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Conquering the permafrost: urban infrastructure development in Norilsk, Russia

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ABSTRACT

The city of Norilsk represents an unprecedented case of massive construction in the permafrost regions of the Arctic. Norilsk's urban expansion can be attributed to the development of engineering practices that maintained the thermal stability of permafrost. However, complex interactions between the urban landscape and permafrost have resulted in permafrost warming and degradation. Negative cryogenic processes started to manifest themselves 10–15 years after the initial development and have intensified with time. Problems were further exacerbated by the poor quality of construction, improper operation of the city infrastructure, socio-economic transitions, and unanticipated climatic changes. The warming and degradation of permafrost have contributed to a widespread deformation of structures in Norilsk. In this paper, we discuss the role of permafrost in the urban development of Norilsk, specific human- and climate-induced geotechnical problems related to permafrost, and innovative economically viable solutions to maintain city infrastructure. The analysis of Norilsk's experiences with permafrost can potentially contribute to the development of sustainable practices for Arctic urbanization.

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Introduction

Over 66% of Russia is underlined by perennially frozen ground or 'permafrost'. Defined as a ground which remains at temperature below 0°C for at least two consecutive years, permafrost affects all hydrologic, geomorphic, and biologic processes in the Arctic and plays an important role in the global climate system (e.g. Rowland et al., 2010). It also impacts human activities in northern regions. Changes in the ground thermal regime can greatly reduce permafrost's capacity to carry structural loads imposed by buildings and structures (e.g. Streletskiy, Shiklomanov, & Grebenets, 2012; Streletskiy, Shiklomanov, & Nelson, 2012a). The thawing of ice-rich sediments leads to ground subsidence and often results in uneven surface deformation and formation of *thermokarst* terrain undermining the stability of engineered structures (e.g. Nelson, Anisimov, & Shiklomanov, 2001). Even a slight anthropogenic disturbance can greatly modify energy and water fluxes at the

ground surface, promoting significant alteration to physical and thermal properties of the frozen ground. As a result, permafrost warming and degradation can develop in response to human activity even under stable climatic conditions. The sensitive nature of permafrost constitutes a distinctive, highly challenging suit of engineering problems. Many applications of construction methods and technologies developed for temperate climates are generally restricted in permafrost-affected regions (e.g. Shur & Goering, 2009).

An evolution of methods for permafrost construction over the twentieth century has permitted substantial expansion of economic activities in the Russian Arctic. It also allowed for the establishment and/or extensive development of urban communities throughout the Russian permafrost regions to support local and regional administrations, military installations, and mineral resources extraction and transportation industries.

The permafrost-related urban development in the Russian Arctic is exemplified by the city of Norilsk (pop 178,800): the largest Arctic city built on permafrost. The city of Norilsk is located in Central Siberia at 69°51'N latitude and 88°13'E longitude, approximately 90 km east of Yenisei River. Norilsk is a highly isolated city. It is not connected to the Russian road or railroad system. The region is characterized by severe subarctic climate and by Siberian forest-tundra/tundra biomes underlined by the permafrost of variable (20–400 m) thickness. The permafrost is continuous in its extent with the exception of major water bodies. The mean annual ground temperature varies within a -7°C to -0.5°C range, depending on surface and subsurface conditions (Ershov, 1989). Norilsk was founded in 1935 as a GULAG mining and metallurgy work camp and experienced intensive urban development between the mid-1950s and early 1990s period. Although several Russian cities were established in permafrost-affected regions as early as seventeenth century (e.g. Yakutsk), it was the widespread proliferation of permafrost engineering and construction methods developed in Norilsk, which contributed to a more rapid urbanization of the Russian Arctic. Correspondingly, the emergence and intensification of the negative permafrost-related geotechnical processes manifested by the structural deformations of Norilsk buildings epitomize problems currently faced by many Russian Arctic communities.

In this paper, we discuss the role of permafrost in the urban development of Norilsk, specific human- and climate-induced geotechnical problems related to permafrost, and innovative economically viable solutions to maintain city infrastructure.

History of permafrost construction in Norilsk

Mid-1930s to mid-1940s

Construction of the Norilsk industrial complex began during the summer of 1935 utilizing predominantly forced labor (e.g. Ertz, 2003). The extensive geologic and *geocryologic* (or permafrost) investigations initiated in 1936 within the area of proposed development indicated the presence of permafrost-affected sediments with massive ground ice (Leon'ev, 1944; Pavlov, 1959). Initial experience with permafrost construction indicated that the ice-rich permafrost is unable to support heat-generating structures built using standard engineering practices (e.g. Shamsura, 1959). Structures erected during the 1935–1937 period developed deformations caused by the differential settlement of the thawing ice-rich sediments just a few years after construction. As a result, permafrost construction

regulations issued in 1939 have explicitly prohibited the building of permanent concrete and/or brick structures on frozen sediments with any detectable amounts of ground ice (OCT, 1939). To avoid ice-rich permafrost, it was proposed to use concrete pylons anchored to the bedrock located at ‘reachable depth’ as a foundation for heavy, heat-generating industrial structures (Kim, 1959). The lack of large areas underlined by the near-surface bedrock has promoted significant changes to the development plan, which originally assumed consolidated cluster of smelters and supporting facilities located in close proximity to mines. Instead, massive industrial structures were built on relatively small patches underlined by the bedrock at 8–10 m depth and arranged in a narrow strip extending from east to west for over 20 km (Pavlov, 1962) (Figure 1(a)).

