad pattern of declining infrastructural stability. However, human and socio-economic factors need to be considered to explain the state of permafrost infrastructure at the local level.

The planning of Arctic cities—including the arrangement of streets and squares, the density of buildings, the location and size of vegetated surfaces, and the type of pavement, among other features—was guided primarily by aesthetic and/or functionality concerns. The primary concession to the presence of permafrost was the use of permafrost-specific engineering designs for infrastructure. However, the complex interactions between different components of the urban landscape and their combined effects on permafrost temperature were never fully considered. For example, during the development of Northern cities, it was generally assumed that storm drainage was not necessary due to the cold temperatures and low level of precipitation associated with the Arctic climate. However, despite low precipitation, snow cover can pile up on city blocks due to altered wind patterns and plowing. Snow piles significantly restrict permafrost cooling in winter and result in meltwater accumulation in depressions formed by the foundation piles. Both factors contribute to permafrost warming and are considered to be major causes of the structural deformation of buildings. Moreover, many normal city activities—such as the construction and maintenance of roads, buildings, and utility lines; the planting and removal of vegetation; and changes in traffic patterns—can heavily impact the mechanical and thermal properties of the frozen ground, negatively affecting the bearing capacity of foundations. Even urban and industrial pollution can greatly affect infrastructure stability, thanks to soil salinization and the related depression of the freezing point and intensification of the chemical distraction of foundation piles. As a result, it is extremely difficult to maintain the thermal regime of permafrost in a highly complex and constantly evolving urban environment, even if all infrastructure is engineered and built properly.

Moreover, the rapid urban development of the Russian Arctic was, in many cases, achieved at the expense of construction quality. The majority of residential buildings erected after 1960 were made of prefabricated concrete panels. The building design and manufacturing process were very similar to those adopted throughout the Soviet Union, without regard for the extreme Northern climate. For example, the reinforced concrete widely used for foundation piles was highly subject to rapid distortions in the Arctic. Moreover, engineers assumed just a 5%–35% decrease in the bearing capacity of the foundation over the lifespan of a building, which rarely exceeded 30 years. Significant variation in permafrost temperature related to both anthropogenic and climatic factors can, however, result in far greater reductions in the bearing capacity, while the exploitation of structures well beyond their operational limit can promote infrastructure failure.

The socio-economic crisis that occurred after the collapse of the Soviet Union in the 1990s had a significant impact on urban permafrost in many Russian cities. As the Soviet political and economic systems crumbled, so too did the support for vulnerable industries and cities. In many Russian Arctic communities, this period was characterized by the termination of construction and development, a reduction in the amount and quality of infrastructure maintenance, and the out-migration of the labor force. Rapid market reforms resulted in the privatization of major city functions such as the maintenance of buildings, roads, and utility lines; snow removal; and permafrost monitoring. A large number of private contractors provided services of unequal quality and without any consideration for permafrost. Many operational practices that had been aimed at stabilizing the ground's thermal regime were neglected. Such socio-economic factors have greatly contributed to the deterioration of the aging urban infrastructure throughout the Russian Arctic, causing further permafrost warming, which has, in turn, affected the structural stability of buildings. Such negative feedback has been further amplified by the acceleration of changes in climatic conditions.

Conclusion

The climatic change observed in the Russian Arctic and Sub-Arctic regions is characterized by an increase in temperature and precipitation. Although such changes can have a pronounced effect on permafrost, the observed climatic signal cannot fully explain the rate of permafrost warming and degradation in many Russian communities. However, climate-induced permafrost changes have put additional stress on aging city infrastructure, the stability of which had already been substantially weakened by technogenic and socio-economic factors. The relative importance of climatic impacts on infrastructure stability is certain to increase.

Although a range of engineering solutions are available to mitigate the negative impacts of permafrost changes on infrastructure, their cost is prohibitive for city-wide applications in many economically vulnerable Russian municipalities. The uncertainty of high-resolution projections of climate change further complicates the problem of developing adequate and cost-effective adaptation and mitigation strategies. It seems that the problem of infrastructure stability on permafrost is recognized at the highest federal level of the Russian government. For example, permafrost degradation and its effect on infrastructure were identified as a matter of national security in the "Russian Strategy of the Development of the Arctic Zone and the Provision of National Security until 2020" issued in 2013 and then again in the "National Climate Change Adaptation Plan" approved by the Russian government in December 2019. However, given current Russian geopolitical priorities and economic problems, it is highly uncertain whether recognition of the problem will actually lead to action.

About the Author

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