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MODERN ASSESSMENT OF TECHNOGENIC GEOCRYOLOGICAL CONSEQUENCES OF NATURAL RESOURCE MANAGEMENT IN RUSSIAN NORTH

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The article shows the relevance of rational use problems of natural resources and the reproduction of natural resources of the Russian North in relation to the permafrost. Large-scale projects as the construction and operation of the gas pipeline called the Power of Siberia and the oil pipeline East Siberia-Pacific Ocean, development of the largest diamonds, gold, coal and uranium deposits significantly influence on this direction. The main aspect of permafrost development associated with its instability under diverse influences and due to its properties and composition is particularly considered. A special landscape approach is highlighted in studying the consequences of development using the concept of "landscape stability". The direction of mining consequences for the permafrost can fundamentally vary depending on the natural conditions of the field. Using various objects (transport, pipeline, mining and etc.) as an example shown that mechanical disturbances are most significant for the permafrost zone arising during the construction and operation of engineering structures, laying of linear communications and mining activities. The most distinct and dangerous for a variety of geotechnical objects of the permafrost zone is the activation of exogenous processes such as thermokarst, thermoerosion, swelling, and etc. Particular emphasis is placed on the fact that the geocryological methods of footings and foundations on the permafrost grounds can improve engineering and geological conditions of the developed territories with any complexity.

Keywords: *rational use and reproduction of natural resources; permafrost grounds; cryogenic processes; compensation measures systems.*

СОВРЕМЕННОЕ СОСТОЯНИЕ ТЕХНОГЕННЫХ ГЕОКРИОЛОГИЧЕСКИХ ПОСЛЕДСТВИЙ ОСВОЕНИЯ ПРИРОДНЫХ РЕСУРСОВ РОССИЙСКОГО СЕВЕРА

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В статье показана актуальность проблем рационального природопользования и воспроизводства природных ресурсов Российского Севера применительно к территории развития многолетнемёрзлых горных пород. Особое значение это направление приобретает также в связи с реализацией таких масштабных проектов как строительство и эксплуатация, соответственно, газового, названного «Сила Сибири», и нефтяного – «Восточная Сибирь – Тихий Океан» трубопроводов, разработки крупнейших месторождений алмазов, золота, угля, урана и т.д. Особо рассматривается основной аспект освоения мёрзлых толщ горных пород, связанный с их неустойчивостью при разноплановых и разноуровневых воздействиях и обусловленный их свойствами и составом. Освещён специальный ландшафтный подход при изучении последствий освоения с использованием понятия «устойчивость ландшафта». На примере разнообразных объектов (транспортных, трубопроводных, горнодобывающих и т. д.) показано, что для криолитозоны наиболее суще-

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ственны механические нарушения, возникающие в ходе возведения и эксплуатации инженерных сооружений и добычи полезных ископаемых – прокладка линейных коммуникаций, горнодобывающая деятельность. Наиболее отчётливым и опасным для разнообразных геотехнических объектов криолитозоны последствием является активизация экзогенных процессов, в числе которых преобладают изменения деструктивного характера: термокарст, термоэрозия, пучение и т. д. Особый упор в статье сделан на том, что существующие в инженерной геокриологии методы стабилизации фундаментов и оснований на мёрзлых грунтах могут улучшить инженерно-геологические условия осваиваемых территорий любой сложности.

Ключевые слова: *рациональное природопользование, воспроизводство природных ресурсов, многолетнемёрзлые породы, вечная мерзлота, криогенные процессы, системы компенсационных мер.*

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Introduction. The problems of rational nature management and reproduction of natural resources of the Russian North remain relevant for many decades. The first attempts to develop the northern territories have already led to large-scale consequences and serious problems in connection with the need to develop a system of compensation measures, their implementation and monitoring the effectiveness [11, 23].

This direction also acquires special significance in connection with the implementation of such large-scale projects as the construction and operation of gas pipeline called as the Power of Siberia, and the oil pipeline East Siberia-Pacific Ocean (ESPO), and the development of the largest deposits of gold, coal and uranium in South Yakutia.

