EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth's Cryosphere, 2021, vol. XXV, No. 6, pp. 3–12 http://earthcryosphere.ru/

FUNDAMENTAL ISSUES OF EARTH'S CRYOSPHERE

ADAPTATION OF ARCTIC AND SUBARCTIC INFRASTRUCTURE TO CHANGES IN THE TEMPERATURE OF FROZEN SOILS

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The problem of sustainable economic development is acutely manifested in the Arctic regions, which is due to the vulnerability of the Arctic infrastructure to climate change and landscape transformations. The reasons for the deformations of buildings and structures in the Russian Arctic are considered. The permafrost monitoring network is identified as the basis for the development of technical solutions for adapting the Arctic infrastructure to climate change; the problems and prospects for its development are considered. The analysis of technological solutions for controlling and ensuring the reliability of the bearing capacity of foundations by regulating the state of permafrost soils is presented, and a preliminary analysis of the economic efficiency of protective measures is carried out. Their cost is at least an order of magnitude less than the expected damage to infrastructure by the middle of the 21st century.

Keywords: *Arctic zone of the Russian Federation, permafrost, frozen ground, climate change, adaptation of infrastructure, thermal stabilization.*

INTRODUCTION

One of the key problems of sustainable economic development is the adaptation of civil and industrial infrastructure to global climate change [*Infrastructure..., 2011; Zimmerman, 2011*]. This problem is especially acute in the Arctic regions, where, on the one hand, warming occurs faster than global trends [*Larsen et al., 2014*], and on the other hand, the vulnerability of the Arctic infrastructure is high under growing air and soil temperature and transforming permafrost and landscapes. In the Arctic zone of the Russian Federation (AZRF) more than 90 % of nickel and cobalt, 60 % of copper, and more than 96 % of platinum metals are mined, and about 80 % of gas and 60 % of oil from the all-Russian production are extracted [*Bryukhovetsky et al., 2014*]. For this zone, warming became a dangerous factor of economic and geoecological risks.

Due to an increase in temperature, the bearing capacity of frozen soils decreases, in many places they thaw from the surface, and destructive cryogenic (permafrost) processes develop. Thus, in the European North, modern climatic changes for the period from 1984 to 2019 caused an increase in soil temperature at a depth of 10 m by 0.5...1.5 °C. At the same time, the southern boundary of the discontinuous permafrost has significantly shifted to the north (in the Pechora lowland – on average by 30–40 km, on the plains near the Urals – up to a maximum of

80 km). In Western Siberia, in the northern taiga and forest-tundra at a latitude of 65–66 N, the mean annual ground temperatures increased by an average of 1–2 °C. In Yamal, in a typical tundra zone (68–71 N), according to more than 40-year observations, the temperature of permafrost at a depth of 10 m increased on average at a rate of 0.05 °C/year [*Melnikov et al., 2021*]. As a result, the increase in the mean annual permafrost temperature compared to the background state in the 1970s–1980s was from 1.5 to 2 °C [*Osokin, 2016*].

As a result of such changes, industrial complexes of the Russian Arctic and the cities serving them that have been created over the past 100 years are under threat. Today they require adaptation to the changed climatic and permafrost environment. Without this, the accident rate of geotechnical systems increases. For example, the number of deformed objects is 25–50 % of their total number. Thus, in Amderma, the number of collapsing buildings is about 40 %, in Dikson – 33 %, in Tiksi – 22 %, and in Pevek – 50 % [*Brushkov et al., 2021*]. The cryogenic factors cause a significant number of failures of technical systems in the oil and gas industry. In a number of studies, including this one [*Melnikov et al., 2021*], estimates of the material damage expected as a result of warming are given for the territory of the Russian Arctic [*Shiklomanov et al., 2019; Streletskiy et al., 2012, 2019*]. It becomes obvious that the design of new infrastructure should be carried out focusing not on modern, but on the predicted permafrost-climatic conditions.

CAUSES OF DEFORMATIONS OF BUILDINGS AND STRUCTURES IN THE ARCTIC

In areas with continuous permafrost, construction is mostly carried out according to the “principle I”, i.e., with the preservation of the frozen ground. To maintain the frozen state, a ventilated crawl space is mainly used as a cooling system, the design of which at the time of construction provides a frozen state of the base. However, in many cases, due to salinity, and now due to warming, the soils are in a plastic-frozen state, and often have high ice content. As a result, as observations in the cities and towns of Amderma, Dikson, Tiksi, Pevek, and others show, the buildings continue to deform for decades. Accordingly, the calculation of the foundations would have to be carried out taking into account both bearing capacity and deformations. However, in practice, this requirement is still rarely met.

