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Methodology for calculating the stability of the polymer operating string in permafrost

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The goal of this paper is to develop a methodology for calculating the stability of an annular cross-section string casing made of polymer material used for the development of mineral deposits by underground leaching in permafrost formations. The aim was to determine the geometric parameters of the casing and to ensure its operational reliability.

The relevance of the research is associated with the peculiarities of external influences on the string, for example, a geotechnological well operating in permafrost formation under conditions of additional exposure to ice pressure during freezing of water in the borehole annulus. This effect is usually accompanied by deformation of the casing due to ice pressure, which can lead to string collapse, abnormal operation and the risk of contamination of the geological environment.

The proposed calculation method for a polymer casing is based on simulation of objects using the finite element method. We used the spatial finite elements to model the interaction of key elements of the geotechnological natural-technogenic complex: a polymer casing, ice in the annulus space and homogeneous or heterogeneous rock masses adjacent to the well.

The results of the study are presented in the form of tables and patterns of displacements, which reflect stresses and strains in the elements of the calculation scheme. The analysis of the obtained results confirms the possibility of using polymer casings of different technological purposes in various conditions of permafrost formation, including extreme ones. The results of the redistribution of pressure created by ice during the freezing of water in the borehole annulus to the rock mass and the string are evaluated. Interdependent deformations of the rock mass and operating string during freezing of water in the borehole annulus are determined. The necessity of considering the properties of the rock mass in determining the pressure on the string is established. The conditions for the collapse of the string with a different combination of its parameters are revealed.

Key words: permafrost formation; well; operating string; sustainability; ice compression; refreezing; collapse pressure

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Introduction. In Russia and abroad many developed and promising mineral deposits are located in the area of permafrost formations [7, 17, 20]. The development conditions [12, 13] require considering the interaction of permafrost rock and operating wells. The process wells are mainly designed using the production string made of polymer materials. Recently improved quality of such materials allowed us to use them in cryolithozone conditions [4, 14]. During the conservation or prolonged shutdown of operating wells in the conditions of permafrost formations propagation, the water in the borehole annulus freezes and the well can collapse. We can assess the reliability of casing made of polymeric materials, by testing their ability to withstand the imposed load, taking into account all production conditions and operation aspects, including the ice pressure when water freezes in annular space.

Many researchers carried out the studies to determine the additional ice pressure force impact on the string during freezing of water in the annulus (the so-called refreezing), the results of these researches produced a wide range of indicators. They suggest that the ice pressure during refreezing is significantly affected by the temperature drop, the gap between the casing and the rock mass, and the composition of permafrost rocks. When water freezes in a sealed cavity, the maximum pressure, depending on the temperature difference, can be quite correctly determined by the Bridgman-



Tamman equation. Using this formula, it was established [9] that with a decrease in temperature by 7.4 °C the pressure on the casing of a sealed cavity rises by 84 MPa.

It is obvious that when water freezes in the annulus, the ice pressure causes deformation, both in the casing and in the rock mass. Thus, according to R.I.Medvedsky, the calculated pressure during refreezing in sand rocks amounted to 17.3 MPa [9]. He also gives the calculation of pressure on the casing at the Prudhoe field (Alaska, USA) in the well with the alternating sand and clay. Depending on the thickness of the clay interlayers, the calculations of R.I.Medvedsky gives pressure values inside the cavity equal to 8.5-11.4 MPa. The author compares his results with the data from field experiments. A pressure of 20.6 MPa was recorded for the permafrost sands at the Messoyakhskoye field, and pressure at the Prudhoe field for alternating sands and clays was 13 MPa. The lower pressure at the Prudhoe deposit is explained by the presence of clay inclusions.

V.G.Kuznetsov [5] presents the results of measuring pressure in the borehole annulus in the Kharasaveyskoye field. At a temperature of $t = -1.38$ °C, the pressure was $p = 14.62$ MPa, after three months at $t = -4.02$ °C, the pressure was $p = 39.53$ MPa. He also cites data from field studies at the Prudhoe Bay field, where the maximum pressure during refreezing was 14.6 MPa.

G.V.Zverev and A.Yu.Tarasov [3] using the empirical Bridgman – Tamman equation, in which the pressure depends only on the temperature difference, calculated the maximum possible pressure for different temperatures of the water cooling in the borehole annulus. At a temperature of $t = -1$ °C, the pressure was $p = 12.6$ MPa, at a temperature of $t = -1.5$ °C, the pressure was $p = 18.8$ MPa, and at a temperature of $t = -2$ °C, the pressure was $p = 24.9$ MPa.