The areas of permafrost development increased by 15–20%, thickness by 20–40 m, but the temperature at a depth of 12 m decreased by 0.6°C according to the results of Melnikov Permafrost Institute (MPI) researches during the development of the Taezhnoye iron ore deposit in South Yakutia [24], thereby reflecting a significant severity of permafrost conditions. Such fairly active and large-scale changes are associated with disturbances, and sometimes even destruction of the soil cover, in local climatic conditions leading to redistribution of snow cover and changes in the heat transfer conditions of the upper horizons of ground with the surface atmospheric stratum.

In the gold deposits of the Kuranakh group the changes had the opposite trend where the ground temperature during mining increased by 0.4–0.8°C that led to a reduction in the area of permafrost islands of frozen rocks, and its complete thawing in some cases. This happened as a result of changes of hydrological and hydrogeological conditions during the development of the facility. Thus, the direction of the mining consequences for the permafrost can fundamentally be changed depending on the natural conditions of the deposits.

The implementation of not complicated rules will reduce the serious negative consequences of the territories development formed by permafrost.

Special approaches to studying the development consequences. The emergence and activation of exogenous geological processes is also advisable to consider from the perspective of the landscape approach, which is based on the concept of the landscapes stability to disturbances [15, 16]. It is usually understood as the ability of a geosystem to withstand the technogenic activation of cryogenic processes with corresponding changes in the natural complexes, in uncontrolled development can lead to irreversible environmental degradation and unacceptable engineering structures deformation. This direction has been successfully developing for many years under the supervision of A.N. Fedorov [17, 18] at MPI.

The systematic approach to the assessment and mapping of the permafrost component of landscapes with the aim of identifying areas with varying degrees of danger to engineering structures has become particularly relevant recently. All factors are typified by three or four grades of risk of the development consequences and then compared in accessible ways. In this case a simple summation of points is excluded, since the landscape response to the activation of hazardous processes taking into account their natural value is encoded in the final score [15]. Various mathematical methods such as correlation, regression, cluster analysis, and others are used to identify the relation of factors.

In using the landscape base and database with specific values, each thematic factor should be displayed in a separate layer (ice content, soil temperature) and then use its overlay. This is quite time-consuming and not always objective. An express assessment of such heterogeneous indicators with the derivation of integral index-coefficients of permafrost sustainability and environmental danger is carried out to facilitate the mapping [15]. The assessment procedure using these indices is as follows [16]: selection of environmental danger factors, compilation of a grade scale chart, assigning a score to each landscape, landscapes ranking by vulnerability to development due to gradations of calculated indices and evaluation mapping.

The main consequences of cryolithozone technogenesis. The mechanical disturbances arising during the construction and operation of engineering structures and mining activity are the most significant for the permafrost zone. The most distinct and dangerous consequence for various geotechnical objects of permafrost is the activation of exogenous processes.

Following cryogenic processes develop as a result of technogenesis under cryolithozone conditions.

Thermokarst is closely associated with the development of large reservoir-forming masses of ground ice and ice-covered Quaternary sediments, confined to floodplain plots, I and II floodplain terraces in the valleys of watercourses and on flat or slightly curved watershed spaces. Two generations can be distinguished among thermokarst forms. First form of thermokarst micro relief includes minor depressions saucers and hollows. The minor depressions are oval-shaped depressions with a diameter of 2–3 m and a depth of 0.2–0.3 m formed by melting of thin layers of migration ice. The hollows have approximately the same size, but more elongated configuration.

The origin of thermokarst forms is due to the general changes in the conditions of heat exchange of the day surface in individual areas.

Thermoerosional origin has depressions formed by this process with a depth of several meters and a length of hundreds meters (Fig. 1, 2). Another generation of the process is erosion cuts, which have several stages of development, depending on the thickness and ice content of the slope deposits. Particularly, erosion cuts weakly expressed on the ground with a depth of only 20–30 cm are usually confined to the slopes of medium steepness with low thick and low-ice deluvium. The erosion cuts of this generation are characterized by straightforwardness.

Delli on gentle slopes are significantly expressed on the terrain, overlained by heavy ice deposits. Such thermoerosional forms are well developed, have a depth of 2–2.5 m and a width of 30 m.

