Valery I. Grebenets[1*], Dmitry Streletskiy[2, 3], Nikolay Shiklomanov[2]
[1]Department of Cryolithology and Glaciology, Faculty of Geography,
Lomonosov Moscow State University; 119991, Moscow, Leninskie Gory;
e-mail: vgreb@inbox.ru
*Corresponding author
[2]Department of Geography, George Washington University; 1922 F St, NW,
Washington, DC, 20052, USA
[3]Earth Cryosphere Institute SB RAS, Tyumen, Russia

GEOTECHNICAL SAFETY ISSUES IN THE CITIES OF POLAR REGIONS

ABSTRACT. Arctic settlements built on permafrostface rather unique set of geotechnical challenges. On urbanized areas, technogenic transformation of natural landscapes due toconstruction of various types of infrastructure leads to changes in heat exchange in permafrost-atmosphere system. The spatial distribution and intensity of dangerous cryogenic processes in urbanized areas is substantially different from natural background settings found prior to construction. Climate change, especially pronounced in the Arctic, exacerbated these changes. Combination of technogenic pressure and climate change resulted in potentially hazardous situation in respect to operational safety of the buildings and structures built on permafrost. This paper is focused on geotechnical safety issues faced by the Arctic urban centers built on permafrost. Common types of technogenic impacts characteristic for urban settlements wereevaluated based on field observations and modeling techniques. The basic principles of development of deformations are discussed in respect to changing permafrost conditions and operational mode of the structures built on permafrost.

KEY WORDS: permafrost, Arctic, urban settlements, engineering, cryogenic processes

INTRODUCTION

In Russia, 66% of the territory is located in permafrost zone. Many key enterprises associated with mineral resource extraction and processing, as well as large administrative centers have been established on permafrost. In the future, development of the vast territories of Siberia and the Far East with their high resource potential is expected. Without it sustainable development of Russia in the XXI century is impossible. In the urban areas on permafrost, a "new reality" of geocryological conditions is being formed. These conditions are very different from the natural parameters. The new conditions are characterized, first, by a radical transformation of landscapes contributing to changes in energy and heat transfer in the "permafrost –atmosphere" system and, second, by engineering and technical impact, on underlying substrate leading to changes of physical, thermal, and mechanical properties of frozen soils. In the cities of the North, this "new reality" causes increase in ground temperatures and intensification of dangerous cryogenic processes leading to overall reduction in geotechnical stability of the environment. The problems become especially acute with noticeable trends of climate warming observed over the last decades in the high latitudes. Adverse changes in the permanently frozen ground have led to emergence and intensification of various geotechnical problems in the Arctic cities, resulting in the development of mass deformations of buildings and structures.

METHODS

Temporal changes in permafrost thermal regime were evaluated by analysis and comparison of data obtained from a series of temperature boreholes at construction sites and surrounding undisturbed areas. This allowed to study the relation between permafrost and geotechnical conditions of the environment in the cities of the polar regions. Geodetic measurements of the surface prior to and after the construction of pads were made to study the nature and intensity of cryogenic processes for the period of sites' operation. Geochemical studies of ground water under technogenic salinization of the permafrost active layer were conducted. Visual and instrumental observations of facilities and structures were carried out. Ultrasound and mechanical (crush test of concrete samples in compression chambers) properties were used to identify strength characteristics of the materials of underground structures and foundations that were subjected to cryogenic weathering. Mapping techniques and methods of quantitative modeling to predict changes in permafrost engineering parameters were widely used along with methods of quantitative modeling for forecast of engineering and geocryological parameters, primarily, through formulation and solution of two-dimensional problems of non-stationary heat transfer in permafrost media considering the Stefan condition (with phase transition of water).

RESULTS AND DISCUSSION

The cities in the Far North are the concentrated nuclei of anthropogenic impacts on the natural environment. Within the economically developed territories, dangerous, for buildings and structures, cryogenic processes are developing. Manifested risks and losses depend on the natural environment (climatic, geocryological, hydrological, etc.), and the intensity of human impacts. In cities, the frozen ground of foundations is subjected to different impacts:

Mechanical: excavation of soils for foundations, establishment of quarries and pits, and construction of mines and tunnels result in changes in the strength and cohesion of frozen soils; construction of dumps, tailing storage facilities, and construction pads contribute to the formation of a new frozen ground or to its degradation.