Since areas with the near-surface bedrock were used primarily for industrial facilities, the majority of the 1930s–1940s supplemental structures, such as administrative buildings and housing (predominantly prison barracks), consisted of temporary, light one- to two-story wooden structures which were less susceptible to the differential settlement (Pavlov,

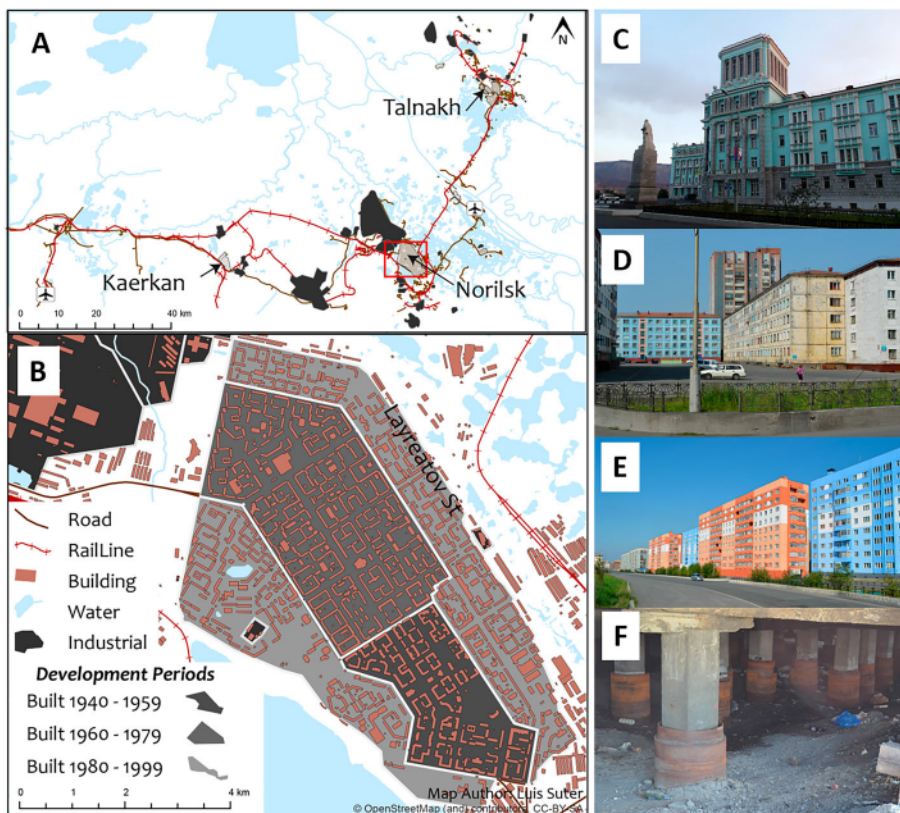


Figure 1. (a) Norilsk Industrial region. Note the spatial arrangement of industrial facilities attributable to distribution of near-surface bedrock. (b) The map of the city of Norilsk and approximate periods of development. Note the large number of thermokarst lakes indicative of ice-rich permafrost in the north-east corner of the map and the location of Layreatov st, mentioned in the text. (c) Neoclassical buildings characteristic of 1946–1957 period. (d) Typical five-story concrete panel residential buildings of 1957–1975. (e) Typical nine-story concrete residential buildings of 1975–1995. (f) Typical 32 × 32 cm concrete foundation piles (Photographs by N.I. Shiklomanov).

1959). However, by the mid-1940s, approximately 50 one- to two-story brick houses and several small industrial facilities were built on coarse, relatively ice-poor sediments using construction principles of preserving underlying permafrost from thawing. These buildings utilized the combination of elevated wooden pile foundations, ventilated basements, and perimeter insulation of load-bearing walls and floor (Kim & Pavlov, 1945).