Ideally, in built-up areas, soil temperatures should be lower than in natural conditions, due to the removal of snow and cooling ventilated crawl spaces. So, in Yakutsk, wherein the natural conditions of the taiga or open spaces, soil temperatures are –3...–5 °C, in the built-up area they drop to –7 °C. The greatest drop in ground temperature under the building occurs in the first 2–3 years after the start of operation [*Ershov, 1989*]. Here, modern construction is carried out on pile foundations, crawl spaces are ventilated, and snow on the streets is removed or compacted, as a result of which the temperature of the soil under the building is generally lower than in the surrounding

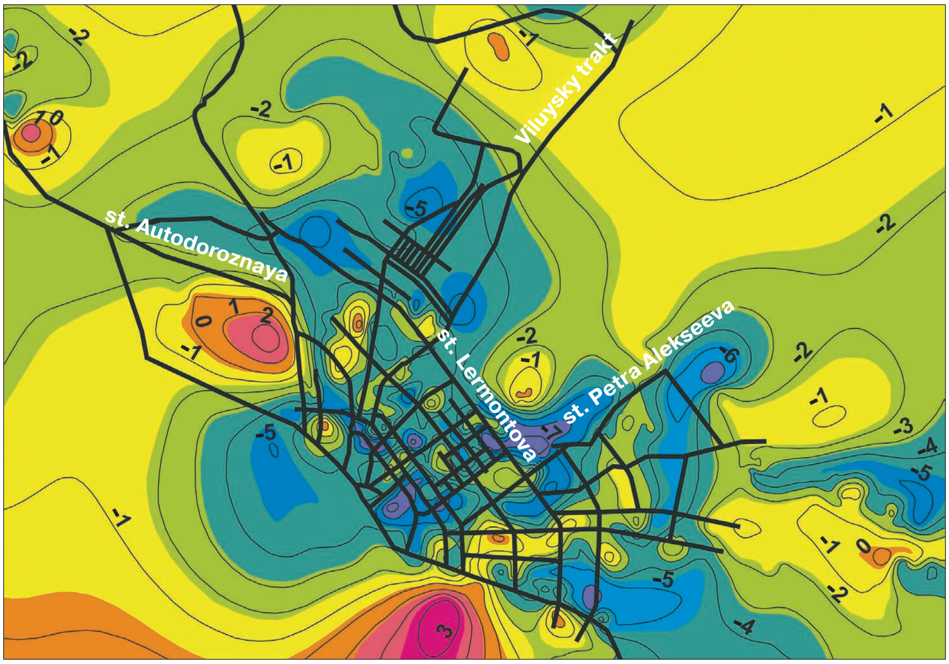

Fig. 1. Isotherms of permafrost soils in Yakutsk and its environs in 2015.

Provided by the Ministry of Construction of the Republic of Sakha (Yakutia), © P. Semenov.

areas (Fig. 1). However, at the same time, the intra-quarter space is often poorly drained, and due to the disturbance of the flow and leaks, new paths for the movement of heating water are formed. This leads to an increase in the temperature of the bases and subsequent deformation of some buildings. In general, unfavorable areas are not typical for Yakutsk, while in other settlements such areas are common, and favorable trends in the change in the thermal state of frozen soils in settlements are not always observed.

As shown by the studies of I.N. Esau and colleagues [*2019*], for example, in Tiksi settlement the temperature of the soil averages about –7 °C, and outside the settlement is up to –12 °C, in Amderma, respectively, –3 °C within the build-up area, and –4.5 °C in undisturbed conditions outside the settlement. Within the city of Nefteyugansk, the ground surface temperature is higher than outside the city by about 3 °C. The main reasons are the irrational redistribution of surface runoff, leaks from water supply and sewerage networks, and the practice of untimely and insufficient snow removal.

Snow drifts are a problem, especially on the Arctic coast. Many settlements in the Arctic are located in areas with an average winter wind speed of more than 7 m/s. The built-up area is an obstacle to the wind flow, and therefore large masses of blown snow are deposited here. At the same time, snow, as a rule, has a strong warming effect, which also causes surface subsidence and deformations of buildings and structures.

An important task during construction remains the maximum possible preservation of the moss and vegetation cover in the immediate vicinity of the building and beyond, capable of cooling the soil by 1–2 °C and more.

