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ОЦЕНКА ЭКОЛОГИЧЕСКОГО СОСТОЯНИЯ ГОРОДА НОРИЛЬСКА

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Аннотация: Оценка современного экологического состояния проводится для территории городского округа Норильск Красноярского края Арктической зоны России. Особенностью территории является функционирование Норильского промышленного комплекса, что оказывает негативное воздействие на рассматриваемую территорию. Выявление очагов захламления наземных объектов в г. Норильске проведено на основе методики комплексной оценки состояния территории, где дислокация механического загрязнения выполнена по данным цифровой спутниковой съемки. В результате исследования авторы пришли к выводу, что общая площадь механических загрязнений составляет не менее 193,88 га. Уровень загрязнения компонентов окружающей среды можно охарактеризовать от «умеренного» до «очень высокого». Авторы подчеркивают необходимость устранения экологического вреда, накопленного в результате продолжительной и интенсивной деятельности.

Ключевые слова: накопленный вред окружающей среде, воздействие на окружающую среду, загрязнение природной среды, захламление, механическое загрязнение, экологическое опробование.

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Assessment environmental condition of the city of Norilsk

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Abstract: assessment of the current environmental conditions is conducted for the urban district of Norilsk, Krasnoyarsk Krai in the Arctic zone of Russia. The peculiarity of the territory is the operation of the Norilsk industrial complex, which has a negative impact on considered territory. Identification of foci of littering of surface objects in Norilsk was conducted based on the methodology of complex assessment of the condition of the territory, where the dislocation of mechanical pollution was completed according to digital satellite image data. As the result of the study, the authors concluded that the total area of mechanical pollution in the Norilsk is not less than 193.88 ha. The level of pollution of environmental components can be characterized from “moderate” to “very high”. The authors stressed the necessity to eliminate the environmental harm resulting from the long and intensive activities.

Key words: accumulated environmental damage, environmental impact, environmental pollution, littering, mechanical pollution, environmental sampling.

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1. Economic use of the territory

The unified municipal entity "Norilsk city" is represented by the cities of Greater Norilsk, as also includes group of settlements (Talnakh, Kaierkan, Oganeri, Snezhnogorsk). The total area of land-use within the jurisdiction of the administration is 4,500 km^2.

The Norilsk industrial complex (hereinafter referred to as the NIC) is on the area of about 2,600 км^2 in the south of the Taimyr Peninsula and represents a unified industrial mining and metallurgical complex. The development of the area has been carried out since 1935.

In the NIC, several key industries are present (Fig. 1) [1], the basis of which is the Transpolar branch of PAO Mining and Metallurgical Company Norilsk Nickel.

The largest enterprise is the Transpolar branch of PAO Mining and Metallurgical Company Norilsk Nickel. The main products of the enterprise are nickel,

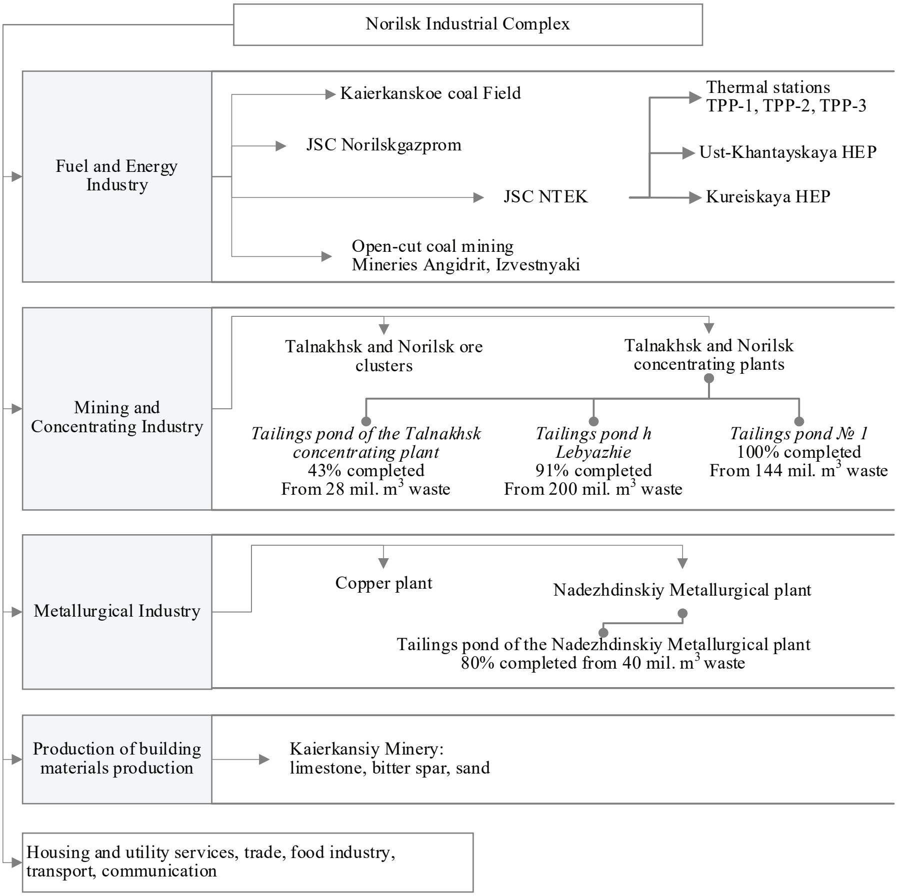

Fig. 1. Structure of NIC [4]

cobalt, copper, platinum metals, aurum, argentum. There are large deposits of sulphur, ruthenium and tellurium, iridium, aurum, and argentum in the subsoil that are also being successfully developed.

High economic and financial efficiency of MMC Norilsk Nickel provides for the development of mineral resource base of the Yenisey North, the introduction of metal products to the global market, and, thereby, the development of the economy of the territory, the region, and Russia as a whole [1–3].

While the NIC adds to the state treasury, but it also damages the environment and the health of the city's population through its negative impact on the state of the environment [5].

2. Assessment of the degree of littering

Identification of foci of littering of surface objects and working out the boundaries of areas with increased risk of NCDs was conducted using the methodology of comprehensive assessment of the state of the territory[6, 7].

Dislocation of mechanical pollution of the studied areas of the NIC was completed according to digital satellite image data, as well as photographic materials integrated into information-mapping systems Google Earth and Google Earth Pro. As an example, space images[1] and photographic materials assessing the present state level of Norilsk city are presented (Fig. 2).

Fig. 2a. Fugitive dumping of construction, utility, industrial-rubber and other waste (69°22'36.96 N, 88°10'34.69 E)

Fig. 2b. Bulk of rail delivery waste (69°19'24.28 N, 88° 3'44.86 E)

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[1] According to Google Earth Pro ©Maxar Technologies, 2019.

Fig. 2c. Piling of industrial waste and metal (69°19'28.81 N, 88°11'24.19 E)

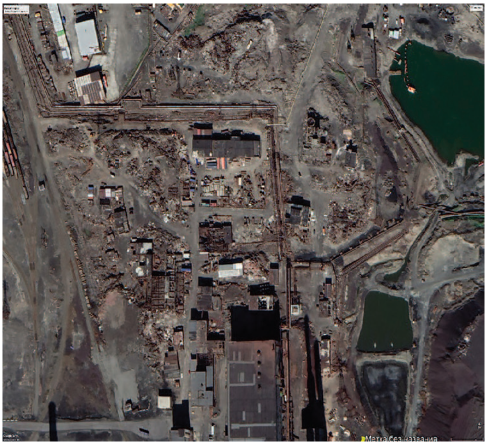

Fig. 2d. Piling of industrial waste and metal 69°19'7.54 N, 88°13'28.37 E

On this territory, there are areas of former economic use, which are pockets of littering and displacement of unaffected natural-anthropogenic complexes. There is also a significant amount of decommissioned or inactive coal-pits, mines, adits with surface facilities of industrial infrastructure, discharge lines, sections of narrow-gauge railroad, uninhabited settlements with ownerless buildings, as well as located within the boundaries of water conservation and water protection areas of water bodies.

The area of the territory subjected to man-made impact was calculated with scaling of space images in the contrast of the objects studied by decoding features using the built-in function of Google Earth Pro.

Therewith, the total area of mechanical pollution makes no less than 1 938 761 m^2 (193,88 ha) or 0,04% of the total area of Norilsk (4,5 thousands km^2 or 450900.85 ha).

The displacement is of the areas is characterized as "strong".

The above sections present the sources of negative environmental processes, insofar as they produce:

1) Mechanical impact due to excavation and construction operations during installation, reconstruction and dismantling of industrial facilities and littering of area with various wastes

2) Physical impact consists in compaction of soil surface by different types of covering and construction. At the same time, there is a noticeable compaction of soil change of its water, thermal, gas and biological regime

3) Chemical impact is manifested in direct and indirect pollution of the soil stratum with toxic components – spills and spillages of toxic materials and fields, erosion of pollutants on the surface and infiltration of grey water from the territories of industrial facilities. At the same time, f the danger of soil contamination increases for the northern regions, because in acidic, cold, hydromorphic and oligohumus conditions the degradation of organic substances is not any faster [8]. The level of chemical impact of the formed areas of littering needs additional elaboration in independent environmental sampling.

The level of chemical impact of the identified littering sites requires additional clarification in the process of independent environmental testing, with the involvement of “Arctic personnel” [9]

3. Impact of NIC production on the environment

3.1. Atmospheric air pollutions

An assessment of the condition of atmospheric air in the NIC area and surroundings, based on the analysis of materials from the Government report [10], showed an insufficient number of observations to obtain an objective assessment of the quality of atmospheric air. According to information from the FSBI Central Siberian Territorial Administration for Hydrometeorological and Environmental Monitoring (TAHEM), it is not possible to provide data on background concentrations of pollutants in the atmospheric air of Norilsk due to a number of reasons: — Monitoring of the condition of atmospheric air in Norilsk has been carried out using a mobile environmental laboratory only since 2014.

– Data on the condition of atmospheric air in 2014 and 2015 are not available, as observations during this period were carried out in test mode.

– Observations in 2016 and 2017 were carried out under a reduced program.

– Since 2018, atmospheric air monitoring has been conducted under an incomplete observation program.

During atmospheric air monitoring for 2016—2019, there is a violation of the homogeneity of data series, the annual volume of data of discrete observation sample from a number of single concentrations is less than 800 [11].

In general, in the atmosphere of the city, there are registered exceedances of MPC average daily and the highest single MPC for the main substances — suspended solids, SO_2, NO_2, NO, H_2S [10].

The main sources of atmospheric air pollution are industrial sources of emissions of pollutants into the atmosphere, coal mines, tailings of industrial enterprises [12], as well as motor transport. The Nadezhdinsky Metallurgical Plant accounted for most of the emissions.

The distribution of emissions in the city of Norilsk looks like most of them fall on the facilities of the Polar branch of PAO MMC Norilsk Nickel (more than 1500 thousand tons). Emissions of JSC NTEK (more than 10 thousand tons) and JSC Norilskgazprom (more than 4 thousand tons) pollute the atmospheric air to a much lesser extent [10].

An indirect indicator of atmospheric air quality is the snow cover. It is a good sorbent and accumulates pollutants contained in the dust and gas emissions of industrial enterprises and the automobile exhaust gases [13, 14].

Information about the properties of the snow cover in Norilsk and its surroundings is limited due to small number of studies. As a result of anthropogenic load, the physical and chemical properties of the Norilsk snow cover have changed: alkalinity has increased, the mineralization of melted snow water has increased compared by 10.4—13.6 times compared to the background, and the ionic composition has changed. City snow water is characterized by sulfate type mineralization, while the background territory is characterized by sulfate-nitrate composition of melt water. The priority pollutants for the solid snow fraction of the city are Cu, Co, Fe, Mn, Ni, Cr, Sr, Ba, Ti, W, Cd, Zn. They come with emissions of enterprises.

3.2. Pollution of vegetative ground cover

Norilsk is located in areas of continuous permafrost. This is due to low moisture evaporation and the development of gley formation processes. The soil cover of Norilsk is highly heterogeneous and consists of tundra clay soils, swamp and alluvial soils. Soil-forming rocks are moraines and heavy loams of marine origin, less often — light and medium loams [15, 16]. The main types of soils are located in the area of strong thermal pollution (metallurgical plant, heating networks), which has a warming effect on the permafrost for many years, and as a result, on its spatial variability and degradation. In the process of production activity of the industrial complex in the territories adjacent to the city of Norilsk, a man-made landscape is formed with technogenic-transformed soils formed as a result of backfilling, deformation, deposition and mixing of man-made substrates, soils and underlying rocks [17]. Anthropogenic impact on soils and vegetation cover is caused by atmospheric transport of gas and dust emissions from industrial plants and through sludge reservoirs.

Anthropogenic emissions of sulfur dioxide and sulfuric acid to the soil cover of the NIC lead to acidification of soil and accumulation of high concentrations of sulf salts of not only of alkali and alkaline earth elements, but also heavy metals and their high mobility in soils. In the upper horizons of contaminated soilsgross content of Cu is higher than Co and Ni, in contrast to the background soils, this is due to a large intake of Cu in the enterprise emissions. Penetration of heavy in the soil profile spreads to an average depth of 25 cm [16].

It is also noted [18] that the proportion of heavy metals soluble in water, specifically sorbed (flexible) compounds associated with organic matter and with amorphous Fe and Mn compounds increases in contaminated soils. The seasonal development of gleying processes increases the mobility of Fe, Mn and associated Cu, Ni and Co compounds, which increases the likelihood of their migration into water bodies.