Technogenic salinization and waterlogging: discharge to the surface of untreated waste water, emergency discharges from utilities, acid rainfall, and penetration of pollutants into the active layer lead to substantial changes in hydrological and salinity regimes. A notable (and sometimes excessive) change in the geochemical background is typical of Vorkuta, Igarka, and many other cities of the cryolithozone. For example, soil moisture in the active layer of Norilsk, which has the world's largest non-ferrous metallurgy plants, is characterized by almost universal sulfate-chloride aggression in relation to the concrete of foundations, with a maximum salinity observed in the territories, built in the earliest periods (up to 21 mg/L in the sands at the Nickel plant, built in 1940) [Grebenets, 1998]. Chemical contamination of soil decreases temperatures of soil freezing and promotes the increase in the active layer depth, thawing of ice-rich horizons, and thermokarst development.

Changes in the conditions of heat exchange at the surface: almost all residential and industrial cities of the Far North have little vegetation and, as a rule, are paved with asphalt. Asphalt promotes increase in the heat flow into the ground due to summer heating and to winter cooling with snow removal. Observations have shown [Grebents, 2003] that in the areas used as snow dumps, the permafrost temperature at a depth of zero annual amplitude is 2–3°C higher than under consistently cleared roads. Proper operation of ventilated crawlspaces may reduce soil temperature under buildings by 2–4°C [Fundamentals of Geocryology, 1999]. However, their operation is often associated with various violations: absence of solid water barrier and water removal ducts, leaks in sewage network, lack of vents, and low position in relief, which leads to waterlogging. For example, about 85% of the surveyed buildings in Dudinka had serious operational violations of ventilated crawl spaces [Grebenets, 2008]. This contributes to the degradation of permafrost soils manifested in the formation of local talik sand zones of soil heating. In addition, under the buildings, the formation of vertically discontinuous permafrost profile often occurs. Construction pads without horizontal impervious screens, in general, have a negative impact on permafrost [Grebenets, 2003]. The pads are usually composed of poorly sorted mining waste products, such as crushed stone, gravel, sand and construction debris. Snow accumulation during pads construction is also common, creating potential for layers with high ice content. Destruction and removal of vegetation due to pad construction increases the heat flow in soils. In addition, significant filtration coefficients of fill material (10–50 m/day) provide penetration of surface waters through the pads. For example, residential buildings on Laureates St. in Norilsk built in 1975–1980, had thick construction pads (from 3–2 m to 8–10 m) , but a few years later had significant deformations associated with the loss of bearing capacity of soils. The temperature of soil under the existing pads in Norilsk varies from 2°C to –2,5°C [Grebenets, 2001].

Thermal: the additional heat input to the ground (heat of industrial facilities, residential buildings, and communications), the discharge of water from plants and leaking pipes, the lack of storm sewer, etc. leads to the degradation of permafrost. A special "contribution" is made by powerful heat producer such as underground utility lines (hot and cold water, sewage). In Talnakh, Vorkuta, Dudinka, and several other large cities, underground lines are interconnected and represent a powerful technogenic grid system buried 4–6 meters into the ground. In situ observations have shown [Grebenets, 2003] that over a year, within the existing utility lines, positive annual average temperatures prevails, forming halos of thawing. In winter, icings are often formed in the reservoirs of utility lines and in summer, there is discharge of thawed and waste water. The above-ground construction of utility lines (e.g., in the towns of Yamburg and Novozapolyarny) allows avoiding these thermal impacts.

The dynamics of permafrost in the Arctic cities (its status, temperature, bearing capacity, the amount of pile heaving, seasonal thawing of soil, the activity of cryogenic processes) is determined by several factors, which can be divided into three main groups: 1) geocryological (characteristics and properties of permafrost in the natural conditions, prior to construction), 2) geotechnical (urban characteristics, the type of anthropogenic impact, intensity and area of its contact with the permafrost), and 3) temporal (the duration of exposure, climate change) [Grebenets, 2007]. The factors often act in different directions and they are often multi-scaled and out of sync, resulting in a mosaic of changes in permafrost soils in urban areas. Man-made effects are the cause of temperature change with depth. For example, our field observations in a deep borehole in the center of the city of Norilsk has shown that at depths of 20–60 m, the temperature of permafrost has increased over the period 1955–1985 by 0,5–1°C. Geothermal measurements in a 135 deep borehole on the outskirts of Norilsk, revealed increasing soil temperature at depths of 20–90 m over the past 50 years from –(3,5–4)°C to –(1,5–2)°C. At a 15–20 m depth, there are no natural seasonal variations in climatic parameters; the changes are due to the long-term combination of technohenic and climatic warming impact. Analysis of changes in air temperature based on the results of observations at the meteorological stations in Norilsk and Dudinka (1949–2010 period) shows increasing trend at 0,03°C/year. The temperature of permafrost at the level of zero annual variations ranged, prior to construction (1940s), from –(0,1–0,5)°C to –(6–7)°C, and the average temperature of the soil within the residential area of Norilsk was –3°C [Grebenets and Sadowski, 1993]; but in 2005, it increased to –2,5°C. At the same time 30% of the study area became occupied by large warming zones (up to the formation of powerful technological taliks). Thermokarst processes that cause the failures of asphalt pavement are intensively developing; with the increase in the thaw depth in built-up areas, frost heaving processes have intensified.