Thermal abrasion causes significant damage to structures in small settlements that were built in dangerous proximity to the sea. When the sea coast retreats at a rate of more than 3 m/year, a zone near the coast with buildings, roads, piers, warehouses for fuels and lubricants, and other materials becomes hazardous and requires protection or relocation of facilities. The destruction caused by thermal abrasion occurred in Dikson, Tiksi, Varandey, Amderma, Kharasavey, Se-Yakha, and other settlements.

Usually, the direct cause of deformations of the foundations of buildings and structures is a violation of the temperature regime of soils during construction and operation, mainly due to the thermal effect of buildings and the ingress of wastewater into the base. There are other organizational and technical reasons for the deformations of buildings. The most frequent among them is insufficient resistance of materials to external factors (for example, to salt waters) and low frost resistance of concrete of building structures. This is manifested in the Arctic (Norilsk) and further south, in areas with a subarctic continental climate (Yakutsk). Apart from foundations, pipes and communication lines are affected. According to *S.S. Vyalov* [*1992*], most of the failures of foundations of buildings and structures (on average 45 %) are due to their improper operation: errors of surveyors and designers account for an average of 22 % and defects of builders – an average of 33 %.

Geotechnical systems (GTS) of the oil and gas complex dominate among the engineering facilities in the Arctic and the North as a whole. Here, most of the hazardous situations develop already in the first 2–3 years of operation of the GTS. Technogenic impact on permafrost is one of the main causes of emergencies, regardless of the stage of the object's life cycle. For example, at the operating gas production facilities of the Yamburg and Medvezhye fields, the permafrost table at the base of some structures decreased over time to 7.5–8.0 m, which exceeded the pile-laying depth and caused a loss of the bearing capacity of the foundations and the occurrence of emergency situations [*Remizov et al., 1997*]. Main pipelines with a product temperature different from the temperature of the enclosing ground are subject to deformation. Technogenic taliks are formed around pipelines with a positive temperature of the transported product, which is accompanied by surface subsidence, thermokarst, thermal erosion and pipeline floatation. A frozen halo appears around the "cold" pipelines, which loiters the ground runoff in the seasonally thawed layer and the underflow runoff in the valleys, initiating other processes. Many problems are associated with old production wells, which were built without proper insulation methods for the casing. The high positive temperature of the gas in the reservoir (up to +36 °C) for the Cenomanian gas of the Medvezhye and Urengoy gas fields has a warming effect on the entire permafrost strata, which is accompanied by the formation of thawing halos around the wellbores, the formation of near-well funnels, the development of thermokarst and collapse of the production strings themselves [*Bereznyakov et al., 1997*].

Thus, examples and causes of deformations of buildings and engineering structures in the Arctic are numerous; they are of natural, man-triggered, and mixed origins. When the need arises, the cost of repairing and restoring of buildings, as shown below, is 25–100 % of their initial cost, depending on the speed of action.

Permafrost monitoring as a basis for the development of technical solutions for adapting the Arctic infrastructure to climate change

State monitoring of the permafrost zone should be an inter-agency system of regular observations, collection, accumulation, processing, and analysis of information (a) to assess the state of permafrost in natural and man-triggered disturbed conditions,

(b) to make forecasts of its changes under the influence of natural factors, land and subsoil use, industry, construction, housing and communal services, (c) to develop methods for regulating the state of permafrost for the protection and rational use of cryogenic resources and sustainable development of the permafrost zone.

For observations, a specialized network is being created, including polygons, stations, and monitoring sites both in natural conditions and within infrastructure facilities [*Melnikov et al., 2018*]: (1) observation wells for a comprehensive study of the geological (geocryological, hydrogeological, etc.) section and for regular measurement of the ground temperature, which is one of the main indicators of the permafrost stability; (2) observation sites for regular measurement of the parameters of the active layer (annual cycle of the depth of freezing and thawing and changes in moisture/ice content); (3) observation platforms for recording the dynamics of exogenous (including cryogenic) processes, changes in hydrogeological, hydrological and landscape conditions.

In Western Siberia, the permafrost stationary (monitoring observations) sites have been laid since the early 1970s in connection with the exploration and the beginning of the development of the largest oil and gas fields. Long-term monitoring observations could be organized only at certain points (Igarka, Yakutsk, Nadym, Marre-Sale, the area of the Urengoy field, etc.). In general, permafrost monitoring remains largely local. Monitoring studies of the permafrost state in the Central Siberian and Yakutsk sectors of the Russian Arctic are not being carried out sufficiently. Regular control points include only five sites near the settlements of Igarka, Tiksi, Chersky, Zhigansk, and on Samoilovsky Island.