Compared to thermokarst and thermoerosion, the effect of frost weathering, which is most active in the clay-carbonate rocks of the Cambrian and Ordovician, and forming a rather thick (2–7 m) cryogenic weathering crust, which differs sharply from underlying bedrock in its properties.

Fig.1. Frost fissure along the ESPO pipeline. Photo by L.A. Gagarin.
Рис. 1. Морозобойные трещины по трассе нефтепровода «ВСТО». Фото Л.А. Гагарина.

Fig. 2. Thermoerosion along the ESPO pipeline. Photo by I.V. Dorofeev.
Рис. 2. Термоэрозия по трассе «ВСТО». Фото И.В. Дорофеева (см. цв. фото на 2 с. обложки).

Frost heaving of seasonal cycle soils occurs on the areas of lake-alluvial and lake-bog development, alluvial sediments of floodplains and low terraces, where a hummocky and tuberous-lowland microrelief is formed. The diameter of the bumps is 30–50 cm, the height is 10–30 cm, rare up to 1.5 m across and 0.3–0.4 m high.

Long-term frost heave is confined to the sites of peatland development. Formed in this separate slightly convex perennial swelling hummocks have a height of several meters.

Frost-cracking is developed only under the condition of a combination of the necessary factors such as high soil moisture and its low temperatures, which cause large temperature gradients in the active layer.

Using the example of one of the largest oil trunk pipelines in Siberia "Eastern Siberia – Pacific Ocean" (ESPO), we show the whole variety of consequences of the technogenic impact on the permafrost, typical for such grandiose linear structures.

During the design and construction of the pipeline, the opinions on the feasibility and methods of its creation were completely ambiguous [19–21]. Among the public and experts, there were both supporters and opponents of the project with their own thoughts and arguments. The main concerns were associated with the features of the natural environment in the zone of influence of the object, which is characterized by complexity and instability. One of the unobvious, but fundamentally correct in terms of reducing the negative consequences of development was the decision of the creators of the pipeline to lay it underground, proposed and justified at the MPI last century, and confirmed its reliability at number of facilities in Yakutia and Eastern Siberia [22].

The diverse and multifaceted problem-oriented control over the consequences of environmental impacts, including the permafrost and infrastructure facilities showed the level of disruption can be assessed as moderate, limited by a track band with width of several hundred meters. Suggested catastrophic intensification of exogenous processes as a result of special preventive and compensatory measures have been prevented, and all major facilities are in a stable condition. It should be especially noted, during pipeline laying at extra dangerous sections, special technologies were used for increasing its stability. In particular, strongly fractured or highly icy grounds were partially, and often completely, replaced by sediments with better engineering and geological properties. This quite expensive approach, called the "excavation method" [22], is very effective. Its application allowed to increase the reliability (Fig. 3–7).

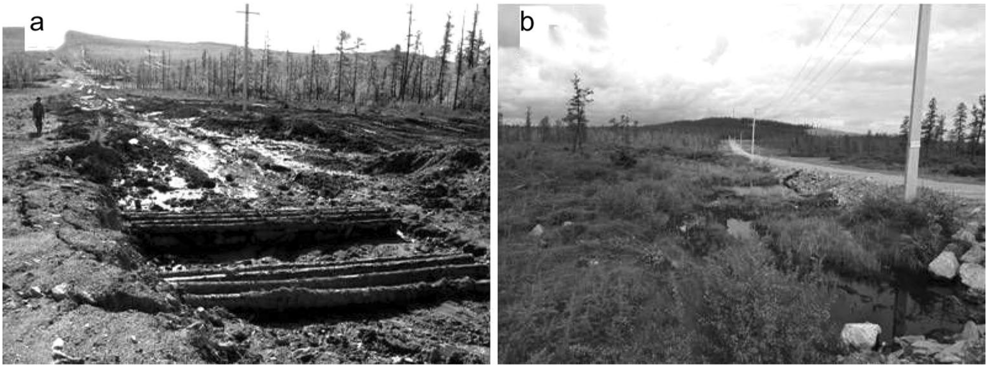

Fig.3. 2362–2364 km of ESPO, Gorbylakh river valley with the active development of thermokarst: a – until the implementation of compensation measures in 2010; b – after 2016. Photo by S.I. Serikov.