Studies [19] have shown that Norilsk city plants accumulate toxic substances that affect the growth and development of higher plants.

The accident that occurred in 2020 at the TPP-3 of AO NTEK with discharge of diesel fuel into the environment resulted in soil contamination of the floodplain territory, while the territory of the industrial zone of AO NTEK, where liquidation works were carried out including excavation and removal of soil from the territory to storage facilities, being affected to a greater extent. Maximum concentrations of petroleum products were recorded in the soils of the land plot adjacent to the industrial zone of AO NTEK, along the artificial watercourse — 30 g/kg of soil. Soils adjacent to the coastal zone, falling within the water protection zones along the Bezymyannaya and Daldykan rivers, were polluted sporadically due to the features of these water bodies (steep shores and their high graveliness); the level of soil pollution did not exceed 2—3 g/kg. The soils of the floodplain of the Anbarnaya River, which has a gentle stream, are polluted, the maximum concentrations of petroleum products were detected in the peat horizons with maximum sorption capacity. The level of impregnation with petroleum products was 15—20 cm, in some cases up to 30 cm, but further their migration was prevented by a geochemical barrier in the form of permafrost. Thus, the level of soil pollution as a result of the accidental spill is characterized as “low””». The area of contamination was about 50 ha.

3.3. Pollution of surface waters

Despite the available information [20, 21] on the characteristic of water bodies in the area of Norilsk, the long-term dynamics of the rivers of the north of the Krasnoyarsk Krai belonging to the Pyasina River basin, where the NIC is located, remains poorly studied [22]. There are no permanent water observation stations here. So, it was only in the summer of 2020 that state monitoring was resumed on the Barna River after the accident that occurred as a result of an accidental release of diesel fuel from the tank of TPP-3 if AO NTEK.

Consistently high concentrations (compared to MPC) of copper and nickel compounds are associated with both natural and anthropogenic factors of water formation. The Norilo-Pyasinsky water system catchment area is characterized by distribution of sulfide copper-nickel ores. Therefore, concentrations of copper and nickel compounds in water bodies are associated with a special geochemical background [21].

The mining and smelting plant discharges into the surrounding water bodies untreated or insufficiently treated wastewater in the amount of about 700 thousand m^3/year [20], containing suspended substances, sulfates of chlorides, oil products. About 3 thousand hectares are occupied by rock dumps [22]. Engineering of the dumps does not prevent heavy metals and other substances from entering streams and water bodies (Fig. 3).

About 3 thousand ha are occupied by rock dumps [23]. Engineering of the dumps does not prevent heavy metals and other substances from entering streams and water bodies (Fig. 3).

3.4. Pollution of bottom sediments

According to research data, in the Norilsk Region there is enrichment of bottom sediments of water bodies with Sg, Ni, V and C, coming from enterprise effluents, as well as from surface water runoff. At the same time, the content of such elements as Rb and Ag is significantly lower [23, 24]. A particular environmental danger to the Pyasino ecosystem pose Hg and As, exceeding the values determined in bottom sediment samples from background areas [25, 26].

4. Conclusion and consequences

In the context of the studies performed it has been established that on the territory of Norilsk there are areas of the current and past economic use, which are centers of flooding of natural-anthropogenic complexes. The total area of mechanical pollution is not less than 193.88 ha. Displacement of territories on these areas is characterized as “strong”. The level of chemical impact of of the formed areas

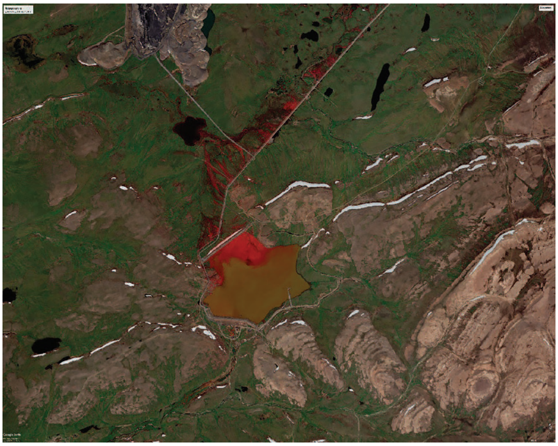

Fig. 3. Tailings pond of the Nadezhdinskiy Metallurgical Plant[1]

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[1] According to Google Earth Pro ©Maxar Technologies, 2020.

of littering needs further elaboration in independent environmental sampling.

The level of pollution of environmental components can be characterized from "moderate" to "very high". Consequently, the need to eliminate environmental damage resulting from long-term and intensive operation of the NIC is more relevant than ever.

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БУРОВОЙ ИНСТРУМЕНТ НА МЕРЗЛЫХ ГРУНТАХ

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Аннотация: раскрывается важность и актуальность буровых работ в районе вечномерзлых грунтов. Рассмотрены проблемы, возникающие при проведении буровых работ в районе Арктики. Существующие буровые инструменты недостаточно эффективно работают и требуют высоких энергозатрат при осуществлении процесса бурения, что приводит к созданию новой конструкции бурового инструмента. Рассмотрена новая конструкция винтового бурового инструмента и принцип её взаимодействия рабочей поверхности с мерзлым грунтом. Целью теоретических исследований являлся анализ процесса взаимодействия второго участка разрушающей части винтовой лопасти бурового инструмента с мерзлым грунтом. Осуществляются выведения зависимостей общего крутящего момента при работе второго участка разрушающей части от исследуемых параметров винтовой лопасти. Проводится результаты исследования взаимодействия винтовой лопасти разрушающей части винтового бура с мерзлым грунтом. Производится построение зависимости величины крутящего момента от исследуемых геометрических параметров винтовой лопасти бура. Определяются диапазоны рациональных значений исследуемых геометрических параметров винтовой лопасти второго участка разрушающей части винтового бура. Делаются выводы об эффективности использования винтового бура на мерзлых грунтах перед существующими буровыми инструментами за счет реализуемого характера разрушения грунта отрывом и дальнейшим сдвигом породы и об перспективности использования его на мерзлых грунтах.

Ключевые слова: винтовой рабочий орган, буровой инструмент, мерзлый грунт, скол грунта.

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Drilling tools on frozen soils

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Abstract: The article reveals the importance and relevance of drilling operations in the area of permafrost soils. The problems arising during drilling operations in the Arctic region are considered. existing drilling tools are not efficient enough and require high energy costs during the drilling process, which leads to the creation of a new design of drilling tools. A new design of screw drilling tool and the principle of its interaction between the working surface and frozen ground are considered. The purpose of the theoretical study was to analyze the process of interaction of the second section of the destructive part of the screw blade of the drilling tool with frozen ground. The dependences of the total torque during operation of the second section of the destroyng part on the studied parameters of the screw blade are derived. The results of the study of the interaction between the screw blade of the destroying part of the screw drill and frozen ground are carried out. The dependence of torque value on the investigated geometrical parameters of the screw drill blade has been plotted. The ranges of rational values of the investigated geometrical parameters of the screw blade of the second section of the destructive part of the screw drill have been determined. The conclusions are made about the efficiency of using the helical drill on frozen soils before the existing drilling tools due to the implementable character of soil destruction by tearing off and further displacement of the rock and about the prospects of its use on frozen soils.

Key words: screw working body, drilling tool, frozen soil, ground chipping.

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The introduction

Currently, the development of the Arctic territories is one of the most important urgent problems. Drilling operations are among the most expensive types of construction works. Special natural and climatic conditions lead to high demands, which complicates the processes of construction and operation of structures. The Arctic zone occupies 25% of the area of Russia, where permafrost soils are widespread. Due to the active development of these territories, difficulties arise in drilling permafrost soils [1—8].

The high cost of drilling for construction in Arctic zones is due to a number of problems.

The main physical and mechanical property of frozen soils, especially frozen sand, is strength. The strength of such frozen soils is comparable to that of concrete, and it is quite energy intensive and expensive to overcome it with a drilling tool. Also, frozen sand is highly abrasive, which leads to wear of the tool surface during drilling [9—15].

Analysis of existing drilling tool designs has shown that current drilling tools used in frozen ground carry out the drilling process by cutting deformation or compression of rock. This nature of interaction of the working surface with frozen ground is not effective enough and is an energy-consuming drilling process [16—20].

Materials and methods

Improvement of existing and creation of new screw drill designs is an urgent scientific and technical task.

A screw drill consists of a core on which a continuous helical blade including a leading part and a breaking parts is placed. The leading part has a constant pitch and radius of the helical blade. The breaking part, in its turn, is shaped as a helical surface with a constant radius increment per one turn relative to the pitch of the tapered section of the blade. The diameter of the blade coil on the breaking part is larger than the diameter of the base of the cone described by the edge of the coils of the blades of the entering part. As a consequence, there is an increase in the pitch of the helical working body, relative to the tapered traction part. The angle of inclination of the forming upper surface of the helical blade on the cylindrical part of the tip to the axis of rotation also changes its value.

The principle of operation is as follows: the screw is brought into contact with the frozen soil, then it is given an axial thrust and torque by means of the drilling equipment. The drill plunges into the soil. At the same time, the soil is pushed apart by the tapered core and the pulling part of the constant pitch helical blade and compacted in the directions normal to their forming surfaces. As a result of compaction, the soil in the intertwist space is hardened and allows the conical part of the blade to develop traction capacity without being destroyed by it [21].

The breaking part of the blade, which works as a helical wedge, contacts the ground after the entry part of the blade. Due to its significant outreach, by increasing the radius, and changing the angle of inclination of the forming upper surface of the helical blade to the rotation axis, relative to the last turn of the traction part of the blade, the edge of the breaking part of the blade destroys the soil, predominantly by shear deformation. Namely, by increasing the radius of the helical blade, the drill enters the ground, working as a wedge, thereby forming a crack and subsequent detachment by changing the angle of inclination of the forming upper surface and further increasing the radius leads to the formation of a borehole and a repeated process.

Let's take a closer look at the destructive part of the screw drill. It can be conventionally divided into two sections, which implement the process of breaking the ground.

The first section begins at the transition point from the entry part of the helical blade. It has a variable radius, which when the tool is rotated by the radius rotation angle, , increases to the value at which the formation of the crack and further soil detachment is observed. In the same way, the angles of inclination of the upper and lower formations of the helical surface of the blade change.

The interaction of the helical blade is comparable to the work performed by an asymmetrically shaped wedge. As a result of such interaction with frozen ground, a wedging force arises due to the angles of inclination of the forming upper and lower surfaces of the helical blade.

When the helical blade interacts with the ground due to friction forces, the force vectors on the ground will deviate in the direction of element introduction by the value of the friction angle. In the same way, the ground impact force will be divided into horizontal and vertical components. The horizontal component will be of great interest for the formation of cracks. At the same time for greater efficiency of detachment of the soil and lower value of energy intensity of this process, it is necessary to comply with the ratio of the following parameters: radius of the screw blade on the second section to the radius of the screw blade on the first section and the radius of the screw blade on the first section to the pitch of the screw blade on the second section of the destroying part of the screw drill.

Next, consider the second section. It has a variable radius, which increases to its maximum value when the tool is rotated by the angle of rotation of the helical blade radius, at which the increment occurs. In this case there is a change in the angle of inclination of the upper formative to 90 degrees and an increase in pitch relative to the pitch of the traction part.

The second section during the operation of the destroying part of the screw drill is necessary to create an open surface, providing the formation of a crack at an angle to the axis of the well, which contributes to obtaining a wellbore with a diameter larger than the diameter of the destroying propeller blade. The process of interaction of the helical blade located on the second section during the work of the destroying part is shown in Fig. 1.

As seen in Figure 1, the helical blade penetrates the ground in the same way as in the first section, and the borehole is formed due to shear deformation. A change in the angle of inclination of the

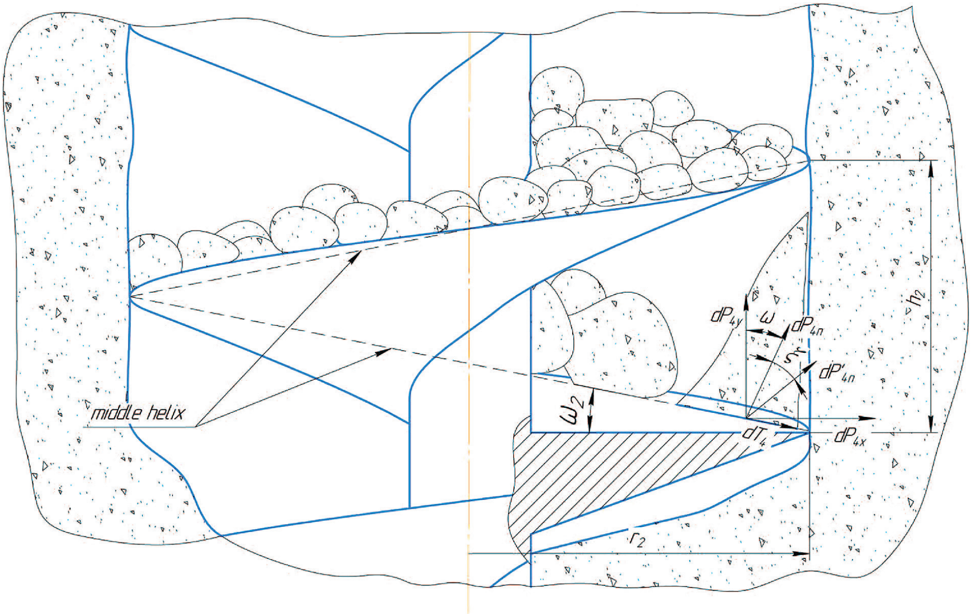

Fig. 1. Calculation scheme for determining the shear force of the soil by the helical blade of the second section from the angle of inclination of the middle helical line

upper forming surface leads to a change in the direction of the horizontal component of the force acting on the ground by the helical blade of the second section, which indicates an increase in the shear force and a decrease in the energy intensity of soil destruction. With the given values of the angles of inclination of the upper and lower surfaces of the helical blade, the maximum effect on the formation of the borehole is achieved.

