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Decreased Stability of the Infrastructure of Russia's Fuel and Energy Complex in the Arctic Because of the Increased Annual Average Temperature of the Surface Layer of the Cryolithozone

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Abstract—The impact of facilities of various branches of Russia's fuel and energy complex (FEC) on the Arctic permafrost zone and their stability due to climate change and the state of the upper horizons of the permafrost zone are discussed. Effective approaches are described in the design, construction, and operation of FEC facilities in permafrost. For the most significant subsectors of the energy sector (oil and gas production and transportation, electricity provision), an assessment of the economic damage as a result of changes in engineering and cryological conditions under the influence of natural and anthropogenic factors was carried out. The necessity of introducing new design and construction methods, carrying out complex background and geotechnical monitoring at the FEC enterprises, and creating a center for analyzing the received data is shown.

Keywords: FEC, cryolithozone, permafrost soils, economic damage, geotechnical monitoring

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Modern climate changes and, as a result, changes in the state of frozen soils in areas with seasonal freezing, as well as permafrost soils, occupying 11.2 out of 17 million km^2, or 65.5% of the country's area, determine the need to develop and implement measures to adapt energy facilities. About 85% of the territory of the Arctic zone of the Russian Federation (approximately 3.5 million km^2) belongs to areas of continuous distribution of permafrost. Due to the development of unfavorable exogenous geological and permafrost processes, there is a risk of a multiple increase in emergency situations at the facilities of the fuel and energy complex (FEC) and a possible loss of the bearing capacity of the foundations of buildings and engineering structures in the oil and gas industry, the electric power industry, and the coal industry: production wells, roads, pipelines, dams, power lines, and mines.

In accordance with the Energy Strategy of the Russian Federation for the period up to 2035, the level of annual oil and gas condensate production is planned at 490–555 million tons, and gas, at 860–1000 billion m^3 [1]. These volumes will be provided by the development of hard-to-recover reserves of the continental part of the country and new deposits in the northern part of Western and Eastern Siberia [2]. The vast majority of promising oil and gas horizons are located in the permafrost zone of Russia. The development of hydrocarbon resources entails a large-scale development of energy and transport infrastructure.

The possible damage during the warming cycle, which lasts for decades, to industrial and civil facilities located only in the Arctic zone of the Russian Federation could be about ₽7 trillion [3]. Damage to fuel and energy facilities has not been assessed; new planned industrial facilities in the permafrost zone may multiply the damage from warming.

At present, due to the lack of systematic historical data and comprehensive monitoring of the permafrost zone, it is not possible to predict changes in the state of permafrost soils in relation to new investment projects of the fuel and energy complex in the permafrost zone of Russia for a period of more than 3–4 years. The possibility of a reliable forecast for the medium term (15–50 years) and long term (over 50 years) is limited primarily by the accuracy of climate forecasting and the lack of data exchange on background and geotechnical monitoring between fuel and energy companies within the regions and at the federal level. The upcoming Federal Law On Industrial Data should become the basis for solving this problem.

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IMPACT OF FEC ACTIVITIES ON THE ENVIRONMENT

FEC facilities have a variety of impacts on the natural environment of the Arctic. The largest herd of deer in the world is concentrated on the territory of the Yamalo-Nenets Autonomous Okrug, which, according to approximate estimates, is about 750000 head. Eighteen thousand representatives of indigenous minorities living in the district lead a traditional nomadic lifestyle: they are engaged in reindeer herding, fishing, and collecting wild plants [4]. One of the most serious problems of the FEC impact on the life of reindeer herders is the reduction in pasture area. This problem is caused by the following factors. The first one is associated with violation of the moss cover and its pollution as a result of poor-quality reclamation of the territories of decommissioned facilities and regular environmental accidents at FEC facilities [5]. The second factor is the obstacles to the movement of deer, which are created by linear structures. Roads and pipelines cut off the migration routes of wild reindeer and also significantly reduce or change the traditional routes of nomadic reindeer herders [5]. The scale of pasture reduction in different regions varies greatly depending on the anthropogenic load of FEC enterprises, reaching 25% in some places [6]. In the course of the reduction of pastures in many areas of the tundra, the trend towards overgrazing of reindeer that has arisen in recent decades, leading to degradation of the vegetation cover, thixotropy, and other soil changes, is intensifying [7]. The development of Arctic oil and gas reserves causes disturbances not only to vegetation and the soil but also to hydrological conditions on the surface, as well as large-scale thermal and mechanical impacts on permafrost soils. In particular, the pollution of rivers by FEC waste has led to a significant reduction in traditional fishing activities for the inhabitants of a number of Arctic regions. The increase in permafrost thawing areas and the change in the dynamics of ice and snow cover formation help reduce the periods of transport accessibility of small remote settlements and also significantly reduce the spatial mobility of hunters and gatherers. To minimize these problems, it is important to integrate geoecological and geocryological monitoring with ethnological expertise [8].