Рис. 3. 2362–2364 км "ВСТО", долина р. Горбылах с активным развитием термокарста: а – до проведения компенсационных мер в 2010 г.; б – после 2016 г. Фото С.И. Серикова(см. цв. фото на 2 с. обложки).

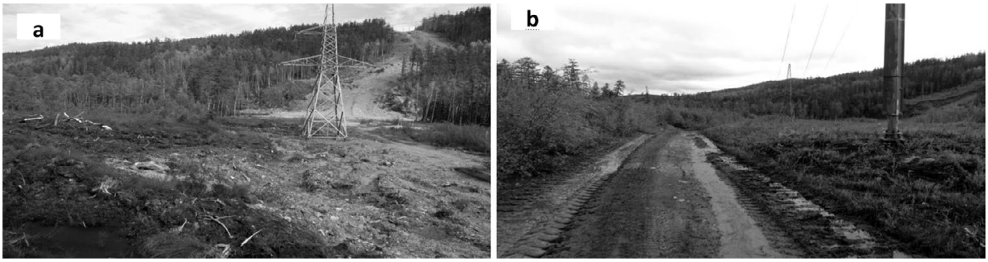

Fig. 4. The damping process of lateral thermoerosion in the area of the Maly Urkan river, 2631 km of ESPO: a – 2010, b – 2016. Photo by S.I. Serikov.

Рис. 4. Затухающий процесс боковой термоэрозии на участке р. Малый Уркан, 2631 км «ВСТО». а – 2010 г., б – 2016 г. Фото С.И. Серикова.

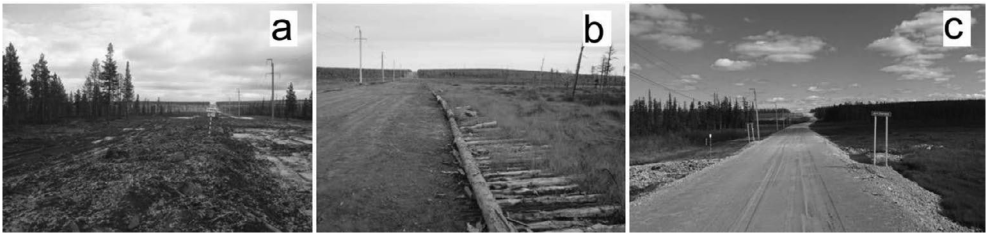

Fig. 5. The transition to the 2125 km of ESPO through the extensive gauge Katera creek: a – 2010, b – 2012, c – 2016. Photo by S.I. Serikov

Рис. 5. Переход на 2125 км «ВСТО» через обширную марь руч. Катера (а – 2010 г., б – 2012, в – 2016 г.). Фото С.И. Серикова

Fig. 6. ESPO sections with an organized technological highway along the pipeline in the conditions of continuous distribution of permafrost. Photo by S.I. Serikov.

Рис. 6. Участки «ВСТО» с организованной технологической автодорогой вдоль трубопровода в условиях сплошного распространения многолетнемёрзлых пород. Фото С.И. Серикова.

The earthquake that occurred on the 12th of December 2016 in the Amur Region with an epicenter 85 km east of Skovorodino with a magnitude of 5 and an intensity of 5–5.5 points became a serious test for the object reliability According to the official deputy of "Transneft" Igor Demin [10], "the impact of such a powerful natural factor did not affect the operation of the pipeline and all ESPO facilities continued to operate normally."

Analysis of Figs. 3–6 convincingly indicates that negative exogenous processes of a destructive orientation (thermokarst, thermoerosion, and etc.), which sharply intensified at the beginning of development, significantly stabilized as a result of correctly selected measures. This made it possible to bring previously disturbed geosystems to a stable state (Fig. 4b, 5b, 6).

In recent years, researchers of Melnikov Permafrost Institute conducted geocryological studies in the areas of ESPO. It has been established that during the operation of the oil transportation system, stabilization of geocryological conditions occurs, which favors an increase in the reliability of the facility. Above the results of compensating measures were given that significantly reduced the negative consequences of the activation of exogenous processes at the beginning of the creation of ESPO. Along with this direction, studies of MPI in all previously developed and repeatedly examined sections of the pipeline have recently recorded a clear trend of decreasing amplitude and lowering the temperature of active layer. So, the average annual temperature of frozen ground in the area on the monitoring geothermal site at the section of the transition "ESPO" across the river Gorbylakh for 2007–16 decreased by 1.1°C – from -1.4 to -2.5°C (Fig. 7). At the same time, on the site of Katera creek (2125 km ESPO), within the development of unfrozen rocks, the amplitude of fluctuations in their temperatures from 2008 to 2016 changed very little and it is close to 4.0-5.0°C – from 1.8 to 6.8°C (Fig. 8).