The second section has an increased pitch, which provides soil shear on the cylindrical surface, covering the edges of the propeller blade.

Research results

An important criterion for the efficiency of the helical drill operating process is the torque, which determines the energy intensity of the drilling process. The main parameters influencing the torque from the process of breaking the ground with the drill are the geometric parameters of the screw blade of the breaking part.

The purpose of theoretical studies was to determine rational parameters of the screw drill, at which the torque value will be the lowest.

The magnitude of the torque arising on the second section during the interaction of the helical blade of the destroying part has the following form:

$$M_2 = P_{4x} \cdot r_2, \tag{1}$$

where, horizontal component of the resultant ground shear force of the helical blade of the second segment of the destroying part.

To determine the torque arising from the operation of the screw blade of the second section of the destroying part, it is necessary to determine the horizontal component of the resultant shear force of the soil by the screw blade.

Horizontal component of the resultant soil shear force by the screw blade, arising on the upper surface of the screw blade of the second section of the destroying part is as follows:

$$P_{4x} = P_{4n} \cdot \sin(\omega_2), \qquad (2)$$

where, P_{4n} — the resultant shear force of the soil arising on the upper surface of the screw blade of the first section.

The resulting shear force of the soil by the helical blade is determined by Coulomb's law:

$$P_{4n} = \tau \cdot F_{\text{сд}}, \qquad (3)$$

where, $F_{\text{сд}}$ — ground shear area, м^2.

The dependence of the horizontal component of the resultant shear force on the geometric parameters is as follows:

$$P_{4x} = \tau \cdot (2 \cdot \pi \cdot r_2 \cdot h_1) \cdot \sin(\omega_2). \qquad (4)$$

Considering the obtained expressions, the value of the torque arising from the action of the screw blade of the second section will be:

$$M_2 = (\tau \cdot (2 \cdot \pi \cdot r_2 \cdot h_1) \cdot \sin(\omega_2)) \cdot (r_2). \qquad (5)$$

Results

The main parameters influencing the value of the torque during operation of the helical blade of the second section of the destroying part are geometrical parameters of the helical blade of the drill.

Dependences of the torque on the angle of elevation of the middle propeller blade on the second section and on the ratio of the propeller blade radius on the second section to the pitch of the propeller blade on the first section are shown in Fig. 2.

Dependences of torque on the angle of rise of the middle screw blade on the second section and on the ratio of the screw blade radius on the second section to the pitch of the screw blade on the first section have a linear character. With an increase in the angle of rise of the mean helical line of the propeller blade of the second section of the breaking part, there is an increase in the value of torque. The same character corresponds to an increase in the ratio of the helical blade radius on the second section to the pitch of the helical blade on the first section, which also leads to an increase in the value of the torque.

It was found that the lowest value of the torque of the drilling process is achieved when using a helical drill with the following geometrical parameters: the angle of rise of the average helical line of the helical blade of the second section of the breaking part is in the range of values , the ratio of the radius of the propeller blade on the second section to the pitch of the propeller blade on the first section is in the range 1.55…1.7.

Further decrease in the values of geometrical parameters, as it can be seen from the graph in Fig. 2, leads to the zero value of the torque value on the second section of the destructive part of the screw drill, which is caused by the termination of the screw blade operating process.

Conclusion

As a result of theoretical research, we obtained that a new design of drilling tools and new method of impact on the ground, which leads to shear deformation and detachment, allows to reduce the

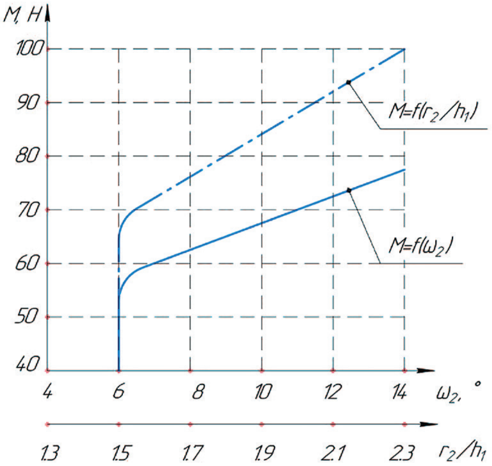

Fig. 2. Dependence of torque on the angle of elevation of the middle propeller blade on the second section and on the ratio of the radius of the propeller blade on the second section to the pitch of the propeller blade on the first section

energy costs of the drilling process in frozen soil. This way of interaction of drilling tool with frozen soil is a promising direction in drilling for construction in the Arctic zone.

As a result of the analysis it has been established that using the obtained rational values of the angle of rise of the average helical line of the upper surface of the screw blade on the second section of the breaking part and the ratio of the radius of the screw blade on the second section to the pitch of the screw blade on the first section, the torque of the screw drill is reduced by 40—50%, and the power consumption of the drilling process by 20—25%.

The conducted theoretical studies showed the necessity and feasibility of further research aimed at determining the rational modes of operation, contributing to achieving the highest efficiency of drilling wells in frozen soils during construction in the Arctic zone.

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КОРРЕКЦИЯ ГЛУБИННО-СКОРОСТНЫХ МОДЕЛЕЙ МЕТОДОМ ГРАВИМЕТРИЧЕСКОЙ РАЗВЕДКИ ДЛЯ ТРУДНОДОСТУПНЫХ УЧАСТКОВ ШЕЛЬФОВОЙ ЗОНЫ

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Аннотация: В настоящее время большое количество месторождений нефти и газа достаточно разведаны, а потребности в топливных ресурсах с каждым годом растет. Поэтому нефтегазовые компании начинают разрабатывать объекты со сложным геологическим строением или объекты, расположенные в труднодоступных местах, к каким относится Арктическая зона. Из-за климатических особенностей не вся территория Арктического шельфа изучена прямыми методами геологоразведки. Однако перспективность территории толкает нефтегазовые компании на разработку новых алгоритмов с использованием быстрых и доступных методов геофизики. Таким образом, в данной работе описан один из алгоритмов интерпретации данных, который предположительно может быть реализован для участков с минимальной априорной информацией. Основная идея статьи — коррекция структурных построений на основе использования метода гравиразведки в условиях отсутствия на изучаемой территории скважин. По результатам исследований авторы предлагают использовать комплексную интерпретацию гравитационных и сейсмических данных для снижения неоднозначности решения обратных задач.

Ключевые слова: сейсморазведка, гравиразведка, совместная инверсия, моделирование, шельфовая зона.

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Correction of Depth-Velocity Models by Gravity Prospecting for Hard-to-Reach Areas of the Shelf Zone

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Abstract: a large number of oil and gas reserves are now well surveyed, while the demand for fuel resources continues to grow year by year. As a result, oil and gas companies have started to develop sites with complex geological structures or located in virtually inaccessible regions, such as the Arctic zone. Due to climatic conditions, not all of the Arctic shelf has been surveyed via direct exploration methods. However, the untapped potential of the region provides an impetus for oil and gas companies to develop new processes that use quick and accessible geophysical methods. This work outlines one such data interpretation algorithm for potential use in locations about which minimal information is known in advance. The main idea of this article is to correct structural constructions based on the use of gravity prospecting in the absence of wells in the study area. Based on the results of the study, the authors propose to use an integrated interpretation of gravity and seismic data to reduce the ambiguity of solving inverse problems.

Key words: seismic survey, gravity survey, joint inversion, modeling, shelf zone.

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Introduction

The trend the mining industry as a whole and of the oil and gas industry in particular is that the already surveyed inland reserves are gradually becoming depleted [1]. In response, oil industry experts are paying significant attention to shelf areas [2, 3]. The Arctic shelf area in Russia is the largest of its kind in the world, and is considered a high-potential region [4–6]. Several oil and gas fields are being developed in the western part of the Arctic basin. However, the eastern part of the region, which also has high-potential oil and gas sites, is very poorly studied in terms of available geological and geophysical data. This is due to unfavorable climatic conditions in the region, due to which the sea is covered with ice for long periods. The study of hard-to-reach territories with inaccessible geological and geophysical data and underdeveloped infrastructure is a topical issue for the long-term development of the oil and gas industry, including taking into account the environmental component [7]. Numerous authors [8–10] have devoted their attention to the problem of hydrocarbon extraction in difficult geological conditions, and prioritize the development of new approaches [11], designed to significantly improve the process of geological exploration.

It is also worth noting that practically no drilling has been carried out in the eastern part of the Arctic, since the lack of preliminary information about the geological structure of the area when drilling is costly and risky for oil and gas companies [12]. In the early stages of geological exploration for any investigated area, in addition to the results of seismic survey, there are also data on potential fields that may be useful for complex interpretation of the data. Accordingly, the development of new techniques for joint processing and interpretation of geophysical data allows for the creation of an initial geological model of the environment that includes all specific features of the seismic survey and data on potential fields. This will significantly reduce the cost of the work and reduce the time of geological exploration.

1.1 Joint Inversion

Physical-geological modeling is an important stage in understanding the geology of the site in question. The creation of a physical-geological model usually involves the use of a range of geophysical methods that enable the creation of a model that accounts for the specifics of each geophysical method. Different approaches to inversion of geophysical fields have their positive and negative results. In this case, inversion is understood as solving an inverse problem, i.e., determining the parameters of the object of study by measuring the geophysical fields. Inversion can be carried out independently for each method, and the final results can be simply collated by the interpreter. It is also possible to conduct a joint inversion using several geophysical methods as part of the process.

The majority of sources analyzed by the authors [12–15] feature examples of the advantages of joint inversion. The use of an additional method in interpretation helps to reduce the ambiguity of the solution of the inverse problem [16, 17]. This approach also helps to reduce the number of model variants of the environment studied [18], which significantly improves the reliability of the interpretation work.

There are several joint modeling approaches [19]:

1) sequential, or iterative, inversion by each method in which the results are ultimately interpreted together. Frequently, formulaic dependencies are used to link the parameters of several methods. In international works, this approach is referred to as “cooperative joint inversion”.

2) Inversion of multiple methods in one dataset. This modeling approach is called “simultaneous joint inversion”.

The term “simultaneous joint inversion” is more precise and includes the aforementioned joint inversion of parameters of each examined geophysical method in one objective function (or matrix). The essence of the method is the selection of the most correct relationship between all the data [20]. As with cooperative inversion, the goal is to reduce the ambiguity of solving inverse problems by utilizing the strengths of each method. In most cases, this approach is automated in nature, and computers are used to significantly simplify the task.

There is no single agreed-upon definition of cooperative inversion, since different researchers interpret it differently in their works [21, 22]. The term is used by a wide range of authors, and mainly in international publications. One group of authors [6, 20] defines “cooperative inversion” as application of measured parameters of different geophysical methods regardless of the process of simultaneous sequential data inversion. An article by a group of researchers led by M. Moorkamp [23] describes the adoption of an iterative approach to conduct the inversion of a certain set of parameters of one method, with the obtained data then being linked by a functional dependency with parameters of another method. The authors of a different article emphasize that in cooperative inversion one method enables the placement of certain restrictions on the other method [24].

1.2 Functional relationships between the physical parameters «velocity-density»

As mentioned above, there is a functional relationship between the velocity and density parameters. This will be discussed in more detail below. The known formulas for recalculating velocity and density are empirical in nature and have been derived based on numerous direct observations of conditions in the field. However, in most cases, real-world geological conditions are complex. It is difficult to link certain dependencies to the parameters of such environments, and sometimes quantitative assessment is not feasible. Birch and Gardner’s empirical relations are used to examine simpler geological conditions.

Birch’s empirical formula is as follows:

$$\sigma = x \cdot \upsilon_p + y, \tag{1}$$

where x and y are coefficients of the linear regression equation, σ is density (g/m^3), and υp is the velocity of longitudinal waves (m/s). This relation is used for deep exploration, and in addition to the usual metrics, also accounts for metrics such as temperature and pressure.

Gardner's empirical relation is of great use in oil and gas geophysics, and is better suited for working with sedimentary rocks [25]:

$$\sigma = a \cdot \upsilon_p^b, \qquad (2)$$

where σ represents density (g/cm3), a and b are coefficients determined from well log data, υp is the velocity of longitudinal waves (m/s). The correlation is based on the tendency for the values of velocity and density to increase with depth [25]. As Gardner's formula is empirical, and derived based on a range of experimental data, its use may more accurately represent real-world environmental properties.

The first relation (1) is used to describe regional data, including studies of the mantle. The second formula (2) is mainly used to describe the parameters of the sedimentary cover, which aligns with the objectives of oil and gas geophysics. For this reason, this relation was chosen for further work.

