ГИАБ. Горный информационно-аналитический бюллетень /
MIAB. Mining Informational and Analytical Bulletin, 2022;(10-1):205—213
ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

УДК 622 DOI: 10.25018/0236_1493_2022_101_0_205

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

Т. Р. Егорова[1], В. Г. Кычкина[1], А. Е. Колесов[1]

[1] Северо-Восточного федерального университета имени М. К. Аммосова, Якутск, Россия

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.

Для цитирования: *Егорова Т. Р., Кычкина В. Г., Колесов А. Е.* Прогнозирование термического воздействия подземного нефтепровода на многолетнемерзлые породы на основе математических моделей // Горный информационно-аналитический бюллетень. — 2022. — № 10-1. — С. 205—213. DOI: 10.25018/0236_1493_2022_101_0_205.

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

T. R. Egorova[1], V. G. Kychkina[1], A. E. Kolesov[1]

[1] Institute of Natural Sciences, M. K. Ammosov North-Eastern Federal University, Yakutsk, Russia

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.

For citation: Egorova T. R., Kychkina V. G., Kolesov A. E. Predicting the thermal impact of an underground oil pipeline on the permafrost zone using mathematical modeling. *MIAB. Mining Inf. Anal. Bull.* 2022;(10-1):205—213. [In Russ]. DOI: 10.25018/0236_1493_2022_101_0_205.

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 $T_0 = -2\,^{o}$C. Assume that the oil temperature in the pipe is constant and is $T_T = 33\,^{o}$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