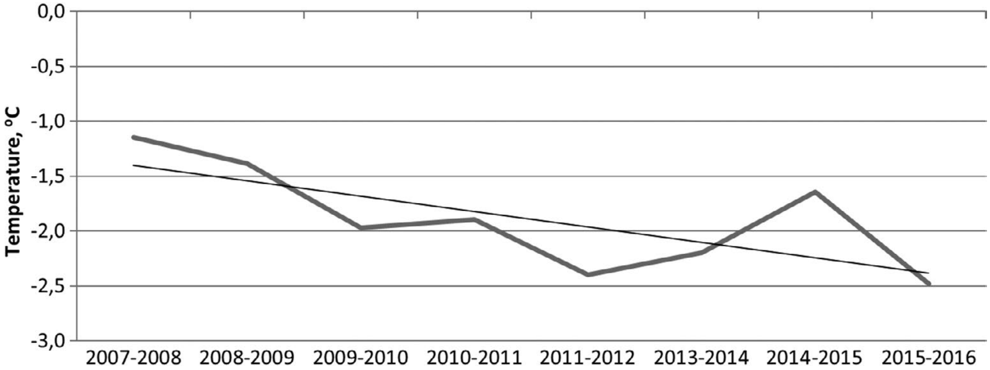

Fig. 7. The average annual temperature at a depth of 1.0 m at the monitoring geothermal site at the ESPO transition section across the Gorbylakh river (2362–2363 km) for 2007–2016.

Рис. 7. Среднегодовая температура на глубине 1,0 м на геотермальном участке мониторинга на переходном участке ВСТО через реку Горбылах (2362–2363 км) за 2007–16 гг.

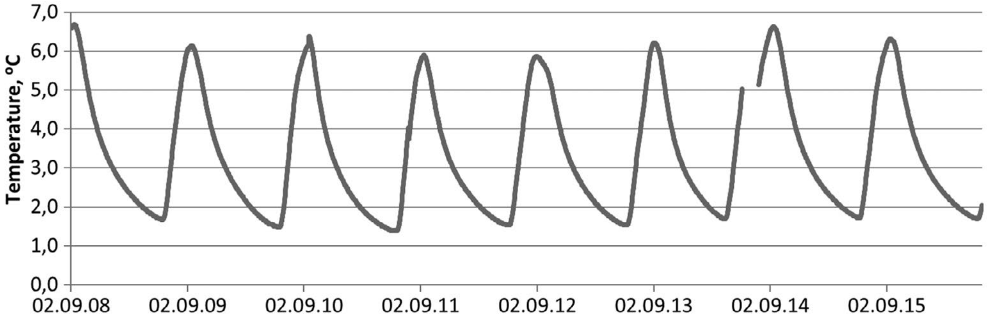

Fig. 8: Long-term course of rock temperature from 2008 to 2016 (at a depth of 1.0 m), section of the Katera creek, 2125 km of ESPO.

Рис. 8: Многолетний ход температуры горных пород с 2008 по 2016 гг. (на глубине 1,0 м), участок ручья Катера, 2125 км ВСТО.

Within the area of the Maly Urkan river (2,631 km of ESPO) a gradual increase in the amplitude of ground temperature fluctuations from 7 to 17°C was recorded from 2009 to 2014., and then until 2016, this characteristic sharply decreased to 5°C (Fig. 9). Thus, changes in rock temperatures occurring in different sections of ESPO, although with different intensities depending on surface conditions, but on the whole clearly indicate a significant improvement in the engineering-geological conditions of the rocks of the route and an increase in the reliability of the pipeline.