EXPLORATION AND DEVELOPMENT OF HYDROCARBON DEPOSITS

The issue of permafrost thawing is especially relevant at Russian gas deposits, since all the main giant gas fields developed by PAO Gazprom (Medvezh'e, Urengoiskoe, Yamburgskoe, Zapolyarnoe, Bovanenkovskoe, and others), as well as a significant part of gas transportation facilities are located in the permafrost distribution zone [9]. The area of permafrost distribution also includes the territory of new deposits in Eastern Siberia (Chayandinskoie and Kovyktinskoe), which the company has begun to develop.

In the 1970s, design institutes did not have sufficient experience in designing bases and foundations on permafrost soils in the Arctic. There were no methods for predicting changes in geocryological conditions of the territory during industrial development. There was no experience of large-scale application and industrial production of cooling devices.

The main technical solution for the construction of foundations for oil and gas complex facilities on permafrost was the use of metal pipes as piles with their immersion in thawed and permafrost soils using precast and drilled methods. To preserve the permafrost state of the foundation soils and ensure the thermal regime of the design, in fact, the only way used was ventilated undergrounds in the foundations of buildings. In the construction sites outside the contours of the buildings within which there were free-standing structures, the equipment, technological pipeline racks, and the thermal regime of the permafrost was declared by the projects but not provided with special technical means. The changes in permafrost–geological conditions due to direct and indirect thermal effects of buildings and structures, the changes in the conditions of snow accumulation and moisture, the composition and the soil moisture of the seasonally thawed (or seasonally frozen) layer and its thickness were not forecast.

As a result, many construction errors were made during field development, which led to the subsequent development of deformations of buildings, structures, and gas pipelines, emergency situations, premature physical deterioration of facilities and the need for significant repair work, and early decommissioning of facilities. Permafrost soils that serve as the foundations of buildings and structures have degraded: they have passed from a solid frozen state to a plastic frozen state, or have thawed, leading to a partial or complete loss of their bearing capacity.

Based on the results of generalization and systematization of the experience of large industrial construction in the north of Western Siberia and the introduction of modern design and construction technologies on permafrost soils, Gazprom has formed a technical policy in the field of permafrost geotechnics, primarily due to the experience of the Gazprom Dobycha Nadym subsidiary.

Actual observations indicate an increase in the average annual temperatures of permafrost soils. Therefore, when designing new facilities on the Yamal Peninsula, starting with the project for developing the Cenomanian deposits of the Bovanenkovskoe oil and gas condensate field, Gazprom has provided for the reservation of their reliability adjusted for the projected warming value, which, in turn, is based on the results of scientific research (Fig. 1).