Formulation of the problem. As can be seen from the materials presented, the range of ice pressure on the casing varies greatly. As a rule, the empirical equations used to determine the ice pressure on the casing during refreezing contain a limited number of parameters. Clarification of the freezing pressure is an urgent task. New methods are required to obtain reliable results when solving this problem [2, 3, 5, 6, 10, 11]. The developed model must correspond to the real production conditions and the mutual influence of its constituent elements on each other. Significant deformability of polymer casings requires a calculation method that takes into account the deformation characteristics of all elements of the design scheme under high-pressure conditions that occur during freezing. The collapse of the production well can lead to major accidents and serious consequences [18]. The most objective description of the stress-strain state of the string and the adjacent rock mass is provided by the application of the finite element method [16] and the solution of the spatial problem of thermoelasticity. The initial input information for this method includes mechanical characteristics and string dimensions, ice parameters in the annular space, and characteristics of the adjacent rock mass.

The purpose of this paper is to develop a methodology for calculating the stability of a polymer operating string located in permafrost rock, considering the widest range of indicators using the finite element method.

Methods. The proposed method presents modeling the effect of water refreezing in the borehole annulus of the operating string and adjacent permafrost rocks based on the finite element method. Figure 1 shows a fragment of the calculation model of the rock mass adjacent to the well, a section of the string and ice in the annular space, limited in height within 1 m, as a finite element model of the target object. The unplasticized polyvinyl chloride (uPVC-U) casing, the ice in the annulus space, and adjacent rocks are modeled by volumetric finite elements. For numerical simulation, the LIRA CAD software package was used. We also specified the physical and mechanical properties of model elements. The proposed method allows the formation of heterogeneous rock mass by assigning various properties to individual finite elements. The required density of the finite element grid, which ensures the accuracy of calculations, is determined by the results of preliminary

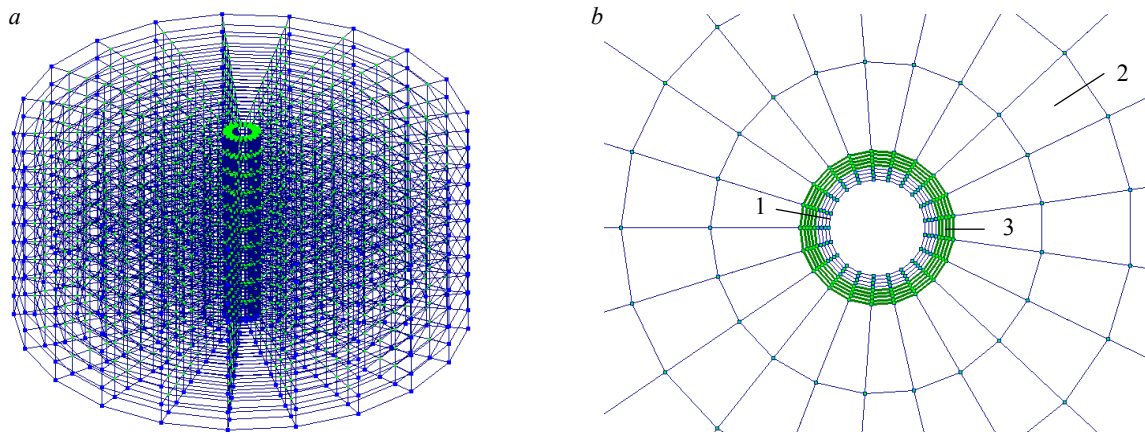


Fig.1. Calculation scheme: *a* – a section of the string in rock mass; *b* – cross-section
1 – uPVC-U casing; 2 – rock mass; 3 – ice

numerical experiments. The radial movement of the rock mass is limited by the links in nodes on the outer contour.

We set the desired values of volumetric strains that simulate the phase transition of water into ice in the annulus space to assess stresses and strains in the target system. The option of uniform freezing of water is considered (symmetric problem). The temperature is set down to $-1.5-2$ °C, which ensures the freezing of water in the annulus space. Using an iterative process, the pressure on the elements of the computational model is determined, caused by an increase in volume during the transition of water to ice. The resulting pressure on the string is compared with the critical pressure determined by the formula [19]

$$P_{cr} = \frac{Eh^3}{4(1-\nu^2)R^3}, \quad (1)$$

where E – Young's modulus; h – casing thickness; R – average casing radius; ν – Poisson's ratio.

The calculations allow determining the displacements of all nodes of the finite element grid and the internal forces of the model elements, including radial and annular stresses in the casing, which enables evaluating the nature of the pressure distribution on individual elements of the design scheme and the ability to absorb the applied load.