In recent years S.P. Varlamov and P.N. Skryabin [5] scientists of MPI using the example of Central Yakutia described in detail the problem of the influence of various

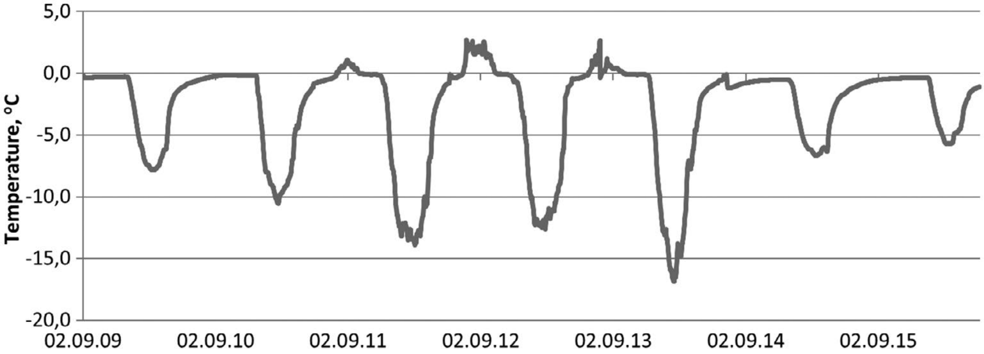

Fig. 9. The long-term course of ground temperature from 2009 to 2015 at a depth of 1.0 m. Site of Maly Urkan river, 2631 km of the ESPO.

Рис. 9. Многолетний ход температуры грунта с 2009 по 2015 г. на глубине 1,0 м. Участок реки Малый Уркан, 2631 км от ВСТО.

types of technogenesis on soil temperature. Various types of disturbance of surface natural conditions are considered: disturbance and destruction of soil cover, fires, and etc., the long-term variability of the average annual temperature of grounds of disturbed landscapes is quantitatively evaluated depending on the types and stages of damage and self-restoration of vegetation. The influence of various engineering objects on the temperature regime of soils is estimated. So car embankments of small height usually have an insulating effect on the underlying soil, as well as in the case of filling with waterlogged material. For railway embankments covered in the cold season, a rise in the upper boundary of the permafrost and penetration of the frozen zone into the body of the object was revealed, and during the filling during the warm period, foci of unfrozen rocks are formed at its base.

To quantify the effect of disturbances on the thermal regime of soils, field observations were organized in the sandy ridge, low terraces, alas, and flat types of terrain [14]. Clear and selective cutting of pine forests in old burnt areas located on the sand ridge and at the top of the watershed led to an increase of the rocks temperature by 0.3–0.5°C and the formation of subpermafrost taliks. Selective cutting in 1992 and fire on a gentle slope with pine-larch in 2002 after 6 years led to an increase of the rock temperature by 0.2°C and an increase of thawing depth by 1.2 m. Selective cutting and ground fire in 1997 on the gentle slope of the watershed with pine-larch increased the rocks temperature by 0.8°C and increased thawing by 0.9 m after 11 years. A sharp increase in the thickness of thaw depth is due to the influence of a high-water spring in the last 2 years.

It has been established that in various types of terrain pyrogenesis leads to an increase in the seasonal thaw depth by 0.3–1.2 m and an increase in ground temperature at the bottom of the layer of annual heat circulation by 0.4–1.1°C. These changes resulting from fires are especially dangerous in the type of terrain with close to surface occurrence at a depth of 1.5–2 m of highly icy deposits with the active development of negative cryogenic processes threaten the stability of engineering objects.

The monitoring studies have made it possible to quantify the spatiotemporal variability of the thermal regime of soils in pyrogenic territories. The dynamics of the thermal state of the rocks is determined by the age of the burnt areas and the stages of vegetation cover development. The research results were used in the construction of the northern section of the Tommot-Yakutsk railway.

Assessment of technogenic effects of on permafrost. Recently, quantitative methods have been developed for assessing the adverse effects of changes in permafrost as a result of technogenesis and forecasts have been compiled for different landscape conditions. In engineering estimates of the geocryological hazards associated with the destruction of buildings and structures on frozen ground, a number of studies have used various options for quantitative forecasts [1–3, 29–31]. In general terms, it was found that the probability of the development of destructive geocryological processes becomes maximum when a large amount of ice is contained in frozen ground, with significant depths of seasonal thawing of soils and disturbance of the soil and plant layer. In such areas precipitation and failure of thawing base soils are possible due to intense thermal karst and thermal erosion.