Mid-1940s to mid-1950s

Although construction of industrial facilities was a priority in the 1930–1940s, plans for building a fully functioning city for approximately 35 thousand people were developed from 1939 to 1943. According to these plans, the city would include 3–5-story neoclassical brick buildings arranged in 7–10 rectangular city blocks each ranging from 1.5 to 4 hectares in size (Nepokojcheskij, 1946) (Figure 1(b) and (c)). The area allocated for urban development was underlined by the bedrock at 0.5–10 m depth overlaid by gravel, boulders, and sandy-loam deposits of glacial origin. The permafrost layer varied between 80 m and 150 m in thickness and had the mean annual temperature of -2°C to -4°C (Anisimov & Ermilov, 1961). Construction began in the late 1940s and involved manual excavation of the frozen sedimentary material, and raising typical heated basements on the bedrock. In areas with the thick sedimentary layer (>10 m), foundations were not continuous but consisted of several 2×2 m concrete pylons anchored to the bedrock, serving as a base for horizontal beams supporting buildings (Kim, 1961).

Despite a solid bedrock foundation, permafrost-related problems arose immediately after construction. *Taliks* (the volumes of thawed soil) formed around heated basements and promoted water accumulation, causing regular flooding of basements. As a mitigation measure, a complex drainage system had to be retrofitted around each building (Nazarova & Poluektov, 1973). Significant problems were related to the underground utility lines such as water, sewer, and centralized (hot water) heating. The unavoidable permafrost thawing around utility lines caused deformation, corrosion, and rupture of pipes, leaving many multi-story buildings, especially those located inside the perimeter of city blocks, without sewer or running water for years (Anisimov & Ermilov, 1961). Based on this initial experience, three guiding principles of city planning on permafrost were developed (Orlov, 1962):

- (1) To minimize the negative effects of permafrost thawing, all utility lines should be placed in a single underground collector (*utilidors*) running along the center of streets at least 10–12 m away from buildings.
- (2) To minimize the density of utility lines, buildings should be as large as possible and have a clear access to streets with utilidors.
- (3) The use of unheated, ventilated basements is preferable all for buildings.

All Norilsk city blocks developed after 1950 have utilized these principles (Nepokojcheskij, 1962).

Mid-1950s to early 2000s

The dismantling of the GULAG system in the mid-1950s resulted in a labor shortage in Norilsk. Quality housing was needed to attract mine and factory workers, making

construction of residential housing a priority. Classical architectural designs used in the late 1940s to early 1950s (Figure 1(c)) were too time-consuming and labor-intensive to implement, and thus were substituted by the simplified, standardized brick buildings. This greatly increased the speed of construction. In 1956, approximately 38,000 m² of residential housing was built, which was twice the amount built in 1955 (Kim, 1964). The completion of the factory producing prefabricated concrete modules for residential buildings in 1957 accelerated the construction process further (Agafonov, 1966). The minimum height of structures within the city limits was set to five stories (Nazarova & Poluektov, 1973).

By the late 1950s, all land suitable for construction was exhausted. City development spread to the areas underlined by the ice-rich, fine-grained lacustrine sediments at mean annual temperature above -2°C and with widespread 0.1-m-thick ice lenses (Kim, 1961). The analysis showed that these sediments could consolidate by as much as 30% after thawing and were prone to significant deformations (Zhukov, 1961). The bedrock, traditionally used in Norilsk to anchor foundations, was dipping below 30 m depth (Golodkovskaya & Shaumjan, 1974). While experiments with construction on frozen sediments were continued since the 1940s, no adequate solution was found. In the early 1950s, several residential buildings were erected on coarse frozen sediments using posts anchored to a thick concrete pad laid three meters below the active layer. However, this method of construction was extremely slow and labor-intensive. It required an excavation of substantial volume of the frozen ground to lay the pad. Moreover, excavation was possible only during the winter to prevent permafrost thawing, inflow of water, and collapse of the construction pit (Kolyada et al., 1978). V. Kim proposed a more effective method of permafrost construction in 1956.

Kim's foundation consisted of several rows of 8–16 m reinforced concrete piles frozen into the permafrost and a set of concrete beams (*grillage*) laid on top of the foundation piles at 1.2–1.8 m height above the ground. Such foundation relied on temperature-dependent freezing bond between piles and permafrost to support the structural load of the building. As such, pile foundation required maintaining the thermal regime of the permafrost throughout the lifespan of the structure. This was achieved by grillage elevation, which effectively used free ventilation to decouple the heat generated by the structure from the permafrost-affected ground. All utility lines were suspended from the grillage or the floor (Kim, 1961).

The first five-story concrete panel buildings on piles-and-grillage foundations were constructed in Norilsk in 1957 on relatively warm (-0.5 to -1.5°C mean annual temperature) ice-rich sediments. The construction involved placing prefabricated 32×32 cm 8–16 m-long reinforced concrete piles (Figure 1(f)) into the mud-filled predrilled holes of slightly larger diameter than the pile. The mud was forced out during the lowering the pile effectively filling all cavities in the hole. After freezing, the mud provided a strong bond between the pile and the permafrost. This method of construction was three times faster, required 6–10 times less labor, and was half the cost of the post-on-pad and pillars-on-bedrock foundations, which were previously used in Norilsk (Kim, 1961). Instrumental monitoring of the first buildings on pile foundations has confirmed the applicability of this method to relatively warm, ice-rich permafrost. In particular, effective ventilation of crawl spaces, absence of snow, and shading of the ground under the

building have contributed to the permafrost temperature decrease and an increased capacity of the frozen ground to support structures (Kim, 1964).