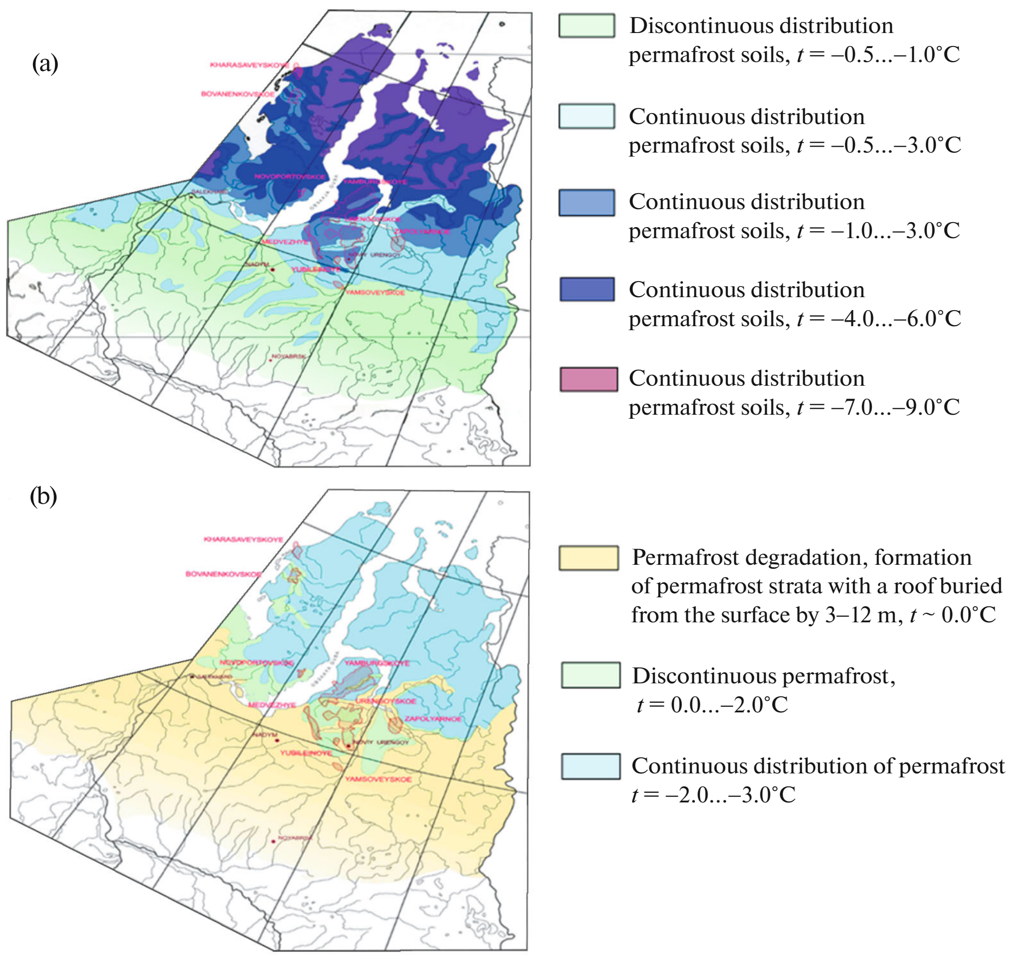

Fig. 1. Dynamics of geocryological conditions in the northern part of Western Siberia at the highest predicted value of the warming trend: the condition (a) by the beginning of the 1990s and (b) by 2050.
Source: according to the Sergeev Institute of Geoecology, RAS, for 2012.

The reliability of the base and foundation is reserved by the design of foundations (pile immersion depths, pile immersion methods, and pile diameters) but mainly by thermal stabilization systems, including seasonal cooling units (SCUs). When designing facilities, the calculated temperature regime of permafrost soils of the bases is substantiated by modeling using specialized software products that implement numerical calculation methods, taking into account the forecast air temperature trend. In fact, arrays of permafrost soils with a programmable thermal state and mechanical properties are created in the foundations of facilities under construction.

Let us note new approaches to ensuring the stability of production wells and their sites in the conditions of continuous distribution of ice-rich permafrost soils on the Yamal Peninsula. It is known that the operation of production wells in permafrost conditions is accompanied by the formation of wellhead thermokarst subsidence, deformations of well piping, and, in some cases, loss of tightness of threaded joints and curvature of casing strings caused by the thawing and deformations of the permafrost hosting wells.

At the PAO Gazprom fields in the Yamalo-Nenets Autonomous Okrug, the upper horizons of gas wells, to a depth of about 120–250 m within the floodplains of large rivers and to 320–340 m within the watersheds (marine terraces), consist of permafrost rocks. During the construction of wells at the Bovanenkovskoe field, for the first time in the company's practice, an integrated heat engineering solution was used to preserve the upper permafrost horizons: the well design provides for heat-insulating lift pipes with vacuum thermal insulation, which are lowered to a depth of 50 to 150 m from the wellhead. Vapor–liquid tubular thermal stabilization systems are installed in wellhead zones. Gas well clusters were placed on the territory of the fields taking into account the results of specialized geocryological mapping and permafrost-parametric drilling (Fig. 2). The experience of the first years of operation of the Bovanenkovskoe field showed that the technical solutions implemented were fully justi-

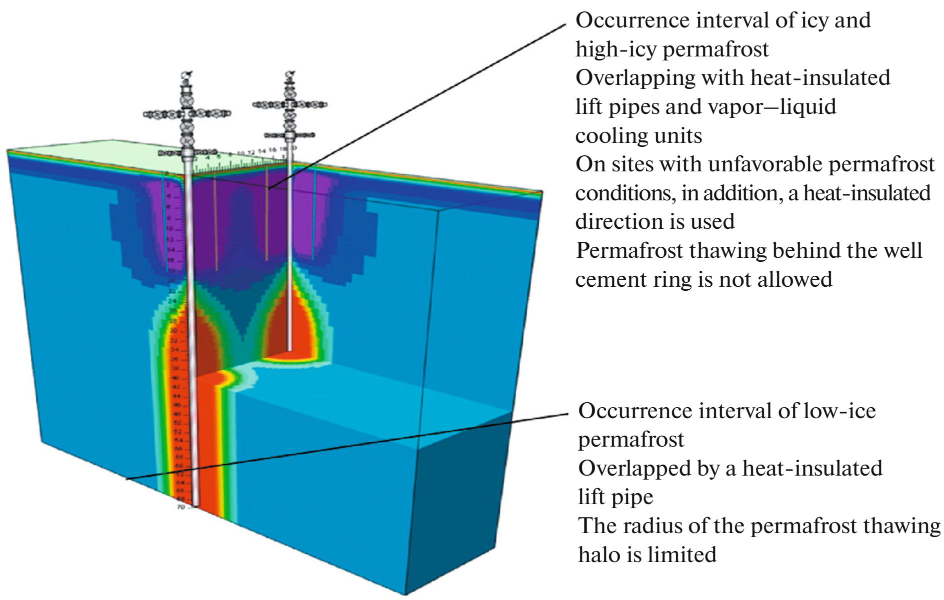

Fig. 2. Technical solutions for thermal stabilization of permafrost soils in the wellhead zones of production wells.
Source: based on the materials of OOO Gazprom design.

fied. In addition, the use of integrated solutions for thermal stabilization of wellhead zones made it possible to bring them closer in the well cluster from the traditional 40 to 20–15 m, which significantly (up to 30%) reduced the cost of well cluster construction due to the reduction in their size, and a significant economic effect was obtained.