Enterprises and companies of land and subsoil users interested in the efficiency of their activities, as well as municipalities, conduct object geotechnical monitoring (GTM), including permafrost observations. However, not everyone realizes the necessity of GTM. In addition, the systemic disadvantage of department-based permafrost GTM is that the regime network covers exclusively the areas of direct impact of engineering facilities and does not contain sites for monitoring the background state of permafrost.

An integral part of monitoring is not only observations but also the analysis of all available data, primarily on the foundations of buildings and structures, as well as the development of technical solutions for the engineering protection of economic and social facilities based on methods of controlling the bearing capacity of foundations by means of regulation methods. Without the development of such solutions, observations are largely irrelevant. An inalienable requirement in all these activities is an environmental component.

Therefore, it is necessary to come to an understanding that both the background and geotechnical permafrost monitoring should be parts of a unified structure of state interdepartmental monitoring of the permafrost zone [*Drozdov, Dubrovin, 2016*]. Background monitoring is carried out in undisturbed natural conditions at special stations and sites of periodic visits, covering, if possible, all the variety of landscape and permafrost conditions of the permafrost zone. Geotechnical monitoring is carried out in the area of industrial and civil buildings. Background monitoring is important for understanding the general and regional trends in the development of the permafrost zone. Geotechnical monitoring solves specific problems of ensuring the stability and reliability of the operation of buildings and structures and provides a comprehensive information basis for the development of regulatory documents. In other words, geotechnical monitoring of natural and technical (geotechnical) complexes should be understood as a system for monitoring, forecasting, and managing their condition to ensure the operational reliability of economic objects at all stages of the life cycle in compliance with environmental safety.

The pioneer in the organization of the institutional GTM system in the oil and gas industry is PJSC Gazprom, where, earlier than others, it was realized the need to introduce into production activities an integrated system for managing the state of GTS built on frozen grounds (back in 2003, a comprehensive program was developed and implemented to ensure the reliability of the operation of engineering structures in the permafrost zone). The current standard "Foundations and foundations on permafrost soils" [*SP 25.13330.2012, 2012*] presupposes carrying out geotechnical monitoring but does not give specific recommendations for its organization.

As in other industries, the main common drawback of the existing GTM system at all facilities of the oil and gas industry is the absence of background sites in the GTM network to control the temperature regime of permafrost, the dynamics of the development of exogenous processes, hydrological and hydrogeological regimes of the territory, the state of ground covers and other important indicators of the permafrost geosystems state in undisturbed natural conditions. Thus, despite the organization of geotechnical monitoring at the facilities of the oil and gas complex, the absence of simultaneous background monitoring reduces the efficiency of both. A similar one-sidedness in observations is typical for municipalities that monitor permafrost in their settlements (Yakutsk, Salekhard). And, most importantly, there is no single center for the collection and analysis of geocryological information. And this leads to a situation in which the scientific community and society as a whole, in fact, do not know what actually happens to the permafrost, especially in built-up areas, in cities and towns, and in the foundations of engineering structures.

A comparison of the organization of geocryological monitoring in Russia and other countries shows that the Nordic countries are developing background permafrost monitoring on the basis of scientific and geological organizations: in the USA and Canada – on the basis of geological services, in Switzerland and Norway – on the basis of universities under the state program, in China – on the basis of the Academy of Sciences together with manufacturing enterprises.

Ensuring reliable bearing capacity of foundations by means of regulation

When building on permafrost soils, the currently used methods can effectively ensure sustainability only for a certain time, since they take into account the peculiarities of the state of the environment before construction (including climatic and hydrological conditions). There are two ways to control the mechanical interaction of structures with frozen foundations: (1) constructive, in which the limits of the stress state, deformations, and creep of frozen soil, ground ice, and structure material are ensured; (2) thermal engineering, in which the temperature regime of the foundations and materials of structures is maintained within the limits ensuring their sufficient strength. These methods, as a rule, are applied simultaneously [*Dostovalov, Kudryavtsev, 1967; Tsytovich, 1973*]. There are also two main methods used for permafrost construction. The so-called *1st principle* assumes the preservation of permafrost soils in their natural state during the entire service life of a building or structure. This method is used in areas of discontinuous or continuous permafrost. *2nd principle* involves thawing permafrost prior to or during construction. This method is used mainly in areas of sporadic permafrost.