Research results. The idea of seismic density modeling

One of the most significant results of seismic surveys are maps of reference surfaces. to determine the depth of the reflecting horizons, it is necessary to know the average velocity of wave propagation in the overburden [6]. When processing seismic data, the effective velocities are determined from the travel time curves of the reflected waves. The correspondence of average velocities to the effective velocities is reliably determined only for a homogeneous isotropic model of the medium. In practice, with non-homogeneous and anisotropic media, an empirical dependency of the average velocity on the effective velocity is established, which requires processing and interpretation of well data. In the absence of well data, it is possible to estimate the effective depth (heff) using the formula:

$$h_{eff} = \frac{t_0}{2} \cdot \upsilon_{st}, \qquad (3)$$

where t_0 is vertical time (round-trip propagation time), and υst is the stacking velocity.

Gravity surveying can serve as a supplementary method for interpreting seismic reflection methods. Gravity explorations are low-cost and logistically simple, which is why they are often used on the shelf alongside seismic exploration. Gravity data can be used in a comprehensive interpretation to limit possible options for solving the inverse problem when correcting for depth-velocity models.

The following procedure is carried out based on Gardner's formula:

1. Conversion of velocities obtained in velocity analysis into interval velocities (using the Urupov-Dix formula) [26].
2. Conversion of interval velocities to density (using Gardner's formula).
3. Density inversion and obtaining corrected densities for each layer.
4. Correction of interval velocities, taking into account density characteristics (using Gardner's formula).
5. Correction of the depths of reference horizons.

The procedure is presented in visual form in the block diagram in Figure 1.

Testing of seismic density modeling algorithm in the shelf zone of the East Siberian Sea

The site is located on the Arctic shelf in the East Siberian sea. The authors of the article [27] consider the sea shelf as a promising location of hydrocarbons. Geological and geophysical data on the region are limited, as the sea is covered with ice for the most of the year [27, 28]. The nearest wells are located at a

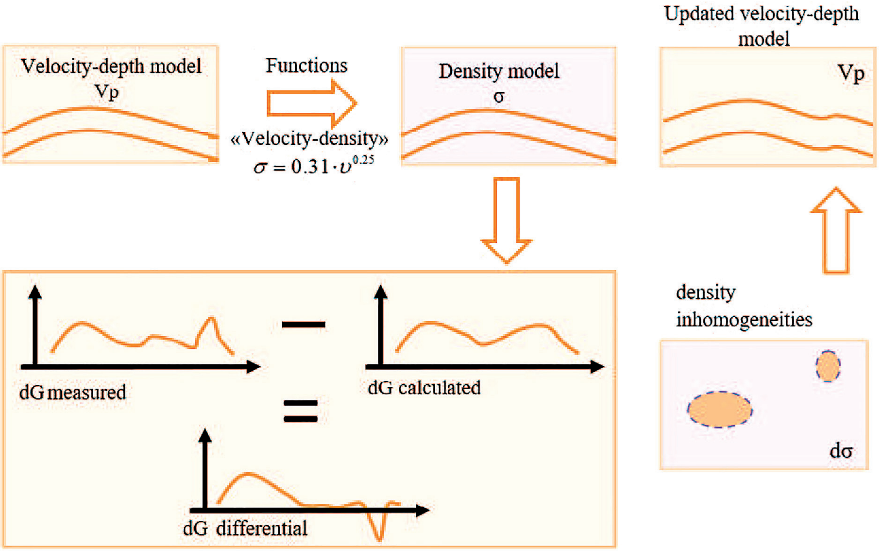

Fig. 1. Block diagram of the implementation of the process

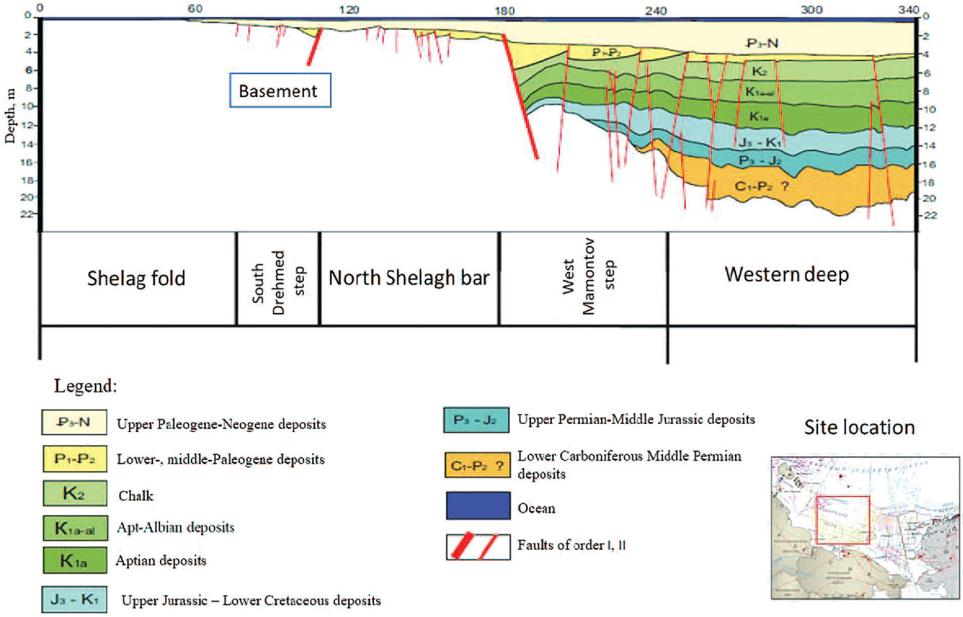

Fig. 2. Geological cross section of the area located on the shelf of the East Siberian Sea

considerable distance. The possibility of drilling parametric wells on the shelf of the East Siberian Sea is still difficult. This is due to difficult weather conditions and, as a result, rather expensive logistics and the cost of geological works. To choose a profitable drilling site, oil and gas companies try to carry out geological exploration using geophysical survey tools in advance because of the cheapness of the methods used. The

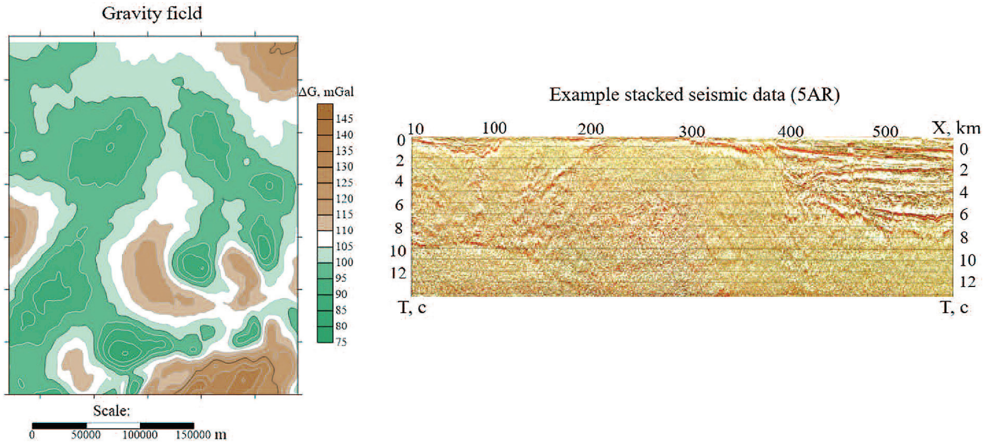

Fig. 3. Initial materials: gravity map (left) and seismic profiles (example on the right)

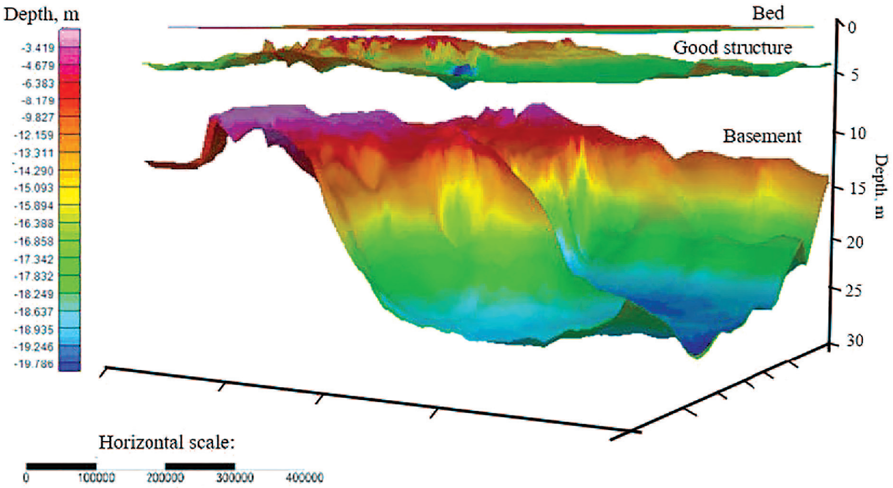

Fig. 4. 3D model of the examined site

geological environment may have a rather complex structure, which may not be reflected in the seismic data. Accordingly, the need to use additional geophysical methods to refine the geological structure of the territory increases significantly. Figure 2 shows an approximate geological cross section of the territory.

The initial data provides a map of the gravity field, velocity cross sections and structural maps for the bottom, potential structure and bedrock (Fig. 3 and 4).

Structural maps formed the basis of 3D models (Figure 11). Depths were established as a result of velocity analysis and were not confirmed by drilling data.

At the first point, the velocities obtained from the hodographs were converted into interval velocities (υi) for each layer according the Urupov-Dix formula [26]:

$$\upsilon_i = \sqrt{\frac{\left(\upsilon_2^2 \cdot T_2\right) - \left(\upsilon_1^2 \cdot T_1\right)}{(T_2 - T_1)}}, \qquad (4)$$

where υ_1 and υ_2 are the effective velocities for the top and bottom respectively; T1 and T2 are the vertical time for the top and bottom, respectively.

The next step was to recalculate the interval velocities in density using Gardner's empirical relation [25]:

$$\sigma = 0.31 \cdot \upsilon_i^{0.25}, \qquad (5)$$

where σ is density (g/cm^3), and υ_i is interval velocity in the layer (m/s).

Each layer of the depth-velocity model received its own density distribution, which was limited to approximately the density range in accordance with the little available information from the drilling data for the nearest surveyed region [27, 30]. The table below shows the density data for each layer before and after the density inversion. The results of the density inversion for the practical model are shown in Table 1.

The density inversion was conducted from the lower to upper layers. The marginal error value was set in the input parameters. Since the goal was to reduce the discrepancy between the calculated gravity fields from each structure and the observed gravity field, the values of the marginal error in the inversion were taken from 1 to 0.1 mGal, decreasing from horizon to horizon. The solution of the inverse problem was based on 'lateral' density inversion. This approach is based on E Packer's algorithm [31], in which density in the layer changes laterally, and vertically is constant. In the density inversion, the gravitaty effect was calculated for each layer and then subtracted from the observed field [32]. Residual local anomalies formed a new distribution over the layer, refining the location of density inhomogeneities. While conducting inversion from layer to layer, the magnitude of the discrepancy between the observed and calculated gravity fields decreased. As a result of the inversion, the densities in each layer were corrected for the existing gravity field (table 1,

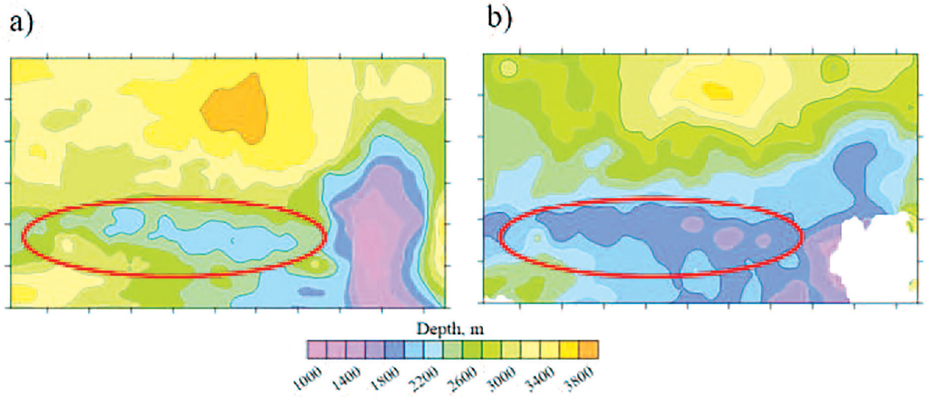

Fig. 5. Fragments of structural maps for the prospective horizon obtained before (a) and after (b) velocity refinement (red line indicates the area of refinement of structural constructions)

Table 1

Results of the density inversion for the examined environmental model

Structure name	Densities before inversion, g/cm^3	Densities after inversion, g/cm^3
Bottom of the sea	1.95	1.95
Perspective structure	2.008 – 2.278	2.001 – 2.282
Foundation	2.007 – 2.762	2.079 – 2.814

column 2). The corrected velocities were then calculated using Gardner's formula and used as the basis for the updated depths in the modeled cross section.

The end result was a corrected depth-velocity model. A structure presumably containing potential areas of oil and gas was used as an example. After seismic density modeling, it was possible to refine the geometry and position of several structures on the map (Fig. 5) so that the resulting model complies with seismic and gravimetric data.

Conclusion

The results of seismic density modeling demonstrate the applicability of the seismic density modeling algorithm for correcting velocity constructions and refining individual structural constructions. the results of the application of the algorithm to real data also made it possible to refine the depths of reference horizons. The algorithm can be used to assess the region's oil and gas potential.

The use of relatively simple gravimetric modeling results allows the method to be widely applied in the future to correct depth-velocity models on land and water areas with limited preliminary information and exploration.