At the Kharasaveiskoe field, which is characterized by even more difficult geocryological conditions than the Bovanenkovskoe field, along with heat-insulated vacuum lift pipes, additional heat-insulated casing strings with polyurethane foam insulation were also used to insulate production wells.

OIL AND GAS PIPELINE TRANSPORT

At the end of 2016, the operating length of the main gas pipelines in Russia was 179000 km, and that of the main oil pipelines and oil product pipelines, 71000 km [10]. The total length of Transneft's main oil pipelines is 7049 km, of which 1252 km are in the Arctic zone of the Russian Federation. At the same time, on oil pipelines in the Arctic, the soil temperature is measured by the Russian oil pipeline company monthly using 5348 thermometric wells.

Transport facilities, due to their large length, are distinguished by a significant variety along the route in terms of natural conditions and applied technical solutions [11]. Therefore, standard approaches and methods for assessing natural and man-made hazards are applicable only after zoning the pipeline route and segmenting it into sections that are similar in terms of natural conditions and applied technical solutions [12].

The impact of pipelines on permafrost soils can be divided into three types depending on the type of anthropogenic impact: mechanical disturbances of the soil surface; thermal effects of engineering facilities; and disturbances of surface runoff in the areas of construction of road embankments, equipment of a pipeline trench, or an earthen rampart above it. Such impacts ultimately lead to a violation of heat transfer through the surface and a change in the thermal regime of permafrost soils. The secondary consequences of changes in geocryological conditions entail the activation of engineering and geological processes and give rise to new natural hazards, such as landslides or floods [13].

The thawing of permafrost soils and ice at the base of engineering facilities leads to uneven soil settlements and deformations [14]. The development of uneven settlements and, as a result, a change in the design-vertical position in different sections of the pipe can lead to a violation of its stress–strain state and subsequent possible ruptures.

Under the thermal effects of engineering facilities in the land right of the main pipeline, one should first of all understand the warming effect of the pipe and the formation of a thawing halo in frozen soils. It is important to take into account that oil pipelines are almost always heated to positive temperatures, and gas pipelines have different temperature conditions, depending on the intensity of gas cooling at compressor stations. The formation of a thawing halo and the subsequent sedimentation of the soil entail a change in the position of the pipeline and the occurrence of emergency situations. Mathematical formulations of the problems of permafrost defrosting are widely presented in the literature and methods for their solution are given [15].

Problems arise when pipelines cross landscape transition zones with high-intensity natural processes. Such zones include, in particular, the shores of rivers, lakes, and seas [16].

In addition to geotechnical problems of construction and operation of main pipelines, it is also necessary to pay attention to environmental protection issues, since unregulated anthropogenic impacts and the consequences of changes in geocryological conditions lead to environmental damage [17].

THE PRACTICE OF HYDROPOWER PLANT CONSTRUCTION

Russia was the first in the world to demonstrate the experience of building dams in the permafrost zone in 1776 on the rivers of Transbaikalia [18]. At the same time, the idea was born to use frozen soil as an impervious barrier in dams. So, in the years 1780–1792, in Petrovsk-Zabaikal'skii on the Mykyrt River, the first frozen-type earth dam 9.5 m high was erected. E.V. Bliznyak [19] was the first to formulate the principles of construction of earth dams in permafrost. In areas with permafrost, the frozen state of the dam core and foundations is preferable. The reliability of dams depends on the mechanical characteristics of the frozen ground. Water infiltration is not allowed; otherwise, over time, the water will contribute to the thawing of the surrounding soils, leading to dam failure.

In the 20th century, several dams appeared in the permafrost zone of North America, in particular, a 31-m high one on the Little Chena River (Alaska) and one 36.6 m high on the Nelson River (Canada) [20]. Currently, seasonal cooling units (SCUs) are widely used to freeze earth dams [21]. However, freezing systems are not always effective. An example of this is some hydraulic structures in Yakutia, Magadan oblast, and in the northeast of Russia, which require large annual costs to maintain in a frozen state. Dams with a significant height operate according to the thawed, or rather, mixed principle—Vilyuiskaya, Kolymskaya, Kureiskaya, and Khantaiskaya hydroelectric power plants. In general, they turned out to be more reliable, which is mainly due to the high degree of design and survey work, as well as the quality of construction and monitoring at all stages of construction and operation. However, these dams also experience problems associated with the formation of a cryogenic regime in the body and foundation of the structure [22].