Most buildings built according to the 1st principle have a ventilated crawl space, which ensures the preservation of the temperature regime of the frozen ground. The height of the crawl space in Russia for buildings on permafrost according to [*SP 25.13330.2012, 2012*] should be chosen according to the conditions for ensuring its ventilation, but not less than 1.2 m from the crawl space surface to the bottom of the protruding floor structures. In such cases, as a rule, a pile foundation is used (Fig. 2) [*Ladanyi, 1984; Vyalov, Gorodetskiy, 1984*]. The piles are frozen into the permafrost and can withstand heavy loads if they are frozen before installation, primarily due to the lateral freezing surface, The difficulty of maintaining ventilated crawl spaces is that they can be covered with snow and wet in the absence of proper drainage.

Recently, the operation of facilities built according to the 1st principle has been complicated by climatic factors. Over the past 30–40 years of the ascending branch of climatic changes, the bearing capacity of frozen soils of the foundations, for example, in Western Siberia, has decreased due to warming by 5–30 %, and the belt of the maximum reduction in bearing capacity runs approximately along the Salekhard – Nadym – Novy Urengoy – Norilsk line. This is an area of oil and gas development at the end of the 20th century, and everything built here at that time is at risk, since the margin of safety on the ground is exhausted [*Streletskiy et al., 2019*].

Both natural and man-made changes in the temperature of frozen soils require compensation. Since

Fig. 2. The building of the dormitory on reinforced concrete piles in continuous permafrost zone, Kharasavey settlement, the Yamal Peninsula.

Photo by A.B. Osokin.

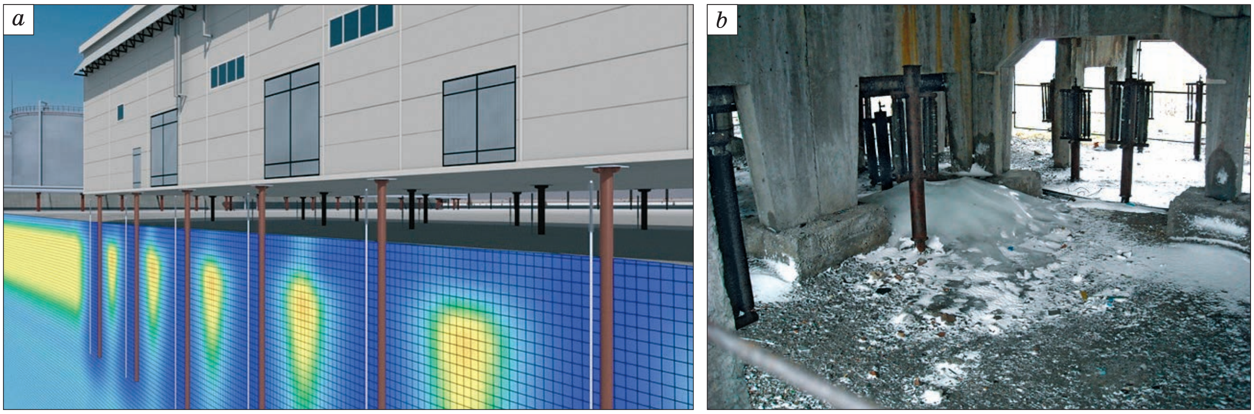

Fig. 3. Thermal stabilizers used to lower the temperature of the base of the building in permafrost zone:

a – along the perimeter of the building (*at the top* – the appearance of the building; *at the bottom* – a diagram of lowering the soil temperature by thermal stabilizers: yellow – positive temperatures, blue – negative); *b* – thermal stabilizers under the building.

the 1950s, in Alaska and in Russia [*Long, 1966; Gapeev, 1969*], the so-called thermosyphons or seasonally-cooling units have been introduced. The thermosyphon operates based on the natural circulation of a heat carrier in a metal pipe that cools down on the surface in winter. Initially, kerosene was used for this, and later carbon dioxide or ammonia. Nowadays, thermal piles are becoming more widespread – these are the piles with a built-in thermosyphon. In several years, the soil temperature around the pile decreases by several degrees, but at a short distance from it – up to about 1.5 m. When using thermal piles, the possibility of secondary heaving of frozen soils should be taken into account when they are additionally cooled. Several structures were damaged in this way, for example, a sports complex in the center of Yakutsk and a compressor station on the Yamal–Center gas pipeline. Nevertheless, the thermosyphon (thermal stabilizer) is today an important part of many construction projects in the cryolithozone (Fig. 3).