The temperature field in Norilsk is very heterogeneous (Fig. 1) [Grebenets and Ukhova, 2008].

Increases in temperature of permafrost and its degradation in Norilsk – the largest city in the Arctic – were promoted by the following factors:

1) the underground heat-radiating lattice-shaped engineering system of underground utility lines was built within a relatively cold frozen massif. However constant excessive heating from utility lines sliced this massif creating extensive network of taliks (from 3–5 m to 18–21 m) and even larger areas of permafrost warming [Grebenets, 1991];

2) motorized redistribution of snow, which is cleaned from the streets and is dumped at the same locations every year resulting in snow piles from 2–3 m to 7–8 m high (usually in the same backyards and on the surfaces above the utility lines, which are located along the medians of the streets). This significantly reduces the flux of winter cold to the ground;

3) the presence of structures with a warm "ground floor" (no basements) or sites with violations in operating conditions of crawl basements (leakage of communications, lower positions and waterlogging of crawl space, and insufficient number or lack of vents).

The change in temperature regime and, consequently, in the soil bearing capacity have led to the increase in deformations of structures [Streletskiy et al., 2012a]. More than 75% of all buildings and structures in the cryolithozone of Russia are built and operated on the principle of the preservation of the frozen ground foundation: the piling foundations are frozen into soils and thus provide the required bearing capacity. At a steady trend of permafrost degradation in the major settlements of the cryolithozone [Grebenets and Sadowski, 1993; Grebenets, 2003] there is an increase in permafrost temperature (and often its thawing) and the associated sharp decrease in bearing capacity of frozen foundations, as well as the increase in the active-layer thickness (ALT), which also leads to expansion of the cryogenic weathering zone of underground structures (the so-called "frost destruction of concrete"), and to increase in the frost heave forces of lightly loaded structures during freezing of the active layer in early winter. All this leads to massive deformations of buildings and structures.

Currently, almost 60% of the buildings and structures are experiencing deformations in Igarka, Dixon, and Khatanga; virtually 100% in the indigenous towns of the Taimyr; 22% in the Tiksi; 55% in Dudinka; 50% in Pevek and Amderma; about 40% in Vorkuta; etc. [Kronik, 2001; Grebenets, 2007]. The number of deformed objects identified in the Norilsk region (including Talnakh, Oganer and Kayerkan) over the past 10 years far exceeds the number of such cases over the previous 50 years. To date, approximately 300 major facilities in the cities of the Norilsk industrial region have a significant strain associated with the deterioration of permafrost-geological conditions; more than 100 facilities are in the state of failure (Fig. 2); nearly 50 nine- and five-story apartment houses, built in 1960s–1980s, have been recently demolished (Fig. 3).

The geotechnical problems associated with increasing permafrost temperature at the base of the buildings and concurrently decreasing soil bearing capacity, is manifested, as a rule, in a gradual increase in the degree of