Experience in the construction of hydropower facilities in the permafrost zone made it possible to identify the features of their construction. The most favorable period for the construction of hydroelectric facilities, paradoxically, was winter. Thus, during the construction of the Vilyuiskaya HPP-1 and HPP-2, a "dry" method was proposed, which consists in the fact that the reserves of fine soils for winter laying are created in summer as they thaw and are laid in piles for winter storage. This method was further developed at the Ust'-Khantaiskaya, Kureiskaya, Kolymskaya, and Ust'-Srednekanskaya HPPs [23].

In Russia, several methods of dam construction have been worked out: the method of layer-by-layer freezing of soil (a dam of 7 m on the Nalednaya River in Norilsk) [24]; the dry method used at the Ust'-Khantaiskaya, Kureiskaya, Kolymskaya, and Ust'-Srednekanskaya HPPs [23]; and the cold stamp method used at a hydroelectric complex in Yakutia (Markha River) for freezing talik. As a result of the use of the latter, the talik was stabilized in one winter period and its dimensions decreased in depth from 6 to 3 m and in width from 20 to 10 m. The temperature of the rocks decreased from –1 to –4°C, and the filtration flow downstream was stopped [24]. Medium and low head dams experience the greatest problems under warming. In this regard, the experience of operating dams on the Myaundzha River in Magadan oblast and on the Matta River in Yakutia is interesting. The thermal state of the dam on the Matta has changed. The right wing has turned into a thawed state (the soil temperature down to a depth of 10 m has increased to +5°C), and the left wing remains frozen, but the temperatures have increased from –3 to –2°C, which brought the hydroelectric complex to a critical state of stability [22]. In general, despite the positive experience in the construction and operation of hydroelectric facilities in the permafrost zone, the issue of ensuring their sustainability is acute. Work continues to improve regulatory documents. The updated version of SP 39.13330.2012 requires revision of the section on hydraulic structures in the permafrost zone [20].

Dams built in such areas require geotechnical monitoring of permafrost soils. Typical problems include seepage of water through the dam, thawing of permafrost around the spillway, changes in dam height, SCU failures, and thawing and erosion of the reservoir banks. An increase in volume due to bottom settlement during thawing was found near the Ust'-Khantaiskoe reservoir, the design level of which was reached only 20 years after filling. However, in the Vilyuiskoe reservoir, due to the engineering–geological structure of the bed and banks, the increase in the volume of the reservoir from 1967 to 1982 is estimated at only 0.05 km^3, or 0.14% [22, 25]. The hydroelectric dam on the Vilyui River was built in such a way that it covers the valley between frozen rocks with ice filling the cracks. After it had been erected, they found that part of the water flow moved along the cracks and was lost. Losses are observed even now; they are unpredictable, posing a potential threat to the facility. Convection can transfer heat with water to the dam, which leads to its thawing and destruction, as was observed at some sites in Russia [26] and Canada.

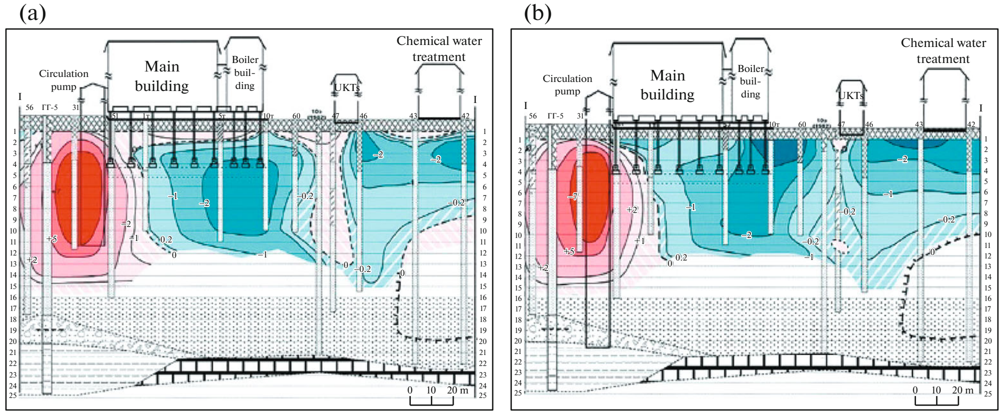

Fig. 3. Average annual soil temperatures at the base of the Yakutsk TPP for (a) 2013 and (b) 2017 with the layout of observation wells [27].