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ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

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ОПТИМИЗАЦИЯ СЫРЬЕВОЙ СМЕСИ С ИСПОЛЬЗОВАНИЕМ ТЕХНОГЕННЫХ ОТХОДОВ ДЛЯ ПРОИЗВОДСТВА ЦЕМЕНТНОГО КЛИНКЕРА

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Аннотация: представлены результаты возможности использования техногенного сырья путем переработки его как вторичного минерального сырья, в частности, техногенных хвостов Надеждинского металлургического комбината, шлаков медного производства горно-металлургического комбината «Норильский никель» путем переработки их как вторичного минерального сырья с целью снижения их антропогенное воздействие на окружающую среду арктического региона. В частности, были проведены исследования по оптимизации состава сырьевой смеси и химико-минералогического состава цементного клинкера. Оптимизация проводилась с помощью программного комплекса «ROCS», предназначенного для расчета и оптимизации цементных сырьевых смесей в зависимости от коэффициента насыщения, с определением покомпонентного химического состава сырьевой смеси и цементного клинкера, минералогического состава цементного клинкера, теплового эффекта образования клинкера (FEC) и расхода топлива на обжиг (Gfuel). В ходе проведенных исследований установлено, что: техногенное сырье в виде отвальных хвостов и шлаков производства меди может быть использовано в качестве вторичного минерального сырья для производства цементного клинкера; в зависимости от коэффициента насыщения возможно получение цементного клинкера определенного минералогического состава, как низкоосновного (белит), так и высокощелочного (алит); в зависимости от минералогического состава клинкера оптимальный состав сырьевых смесей для белитового (низкоосновного) цементного клинкера-известняка – 72,97%; отвальные хвосты – 0,71%; шлак – 26,32%, а для алита (высокопрочный) – известняк – 81,71%; отвальные хвосты – 3,52%; шлак – 14,77%.

Ключевые слова: цементный клинкер, техногенные отходы, оптимизация.

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Optimization of raw mix using technogenic waste to produce cement clinker

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Abstract: This article presents the results of the possible utilization of technogenic raw materials, in particular, technogenic tailings of the Nadezhdinsky Metallurgical Plant, slags of copper production of the mining and metallurgical plant Norilsk Nickel by processing them as secondary mineral raw materials in order to reduce their anthropogenic impact on the environment of the Arctic region. In particular, studies were conducted to optimize the composition of the raw material mix and chemical and mineralogical composition of cement clinker. optimization was carried out using the software package "ROCS", designed for the calculation and optimization of cement raw mixes depending on the saturation coefficient, with determining the component chemical composition of the raw mix and cement clinker, mineralogical composition of cement clinker, the thermal effect of clinker formation (FEC) and fuel consumption for firing (Gfuel). In the course of the research it was found that: technogenic raw materials in the form of tailings and slags of copper production can be used as secondary mineral raw materials for cement clinker production; depending on the saturation coefficient, it is possible to obtain cement clinker of a certain mineralogical composition, both low — base (belite) and high-base (alite); depending on the mineralogical composition of clinker, optimal compositions of raw mixtures for belite (low-base) cement clinker-limestone are as follows: 72.97%; dump tails-0.71%; slag-26.32%, and for alite (high — base) — limestone-81.71%; dump tailings-3.52%; slag-14.77%.

Key words: cement clinker, industrial waste, optimization.

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Introduction

The Russian Arctic zone today is one of the priority areas of development in economic and environmental terms. Over the years of industrial development of the Arctic zone of Russia, a significant number of industrial enterprises of chemical oil, gas, mining and processing, mining and metallurgical, and a number of other industries have been put into operation. [1—16].

Today, the Arctic produces products that provide about 11% of Russia's national income (with a population of 1% living there) and account for up to 22% of all-Russian exports. The region has a multidisciplinary industrial and social infrastructure, which consists mainly of the raw materials sector of the economy, as well as military-industrial and transport (the Northern Sea Route — NSR) complexes [1—4, 17].

Most types of specialized products of the North have no alternative in terms of possible production in other regions of the country or import purchases. In fact, no branch of the Russian economy and social sphere can function without fuel, energy and other resources extracted and produced in the northern regions. At the same time, the development of a significant number of fields in the Arctic zone creates many problems and requires significant economic investments. In addition, new mining and transportation technologies are needed to ensure the preservation of the Arctic environment [2—4, 17].

In the Russian part of the Arctic zone, 27 sites have been identified (11 on land, 16 in the seas and the coastal zone), which have received the name "impact sites" and which represent the four main centers of anthropogenic tension — the Murmansk region (with a total emission of pollutants — 10%), the Norilsk industrial area (just over 30%), areas of development and operation of oil and gas fields in Western Siberia (just over 30%), and the Arkhangelsk region, where a high degree of pollution by specific substances is observed) [2—4, 18].

In these regions, the anthropogenic impact on the environment has already led to serious violations of the natural geochemical background, significant pollution of air, soil, subsoil, vegetation, penetration of harmful substances into the food chain and growth of morbidity of the living population [19—22, 57].

An extremely acute problem for the Arctic is the disposal of accumulated industrial waste, which has accumulated in huge quantities and continues to accumulate around industrial enterprises in the form of dumps, tailings ponds, sludge reservoirs, etc. [2—11, 23—30].

Today, the accumulated industrial waste is a constant source of environmental threat objects of pollution in the Arctic territories. One of the most dangerous are wastes and abandoned areas of mining and industrial production, especially those associated with the extraction of raw materials for non-ferrous metallurgy and with the use of amalgamation method in the technological cycle of their production [1—4, 23—36].

The Arctic, due to its natural and climatic conditions at the present stage of its development, is not able to recycle huge amounts of accumulated waste from various industries and enterprises even over hundreds of years [1—4, 23—38]. In this regard, today the problem of processing [39] and disposal [40] of daily generated industrial and accumulatedindustrial waste, which is the main problem of pollution of the natural environment of the region is acute.

A similar technogenic source of pollution of the Arctic environment is the accumulated dump tailings of the Nadezhdinskiy Metallurgical Plant (NMZ) and slags from copper production at the Norilsk Nickel Mining and Metallurgical Plant. They have accumulated in huge quantities, amounting to tens of millions tons and occupy large areas of land for waste dumps and tailings, while polluting the environment, having negative impact on the air, soil, surface and underground water, flora and fauna, and, of course, negatively affecting the lives and health of people living there. Currently functioning industrial enterprises and production facilities of Norilsk mining and metallurgical Plant are foci of anthropogenic pollution of the natural environment of the city of Norilsk and the Krasnoyarsk Krai.

Having considered [41—45] and studied the chemical composition of the dump tailings of the Nadezhdinsky Metallurgical Plant, which are a fine powder, wefound that they contain compounds of oxides of silicon, aluminum, calcium, iron, magnesium, the presence of which makes it possible to use them as secondary mineral raw materials in the chemical industry, as an iron-containing component in the raw material charge for the production of cement clinker. Similar to the waste tailings of the NMZ, the slag of the copper production of the Norilsk Nickel mining and Metallurgical combine also contains in its chemical composition such useful compounds as compounds of silicon, aluminum, iron, calcium, and magnesium oxides [46—50] and is able to act as a silicon-containing component of the raw charge for the production of cement clinker. Limestone of the Kalargonskoye deposit with CaO content from 46 to 52% is considered as the main component of the raw charge containing $CaCO_3$ [58—60].

In the standard technological scheme for the production of cement clinker, currently is used a three-component charge mixture of limestone, loess clay and iron ore. In this case, limestone, clay and iron ore must be extracted in quarries which must be developed and maintained, and the raw materials extracted from them must undergo a multi-stage crushing and grinding to prepare the component of the raw material mixfor clinker, which requires a huge financial investment, which in the future will affect the high cost of obtaining cement clinker [61 — 63].

In this regard, the use of waste, which by its chemical composition can replace the two classical components (clay and iron ore), as well as save financial resources intended for the development of clay and iron ore quarries and their preparation in the form of crushing, grinding and grinding, which is beneficial in terms of finance — the cost cement clinker will be significantly reduced, while at the same time recycling waste from the mining and metallurgical industry, and, accordingly, reducing the anthropogenic load on the environment. Therefore, at present, research aimed at reducing the anthropogenic load on the environment, reducing the cost of mining and preparing mineral raw materials, and recycling industrial waste by involving it in the production cycle as secondary mineral raw materials is relevant.

The purpose of the research was to calculate and optimize the raw mix with the involvement of technogenic waste as components of the raw mix for the production of cement clinker, using the software package “ROCS” [51], designed to calculate and optimize multi-component raw mixes of mineralogical composition of Portland cement clinker for cement production.

Materials and Methods

The “ROCS” program, in comparison with all existing in our country and abroad programs and methods [52 — 56], has a number of new features and allows [51]:

– calculate mixes with any number of components

– take into account introduction of an unlimited number of additives (components with specified consumption) into the raw mix or directly into the furnace);

– calculate special cements and perform calculations using various methods (e.g., those used in the UK or the USA);

– optimize the composition of the raw mix and clinker in terms of various characteristics, including the energy intensity of the resulting mixes

– make recommendations for the preparation of mixes based on the raw material base of a particular plant

– perform a graphical analysis of the characteristics of mixtures and clinker, including depending on the consumption of additives

– expand and customize the program to account for the raw material base of the plant, the products produced, the calculation of new types of clinkers and the application of new calculation methods.

Implementation of these differences became possible as a result of the fact that the program is based on fundamental scientific work — methods of calculation and optimization of multicomponent silicate-containing systems and raw mixes [28].

In the course of research by optimization method, a three-component mixture consisting of limestone of the Kalargonskoye deposit, dump tailings and slag of copper production was developed with the following chemical composition, given in Table 1.

Results and Discussion

Using the software package ROCS, in order to optimize the raw mix and mineral composition of clinker, we conducted a series of calculations with a different saturation coefficient (KN) in the range of 0.70 — 0.90 with a step of 0.02, with a constant silicate modulus (n), which was taken in all calculations equal to 1.8.

Table 1

Chemical composition of raw materials intended for optimization in the production of cement clinker

Compounds	**Components, %**		
	Limestone	**Dump tails**	**Slag**
SiO_2	6.67	15.28	54.75
Al_2O_3	2.73	4.46	13.45
Fe_2O_3	0.38	49.73	9.38
CaO	50.12	10.25	18.3
MgO	0.21	0.85	1.2
SO_3	0.1	1.58	0.25
Na_2O	0.52	0.23	–
K_2O	0.38	0.12	–
Losses	38.63	11.46	–
Other	0.76	6.39	2.67

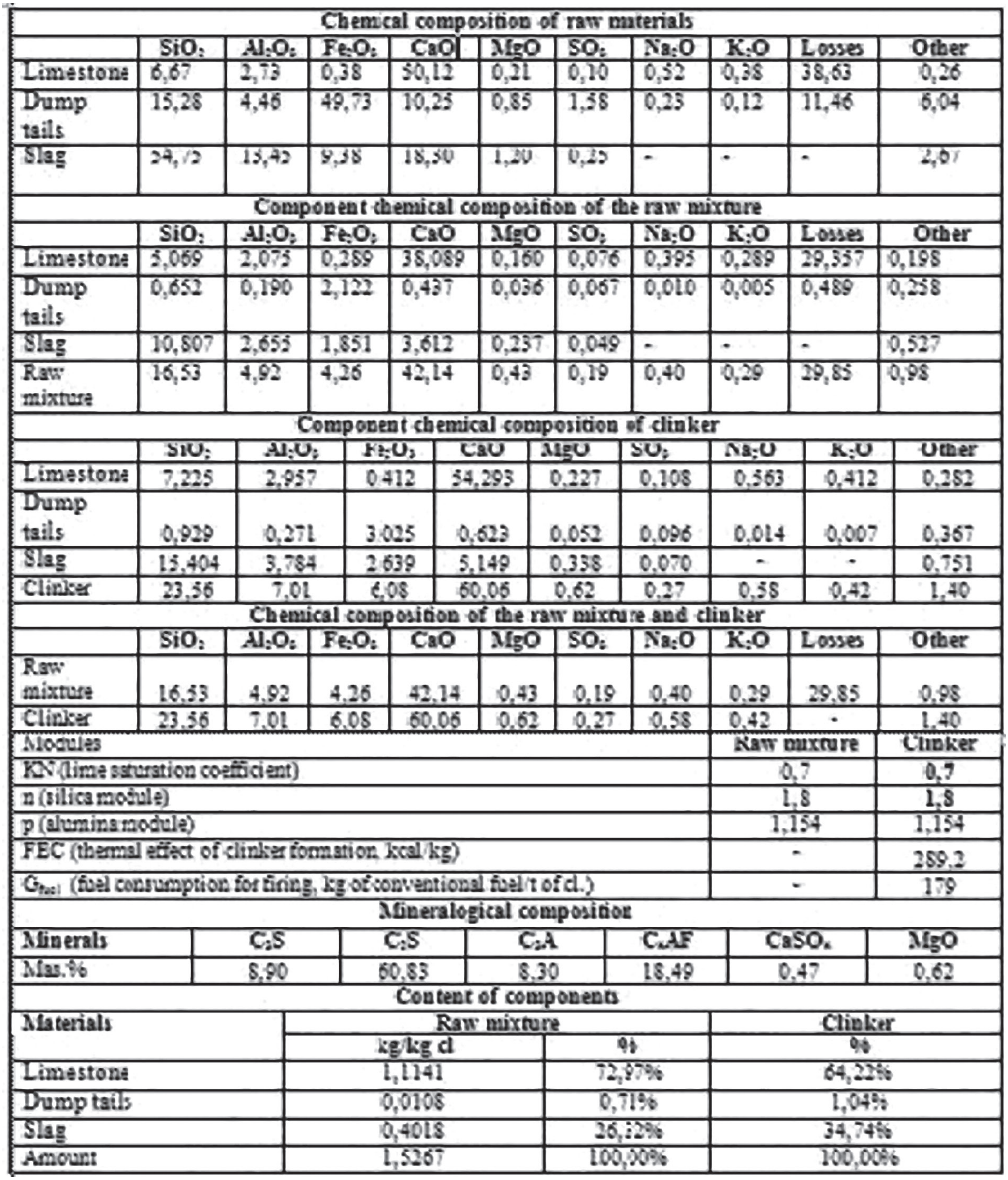
At the same time, the alumina modulus (p) during optimization, depending on KN, varied from 1.154 to 1.,270. Of all the calculations carried out, we took and presented three calculations, in particular, for KN equal to 0.70 (Figure 1), for KN equal to 0.80 (Figure 2) and for KN=0.90 (Figure 3). Optimization was carried out according to the following parameters: mineralogical composition of clinker, in particular, the phase content of the main minerals in cement clinker; fuel consumption (G_{fuel}); thermal effect of clinker formation (FEC); composition of raw materials in the raw mixture.