From 1959 onwards, the pile foundation became the dominant method of permafrost construction in Norilsk. However, maintaining the thermal regime of the ice-rich frozen sediments in densely built-up area was a major engineering challenge. Significant difficulties were associated with the optimum design of roads and heat-generating utility lines (e.g. water, sewer, centralized heating). To protect the permafrost, all city streets were constructed on 1.5–2.0-m-thick gravel pads laid directly on the undisturbed natural vegetation cover (Anisimov & Ermilov, 1961). Within the residential area, all utility lines were placed inside the two-level ventilated concrete underground utilidors built along the center of wide streets. To minimize the number of utility entry points, the majority of buildings constituting a single city block were connected to allow the distribution of pipes between the structures in either ventilated crawl spaces or inside buildings (Porhaev et al., 1978). Almost all residential buildings as well as several streets and utilidors were equipped with thermometric boreholes for permafrost temperature monitoring.

The results of extensive ground temperature observations have indicated that the implementation of new engineering designs has resulted in a decrease of the permafrost temperature under buildings by 3–6°C within 3–5 years after construction (e.g. Kim, 1964; Kolyada, Anisimov, Poluektov, & Zavenyagin, 1978; Maksimov, Zanjatin, & Konovalov, 1978). Although permafrost thawing was observed under utilidors (e.g. Orlov, 1962; Pchelkin, 1959a; Vershinin, 1963), taliks did not extend to nearby structures due to an enhanced winter freezing beneath plowed streets (Ahbulatov, 1961). It was concluded that the relatively constant, spatially uniform permafrost temperature of –3 to –5°C could be maintained within each city block. As a result, in the late 1960s, it was widely proclaimed that ‘The Permafrost is Conquered’ in Norilsk (e.g. Cheshkova, 1970).

New, quick, relatively cheap, and reliable methods of permafrost construction contributed to the accelerated rate of development in Norilsk. During the 1960–1990 period, approximately 18–20 new residential buildings were erected per year. The majority of 1960s structures consisted of five-story concrete panel buildings (Figure 1(d)). During the 1970s–1990s, the height of buildings increased to 9–12 stories (Figure 1(e)). In 1989, the population of Norilsk reached 179,757 people. Two additional cities were developed in proximity to Norilsk in the 1960s–1980s: Talnakh (1989 population 65,710); and Kaerkan (1989 population 29,824) (http://demoscope.ru/weekly/ssp/rus89_reg2.php) making the Norilsk industrial complex the largest Arctic metropolis on permafrost.

Permafrost warming and degradation

Although permafrost assessments in the 1960s–1970s indicated the stability of the ground thermal regime, progressive widespread permafrost warming in the city became apparent by the end of the 1980s. Permafrost degradation was observed under 39 residential buildings in 1989, 145 buildings in 1995, and 393 buildings in 2000 (Uhova, Grebenets, & Kerimov, 2007). Analysis of temperature measurements obtained in 2006 from the sample of 48 residential buildings in the different parts of the city detected progressive permafrost degradation in 70% of cases (Grebenets, Streletskiy, & Shiklomanov, 2012).

The major permafrost-related infrastructure problems in Norilsk first occurred in the mid-1980s when 15 nine-story residential buildings constructed on the eastern side of

Layreatov street (Figure 1(b)) between 1974 and 1979 developed significant deformations, and had to be demolished (Gunina, 2013). By the early 1990s, an additional 17 houses in different parts of the city were demolished due to deformations attributable to permafrost thawing. Between 1995 and 1999, residents were moved out of 49 multi-story buildings while another 79 occupied buildings were identified as structures with ‘progressive deformations.’ This accounted for approximately 10% of buildings in Norilsk (Kronik, 2001).

Permafrost changes in urban environment

Based on the literature review and field investigations, we have identified four major factors responsible for the pronounced permafrost changes in Norilsk and corresponding degradation of the urban infrastructure (Figure 2). These include: (1) complexity of the interactions between different components of the urban infrastructure and the permafrost; (2) quality of construction and improper operation of the urban infrastructure; (3) problem associated with the socio-economic transitions; and (4) climate-induced environmental change. Each of these factors is discussed below.

Complexity of the urban permafrost system

Extensive work was conducted in Norilsk to develop an optimum method of urban permafrost construction, including experimental field-testing aimed at the analysis of potential impacts exerted by individual elements of the urban infrastructure on the permafrost (e.g. Maksimov, 1959; Pavlov, 1962). However, the complex interactions between different components of the urban landscape and their combined effects on the ground thermal regime were never fully considered.