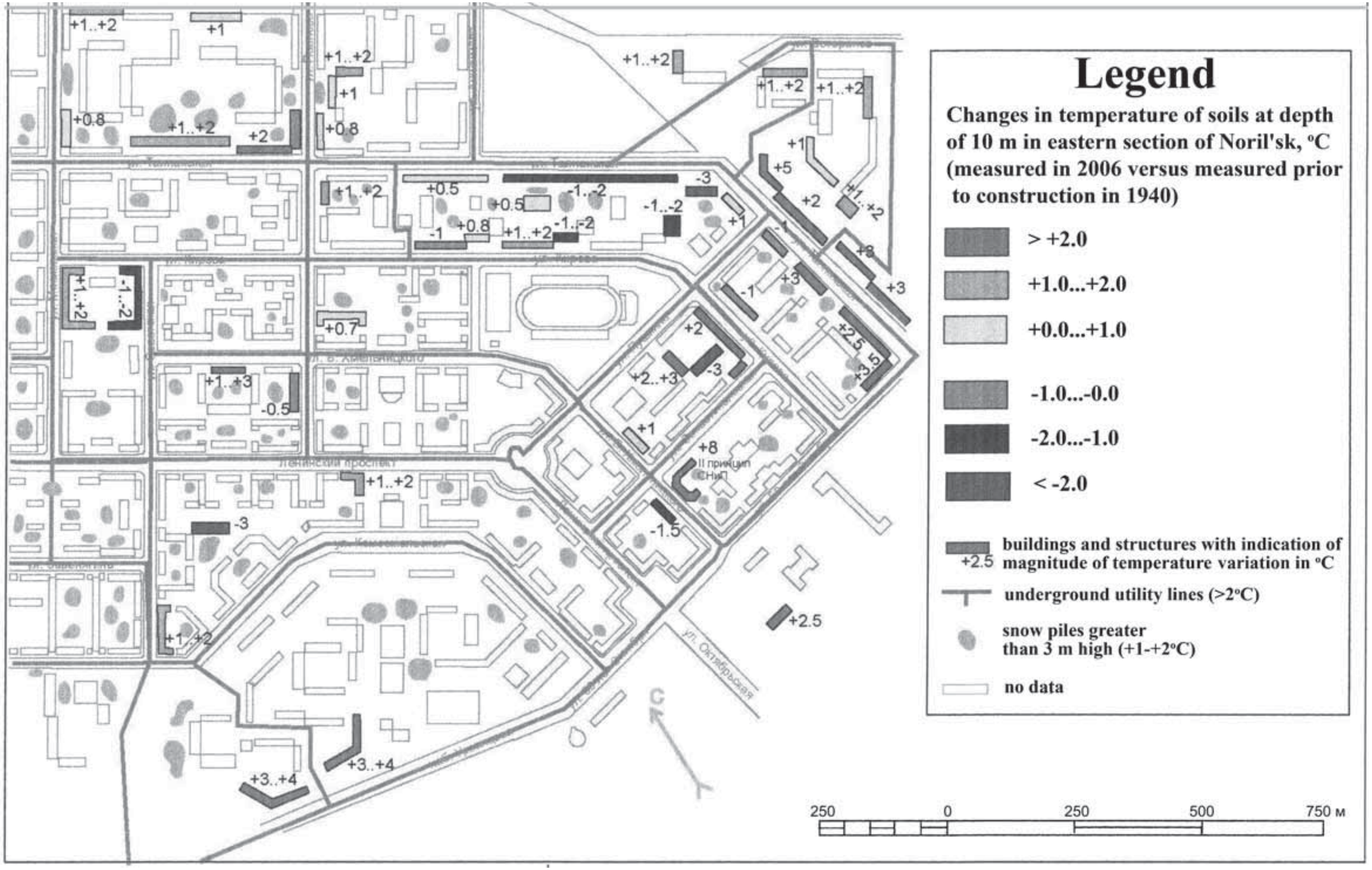

Fig. 1. The change in soil temperature at a 10 m depth in the eastern part of Norilsk (2006 compared to 1940)

Fig. 2. Thawing of an ice-rich permafrost in the area of installation of underground utility line and resulting deformation of structure in the residential area of Oganer near Norilsk. July 2003

deformation of buildings and structures up to their partial or complete collapse.

Another intractable problem – the geotechnical-cryogenic weathering of underground structures, especially of pile foundations made of reinforced concrete (the so-called "frost destruction of concrete") – usually leads to a sudden collapse of piles within the active layer zone as they are

Fig. 3. Demolition of a nine-story residential building on Laureates St. in Norilsk after 21 years of operation, July 2001

Fig. 4. Bands of "frost destruction" of reinforced concrete piles within the active-layer, Norilsk

thinned by the cryogenic weathering. This aspect has become particularly apparent after a disaster at cafe "White Deer" in Kayerkan (Norilsk area) in 1976, which took away several lives.