From the results of optimization of composition of raw mix and mineralogical composition of cement clinker with saturation coefficient (KN) of 0.70, shown in Figure 1, it can be seen that, depending on the KN, with a silicate module of 1.8, it is possible to obtain cement clinker of the following mineral composition: C_3S (alite) – 8.90%; C_2S (belite) – 60.83%; C_3A (tricalcium aluminate) – 8.30%; C_4AF (four – calcium aluminoferrite) – 18.49%; $CaSO_4$ (gypsum)-0.47%; MgO (magnesium oxide) – 0.62%.

The predominance of the belite phase in the mineralogical composition means that the resulting cement clinker will be belite, which meets the requirements for cement clinkers according to GOST 31108–2016. The raw mix for the production of belite cement clinker is represented by the following percentage of the components of the raw material mixture, in particular: limestone-72.97%; dump tailings-0.71%; slag-26.32%.

At formation of the fuel and energy complex (thermal effect of clinker formation) equal to 289 kcal/kg, the consumption of the standard fuel equivalent for burning (G_{fuel}) is equal to 179 kg of conventional fuel/t of cl.

Fig. 2, which presents the results of the optimization of the composition of the raw mix and mineralogical composition of cement clinker at KN=0.80 and n=1.8. shows that the formation of cement clinker of the following mineral composition occurs: C3S – 33.43%; C2S – 37.94%; C3A- 8.39%; C4AF – 16.85%; CaSO4 – 0.45%; MgO – 0.58%. from which it follows that this cement clinker by its mineralogical composition does not meet the requirements of GOST 31108–2016. In this case, the thermal effect of clinker formation was 320.8 kcal/kg, and the consumption of conventional fuel equivalent for burning (G_{fuel}) was



Chemical composition of raw materials

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Limestone	6,67	2,73	0,38	50,12	0,21	0,10	0,52	0,38	38,63	0,26
Dump tails	15,28	4,46	49,73	10,25	0,85	1,58	0,23	0,12	11,46	6,04
Slag	24,75	15,45	9,38	18,50	1,20	0,25	-	-	-	2,67

Component chemical composition of the raw mixture

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Limestone	5,069	2,075	0,289	38,089	0,160	0,076	0,395	0,289	29,357	0,198
Dump tails	0,652	0,190	2,122	0,437	0,036	0,067	0,010	0,005	0,489	0,258
Slag	10,807	2,655	1,851	3,612	0,237	0,049	-	-	-	0,527
Raw mixture	16,53	4,92	4,26	42,14	0,43	0,19	0,40	0,29	29,85	0,98

Component chemical composition of clinker

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Other
Limestone	7,225	2,957	0.412	54,293	0,227	0,108	0,563	0,412	0,282
Dump tails	0,929	0,271	3.025	0,623	0,052	0,096	0,014	0,007	0,367
Slag	15,404	3,784	2.639	5,149	0,338	0,070	-	-	0,751
Clinker	23,56	7,01	6,08	60,06	0,62	0,27	0,58	0,42	1,40

Chemical composition of the raw mixture and clinker

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Raw mixture	16,53	4,92	4,26	42,14	0,43	0,19	0,40	0,29	29,85	0,98
Clinker	23,56	7,01	6,08	60,06	0,62	0,27	0,58	0,42	-	1,40

Modules	Raw mixture	Clinker
KN (lime saturation coefficient)	0,7	0,7
n (silica module)	1,8	1,8
p (alumina module)	1,154	1,154
FEC (thermal effect of clinker formation, kcal/kg)	-	289,2
G_{fuel} (fuel consumption for firing, kg of conventional fuel/t of cl.)	-	179

Mineralogical composition

Minerals	C_2S	C_3S	C_3A	C_4AF	$CaSO_4$	MgO
Mas.%	8,90	60,83	8,30	18,49	0,47	0,62

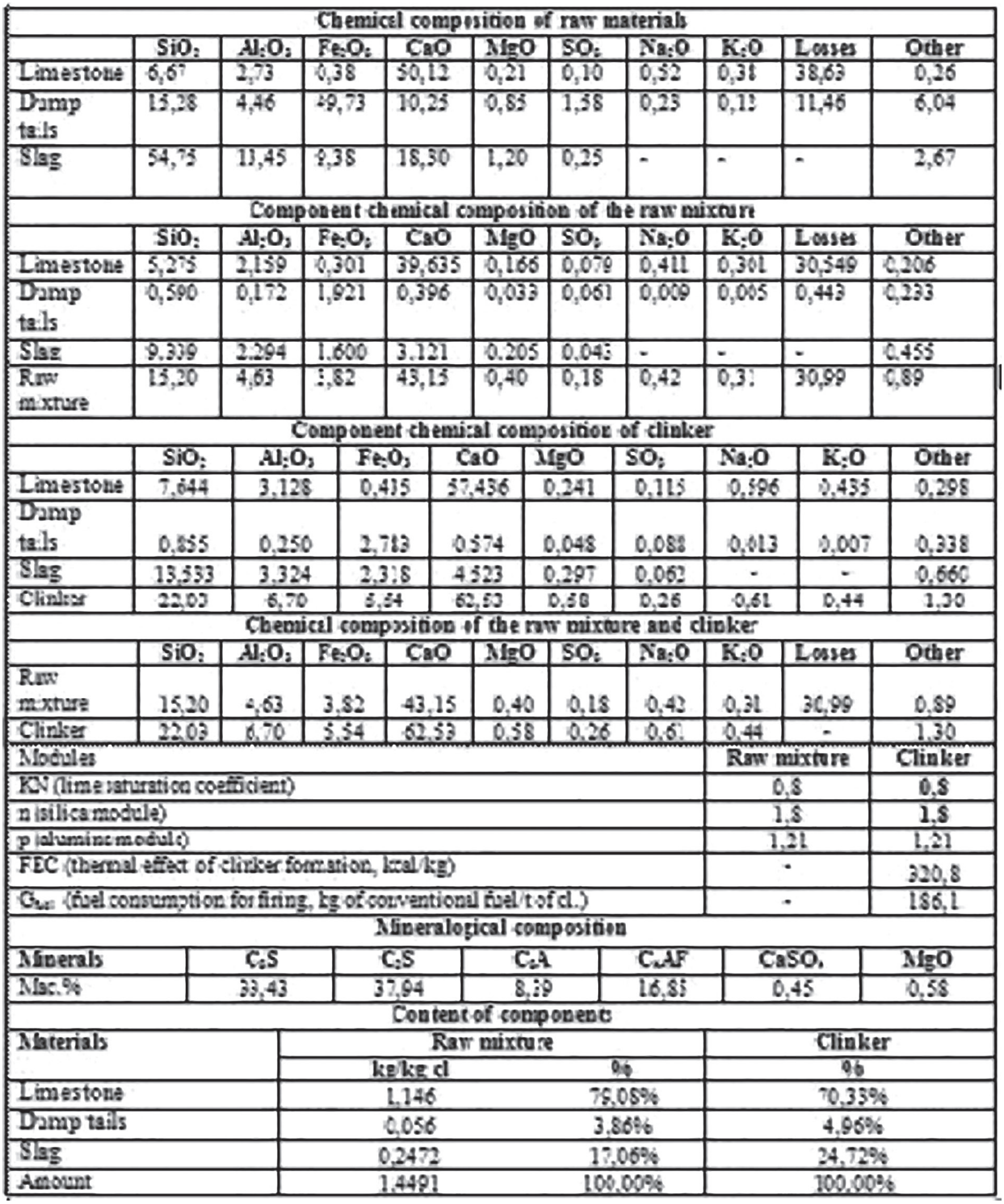
Content of components

Materials	Raw mixture		Clinker
	kg/kg cl	%	%
Limestone	1,1141	72,97%	64,22%
Dump tails	0,0108	0,71%	1,04%
Slag	0,4018	26,32%	34,74%
Amount	1,5267	100,00%	100,00%

Fig. 1. Results of the calculation of the chemical and mineralogical composition of the raw mixture and clinker at KN=0.70 and n=1.80

186.1 kg of fuel equivalent/t of clinker. The components of the raw mixture are presented in the following percentage ratio: limestone-79.08%; dump tailings-3.86%; slag-17.06%.

From the results of the optimization and calculation of the chemical and mineralogical composition of the raw mix and clinker at KN = 0.90 and n = 1.80, shown in Figure 3, it can be seen that the mineralogical composition of cement clinker is represented by the main minerals in the following percentage ratio: C_3S-54.98%; C_2S-17.84%; C_3A-



Chemical composition of raw materials

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Limestone	6,67	2,73	0,38	50,12	0,21	0,10	0,52	0,31	38,63	0,26
Dump tails	15,28	4,46	49,73	10,25	0,85	1,58	0,23	0,13	11,46	6,04
Slag	54,75	13,45	9,38	18,30	1,20	0,25	-	-	-	2,67

Component chemical composition of the raw mixture

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Limestone	5,275	2,159	0,301	39,635	0,166	0,079	0,411	0,301	30,549	0,206
Dump tails	0,590	0,172	1,921	0,396	0,033	0,061	0,009	0,005	0,443	0,233
Slag	9,339	2,294	1,600	3,121	0,205	0,043	-	-	-	0,455
Raw mixture	15,20	4,63	3,82	43,15	0,40	0,18	0,42	0,31	30,99	0,89

Component chemical composition of clinker

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Other
Limestone	7,644	3,128	0,415	57,436	0,241	0,115	0,596	0,435	0,298
Dump tails	0,855	0,250	2,783	0,574	0,048	0,088	0,013	0,007	0,338
Slag	13,533	3,324	2,318	4,523	0,297	0,062	-	-	0,660
Clinker	22,03	6,70	5,54	62,53	0,58	0,26	0,61	0,44	1,30

Chemical composition of the raw mixture and clinker

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Raw mixture	15,20	4,63	3,82	43,15	0,40	0,18	0,42	0,31	30,99	0,89
Clinker	22,03	6,70	5,54	62,53	0,58	0,26	0,61	0,44	-	1,30

Modules	Raw mixture	Clinker
KN (lime saturation coefficient)	0,8	0,8
n (silica module)	1,8	1,8
p (alumina module)	1,21	1,21
FEC (thermal effect of clinker formation, kcal/kg)	-	320,8
G_{fuel} (fuel consumption for firing, kg of conventional fuel/t of cl.)	-	186,1