For example, theoretical considerations and experimental testing have suggested that the coarse sediments are preferable for the cold climate construction since they inhibit ice segregation and surface heave (e.g. Maksimov, 1959; Pavlov, 1950). As a result, 80% of the Norilsk built-up area is situated on the artificial surfaces composed of coarse material derived from the mine tailings and used for roadbeds and leveling of construction sites (Demedyk, 1972). Simultaneously, storm drainage systems were never considered for

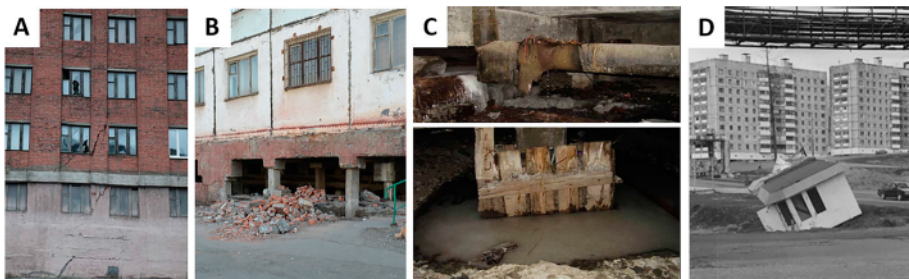


Figure 2. (a) Example of structural deformation of building caused by inadequate structural design exacerbated by permafrost warming. (b) Example of cryogenic weathering of the foundation. (c) Water leakage and accumulation around foundation piles. (d) Ground settlement developed under small heated kiosk due to permafrost degradation (Photographs by V.I. Grebenets and N.I. Shiklomanov).

Norilsk due to the cold and arid Arctic climate (e.g. Nepokojcheskij, 1962; Pchelkin, 1959b). The combination of these two factors has produced an unanticipated effect on the urban permafrost. Despite low precipitations, substantial surface and subsurface runoff forms annually from melting snow piles accumulated in the city, due to altered wind patterns and plowing. High permeability of coarse material led to high infiltration, unrestricted movement, and subsurface accumulation of water in depressions formed by foundation piles, which, in turn, enhanced permafrost warming. Warming influence of the city-generated runoff initially affected buildings erected in the topographically lowest parts of the city (e.g. Layreatov street) (Poluektov, Mezhenkij, & Rumjancev, 1981); however, with time, water-related permafrost warming became apparent through the city (Grebennets & Kerimov, 2001).

Significant problems were related to the complexity of thermal interactions between the permafrost, underground utilidors, and city buildings. By the mid-1980s, permafrost degraded to a 20 m depth under utility lines and the thaw had spread horizontally far beyond the streets in many parts of Norilsk (Grebennets, 1998; Protasova, 1987). An expanding net of taliks dissected the continuous layer of frozen ground, causing permafrost warming and thawing under city blocks. Moreover, ground freezing under the pipes in abnormally cold winters promoted the ice segregation and frost heave followed by thaw subsidence. Such differential vertical movements contributed to frequent rupture of pipes and water leakages. The coarse sediments complicated the detection of leakage from aging utility pipes due to high infiltration, and contributed to the fast redistribution of water by the subsurface flow. The most severe problems were associated with the distribution lines connecting the main utilidors with buildings. These pass over alternating patches of thawed and frozen ground and are subjected to a highly differential rate of heave and subsidence. In such situations, 40% of the heat carried by the pipes was lost to the ground due to the pipe insulation damages and ruptures (Protasova, 1987).

The problem related to the complexity of the interactions between the urban landscape and the permafrost was further exacerbated by the rapid rate of construction. Elements of the city infrastructure were engineered using results of permafrost observations conducted in the undisturbed areas planned for development. However, various temporary roads, facilities, and structures associated with the simultaneous construction in different parts of the city resulted in a spatially extensive disturbance surrounding Norilsk. In addition, potential development of unique micro-climatic characteristics attributable to the urban heat island effect resulting from operation of the large urban and industrial complex (e.g. Varentsov, Konstantinov, Samsonov, & Repina, 2014) were not fully considered. As a result, structures were erected on permafrost, which was warmer than was assumed in engineering designs.

Many permafrost-related problems started to manifest themselves 10–15 years after construction, due to the high thermal inertia of permafrost. By that time, significant portions of the city were fully developed. Although continuous permafrost monitoring was implemented within the developed areas, it was aimed primarily at detecting and mitigating the problems with individual structures. Observational results were never analyzed to provide an integrative assessment of the spatial and temporal dynamics of the ground thermal regime of the city and to correspondingly adjust development plans.