The rapid destruction of the material is primarily due to various temperature deformations of the multicomponent medium (reinforced concrete), especially at temperatures below –(35–40)°C; to a wedging

Table 1. The reduction in the strength of the foundations (based on the surveys of buildings of the city of Dudinka)

N	Facility type	Duration of operation, yr	Type of foundation	Bearing capacity (% from designed)		
				Based on in-situ observations		Estimated
				above-ground part	at the depth of 0.5 m	At 0.5 m
1	2-storey building	45	concrete piles	60–70		
2	2-storey building	37	rubble-concrete piles	60–70		
3	3-storey building	30	reinforced concrete piles	70–80		
4	2- storey building	25	reinforced concrete round piles	70–80		30–40
5	4- storey building	24	reinforced concrete round piles	100		65–75
6	2-storey building	23	reinforced concrete square piles	80–90		25–35
7	5-storey building	22	reinforced concrete round piles	100		50–60
8	5-storybuilding	20	reinforced concrete square piles	80–85		50–60
9	5-storey building	17	reinforced concrete square piles	70–80	20 (locally)	30–40
10	5-storey building	15	reinforced concrete square piles	90–100	65	65–75
11	3-storey building	12	reinforced concrete square piles	80	30 (locally)	50–60
12	5-storey building	10	reinforced concrete square piles	90–100		60–70
13	4-storey building	9	reinforced concrete square piles	100		90–100
14	5-storey building	8	reinforced concrete square piles	100		90–100

action of water films in microcracks; to water-to-ice phase transitions in cracks and cavities, etc. [Grebenets et al., 2001]; the important factors are the active layer thickness (the zone of frost destruction), soil moisture, and aggressive nature of ground moisture in respect to the material of underground structures.

Survey of about 12,000 foundations in Dudinka, Khatanga, Norilsk, and other northern cities have shown [Grebenets et al., 2001] that the material of the foundations of the surveyed buildings is often in poor condition and the destruction of the concrete foundations occurs within the active-layer and 20–30 cm above the ground surface, which is manifested in the visible defects on the surface of the concrete: cracks, cavities, peeling and flaking of coarse aggregate, exposure of reinforcement (Fig. 4). Within the permafrost (in the depth range of 0,5–3 m below the permafrost table), the visible defects (other than technological) are generally were not detected.

An important factor is the duration of the operation (Table 1); however, cryogenic weathering markedly accelerates the deterioration of the foundations compared with the more southern regions (outside of the cryolithozone).

Studies have shown that under specific conditions, technogenic water-logging and salinization of soils of the active layer are very active factors in the destruction of underground structures, which is associated with emissions of pollutants into the environment in Norilsk (Fig. 5). In Norilsk, the thick layer of permafrost prevents drainage of groundwater and leads to the preservation and further accumulation of corrosive substances in the active layer not only in clay, but in sandy soils as well. Chemical analysis of soil moisture showed [Grebenets, 1998] that it contains 300 to 800 mg/L of SO_4^{2-} – ions, i.e., is aggressive to concrete foundations; it is characteristic that the concentration maxima are confined to a 0,4–0,6 m depth, where the largest cryogenic pressure of water (and its penetration into the body of the foundation) is recorded during the freezing of the active layer.

The decrease of geotechnical safety at facilities (buildings, utility lines, oil pipelines,

Fig. 5. Emissions of pollutants from the factories of Norilsk into the environment; in the foreground – a moving technogenic rock glacier, destroying facilities of various functions, July 2009

industrial plants, etc.) increases the technogenic pressure on the permafrost in urban areas, which leads to a new cycle of changes in permafrost, i.e., to the formation of the "other reality" of geocryological conditions. Due to physical geography and economic factors, the industry is evolving focally in the permafrost regions. In urban areas of the cryolithozone, cryogenic processes are often different from those developing in the nature: they take place more rapidly, or conversely, fade under the influence of anthropogenic factors, and in some places there are new cryogenic processes and phenomena that have not previously been characterized for the region. The possibility of occurrence, activity, intensity, reversibility, geographic extent, formation of paragenetic series, and other characteristics of cryogenic processes in this situation are substantially different from the natural setting or do not have analogues in the natural conditions.

In urban areas, special natural and technogenic geocryological complexes are formed, within which the dynamics of permafrost is different from the natural conditions: for example, in the Norilsk industrial area, we isolated [Grebenets, 2001] 13 main types of such complexes: from technogenic badlands (sludge and ash disposal areas, tailings), where permafrost is damaged and natural landscapes are destroyed, to little affected, by technogenesis, areas of tundra and forest tundra, within which there is still a marked distinct tendency toward the increase in the depth of seasonal thawing associated with the increase in thermal conductivity of soils due to "acid" rain and technogenic salinization of soils. Within the residential areas of Norilsk, there is a very noticeable differentiation of impact of the elements of the urban environment on the engineering geocryological situation (Table 2) [Grebenets and Kerimov, 2001]. Currently, under the influence of technogenesis in Norilsk, there is a clear tendency toward the degradation of permafrost, as about 25% of the elements of urban development provide a warming effect on permafrost (Table 2). According to our observations, about 16% of the residential area of Norilsk is occupied by buildings (building density ranges from 5,5% to 32%, being the highest in the cities of the Arctic).