THERMAL POWER PLANTS (TPPs)

The Yakutsk TPP was put into operation on November 7, 1937. The TPP building is one of the first large industrial facilities in the country and the world, built on the principle of using soil as a foundation in the frozen state. Geocryological monitoring was organized on the territory, and 54 wells were drilled. Observations showed that the nature of changes in the average annual temperature of the foundation soils coincided with the interannual variability of air temperature, apart from the areas of activation of the thermal anthropogenic impact. Over 80 years of operation, problems arose in ensuring the stability of structures due to the partial thawing of permafrost soils, mainly due to leakage of heated industrial waters. Thus, in 1986, the total volume of aufeis ice formed under the main building of the Yakutsk TPP was about 600 m^3 [27]. In 1967, to freeze the soil near the wall of the main building, multipipe seasonally operating cooling units of the Gapeev system were installed.

In 2009–2010, thawing of soils occurred, but in 2011, the restoration of the temperature regime of soils in the range of 1.7–2.6°C began (Fig. 3b). The building is still in operation; the columnar foundations 4.5 m deep are in a satisfactory condition.

However, there are several negative examples regarding power plants. The building of the diesel boiler house at the Gorizont site near the village of Amderma experienced a settlement of 1 m due to pile deformations at the base, composed of saline loams, as the base temperature increased slightly (up to 1°C). The building of the boiler house on Lenin street in the village of Amderma experienced settling exceeding 1.5 m. Of the 19 small thermal and electric plants in this village, only two have minor deformations, and ten are in a disastrous condition. One of the largest man-made disasters—the destruction of the concrete base of a reservoir with diesel fuel for a power plant—occurred on May 29, 2020, 12 km from the central district of the city of Noril'sk, due to the settling of permafrost soils. Rosprirodnadzor estimated the amount of environmental damage from a spill of 21 000 tons of fuel at TPP-3 of PAO Noril'sk Nickel at almost ₽148 billion.

CONSTRUCTION OF ELECTRIC TRANSMISSION LINES IN THE CRYOLITHOZONE

When the intensive development of Siberia began in the 1960s, five transmission networks had to be installed throughout the country. The eastern, central, and northern lines had to cross the permafrost zones. The Northern Energy System crosses over 86 000 km of territory.

The main problems for the construction of power transmission lines in the permafrost zone are frost heaving, subsidence during thawing [28], ice formation, changes in vegetation cover, and desertification and degradation of permafrost soils [29]. Frost heaving is the biggest problem in Russia and North America. In Alaska, there have been cases of 10-m piles rising by 1–2 m due to frost heaving, which led to high repair costs [30]. In Russia, heaving with a growth gradient of up to 20 cm/year was found north of Tyumen'. After 20 years of operation, the maximum deviation of electric poles can be 2.5–2.7 m [31]. In northeast China, several power poles collapsed due to frost heaving.

In the United States and Canada, shallow foundations are used for low-voltage transmission lines. For example, the Ontario transmission route with a single-loop 115-kV line is equipped with vertical wooden piles with steel cantilevers and an average span of 150 m. The piles are placed in drilled holes 2.4–2.7 m deep, which are filled with backfill soil. In humid areas, they can be placed in corrugated iron round caissons filled with rock fragments.

In Russia, 6–10-kV power line foundations use steel pipes or stainless steel screw piles installed at a depth

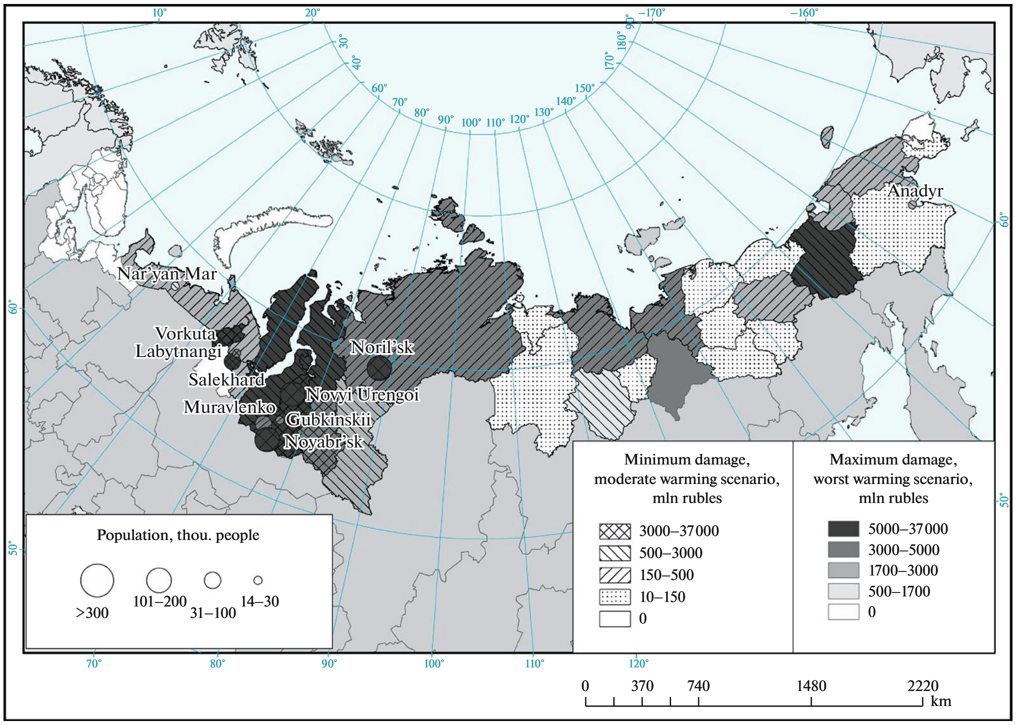

Fig. 4. Distribution of possible damage to fuel and energy facilities by municipalities of the Arctic zone of the Russian Federation.