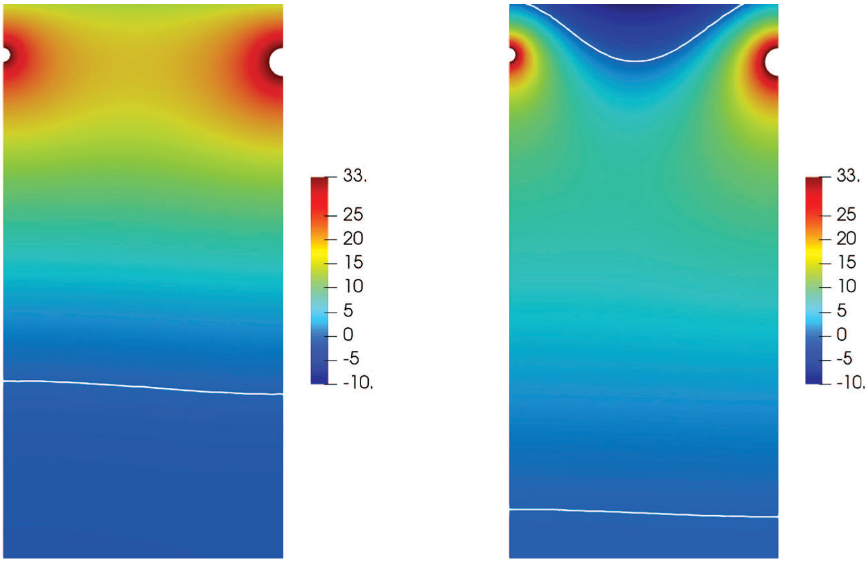

Fig. 2. Temperature distribution without thermal insulation

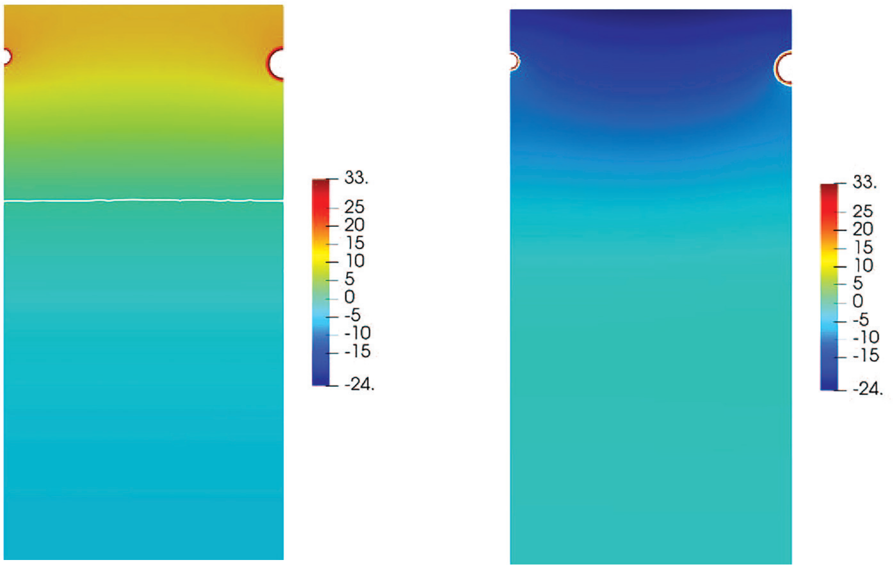

Fig. 3. Temperature distribution with thermal insulation

the second. The solid white line shows isotherms with a temperature of 0°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

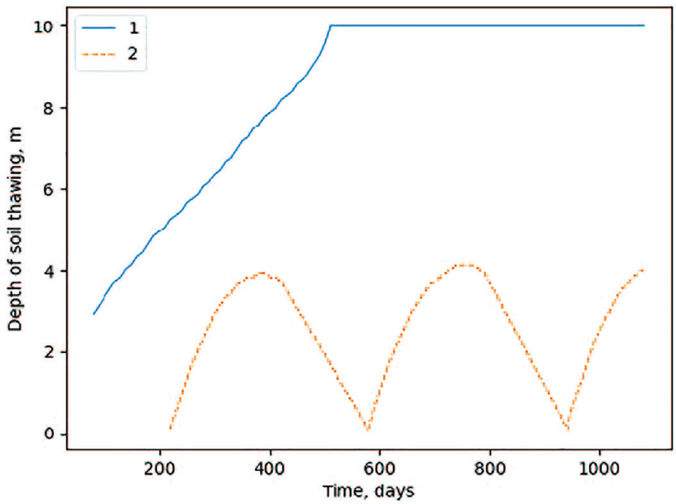

Fig. 4. The depth of permafrost thawing

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].

REFERENCES

1. Oswell, J. M. (2011). Pipelines in permafrost: geotechnical issues and lessons. Canadian Geotechnical Journal, 48(9), 1412–1431.

2. Resolution of the Council of Ministers of the USSR of November 10, 1967 N 1029 On the procedure for applying the Decree of the Presidium of the Supreme Soviet of the USSR of September 26.

3. Efimov, V. M et al. (2019). Geotechnical monitoring in permafrost zone as a condition for ensuring engineering and environmental safety of industrial development of the territory. Materials of the XV All-Russian Scientific and Practical Conference «Prospects for the development of engineering surveys in construction in the Russian Federation» (Moscow).

4. Zhang, J et al. (2010). Estimates on thermal effects of the China–Russia crude oil pipeline in permafrost regions. Cold Regions Science and Technology, 64(3), 243–247.

5. Samylovskaya, E., Makhovikov, A., Lutonin, A., et al. (2022). Digital Technologies in Arctic Oil and Gas Resources Extraction: Global Trends and Russian Experience, Resources, 21100808642, 11. DOI: 10.3390/resources11030029.

6. Nagare, R M et al. (2021). Modeling shallow ground temperatures around hot buried pipelines in cold regions. Cold Regions Science and Technology, 187, 103295.

7. Osterkamp, T. E. and Burn, C. R. (2003). Permafrost Encyclopedia Atmospheric Sciences Ed,1717–1729.

8. Buslaev, G., Morenov, V., Konyaev, Y., et al. (2021). Reduction of carbon footprint of the production and field transport of high-viscosity oils in the Arctic region, Chemical Engineering and Processing. Process Intensification, 02552701, 159 DOI: 10.1016/j.cep.2020.108189.

9. Taranov, R. A. and Marchenko, A. V. (2019). Features of the design, construction and operation of oil trunk pipelines in permafrost zones. Journal of Science and Education, 12(66–1).