Ventilation ducts are one of the most well-known and widely used methods for cooling the foundation of embankments and other bankings [*Recommendations..., 1985*]. In the body of the embankment, culverts or air ducts with a diameter of 0.5–1.0 m are laid in order to let the cold winter air through themselves (in the summer the air ducts are muffled). In the PRC in Tibet, this method is used in addition to transport embankments for airfield facilities; in Canada in Inuvik – for cooling the foundations of oil reservoirs and related structures. To cool the base and slope of the embankments, rock placement [*Minaylov et al., 1985; Ashpiz, 1989*] and shading visors [*Kondratyev, 2013*] are also used. The latter significantly improved the cooling of the Tommot-Kerdem railroad embankment and the problem section of the Baikal-Amur Mainline at 1841 km.

Examples of maintaining the reliability of the bearing capacity of foundations by means of regulation

The use of thermal stabilizers is probably the most effective method among considered above, which is especially common in operational practice. Let's look at some examples.

In the city of Norilsk, Talnakh district, a residential building, which is deformed as a result of the increase in soil temperature, was stabilized with vertical thermostabilizers. In conditions of general warming and groundwater filtration, the temperature of the building base by the beginning of 2020 reached +1.4 °C. The operating system of temperature stabilization for the winter periods of 2020/21 lowered the temperature of the soil directly under the foundation to –7.2 °C (according to the data of "Fundamentstroyarkos").

In the city of Nadym in the 1990s–2000s, about a dozen buildings were subjected to deformations (5–7 % of the total number of permanent structures in the city), which was caused by uneven subsidence of foundations due to the thawing of icy soils at their base. Four residential multi-storey buildings, which received unacceptable damage, were dismantled. The load-bearing capacity of the frozen basement of two other residential buildings, which had decreased due to thermal effects, was restored by forced freezing with the use of vapor-liquid heat stabilizers. In two more buildings, the bearing capacity of the soils of the building foundations was restored by pumping cement mortar (according to the data of *A.B. Osokin*).

In the Amderma settlement, the building of the diesel boiler house of the Building and Construction Department built according to 2nd principle (on Proterozoic fractured shales on a strip foundation without a ventilated crawl space), experienced subsidence. The use of about ten simpler thermosyphons filled with diesel fuel made it possible to partially freeze the base, ensure its stabilization and prevent further development of deformations.

Ensuring the reliability of the bearing capacity of the foundations of buildings and structures by means of redundancy

When designing the infrastructure of the Bovanenkovo gas field (PJSC "Gazprom"), optimization of the location of well pads was carried out on the basis of zoning of the territory according to geocryological conditions. For obvious reasons, reserving extra reliability of foundations taking into account climate warming causes additional investment in construction. But the positive operational effect made the requirement "on reserve reliability of foundations on permafrost soils adjusted for warming" became a standard in Gazprom when developing technical specifications for the design of new construction and reconstruction. Redundancy of the reliability of foundations is achieved not only due to the design of foundations (depth of immersion of piles, the method of immersion, and diameters of the piles used) but mainly due to the use of thermal stabilization systems. The calculated temperature regime of permafrost soils of foundations is justified when designing objects by means of modeling using specialized software products that implement non-stationary numerical methods of calculation, taking into account the predicted trend of air temperature. Unfortunately, the approaches used in the gas industry have not yet found their continuation in other industries.

Cost-effectiveness of protective measures

During the construction of wells at the PJSC "Gazprom" field, a complex thermal engineering solution was used, which ensures the preservation of the host deposits of the wells in a perennially frozen state. The experience of the first years of operation has shown that the implemented technical solutions justify themselves. In addition, the thermal stabilization of the wellhead zones made it possible to bring wells in the cluster closer from the traditional 40 m to 20–15 m, which significantly (up to 30 %) reduced the cost of arranging the cluster pads [*Melnikov et al., 2019*].

Another example is the use of thermal stabilizers when laying power lines. This makes it possible to shorten the length of the piles for the foundation of the supports. For example, during the development of the Lodochnoye field (Krasnoyarsk Territory, 130 km west of Igarka), about 20 million rubles were saved, or 26 % due to the cost of the foundations of the supports.

However, despite the obvious efficiency, the failure rates of thermostabilizers in the permafrost zone are still high (for the thermosyphons it is up to 20–30 %) [*Strizhkov, 2015*]. They fail due to corrosion, damage during operation, and factory defects. To increase the reliability of the operation of seasonally operating cooling devices, it is advisable to conduct a technological audit of the manufacturers and to increase the competition between them.