of 5–9 m. For 35–110-kV and 220-kV power lines, the pile diameter is increased to 630 or 720 mm with an installation depth of 10–30 m, which depends on the stress, type of permafrost, location of the line, and frost heaving forces [32].

ECONOMIC CONSEQUENCES OF PERMAFROST THAWING IN THE ARCTIC ZONE OF THE RUSSIAN FEDERATION

One of the objectives of this study is to assess the damage to fixed energy assets at the mesolevel, that is, to obtain numerical results for the permafrost territory of the Russian Arctic zone. Since this work is pioneering for Russia, an initial small-scale assessment is necessary with the prospect of further refinement and expansion of the results obtained. We propose to estimate the magnitude of damage from changes in engineering and cryological conditions for buildings and structures of the key energy subsector that are most socially significant, especially in Arctic conditions—the provision of electricity, gas, and steam and air conditioning. It includes activities for the supply of electricity and heat, gas, steam, and hot water using a permanent infrastructure (network) of pipelines and transmission lines. The key buildings and structures in this case are power plants of all types, power lines, gaseous fuel production facilities, gas pipelines (excluding trunk lines), boiler houses, and heating networks.

To estimate the cost of energy buildings and structures at the level of municipalities, the methodology developed and tested by the authors in previous works [33, 34] was applied. It is based on the principle of structural homogeneity, identified for certain groups of socioeconomic indicators, to reevaluate unknown parameters at the municipal level. Briefly, the algorithm consists of the following steps:

(1) It is assumed that the indicator of the cost of fixed assets by the type of economic activity—provision of electricity, gas, and steam and air conditioning—in each municipality is proportional to the volume of gross production in this industry (the regional value of the cost of fixed assets for 2019 is distributed in appropriate proportions).

(2) Isolation of the total cost of fixed assets of buildings and structures as the most susceptible component to the degradation of permafrost soils (through calculated industry-average reduction factors). The reduction factor for the industry "production and distribution of electricity, gas, and water," according to our calculations, is 0.63 (2019 data).

According to the calculations, the total cost of buildings and structures for the type of economic activity "production and distribution of electricity, gas, and water" in the Arctic zone of the Russian Federation is about ₽368 billion. Based on our earlier published estimate [3] and using the same method, by 2050 the total damage to this industry, in the event of continued warming and a decrease in the bearing capacity of foundations, could range from ₽128 to ₽244 billion. The distribution of possible damage by the municipalities of the Arctic zone is shown in Fig. 4.

MONITORING OF PERMAFROST SOILS IN THE FEC

Over the past 20 years, there has been a tendency toward an increase in the temperature of permafrost soils. In the Russian Federation, the temperature of the upper horizons has increased by an average of 2°C over the past 30 years. The system of automated geotechnical monitoring of permafrost at each FEC facility in the short term (5–10 years) will become uncontested.

To obtain practical production results, it is necessary to combine the monitoring systems of individual FEC enterprises into one software-analytical system with the ability to predict changes in permafrost in the period from one week to several years within the boundaries of individual subjects of the Russian Federation and in the whole permafrost zone of the country. The FEC monitoring system should serve as the basis for the planned fundamental system for monitoring permafrost soils throughout the Russian Federation.

It has been practically proven that the use of only relatively available data on the average annual air temperature will not make it possible to predict the change in permafrost. A set of methods is required: remote sensing of the earth (ERS), geophysical methods, and a geotechnical control system, including observation wells and ground surveys. Remote sensing methods, including aerial photography and satellite imagery with the development of a satellite constellation, make it possible to estimate the surface temperature, the distribution and thickness of snow cover, surface water, the structure of vegetation cover, the consequences of economic activity, and changes in the relief, indicating the thawing of permafrost soils, for example, the appearance of new thermokarst lakes. Data from remote sensing received regularly will make it possible to assess the variability of permafrost on the scale of the subjects of the Russian Federation, taking into account short-term and long-term climatic fluctuations. The use of geophysical methods to obtain data on the distribution and thickness of permafrost, the ice content, and the thickness of its active layer is especially important in Russia with a well-developed industry of geophysical services, primarily for the oil and gas industry. Geophysical methods, primarily electrical and seismic prospecting (borehole and surface), allow obtaining detailed information about the geocryological structure of the section on a large scale, the physical and mechanical properties, the ice content, and the moisture content of the active layer and permafrost. As in the oil and gas industry, geophysical data must be confirmed by the equipment of parametric wells with regular observations.