Quality of construction and operation of the urban infrastructure

The high rate of development was, in many cases, achieved at the expense of construction quality. For example, the ‘safety coefficients’ of typical pile foundations in Norilsk was set to 1.05–1.56. This means that the engineered stability of structures assumed just a 5–35% decrease in the ability of permafrost to support building (Streletskiy et al., 2012a). Moreover, prognostic estimates of the infrastructure stability in response to possible permafrost warming did not extend beyond three to four years post-construction (Nazarova & Poluektov, 1973). The permafrost temperature changes experienced by the 1990s exceeded engineered safety coefficients in many parts of the city.

For the majority of Norilsk’s residential buildings erected after 1960, the design and materials were very similar to those adopted throughout the Soviet Union, but without considerations for the extreme Arctic climate. As a result, the lifespan of typical Norilsk concrete panel residential buildings is 25–30 years (Anisimov et al., 2010). For example, reinforced concrete, widely used for foundation piles, was susceptible to an intense cryogenic weathering under the extreme freeze and thaw cycles and acidity of the Arctic soils. A survey of 12,000 pile foundations conducted in several Russian Arctic cities indicated a pronounced cracking, peeling, and thinning of concrete piles within the layer of seasonal thawing, and 20–30 cm above the surface (Grebenets & Kerimov, 2001). In Norilsk, the concrete and brick weathering was augmented further by the aggressive corrosive environment caused by the industrial pollution (Figure 2(b)). Intense foundation weathering was found to be the primary cause of the two-story restaurant collapse in Kaerkan in July of 1976, where 12 people died and 30 were seriously injured.

Another set of problems stems from the improper maintenance and operation of the city infrastructure. An analysis conducted by Grebenets and Ukhova (2008) demonstrated numerous serious violations in operation of ventilated crawl spaces. These include accumulation of snow and debris along buildings, installation of enclosures, and other types of ventilation blockage. The critical situation was observed in older (1950–1970) parts of Norilsk, where numerous repairs increased the elevation of paved surfaces such as roads and sidewalks. Ventilated basements became 0.5–1 m below the grade, resulting in significant reduction in airflow and water accumulation under buildings. Plowing caused formation of snow piles 2–8 m high, restricting the ground cooling during the winter. In many instances, annual snow accumulation inside city blocks has contributed to the formation of taliks and their expansion to the nearby structures (Grebenets et al., 2012; Il’ichev et al., 2003). Numerous authors have identified the lack of adequate maintenance of leaking utility pipes as a major cause of building deformations throughout the Russian permafrost region, including Norilsk (e.g. Alekseeva et al., 2007; Grebenets & Sadowski, 1993; Grebenets & Ukhova, 2008; Khrustalev, Parmuzin, & Emelyanova, 2001). The majority of the leakage occurs under individual buildings due to neglect (Figure 2(c)). However, frequent intentional release of water due to the pipe maintenance and repairs affects entire blocks or groups of buildings. For example, to prevent freezing, all water and sewer from 111 residential buildings and their supply lines were quickly released in February 1994 due to an accident at the Centralized Heating Plant. This caused significant permafrost warming over substantial parts of the city, which continues to spread (Kerimov, private communications).

Change in socio-economic conditions

Throughout its 80-year history, the city of Norilsk has undergone two major socio-economic transitions: (1) from the forced-labor GULAG system to post-Stalin socialist economy in the mid-1950s and (2) from the Soviet planned to market-driven economy during the 1990s. Changes in the socio-economic state associated with these transitions had an important impact on urban permafrost.

During the 1930s–1950s, the majority of scientists and engineers in Norilsk were either prisoners or semi-free employees of the GULAG. All permafrost investigations, engineering development, and construction were tightly controlled and highly classified. Before 1954, Norilsk – the city of almost 100,000 people – did not exist on any Russian maps. The rapid outmigration of liberated workers and the dismantling of the existing management and administration systems followed by the abolishment of the GULAG resulted in discontinuity of permafrost research, engineering development, and construction practices in Norilsk. The large body of research generated between the 1930s and 1950s was never systematically analyzed and was essentially lost. The development of many promising engineering solutions to permafrost problems was aborted. The lack of adequate knowledge and experience, as well as the fast rate of development in more challenging permafrost conditions precluded detailed permafrost investigations and resulted in many engineering mistakes (Nazarova & Poluektov, 1973).