Areas with the highest geocryological risk include the coast of the Kara Sea, a significant part of the West Siberian Plain, Novaya Zemlya Island, the upper reaches of the Indigirka and Kolyma basins, the southeastern part of Yakutia, Chukotka Peninsula and also part of the permafrost in the north of European territory. In these areas, there is a developed infrastructure of large settlements, in particular gas and oil producing complexes and pipelines, the Bilibino nuclear power plant and related power lines. Permafrost degradation on the coast of the Kara Sea can lead to a significant increase in coastal erosion, the coast will recede annually by ten meters, as it is currently happening in the eastern Arctic sector [13].

The particular danger is the permafrost thawing on Novaya Zemlya in the territory of radioactive waste storage. At the same time, in large areas of Yakutia and Western Siberia, the reliability margin of engineering structures and permafrost structures, calculated taking into account modern climatic trends allows them to remain in a stable state.

Another consequence of technogenesis in the North is the long-term development of natural resources with the use of imperfect technologies of extraction and processing of various types of raw materials, leading to the accumulation of several millions of tons of dangerous toxic radioactive pollutants. An example of the formation of such negative phenomena is the Norilsk industrial district [8], where the content of sulfates in the soils of the enclosing dams of the tailing dump No. 1 of the Norilsk enriching factory reaches 25–30 g/l, 5–8 g/l of chlorides, and concentrations of copper, nickel and other heavy metals are excessive. Currently, the pollutants inside the drives are located in a conserved frozen bound state, however, when permafrost thawing would engage in the cycle of nature, through the transit water streams going to the Arctic and Pacific basins, can destroy not only the ecosystems of the North, but also ecosystems of the World Ocean

With an increase of river flow associated with the thawing of ground ice, it is possible to increase the desalination of the seas and the warming of the Arctic basin, the subsequent tangible increase in flow to the World Ocean, and increasing its level

One important circumstance of particular note is the reduction in geocryological severity as a result of recent climate change. Most of the specialists who noted this phenomenon, assign a negative effect to frozen ground and cause an increase in the depth of seasonal thawing of rocks, which causes activation of cryogenic processes, a decrease in the bearing capacity of the bases of geotechnical objects and a violation of their stable state, etc. [6, 13]. At the same time, many of the predicted consequences of changes in permafrost conditions are very favorable for the nature of Russia. These include: reducing the severity of the climate in the Northern regions and the associated significant reduction in heating costs; reducing peak loads in power systems, energy consumption, improving conditions and lengthening the period of outdoor work in winter, a positive impact on the health of the population; improving agro-climatic indicators, expanding the productive land area, increasing the length of the growing season and the possibility of more intensive and productive agricultural activities.

Conclusion. The results indicate the possibility to predict the future dynamics of permafrost in the context of climate change, as well as quantify assessment. Thus, the zoning of the territory according to the degree of geocryological danger allows to predict the possibility of emergency situations and its specifics, and to take the necessary measures to minimize the negative consequences, including the development of compensation measures. Previously, such constructions were made by us to differentiate the territory of the Russian Federation by living conditions, taking into account the geocryological situation [28].

The research results of Melnikov Permafrost Institute in different parts of permafrost zone strongly suggest that sharply increasing in the early development of negative exogenous processes of a destructive nature (thermokarst, thermoerosion, and etc.) can substantially stabilize, what allows to lead a previously disturbed landscape in a stable state.

In recent years, scientists of MPI conducted geocryological studies on the sites of the existing ESPO oil pipeline. It is established that during the operation of the oil transportation system there is a stabilization of geocryological conditions, conducive to improving the reliability of the object. Along with this direction researches of MPI on all earlier mastered and repeatedly surveyed sites of the oil pipeline have recorded unambiguous trend decrease in amplitude and decrease in temperature of active layer.

Existing methods of stabilization of footings and foundations on the permafrost ground can be proposed as part of the overall strategy of adaptation to the upcoming changes in the natural conditions of the Northern regions, aimed at minimizing the negative technogenic consequences.

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