10. Tsarapov, M. N. and Kotov, P. I. (2013). Properties of frozen soils during thawing. Railway Track and Facilities, 31–34.
11. CR 36.13330.2012 Code of practice trunk pipelines.
12. Romasheva, N., Dmitrieva, D. (2021). Energy resources exploitation in the russian arctic: Challenges and prospects for the sustainable development of the ecosystem, Energies, 62932, 14. DOI: 10.3390/en14248300.
13. Zhukovskiy Y, Tsvetkov P, Buldysko A, Malkova Y, Stoianova A, Koshenkova A. (2021) Scenario Modeling of Sustainable Development of Energy Supply in the Arctic. Resources, 10(12):124. DOI: 10.3390/resources10120124.
14. Russian Federation Government Decree № 613 from 21.08.2000. «On urgent measures to prevent and eliminate emergency spills of oil and oil products».
15. Vabishchevich, P. N. et al. (2016). Numerical analysis of temperature dynamics of railway embankment in permafrost, Mathematical Models, 28(10), 110–124.
16. Alnæs, M. S. et al. (2015). The FEniCS Project Version 1.5 Archive of Numerical. Software 3(100) 9–23.
17. Novikov, P. A. (2016). Identification of dangerous sections of trunk oil pipelines based on long-term forecasting of the halo of thawing of permafrost zones. Dissertation of the Candidate of Technical Sciences (Moscow) .
18. Afanaseva, N. V. and Kolesov, A. E. (2016). Numerical solution of the thermal influence of oil well cluster on permafrost. AIP Conference Proceedings, 1773(1), 110001.
19. Buslaev, G., Tsvetkov, P., Lavrik, A., et al. (2021). Ensuring the sustainability of arctic industrial facilities under conditions of global climate change, Resources, 21100808642, 10. DOI: 10.3390/resources10120128.
20. Fedorov, A. N., Gavriliev, P. P., Konstantinov, P. Y., Hiyama, T., Iijima, Y. and Iwahana, G. (2014). Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia. Ecohydrology, 7, 2, 188–196. DOI: 10.1002/eco.1378.
21. . Pugach A. S. Mathematical model of rock compaction for operation in zones of high tectonic stresses. *MIAB. Mining Inf. Anal. Bull.* 2022;(6):167-181. [In Russ]. DOI: 10.25018/0236_1493_2022_6_0_167. ГИАБ

ИНФОРМАЦИЯ ОБ АВТОРАХ

Егорова Туйаара Руслановна[1] — зав. лабораторией, e-mail: tuyaruslanovna@mail.ru, ORCID ID: 0000–0002–7117–9218;
Кычкина Вилена Григорьевна[1] — старший преподаватель, e-mail: kychkina.v.g@gmail.com, ORCID ID: 0000–0003–1419–3715,
Колесов Александр Егорович[1] — кандидат физ.-мат. наук, доцент Геологоразведочного факультета, e-mail: Ae.kolesov@s-vfu.ru, ORCID ID: 0000–0001–9969–1195;
[1] Северо-Восточный федеральный университет им. М. К. Аммосова.
Для контактов: *Егорова Т. Р.*, e-mail: tuyaruslanovna@mail.ru.

INFORMATION ABOUT THE AUTHORS

Egorova T. R.[1], Head of Laboratory, e-mail:: tuyaruslanovna@mail.ru, ORCID ID: 0000–0002–7117–9218;
Kychkina V. G.[1], Lecturer, e-mail: kychkina.v.g@gmail.com, ORCID ID: 0000–0003–1419–3715;
Kolesov A. E.[1], Cand. of Phys. and Mathem. Sci., Docent Faculty of Geology and Survey, e-mail: Ae.kolesov@s-vfu.ru, ORCID ID: 0000–0001–9969–1195;
[1] M. K. Ammosov North-Eastern Federal University, 677000, Yakutsk, Russia.
Corresponding author: *Egorova* T. *R.*, e-mail:: tuyaruslanovna@mail.ru,

Получена редакцией 20.03.2022; получена после рецензии 27.06.2022; принята к печати 10.09.2022.
Received by the editors 20.03.2022; received after the review 27.06.2022; accepted for printing 10.09.2022.