Industrial and civil buildings and structures require the development of systems for monitoring and calculating the stress–strain state. At all FEC facilities of the Arctic zone, in order to prevent environmental disasters, it is necessary to implement a geotechnical control system to ensure the mechanical safety of buildings and structures as far as the stability of their bases and foundations is concerned. The geotechnical control system is considered as an integral part of the production operational control of buildings and structures and the industrial safety system. The geotechnical control system implies the creation of specialized units and geotechnical monitoring services—centers of responsibility for this area of work.

Geotechnical control at all stages of the existence of facilities, starting with their design and engineering surveys, including the stage of construction and operation, solves the following set of objectives:

- continuous instrumental monitoring of the dynamics of geocryological conditions in the foundations of engineering facilities and the spatial position of supporting structures, equipment, and pipelines and their compliance with design and regulatory requirements;
- monitoring the dynamics of dangerous exogenous permafrost–geological processes in the zone of potential impact on engineering structures;
- integrated geotechnical forecast of the dynamics of geocryological conditions and the stability of bases and foundations, including the use of numerical methods of thermal engineering and thermomechanical modeling;
- monitoring the stress–strain state of buildings, structures, equipment, and pipelines using instrumental and calculation methods;
- control over the process of designing bases and foundations of facilities, including the volume and quality of engineering surveys, selection of construction sites, making fundamental construction decisions;
- development and implementation of technical measures to prevent unacceptable deformations of buildings and structures, stabilization of bases and foundations;
- improvement of the regulatory and methodological base for design and construction on permafrost soils.

* * *

In order to continue the economically justified industrial development of permafrost territories, including the Arctic zone of the Russian Federation, the participants in the fuel and energy complex of the country in the next three to five years must solve several priority tasks. First of all, it is necessary to analyze the possible damage as a result of permafrost degradation at the facilities of the oil and gas, electric power, and coal industries in the period up to 2050. In this work, it is necessary to take into account the capital and operating costs of FEC companies.

Today, the background monitoring of the natural environment in the Russian Federation by the institutions of the Russian Ministry of Natural Resources, the Russian Academy of Sciences, and the Russian Ministry of Education and Science is carried out in insufficient volume. Geotechnical monitoring, partially including temperature measurements, is carried out by FEC companies, as well as by regional organizations using various methods and in an incomplete scope, often without taking into account natural trends and surface conditions and appropriate analysis and forecasts, and also without a data exchange system.

An important part of adaptation to climate change should be a governmental system of geocryological monitoring of the state of the permafrost, including both observations and their analysis and development of forecasts and technical solutions for engineering protection. As a first step, it is possible to implement pilot projects in the form of regional systems for monitoring permafrost soils at FEC facilities based on individual constituent entities of the Russian Federation, where permafrost occupies a significant part of the area and where the problems of climate change, the state of permafrost, and ensuring the stability of buildings and engineering structures are most relevant. Pilot regions can be the Yamalo-Nenets Autonomous Okrug, the Nenets Autonomous Okrug, Krasnoyarsk krai, the Republic of Sakha (Yakutia), and other regions.

At the same time, it is necessary to carry out systematic work on import substitution of equipment for permafrost monitoring and stabilization, the creation of sectoral technical specifications for the domestic electronics industry for thermal sensors, connectors, microcontrollers, indicators, instrument cases, batteries, and digital processing equipment. Currently, domestic components include only cable products and test thermostats in Russian permafrost monitoring systems. The analysis of a large amount of data requires the participation of artificial intelligence systems.

Taking into account the predicted warming trend in the Arctic, when designing capital construction projects on permafrost soils, special attention should be paid to ensuring the backup of the reliability of bases and foundations and the development of advanced stabilization methods. Now the optimal types of permafrost stabilization are various seasonal cooling devices that make up no more than 5% of the capital costs for the construction of buildings and structures. However, the development of new methods for ensuring the stability of bases and foundations is also required.

In the field of legal regulation, it is required to develop new and updated industry standards for the design, construction, and operation of FEC facilities in the Russian permafrost zone, including the standardization of soil temperature measurements that provide an accuracy of 0.1°C over the entire range of measured soil temperatures when external conditions change from –40 to +50°C.

Russia has only one active law on conducting business activities in the permafrost zone, On the Conservation of Permafrost in the Republic of Sakha (Yakutia), no. 1572-V, adopted on May 22, 2018. In 2021, to create the legal basis for the state permafrost monitoring system, the Russian Ministry of Natural Resources proposed to amend two federal laws: On Environmental Protection and On Hydrometeorological Service. In addition to these initiatives, there is a need to develop a draft Federal Law On Permafrost based on the relevant law in force in the Republic of Sakha (Yakutia).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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