More significant impact on urban permafrost in Norilsk is associated with the socio-economic crisis that occurred after the collapse of the Soviet Union in the 1990s. That period was characterized by the outmigration of the labor force and termination of construction. The last multi-story residential building was erected in Norilsk in 2002. Rapid market reforms resulted in privatization of major Norilsk city functions, such as maintenance of buildings, roads, and utility lines, snow removal, and permafrost monitoring. A large number of private contractors frequently provided services of unequal quality, without any consideration for permafrost. Many operational practices, aimed at stabilizing ground thermal regime, were neglected. For example, an economic liberalization has resulted in proliferation of small, cheaply constructed retail structures (kiosks), which were erected throughout the city directly on the ground. The heat produced by such structures contributed to permafrost warming and uneven surface subsidence, which spread to nearby residential buildings (Figure 2(d)). Partial privatization of individual apartments in the city-owned buildings resulted in highly confusing property ownership structure. Shared responsibility for the buildings has led to an inadequate maintenance of the commonly used infrastructure, such as foundations and utility lines. These factors greatly contributed to the deterioration of the aging city infrastructure, causing further permafrost warming, which, in turn, affected structural stability of buildings. Such negative feedback was amplified further by the accelerated changes in climatic conditions.

Climatic changes

Observed trends indicate that the Arctic climate has been changing at double the rate observed anywhere else on the globe (IPCC, 2014). Data from the Norilsk weather station (WMO ID# 23073) indicated a 1.4°C increase in mean annual temperature and 10 mm increase in annual precipitations between the decades of 1965–1975 (the period

of most intensive urban construction in Norilsk) and 2005–2015. Such warming can have a pronounced effect on permafrost parameters, such as its temperature and the active layer (Streletskiy, Sherstiukov, Frauenfeld, & Nelson, 2015), which are important factors in determining the stability of pile foundations. Streletskiy et al. (2012, 2012b) have provided a methodology for the geographic assessment of changes in engineering properties of the frozen ground due to observed climatic changes. The analysis utilizes the bearing capacity for ‘standard foundation pile’ imbedded in permafrost as a primary variable for assessing engineering properties of permafrost.

The analysis of climate-induced changes in bearing capacity was conducted for several settlements on permafrost, representing different parts of the Russian Arctic (Shiklomanov & Streletskiy, 2013; Streletskiy et al., 2012a). Results for the city of Norilsk show that between the decades of 1960s–2000s, the climate-induced permafrost warming has caused on average a 10% decrease in the ability of permafrost to support structures. The analysis of results indicates that the accelerated rate of permafrost warming and degradation in Norilsk, which occurred over the last 25 years, cannot be fully explained by climatic changes. Infrastructure-related problems in Norilsk were likely initiated by the anthropogenic factors, and climate-induced permafrost changes have inflicted additional stress on aging city infrastructure. However, the relative importance of climatic effects on the ability of frozen ground to support structures is likely to increase in the near future (Streletskiy et al., 2015; Shiklomanov, Streletskiy, Swales, & Kokorev, 2016).

Present state of urban infrastructure in Norilsk

The combination of the aforementioned factors has led to a challenging situation with Norilsk urban infrastructure. In 2005, the previously incorporated cities of Talnakh, Kaerkan, and Norilsk were combined into a single municipal unit ‘Norilsk.’ By 2015, the population the newly classified industrial region Norilsk had shrunk to 179 thousand people (Russian Federal State Statistics Service, <http://www.gks.ru/>). At present, the total residential housing stock of greater Norilsk is 4647.6 thousand m² distributed among 865 structures. The majority (59%) of structures are at least 30 years old, and 278 residential buildings (or 30%) have structural deformations due to human- and climate-induced warming and thawing of the permafrost (Development, 2015). The lack of funding and equipment resulted in an inability for the city to renew its housing stock. It should be noted that the practice of Soviet centralized development funded by the municipal, regional and/or federal, government continues today. Extremely harsh environmental conditions and the high cost of construction preclude any type of private investment in residential housing. High population turnover significantly limits potential for individual construction. Although Norilsk has lost almost 50% of its population since 1989, the lack of new construction and an accelerated rate of structural damage of residential buildings are causing an acute shortage of housing.

An equally critical situation has developed with utility lines. According to the latest assessments, out of 60 linear kilometers of underground utilidoros in Norilsk, 20.3 km (or 30%) are in dilapidated condition due to structural degradation and are considered dangerous (Development, 2015). More than 90% of the city budget allocated to the operation and maintenance of heating, water, sewer, and electrical lines is spent on emergency

repair of utilidors, making it impossible to implement systematic reconstruction and upgrades of the city utility system.

The critical state of Norilsk urban infrastructure has stimulated discussions of adaptation and mitigation plans for the city at both municipal and federal levels. At the municipal level, a comprehensive plan for the 'Development and repair of communal infrastructure and housing stock of the municipal unit Norilsk for the 2011–2020 period' was adopted in 2010 (Plan, 2010). The plan was based on a critical assessment of the present state of Norilsk's infrastructure and the realistic municipal budget. Correspondingly, it provided several cost-effective development strategies.