Mineralogical composition

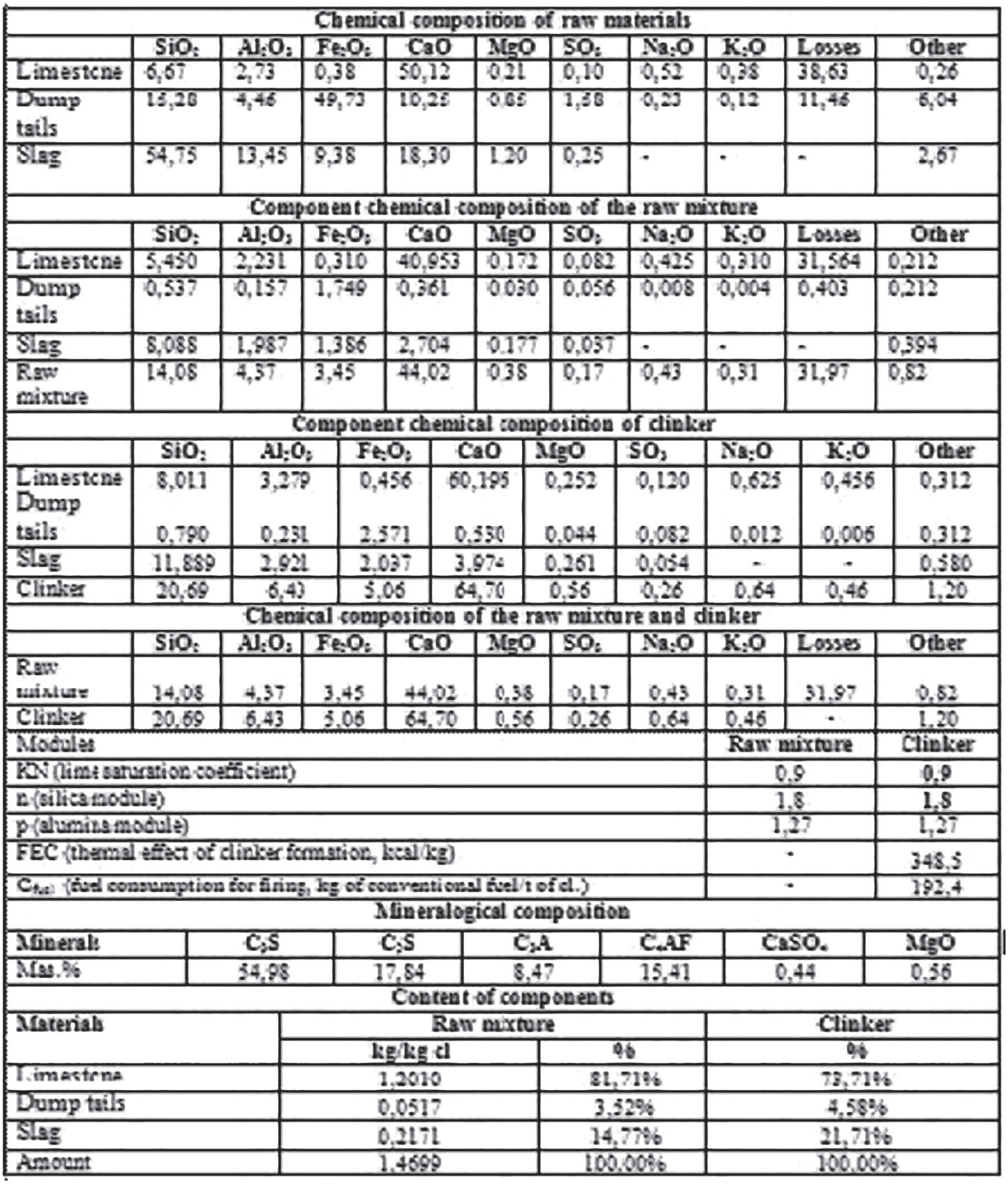
Minerals	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	MgO
Mac.%	33,43	37,94	8,39	16,83	0,45	0,58

Content of components

Materials	Raw mixture		Clinker
	kg/kg cl	%	%
Limestone	1,146	79,08%	70,33%
Dump tails	0,056	3,86%	4,96%
Slag	0,2472	17,06%	24,72%
Amount	1,4491	100,00%	100,00%

Fig. 2. Results of the calculation of the chemical and mineralogical composition of the raw mixture and clinker at KN=0.80 and n=1.80

8.47%; C_4AF-15.41%; $CaSO_4$ – 0.44%; MgO – 0.56%. based on which it follows that the resulting clinker is alitic due to the predominance of the mineral C_3S and highly basic in accordance with GOST 31108 – 2016, with a thermal effect of clinker formation – 348.5 kcal/kg and the consumption of fuel equivalent for burning (G_{fuel}) – 192.4 kg of fuel equivalent/t of clinker. The components



Chemical composition of raw materials										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Limestone	6,67	2,73	0,38	50,12	0,21	0,10	0,52	0,38	38,63	0,26
Dump tails	15,28	4,46	49,73	10,25	0,85	1,58	0,23	0,12	11,46	6,04
Slag	54,75	13,45	9,38	18,30	1,20	0,25	-	-	-	2,67

Component chemical composition of the raw mixture										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Limestone	5,450	2,231	0,310	40,953	0,172	0,082	0,425	0,310	31,564	0,212
Dump tails	0,537	0,157	1,749	0,361	0,030	0,056	0,008	0,004	0,403	0,212
Slag	8,088	1,987	1,386	2,704	0,177	0,037	-	-	-	0,394
Raw mixture	14,08	4,37	3,45	44,02	0,38	0,17	0,43	0,31	31,97	0,82

Component chemical composition of clinker									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Other
Limestone	8,011	3,279	0,456	60,195	0,252	0,120	0,625	0,456	0,312
Dump tails	0,790	0,231	2,571	0,530	0,044	0,082	0,012	0,006	0,312
Slag	11,889	2,921	2,037	3,974	0,261	0,054	-	-	0,580
Clinker	20,69	6,43	5,06	64,70	0,56	0,26	0,64	0,46	1,20

Chemical composition of the raw mixture and clinker										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Losses	Other
Raw mixture	14,08	4,37	3,45	44,02	0,38	0,17	0,43	0,31	31,97	0,82
Clinker	20,69	6,43	5,06	64,70	0,56	0,26	0,64	0,46	-	1,20

Modules	Raw mixture	Clinker
KN (lime saturation coefficient)	0,9	0,9
n (silica module)	1,8	1,8
p (alumina module)	1,27	1,27
FEC (thermal effect of clinker formation, kcal/kg)	-	348,5
C_{fuel} (fuel consumption for firing, kg of conventional fuel/t of cl.)	-	192,4

Mineralogical composition						
Minerals	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	MgO
Mas.%	54,98	17,84	8,47	15,41	0,44	0,56

Content of components			
Materials	Raw mixture		Clinker
	kg/kg cl	%	%
Limestone	1,2010	81,71%	73,71%
Dump tails	0,0517	3,52%	4,58%
Slag	0,2171	14,77%	21,71%
Amount	1,4699	100,00%	100,00%

Fig. 3. Results of the calculation of the chemical and mineralogical composition of the raw mixture and clinker at KN=0.90 and n=1.80

of the raw mixture are presented in the following percentage: limestone- 81.71%; dump tailings-3.52%; slag-14.77%.,

Results and Discussion Conclusions

Thus, based on the research we can draw the following conclusions:

– Technogenic raw materials in the form of waste tailings and slags of copper production, can be used as secondary mineral raw materials in the production of cement clinker.

– Depending on the saturation coefficient, it is possible to produce cement clinker of a certain mineralogical composition, such as belite, with a fuel consumption of 179 kg of equivalent fuel/t of cl. and C2S content of 60.83%, and alite, with C3S content of 54.98% and a fuel consumption of 192.4 kg of equivalent fuel/t of clinker.

– In the course of optimization, depending on the mineralogical composition of cement clinker, optimal compositions of raw mixes for the belite-containing cement clinker were found in the following ratio: limestone-72.97%; dump tails-0.71%; slag-26.32%. and for the alite — containing limestone-81.71%; dump tails-3.52%; slag-14.77%.

– Organizing the processing of technogenic dump tailings of the Nadezhdinsky Metallurgical Plant, copper slag of the Norilsk Nickel Mining and Metallurgical Plant, and limestone to produce cement clinker using the above technology in the Arctic region, will improve the social, investment, economic and environmental climate, which in its turn will contribute to the development of the Arctic.

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ПРОГНОЗИРОВАНИЕ ТЕРМИЧЕСКОГО ВОЗДЕЙСТВИЯ ПОДЗЕМНОГО НЕФТЕПРОВОДА НА МНОГОЛЕТНЕМЕРЗЛЫЕ ПОРОДЫ НА ОСНОВЕ МАТЕМАТИЧЕСКИХ МОДЕЛЕЙ

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Аннотация: при подземной прокладке нефтепроводов, в условиях залегания многолетнемерзлой породы (ММП), по которой осуществляется перекачка нефти с подогревом, кроме процессов, связанных с сезонным оттаиванием и замерзанием грунтов, может произойти процесс оттаивания мерзлоты от термического воздействия трубопровода. При оттаивании и замерзании ММП возможно пучение и просадка грунтов, образование наледи, заболачивание трассы нефтепровода и т. д. Вследствие этого существует вероятность пространственного перемещения, выпучивания участков, деформации трубопроводов, что в итоге может привести к аварийным ситуациям. В работе исследуется термическое воздействие нефтепровода на ММП на основе математических моделей. В ходе исследований была изучена математическая модель Стефана. Для получения наглядных результатов были использованы математические методы моделирования на общедоступных программах. В результате моделирования предложен вариант использования нефтепровода с теплоизоляцией и осуществления заблаговременного проведения мероприятий по предупреждению чрезвычайных ситуаций обусловленного нефтеразливом и максимально возможного снижения ущерба.

Ключевые слова: замерзание, оттаивание, многолетнемерзлые породы, нефтепровод, математическое моделирование.

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Predicting the thermal impact of an underground oil pipeline on the permafrost zone using mathematical modeling

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Abstract: In underground oil pipelines constructed on permafrost, where oil is transported with heating, in addition to the processes associated with seasonal thawing and freezing of soils, the thawing of permafrost from the thermal effect of the pipeline may occur. During the thawing and freezing of the permafrost zone, ground soil heaving and subsidence of, ice formation, waterlogging of the pipeline route are possible. As a result, there is a probability of spatial displacements, section buckling, pipeline deformations, which may ultimately lead to emergencies. The paper investigates the thermal effect of an oil pipeline on the permafrost zone using mathematical models. Stefan's mathematical model is studied. It is proposed to use an oil pipeline with thermal insulation and to take measures in advance to prevent emergencies caused by oil spills and to reduce damage as much as possible.

Key words: Freezing, thawing, permafrost, oil pipeline, mathematical modeling.

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1. Introduction

The active development of oil and gas fields in northern regions with permafrost creates significant artificial impacts on the fragile nature of the Far North [1].

One of the most important projects that have been implemented is the Eastern Siberia — Pacific Ocean (ESPO) trunk oil pipeline system, which connects the fields in Eastern Siberia with the ports of Primorsky Krai, which provides for the development of international exports.

In the territory of the Mirny and Lensk Districts of the Republic of Sakha (Yakutia), which belong to the Far North regions [2], a two-threaded trunk oil pipeline from the Srednebotuobinskoe oil and gas condensate field to the ESPO (SBOGSF- ESPO) was built. The pipeline transports commercial oil with heating from the Central Collection Point (CCP) of the Srednebotuobinskoe field to the Crude Metering Station of the Oil Delivery and Acceptance Station (DAS) Lensk to the Main Oil Pipeline of the ESPO The pipeline is underground and has a standard factory polymer insulation without thermal insulation.

To prevent unproductive costs and negative environmental consequences, and to ensure safe and reliable operation of pipelines built on permafrost, it is necessary to take into account various factors: movement and deformation of the pipeline, thermokarst processes of ground ice; frost cracking and ice formation; heaving processes; erosional activity of temporary watercourses; dismemberment of the terrain relief [3].

Mathematical modeling of heat transfer problems is necessary to study the thermal impact of pipelines on permafrost. The finite element method is widely used for numerical solution of heat transfer problems. For instance, in [4,5], the finite element method is used to estimate the thermal impact of a Sino-Russian crude oil pipeline in permafrost areas. In [6], the temperature around a hot buried pipeline in northern Alberta, Canada, is modeled.

The purpose of the work is to predict the temperature interaction of the pipeline with the permafrost. To achieve this goal, we set the following tasks:

1. To investigate a mathematical model of the heat transfer process with phase change.
2. To model the thermal interaction of the frozen ground with the oil pipeline.
3. To predict possible volumes and areas of oil spills in case of pipeline accidents.

2. Theory

Permafrost covers about 24% of the land area and more than 60% of the territory of the Russian Federation [7]: North America, Europe, Asia, Arctic Ocean Islands, Antarctica. Permafrost soils are complex multicomponent and multiphase systems [8].

The design, construction, and operation of trunk oil pipelines in areas of permafrost distribution pose a number of problems due to the climatic and geocryological conditions of the area. These problems are caused both by changes in the properties of frozen soils, depending on the temperature of the product being pumped and the environment, and by the occurrence and development of hazardous engineering-geological processes in the zone of influence of the pipeline (thermokarst, waterlogging, frost cracks, soil swelling). Variability and heterogeneity of soil properties along the pipeline route and uneven distribution of ice inclusions of different shapes and sizes are observed. Changes in thermal, physical, and mechanical properties of soil during the operation of pipelines rs in inhomogeneous thawing of permafrost. Thawing of permafrost, in its turn, is accompanied by formation of a thawing halo around the pipeline, uneven subsidence, and deformation of the soil. As a consequence, this can lead to bending deformations of the pipeline, overstressing, and destruction [9]. Permafrost rocks give different sediments depending on their structure [10].

2.1. SBOGSF — ESPO Trunk Oil Pipeline

The first SBOGSF- ESPO trunk oil pipeline was built of 273 mm diameter pipes with10 mm wall thickness, factory polymer insulation, and 09G2S steel grade. The pipeline was put into operation in 2013. The second pipeline had a diameter of 530 mm, wall thickness of 14 mm, polymer insulation, and steel grade 17G1C-U and was put into operation in 2017. These oil pipelines are located underground.

To protect oil pipelines from mechanical damage [11], the depth of the pipeline should be no less than 0.8 m to the top of the pipe in mineral soils and 0.6 m to the top of the ballast structures in marshes of types I and II. The facility is classified as a hazardous production facility based on the equipment operating under overpressure greater than 0.07 MPa and handling of a hazardous substance, i. e., commercial oil.

2.1.1. Hydrometeorological and environmental features of the site

The climate of the Mirny and Lensk Districts is sharply continental, with low temperatures in winter and high temperatures in summer, little cloudiness and relatively weak winds, especially in winter. Peculiarities of the winter period are manifested in very low temperatures. The absolute minimum reaches −57 °C. The air temperature of the coldest five-day period is −52 °C. Spring and early summer are drier, with little precipitation and low values of relative humidity in the daytime. Annual precipitation ranges from 371 mm to 482 mm. Of these, 267 mm of precipitation falls in April-October is. The distribution of precipitation over seasons is very uneven. Stable transition after +5° average daily temperature usually occurs on the first days of June, when the growing season begins. Summer temperatures are low — the absolute maximum air temperature is +39 °C. The average maximum air temperature of the warmest month 24.8 °C.