For a more modern Yamburg gas field (there, the experience of building and operating facilities in the Arctic has been utilized) the following main types of natural-technogenic geocryological complexes are isolated [Grebenets, 2008]: 1) the area occupied by modern gas treatment complexes equipped with the surface drainage systems, and systems with supplemental freezing of foundation bases – this zone has a marked stability of engineering geocryological conditions and geotechnical situations; 2) modern urban residential development, with a regular snow removal and good surface drainage systems, above-ground networks, and normally ventilated operated underground spaces – this zone is characterized by a tendency toward aggradation of permafrost, the damping of cryogenic processes, and the absence of deformation of buildings and structures; 3) the area of residential buildings and utility-industrial buildings of the 1980s – early 1990s, with numerous heat-radiating objects – there is a tendency toward the degradation of permafrost and there have been numerous deformations of objects; 4) sites with the infrastructure industrial facilities (port complex, the industrial area) built and operated with disturbance of permafrost conditions of soils – there, large areas of warming and thawing of permafrost have been formed, thermokarst and heaving have intensified, and a number of facilities are destroyed or severely deformed; 5) sites of storage of solid waste– there, due to chemical reactions, warming of permafrost is occurring; 6) linearly oriented zones along numerous lines – there, the conditions of heat transfer through the surface are radically altered, activation of cryogenic heaving of pipeline piles is taking place, and thermokarst and thermoerosion are present; and 7) relatively stable tundra areas – there, in the locations of heavy equipment movement,

Table 2. Changes in geocryological conditions in Norilsk within various elements of the urban development area

Element of urban development	Area, th. m^2	Surface temperature			Character of changes in temperature (°C) and permafrost top
		Range of changes		Average-weighted value	
		from	to		
1. Buildings with ventilated basements, including:	1160				
a) without leakages from engineering systems and with normal operation of basements	780	−6.0	−0.5	−3.5	Decrease in temperature, decrease in ALT
b) with violations of normal operations of utility networks and basements ventilation	380	−3.0	+1.5	−2.5	Increase in temperature, substantial increase in ALT
2. Heated buildings with floors on the ground surface	5	+6.0	+12.0	+7.5	Formation of local thawed zones, temperature increase
3. Underground heat-radiating facilities (network collectors, pumping stations, civil defense facilities, etc.)	80	−0.1	+5.0	+3.0	Thawing and waterlogging of soils, temperature increase
4. Surfaces regularly cleared of snow (paved ways, sidewalks)	1320	−3.5	−1.0	−2.5	Decrease in temperature, decrease in ALT
5. Backyards , including:	4774				
a) sites regularly cleared of snow	3280	−3.5	−2.5	−3.0	Decrease in temperature, decrease in ALT, especially significant at sites shaded in summer
b) sites of snow piles from mechanized snow removal operations	1490	−0.1	0.0	−0.5	Increase in temperature, increase in ALTdepth
6. Athletic fields, park zones	150	−3.5	−2.5	−3.0	Sustained temperature and ALT or insignificant decrease in temperature
7. Inter-city lakes	30	0.0	+4.0	+0.5	Thawed areas

thermokarst, thermoerosion, and gullying are developing.

It appears that these particular changes in the geotechnical, geocryological, landscape, and geoecological situation can be explained through the concept of tehnocryogenesis that has four main characteristic features. Technocryogenesis is a specific exogenous process developing in urban areas of permafrost (1), resulting from the interaction of man-made (technogenic) impacts and cryogenic conditions (2), irreversible (3), and manifested in the formation of specific natural-territorial geocryological complexes (4). Studies in individual Arctic cities have shown significant differences in the degree of influence of technocryogenesis on the permafrost-ecological conditions and the geotechnical situation, i.e., on the stability of buildings and structures.

Distinct cryogenic environmental problems arise with increasing density of development or during reconstruction of facilities in the areas where earlier (over several years or decades) permanently frozen foundations were impacted by various technogenic loads. For example, during such reconstruction in the city of Talnakh (North Siberia), at the sites of demolished buildings (25–30 years of operations), it was necessary to increase the depth of the new buildings' pile foundations in permafrost by 50–70%. For Novy Urengoy, Yakutsk, and some districts of Norilsk during the secondary construction on the sites of the demolished sections of deformed buildings, the challenge was the presence of anthropogenic cryopegs, whose strong aggression of media caused excessive corrosion of reinforced concrete piles of the new buildings.