For example, the shortage of housing was addressed by utilizing existing pile foundations (Figure 3). The building demolition process involves removing the structure, but leaving piles and grillage in place (Figure 3(a)). Many such foundations dot the city landscape. Although deformations related to the permafrost thawing were the prime reason for the demolition of the structure, the removal of the heavy, heat-generating building results in ground cooling and/or refreezing in just three to four winters. While the permafrost might never cool to its original temperature due to the influence of the nearby infrastructure and the climatic warming, the cooling under existing foundation may be sufficient to support much lighter structures (Figure 3(b)). Utilizing an existing foundation contributes to significant cost savings, as the construction of a proper permafrost foundation in a complex urban environment may account for up to 40% of the total building cost. Over the last few years, the city has started to implement *foundation recycling* by auctioning the old foundations to private investors for low-rise retail, office, and restaurant facilities. Several foundations were used for playgrounds. A school was constructed using a steel frame and insulated panels on recycled foundation in 2010. The 2010 development plan called for the expansion of this program by initiating a residential construction on old foundations in the urban core of Norilsk. The first three residential buildings with 40 apartments each were completed in 2013 using materials shipped to Norilsk (Figure 3(c)). The 2010 plan considered establishing a local manufacturing facility for light composite building materials; however, the nation-wide economic crisis caused these plans to be scaled down. A proposed city-wide initiative to replace utilidors with new, more efficient systems has also been put on hold. Presently, the city is focused primarily on stabilizing structures that can still be saved, and on the continued demolition of structures damaged beyond repair (Development, 2015).



Figure 3. Foundation recycling in Norilsk. (a) Example of pile foundation left after removal of damaged concrete/brick building. (b) Construction of light frame and composite panel structure on old pile foundation. (c) One of the three light residential buildings erected on recycled foundations in 2013 (Photographs by N.I. Shiklomanov).

Despite the unforeseen difficulties associated with the implementation of the infrastructure development plan, the full realization of the problem was in and of itself a major step forward. The special task force consisting of scientists, engineers, and city planners was established in 2014 to advise the mayor and the city council on all issues related to permafrost (Zapolarniy Vestnik, 2014). Efforts are also underway to reestablish a city-wide system for monitoring the ground thermal regime and to develop a comprehensive modeling of the urban permafrost.

Simultaneously, the permafrost-related problems in the Russian Arctic cities were recognized at the federal level. Permafrost degradation was 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' (<http://government.ru/info/18360>). More recently, the Arctic Development Commission of the Russian Federation indicated the critical need for addressing permafrost-related problems in Norilsk (http://www.arctic-info.ru/news/06-10-2015/dmitrii-rogozin--neobhodimo-peresmotret_-normi-stroitel_stva-jil_a-v-arktike/). However, given the current Russian geopolitical priorities and economic problems, it is highly uncertain if the understanding of the problem will lead to action.

Summary and conclusion

The city of Norilsk represents an unprecedented case of massive urban construction in permafrost regions of the Arctic. Developed and implemented engineering practices were aimed at maintaining the thermal stability of permafrost and its ability to carry the structural load imposed by infrastructure. Observations conducted in the 1950s–1960s demonstrated that new engineering designs enhanced permafrost cooling, and promoted a rapid urban expansion of Norilsk. Moreover, construction methods developed in Norilsk were proliferated throughout the Russian permafrost regions, and contributed to the urbanization of the Soviet Arctic during the 1960s–1980s.

However, permafrost warming and degradation became apparent 10–15 years after initial development and have intensified further with time, causing a widespread deformation of structures. Permafrost changes can be attributed to the complexity associated with the spatial interactions between various elements of the urban geotechnical environment, and their combined effect on the ground thermal regime. While it was difficult to predict permafrost evolution in the complex urban environment, some aspects of the problem could have been addressed by systematic empirical assessments. The problem was further exacerbated by the poor quality of construction, improper operation of the city infrastructure, difficulties associated with socio-economic transitions, and unanticipated climatic changes.

Now faced with widespread deformation of structures, the Norilsk administration has developed a comprehensive plan for revitalizing the city infrastructure through innovative, cost-effective construction practices, city-wide monitoring of the ground thermal regime, and comprehensive modeling of the urban permafrost. However, political and economic problems may hinder implementation of these plans. The high uncertainty surrounding the rate and magnitude of potential climatic impacts further complicates the problem of developing adequate and cost-effective adaptation and mitigation strategies (e.g. Shiklomanov et al., 2016).

Although Norilsk is rather unique due to its location, isolation, size, and the level of urbanization, many Russian communities are facing similar permafrost-related problems. Moreover, the level of Arctic urbanization outside of Russia is increasing due to accelerated Arctic development (e.g. Rasmussen & Roto, 2011). The city of Norilsk presents an opportunity for a comprehensive analysis of the urban permafrost evolution under both anthropogenic and climate forcings. Such studies can contribute to our understanding of the complex interactions between urban and natural systems in the Arctic, and will help to avoid making critical mistakes in Arctic development.

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