Heat pumps are one of the alternatives to thermal stabilizers and freezing units [*Koloskov, Gamzaev, 2015*]. In a heat pump, the condenser is a heat exchanger that generates heat for consumer needs (for example, for heating buildings), and the evaporator is a heat exchanger that removes heat from the soil mass. It was proposed to use heat pumps during construction in the permafrost zone abroad [*Stenbeak-Nielson, Sweet, 1975*] and in Russia [*Perlstein et al., 2000*]. The technical and economic efficiency of using heat pumps is determined by the density of heat fluxes entering the evaporator during the cooling of the soil [*Kibl, 1983*]. Heat pumps are the basis of a technical solution for low-rise buildings under the program of resettlement of residents from nearby villages to Vorkuta. It is planned to build 40 such houses with a heating system and thermal stabilization of the base, which will optimize the construction in terms of timing and reliability [*Koloskov, Gamzaev, 2015*]. A specific calculation of the economic efficiency of using heat pumps in the permafrost zone was carried out by G.Z. Perlstein in 2012 for the conditions of Yakutsk [*Report..., 2012*] and showed that, as a result, the annual savings per building can be approximately 41 thousand rubles. However, heat pumps have not yet become widespread.

The cost of adapting the housing stock to changing permafrost conditions on the example of the city of Norilsk

Approbation of the proposed approach to assessing the cost of ensuring the sustainability of buildings at a large object in the permafrost zone was carried out using the example of the urban district of Norilsk. According to forecasts [*Melnikov et al., 2021*], the maximum damage under a moderate warming scenario and established management practices will reach about 600 billion rubles in Norilsk by the beginning of the second half of the 21st century. At the same time, according to the authors' estimates, the total cost of buildings and structures in 2020 prices on the territory of the urban district is about 631 billion rubles, of which: 117 billion rubles – the cost of the housing stock, 514 billion rubles – the cost of buildings and construction of the industrial sector, that is, such key sectors as industry, agriculture and forestry, construction, transport, sectors of market and non-market services. For a clear understanding of the scale of the likely damage, it should be noted that the budget of Norilsk for 2020 amounted to only 20.6 billion rubles (only 61 % of them are own income).

The cost of thermal stabilization consists of the costs of manufacturing, transportation, construction, and installation of thermal stabilizers. The selection of their number and geometrical arrangement is carried out according to the results of thermal engineering modeling. According to average estimates, in the zone of continuous permafrost, on average, one thermal stabilizer is needed to maintain two piles of a residential building [*Gamzaev, Kronik, 2016*]. The number of piles per unit area of a building is determined by its design features. For example, for a two-storey residential rotational complex for 850 people at the Vankor field in the Krasnoyarsk Krai (according to "Fundamentstroyarkos" [*Volkova, 2021*], etc.), 12 thermal stabilizers are needed per 100 m^2 of the object area. On average, according to "Fundamentstroyarkos", one average thermal stabilizer provides a freezing area of about 4 m^2 [*Anikin et al., 2013*], and, thus, about half of the area of its base is frozen at this object.

The unit cost of stabilizing 1 m^2 of frozen soil in the building plan ranges from 10,000 to 80,000 rubles/m^2. Such a range of prices is associated with technical solutions and prices depending on the category of soil and drilling depth. The work [*Svetlyshev, 2018*] gives an example of a 9-storey 4-entrance residential building made of prefabricated reinforced concrete structures with a reinforced concrete monolithic strip foundation in Nadym (building dimensions 101.0 by 14.4 m). According to the author's data, the costs of setting up a soil thermal stabilization system, i.e. further application of the first principle of construction, amounted to 47 million rubles. Of these: temperature stabilization of the soil – 19 million rubles, emergency restoration work on the repair of the foundation and supporting structures – 28 million rubles at the cost of construction of a similar building in comparable prices – 127 million rubles.

Based on the structure of the Norilsk housing stock (Table 1), the authors calculated the average area of the foundations of residential buildings of various series. The approximate cost of thermal stabilization systems was calculated at the rate of 10 thousand and 80 thousand rubles per 1 m^2 of the base. This did not take into account the costs of transportation and installation of systems. The calculation results are presented in Table 1. Panel 9-storey dormitories series 1-464.D-82 were excluded from the calculation. Unlike the others, they are primarily subject to gradual demolition and will not be either reconstructed or major repaired.

Thus, as a first approximation, it was possible to estimate that the costs of thermal stabilization of the Norilsk housing stock will be from 10 to 81 billion rubles, while the cost of the existing housing stock is estimated by us at 117 billion rubles. According to our estimates, the damage to the housing stock in Norilsk may amount to about 60 billion rubles by 2050 [*Melnikov et al., 2021*]. Close proportions of the costs of preventing negative consequences and the magnitude of the probable damage, apparently, are typical for the rest of the urbanized territories of the permafrost zone of the Russian Arctic, depending on how early measures are taken to thermostabilize the soils of the foundations. It should be emphasized that the maintenance of the thermal regime of the bases must be carried out not only with the help of thermal stabilizers (the reliability of which must be increased in the future) but also with other, proven methods (ventilated crawl space) and new methods, including the use of heat pumps.