There is a possibility of exacerbation of geotechnical problems in the cities of the Arctic in relation to the observed warming trends there. Climate warming can be traced within much of the Arctic [ACIA, 2004], and in its Russian sector as well [Pavlov and Malkov, 2005]. A similar situation is observed in the north-western Canada and Alaska (Fitzpatrick et al, 2008). Climate warming has already led to an earlier period of snow melting, reduction in the area of pack ice, retreat of glaciers, and an increase in temperature of the permafrost [Hinzman et al, 2005]. According to [Romanovsky et al., 2010], the temperature of permafrost at a depth of zero annual fluctuations increased by 0,5–2,0°C over the past 20–30 years in the entire cryolithozone of Russia. More severe changes were in Alaska [Osterkamp, 2007]. The situation became potentially an additional, but a very important cause of massive deformities and, in some cases, of the collapses of buildings and structures reported in various settlements in the Arctic.

Buildings and structures. According to Ya.A. Kronik [Kronik, 2001], about a quarter of all deformations may be due to changes in climatic factors outside of the safety coefficients during the construction. Using the method of spatial modeling, we calculated [Streletskiy et al., 2012a] changes in bearing capacity of typical piles in the northern part of Western Siberia for the foundations of structures built based on the principle I SNiP [SNiP 2.02.04–88, 1990], i.e., with the conservation of the frozen state of the ground during construction for the entire period of the operation. Calculations showed that warmer climate of 1990–2010, in comparison with the 1960–1990 climatic norm, led to a decrease in the bearing capacity of the foundations of buildings and structures by 17% in the region on average and in some areas – by up to 45%. A similar study carried out for several regions of the Russian Arctic has shown a significant reduction in the bearing capacity in the western part of the Chukotka AO, Sakha Republic, and the southern part of the Yamal-Nenets AO [Streletskiy et al., 2012b]. The reduction in the bearing capacity of foundations and buildings constructed on the basis of principle I, in comparison with 1970, was 5–10% lower in Norilsk, Neryungri, Mirny, Yakutia, and Chersky; 10–15% lower in the Bilibino and Dudinka areas; 15–20% lower in Salekhard, Nadim, Pevek, and Anadyr; and over 20% lower in Noyabrsk and in Provideniya. The calculation of the bearing capacity for northern Alaska with the data of climatic scenario A1B (increase in air temperature by 1–2°C by 2020 and by 3–4,5°C by 2040, compared with 1980) showed a decrease in the bearing capacity for the whole region by 22% in 2000, by 26% – by 2020, and by 52% – by 2040 [Streletskiy et al, 2012c]. The coefficients of safety in construction in Alaska and northern Canada are typically 2–3, while in Russia, there are lower, i.e., about 1,6. Therefore, one should expect a more favorable situation in terms of bearing capacity in the cities of the North American sector of the Arctic compared with the Russian sector. At the same time, widespread ice-rich soils in the places of residence in Alaska, bring the processes of ground settlement atop [Instanes et al., 2005]. [Larsen et al., 2008] conducted an economic impact assessment of changes in permafrost conditions under climate warming; according to this estimate, an additional 3,6–6,1 billion U.S. dollars will be required to maintain the existing infrastructure in Alaska in 2030 and approximately 5,6–7,6 billion dollars – by 2080.

Transportation. A potentially dangerous situation can be traced in the area of railway transport. According to [Kronik, 2001], as of 1998, approximately 46% of the sub-bases of the Baikal Amur Major Railway (BAM) has been subjected to deformation due to uneven thawing of permafrost, which is 20% higher than in 1990. Studies of the Seida – Vorkuta track have shown that the settlement of the roadway increased from 10–15 cm in the mid-1970s to 50 cm in the mid-1990s, due to the increase in temperature of permafrost from –(6–7)°C to –3°C (Evaluation Report, 2009). The railroads in Norilsk, the Yamal Peninsula, and near Novy Urengoy are also in critical condition. Warming of climate and of permafrost is alarming in respect to road maintenance in the north of Canada and Alaska, especially in the areas with the high-temperature ice-rich permafrost (Natural Resources Canada, 2008). The cost of railroad operations in Alaska increases each year due to the cost of eliminating deformations associated with uneven settlement of soil (US Arctic Research Commission Permafrost Task Force, 2003).