Summers are short but hot. The average duration of the frost-free period is 162 days. Due to the possibility of Arctic invasion, temperatures can be expected to be relatively low in any summer month. Absolute July minimum ranges from 0 to minus 3 °C. The average duration of snow cover is 202 ÷ 205 days per year.

The combination of severe frosts with little snow cover causes the soil to freeze to a considerable depth. Soil freezing begins in late September and continues late April. The average annual temperature on the soil surface is negative, an is minus 6 °C ÷ minus 8 °C.

2.1.2. Geological and engineering conditions of the territory

The pipeline area is located in an island permafrost zone. The thickness of frozen

Fig. 1. Photographs of the soil in the pipeline area

soil is 3.4–13.5 m. Their roof depth is from 1.5 to 7.6 m. In terms of ice content, the soil is soft. The prevailing temperatures range from minus 0.2 to minus 1.3 °C. The total length of the permafrost sites is 2427 m.

The ground is slightly aggressive towards concrete. Corrosion activity of soils in relation to steel is low to medium. Hydrogeological conditions of the route are characterized by the presence of suprapermafrost and subpermeable groundwater aquifers. Regarding the degree of frost heave risk, seasonally frozen soils are characterized as frost heave, strong, excessively fluctuating.

2.2. Forecasting the volume and area of oil spills

The construction and operation of oil pipelines in permafrost zones disrupt the dynamic balance, activate dangerous natural processes, and adversely affect the technical condition of oil pipelines, often resulting in emergencies [10,12].

Accidents at the second pipeline are the most dangerous with respect to large volumes and areas of oil spillage. Due to the nature of the construction sites (marshes and water barriers), long distance, high operating pressures, and other factors, significant oil spills and contamination of large areas are possible.

Oil spills destroy virtually all life. When contact with oil, vegetation dies completely within 2–3 years, without regenerating for a long time. Invertebrate animals also die almost completely in the highly polluted zone, and birds and mammals usually avoid it [13].

The volume of oil spills is predicted according to the requirements [14]:

- pipeline at burst – 25% of the maximum flow volume of 6 hours of pumping and the volume of oil between the shut-off bolts of the damaged pipeline
- pipeline at puncture – 2% of maximum flow within 14 days.

Table 1 shows the maximum possible oil spills in case of an accident at the pipeline.

Table 2 shows the area of the oil spill in the area.

The most dangerous emergency situation caused by oil spills on the oil pipeline system is an oil spill and leakage from oil pipelines. The likely consequences of a possible oil spill during accidents on oil pipelines are:

- Release of pollutants into the atmosphere as a result of evaporation of oil from the spill surface
- Fire as a result of oil spill
- Explosion (flare) of fuel and air mixture

Table 1
Maximum possible oil spills in pipeline accidents

№	Maximum possible oil spill in an accident on a pressure pipeline, т			
	Pipeline name	**Name of simple pipeline section**	**Mo_b**	**Mo_p**
1	SBOGSF — ESPO trunk oil pipelines D 273	Oil pipeline from CCP to bolt № 5 (P200+30)	1069.7	862.4
2	SBOGSF — ESPO oil pipeline D 530	Oil pipeline from CCP to bolt № 4	2251.2	3835.4
3	SBOGSF — ESPO oil pipeline D 530	Oil pipeline from bolt № 13 to bolt № 14	1910.9	3835.4
4	SBOGSF — ESPO oil pipeline D 530	Oil pipeline from bolt № 22 to RDP	2795.6	3835.4
5	Oil-collecting inland pipeline	Pipeline Node 2 — Node 4	113.1	333.4

Table 2
Oil spill area in the territory

№	Pipeline		Spill area, m^2	
	Pipeline name	**Name of simple pipeline section**	**So_b**	**So_p**
1	SBOGSF — ESPO trunk oil pipelines D 273	Oil pipeline from CCP to bolt № 5 (P200+30)	6219.3	5014.0
2	SBOGSF — ESPO oil pipeline D 530	Oil pipeline from CCP to bolt № 4	13088.2	22299.1
3	SBOGSF — ESPO oil pipeline D 530	Oil pipeline from bolt № 13 to bolt № 14	11110.0	22299.1
4	SBOGSF — ESPO oil pipeline D 530	Oil pipeline from bolt № 22 to RDP	16253.4	22299.1
5	Oil-collecting inland pipeline	Pipeline Node 2 — Node 4	657.5	1938.3

- Release of toxic products of oil combustion into the atmosphere in the event of a spill
- Death and injury to personnel (pipeline traversers) located in the area of fire and explosion hazard zone during an oil spill
- Pollution of the surrounding area
- Economic loss due to the disruption of regular operation of the plant.

2.3. Modeling the thermal interaction of an oil pipeline with permafrost

To mathematically model the temperature interaction between the pipeline with the soil, we use the Stefan equation, which describes the thermal processes taking into account the phase transition, absorption, and release of latent heat [15]

$$\left(C(\phi)+m\rho_w L\phi'\right)\frac{\partial T}{\partial t}-\nabla\cdot\left(\lambda(\phi)\nabla T\right)=0, \quad (1)$$

where T is the temperature distribution, m is the porosity factor, L is the specific heat of ice melting, ρ_w is the density of water. The coefficients of heat and heat conductivity are defined as

$$C(\phi)=(1-\phi)C_f+\phi C_{th},\lambda(\phi)= \\ =(1-\phi)\lambda_f+\phi\lambda_{th}, \quad , \quad (2)$$

where C_M, C_T, λ_M, λ_T are the volumetric heat capacity and heat conductivity of the thawed and the frozen soils, respectively;

ϕ is the Heaviside function, which is equal to 1 at positive temperatures and to 0 at negative temperatures.

Equation (1) needs to be supplemented with initial and boundary conditions. The initial temperature of the ground will be T_0. Convective heat exchange with the environment will take place on the day surface. There is no thermal interaction on the lateral and lower boundaries of the soil. Finally, we also use a constant temperature at the boundary between the soil and the pipeline T_P.

To solve equation (1), we use the FEniCS computational package [16] to automate the numerical solution of mathematical physics equations by the finite element method in the Python programming language. We use Gmsh to generate the geometry and computational mesh, we use Gmsh. All programs used in the study are free and open source.

We model the temperature interaction of an oil pipeline without thermal insulation and with thermal insulation with permafrost. We consider the two-dimensional model problem [17]. The total depth of the domain is 10 m, the width is 5 m. The domain has the following structure: sand from 0 to 4 m, sandy loam from 4 to 5.5 m, and sand-gravel mixture (SGM) from 5.5 to 10 m. The distance between the two oil pipelines on the axis is 5 m. Characteristics of the pipelines are given in Table 3.

The initial soil temperature is $T_0 = -2\,^{\circ}$C. Assume that the oil temperature in the pipe is constant and is $T_T = 33\,^{\circ}$C. Thermal properties of thawed and frozen soil (sand, sandy loam, SGM), steel, and polyurethane foam are presented in Table 4.

We use the computational mesh with 53,377 cells for pipelines with thermal insulation and the computational mesh with 15,032 cells for pipelines without insulation. The calculations were performed with a time step of 1 day over 3 years (1,095 time steps).

The results of the calculations are shown in Fig. 2 and 3, where on the left is the temperature distribution in September of the first year, and on the right is the temperature distribution in February of

Table 3
Characteristics of oil pipelines

	I pipeline	**II pipeline**
Outer diameter, mm	273	530
Wall thickness, mm	10	14
Steel grade	09G2S	17G1S-U
The location of pipeline center, mm	936.5	1065
The thickness of polyurethane foam, mm	44	70

Table 4
Thermal properties

Elements	**Heat volume $C_p \cdot 10^{-6}$**		**Heat conductivity k**		**Latent heat $L \cdot 10^{-6}$**
	thawed	**frozen**	**thawed**	**frozen**	
Sand	1.51	2.01	1.86	1.67	60.437
Sandy loam	3.15	2.35	1.51	1.7	71.957
GSM	2.51	2.06	1.42	1.84	64.769
Steel	461		80		7890
Polyurethane foam	1470		0.028		40

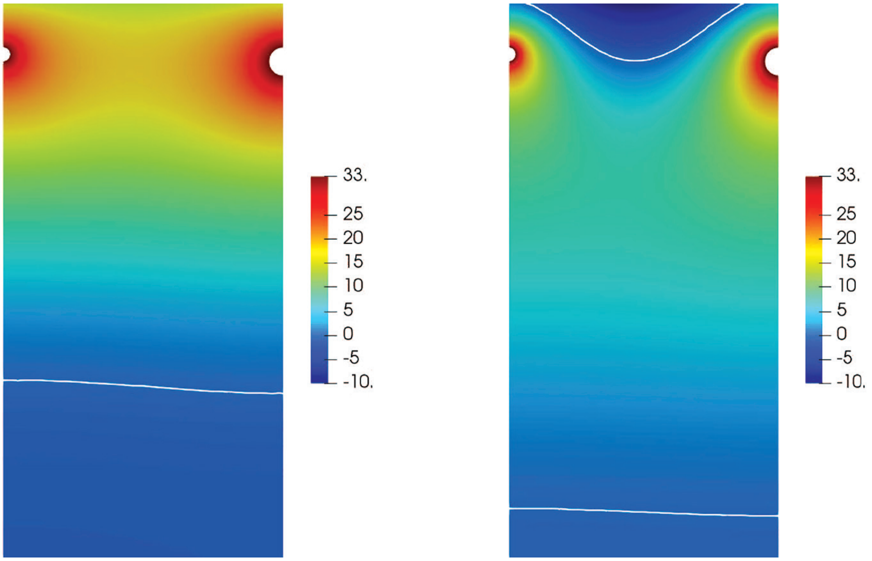

Fig. 2. Temperature distribution without thermal insulation

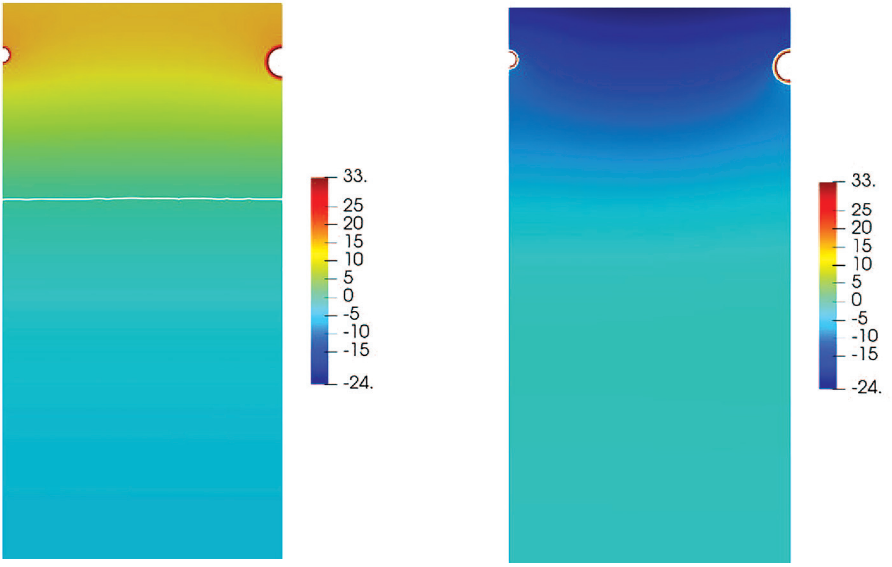

Fig. 3. Temperature distribution with thermal insulation

the second. The solid white line shows isotherms with a temperature of 0^{o}C, i. e., the thawed soil zone.

Fig. 4 shows that if the oil pipeline is not insulated, the permafrost will completely thaw within a year and a half. That will lead to soil subsidence. Note that the subsidence of soils will be uneven depending on their properties [18]. With thermal insulation, the depth of soil thawing will reach up to 4 m in summer, and in winter, the soil will be completely frozen [19].

Conclusion

We conclude that when designing an oil pipeline with heating in a permafrost

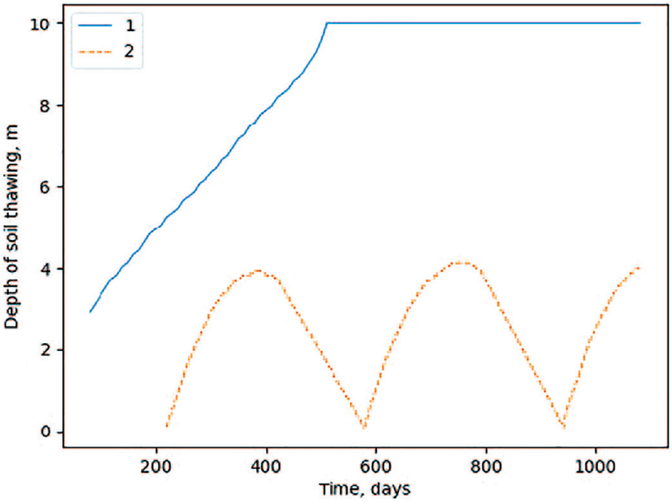

Fig. 4. The depth of permafrost thawing

area, it is necessary to provide for thermal insulation. Construction of oil pipelines with thermal insulation prevents interaction of thawing of the surrounding soil with the pipeline [20].

Also, we study the maximum possible oil spills from a pipeline accident and the area of oil spill in the territory and the consequences of possible oil spills from accidents on oil pipelines [21].

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