Table 1. **The cost of thermal stabilization of the housing stock in Norilsk**

Building type	Number of buildings	The total area of the foundations of the houses, m^2	Number of floors	Estimated cost of thermal stabilization*, million rubles
Houses designed in the 1960–1970s	305	334 601	5	3346/26 768
K-69	62	95 828	9	958/7666
Series-84	255	257 675	9	2577/20 614
Series 111–112	140	153 592	9	1536/12 287
NK-12	15	21 553	12	216/1724
Houses designed in the 1930–1950s	44	91 379	5	914/7310
Hotel-type houses**	12	14 584	9	146/1167
Brick apartment buildings in Snezhnogorsk settlement	6	7389	5	74/591
Total dormitories, including:	26	30 809	–	308/2465
general type (5-floor)	8	8955	5	90/716
apartment type (9-floor)	18	21 854	9	218/1749
Total:	865	1 007 410	77	10 075/80 592

* *Left*: based on the coast of 10,000 rubles per 1 m^2 of frozen soil; *right*: based on the coast of 80,000 rubles per 1 m^2 of frozen soil.

** Gostinka (hotel-type house) – a type of dwelling, which is a small one-room apartment or a room with a kitchen niche and a bathroom.

CONCLUSIONS

Current trends in the state of permafrost are largely determined by global climatic changes. According to the ideas existing today, climate warming inevitably contributes to the emergence of trends toward quantitative and qualitative changes in the state of the Arctic cryolithozone.

Changes in the thermal state of permafrost under the influence of climatic variations occur over many years but have not reached their maximum. This circumstance significantly increased the risks in construction, land and subsoil use, and increased epidemiological and environmental threats in the Russian Arctic, and in the permafrost zone as a whole. Everywhere in the Arctic zone, there is a loss of the bearing capacity of the soils of the foundations of buildings and structures. The overwhelming majority of data on the state of the permafrost, as well as on its interaction with infrastructure facilities, need to be updated and renewed.

Over the past 35–40 years, the temperature in the upper part of the permafrost under natural conditions has increased by 0.5–2.0 °C, and on the plains of Western Siberia built up with gas industry facilities – by 2.0 to 4.0 °C. The bearing capacity of frozen soils of the foundations of structures at the same time, only due to natural changes, decreased by 5–30 %, depending on local geocryological conditions.

Technogenesis is seriously complementing the impact of background climate change. As a result of the combined influence of climate warming and large-scale anthropogenic impacts on the permafrost, a cumulative effect arises, the consequences of which already lead to the loss of stability of the frozen ground, major accidents, environmental disasters and, in general, to an increase in the risk of natural resource use in the developed areas of permafrost zone.

For an economically justified response to ongoing changes, a system of state monitoring of permafrost should be created, including background permafrost observations and object-based geotechnical monitoring with a unified system of data accumulation and forecasting. This will help to significantly reduce the managing risks in the permafrost zone, to solve planning issues, and to evaluate the effectiveness of design solutions and protective measures. In this case, the cost of protective measures, in particular, thermal stabilization, turns out to be an order of magnitude lower than the possible damage in case of its absence, and, thus, the effectiveness of protective measures is quite high.

An approach to the design of permanent construction projects in the permafrost zone seems to be justified and subject to dissemination, assuming redundancy of the reliability of foundations through the use of thermal stabilization and other methods that compensate for the predicted decrease in the bearing capacity of permafrost soils caused by climatic and technogenic factors. With a relatively small amount of additional investments (the first percent of the cost of construction), reliability redundancy will ensure the stability and mechanical safety of facilities.

Acknowledgements. *The article was prepared within the framework of the state assignment and the research plan of the IEG RAS on the research topic AAAA-A19-119021190077-6; state assignment of the Earth's Cryosphere Institute of Tumen Scientific Centre SB RAS No. 121042000078-9; agreement between FASI "Eastern State Planning Center" and FSBI "Gidrospetsgeologiya" No. K-26092/1-1-2020; directions of exploratory and fundamental research SB RAS 1.5.12. "Cryosphere of the Earth and its space-time evolution", with the support of the YaNAO administration.*

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Received July 29, 2021
Revised August 2, 2021
Accepted August 26, 2021

Translated by A.V. Muravyov