Winter roads play an important role in the transport system of the Arctic countries. Global warming has caused a reduction in the operating period of winter roads as well as a reduction in the bearing capacity of roads both in the Russian and the American sectors (Lonergan et al. 1993). The most severely affected is Russian North where, in contrast to Alaska and Northern Canada, air transport is poorly developed. Only in Alaska, there are more than 3,000 airstrips and 84 commercial airports.

Increasing depth of the ALT leads to an increase in frost heaving, adversely affecting roadways, as well as lightly loaded bearings of aboveground pipelines in the north of Western Siberia. The majority of permanent roads are in the area of the discontinuous permafrost where frost heave and thaw settlement processes are most pronounced. Much of the road budget of Alaska is spent on road maintenance due to uneven soil settlement (NRC 2002).

CONCLUSION

Studies have shown that the stability of geotechnical environment in the Arctic cities is determined not only by natural geocryological conditions, but also by the type, intensity, duration, and area of contact between the man-made impacts and permafrost. Negative anthropogenic impact caused activation of hazardous engineering-cryogenic processes and an increase in structural deformations in the cities and towns of the North. In the last decade, this process has intensified. The situation is compounded by a complex socio-economic status of the northern regions, many unresolved engineering geocryological problems, and warming Arctic climate. It is necessary to use a wide range of activities aimed not only at ground stabilization in local areas (under isolated buildings or structures), but also at monitoring and forecast of the permafrost and the geo-ecological situation at the scale appropriate to each urbanized area.

ACKNOWLEDGMENTS

This work was supported by the grant of the Russian Foundation for Basic Research, “Leading Scientific Schools of Russia”, project НШ – 1097.2012.5, and by the NSF grantsARC-1002119 (CALM), and ARC-1231294 (RCN-SEES: Building a Research Network for Promoting Arctic Urban Sustainability in Russia). ■

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Valery I. Grebenets is Associate Professor, Department of Cryolithology and Glacilology, Faculty of Geography, Lomonosov Moscow State University. He is PhD. in Geological and Mineralogical Sciences. His research interests are permafrost engineering, regional cryolithology, urban cities of Murmansk region, deformation of structures in the cryolithozone, thermal-physical and thermal-technical calculations of permanently frozen foundations in their interaction with buildings and structures, management of engineering geocryological conditions for permafrost-environmental and geotechnical stability. He has participated in many expeditions and conducted field research on the Taimyr Peninsula, north of Western Siberia, and the Bolshaya Zemlya tundra. He is the organizer and director of international student field courses on permafrost in Siberia, including the International Polar Year. From 1993, he has been a member of the International and the Russian National Committees on Soil Mechanics and Geotechnical Engineering. He is a member of the Russian Geographical Society. He is the author of over 110 scientific publications, including several monographs (in collaboration) and articles in leading scientific journals on geography, geocryology, and geotechnology.

Dmitry Streletskiy is a research scientist at Geography Department of George Washington University. Dr. Streletskiy's research interests include cold region climates, modeling and spatial techniques, permafrost engineering and human-environment interactions in the Arctic. He is originally from Moscow, Russia where he completed his B.S. and M.S. in Geography from the Lomonosov Moscow State University working on snow cover, glaciers, and permafrost at the Department of Cryolithology and Glaciology. He obtained his Ph.D. in Climatology from the Department of Geography at the University of Delaware. His dissertation was focused on problems involving spatial and temporal variability of climatic and permafrost parameters at range of geographical scales, and effects of climate-permafrost interactions on northern infrastructure. He presented his research in journals, book chapters and proceedings of several international conferences held in US, Canada, Germany, Switzerland, Norway, China, and Russia.

Nikolay Shiklomanov is a faculty at the Department of Geography, George Washington University, Washington DC, USA. His main area of research is the response of the permafrost-affected environments to climatic variability and change. He is also interested in geomorphology, history of Arctic research, and socio-economic problems associated with development in Arctic regions. Dr. Shiklomanov's educational background includes a master's (MS) in physical geography from SUNY-Albany, USA and a Ph.D. in climatology from the University of Delaware, USA. Dr. Shiklomanov's NSF- and NASA-sponsored projects include both field-based investigations in northern Alaska and Siberia and simulation studies at regional and circumarctic scales. He has authored and co-authored more than 50 peer reviewed publications and has contributed to several books and reports. Dr. Shiklomanov strongly believes in international collaboration between scientists in all aspect of Arctic research through development of joint projects and of promoting international scientific exchange (including students). Native of St. Petersburg, Russia, Dr Shiklomanov maintains close personal and professional ties with his home country. In the course of his research he has developed productive relationships with scientists from a wide range of Russian research and educational institutions.