Discussion. The calculation results for casings with different characteristics and adjacent rock masses are presented in Tables 1 and 2. During the calculations, wall thickness, casing diameter, ice layer dimensions, and rock mass properties varied. Row 1 of Table 1 shows the results of the calculation of the casing with the dimensions and properties specified in the regulatory documents GOST R 51613 (GOST R 51613-2000. The pressure pipes made from unplasticized polyvinyl chloride. Specifications), SP-40-102-2000 (SP-40-102-2000. Design and installation of pipelines of water supply and sewage systems made of polymer materials. General requirements). We consider the casing with an outer diameter of 140 mm, a wall thickness of 10.3 mm, Young's modulus $E_{cs} = 3000$ MPa, Poisson's ratio $\nu_{cs} = 0.36$, and density $\rho_{cs} = 1.4$ t/m³. The host rock mass – permafrost sand – has a density $\rho = 1.6$ t/m³ and the following mechanical characteristics: Young's modulus $E = 3650$ MPa and Poisson's ratio $\nu = 0.2$ [8]. The following ice characteristics were taken into account: $E_i = 900$ MPa [15], Poisson's ratio $\nu_i = 0.34$ [1]. The casing is located in a well with a diameter of 171.4 mm. The gap between the casing and the borehole wall is 15.7 mm. As follows from the results given in Table 1, the pressure on the casing during freezing of water exceeds a critical value, which leads to loss of stability and collapse of the well. As can be seen from the second row of Table 1, the use of a similar casing from a material with a smaller Young's modulus



leads to a decrease in pressure on the casing. This is due to an increase in casing deformations. At the same time, a decrease in Young's modulus leads to a decrease in critical pressure. The condition for the loss of stability of the production string is preserved.

Table 1

Calculation results for casing with a diameter of 140 and 160 mm

Item N	Option parameters, rock	Size of ice layer, mm	Casing wall thickness, mm	Pressure on casing, MPa	Critical pressure, MPa	Ring strength, MPa	Pressure on rock, MPa
140 mm diameter							
1	Casing according to GOST, sand, $E_{cs} = 2000$ MPa	15.7	10.3	7.15	2.30	15.4	6.26
2	Casing according to GOST, sand, $E_{cs} = 3000$ MPa	15.7	10.3	9.59	3.45	22.3	7.21
3	Casing with thickened wall, sand, $E_{cs} = 3000$ MPa	15.7	15	12.0	11.9	21.2	10.5
4	Casing with thickened wall, sand, $E_{cs} = 3000$ MPa	15.7	16	12.6	14.8	21.3	11.1
5	Casing with thickened wall, sand, $E_{cs} = 3000$ MPa	15.7	17	13.4	18.2	21.4	11.7
6	Casing with thickened wall, clay soil, $E_{cs} = 3000$ MPa	15.7	16	9.89	14.8	16.2	7.44
7	Casing with increased gap, sand, $E_{cs} = 3000$ MPa	28.5	16	20.9	14.8	34.9	15.7
160 mm diameter							
8	Casing according to GOST, sand, $E_{cs} = 3000$ MPa	15.25	11.8	7.61	3.48	17.7	5.73
9	Casing with thickened wall, sand, $E_{cs} = 3000$ MPa	15.25	16	9.78	9.46	18.1	7.36
10	Casing with thickened wall, sand, $E_{cs} = 3000$ MPa	15.25	18	10.8	14.04	18.3	8.14

Since the thickness of the wall exerts the greatest influence on the casing stability, casings with a wall thickness different from the one specified in the standard were considered. As follows from Table 1, an increase in the casing wall thickness up to 15 mm does not ensure the stability of the structure, since the ice pressure exceeds the critical value. In other options, when calculating a casing with a wall thickness of 16 and 17 mm, the degree of influence of the wall thickness on the critical ice pressure was determined. In both options, the pressure on the casing does not exceed critical values.

The stress-strain state of the “casing – rock mass” system with an increase in the gap between the casing and the borehole wall to 28.5 mm is considered. This option was obtained by increasing the diameter of the borehole to 197 mm and by placing casings with a diameter of 140 mm and a wall thickness of 16 mm. With an increase of the ice layer, the ice pressure on the polymer casing increases sharply and its stability is not ensured. We considered the option with hosting clay soil to determine the influence of the composition of the rock mass on the stress-strain state of the casing and the rocks. As a result, it was found that when a well is placed in clay rocks (row 6 in Table 1), significant deformations of soil lead to a decrease in ice pressure on the polymer casing, which does not exceed the critical value. This is explained by large differences between the elastic moduli of the rocks under consideration.

We calculated the option for a casing with an increased diameter (Table 1) to evaluate the results. As can be seen from the Table, a casing with dimensions of 160×11.8 mm, matching the GOST R 51613-2000 requirements, has the ice pressure exceeding the critical value and cannot be

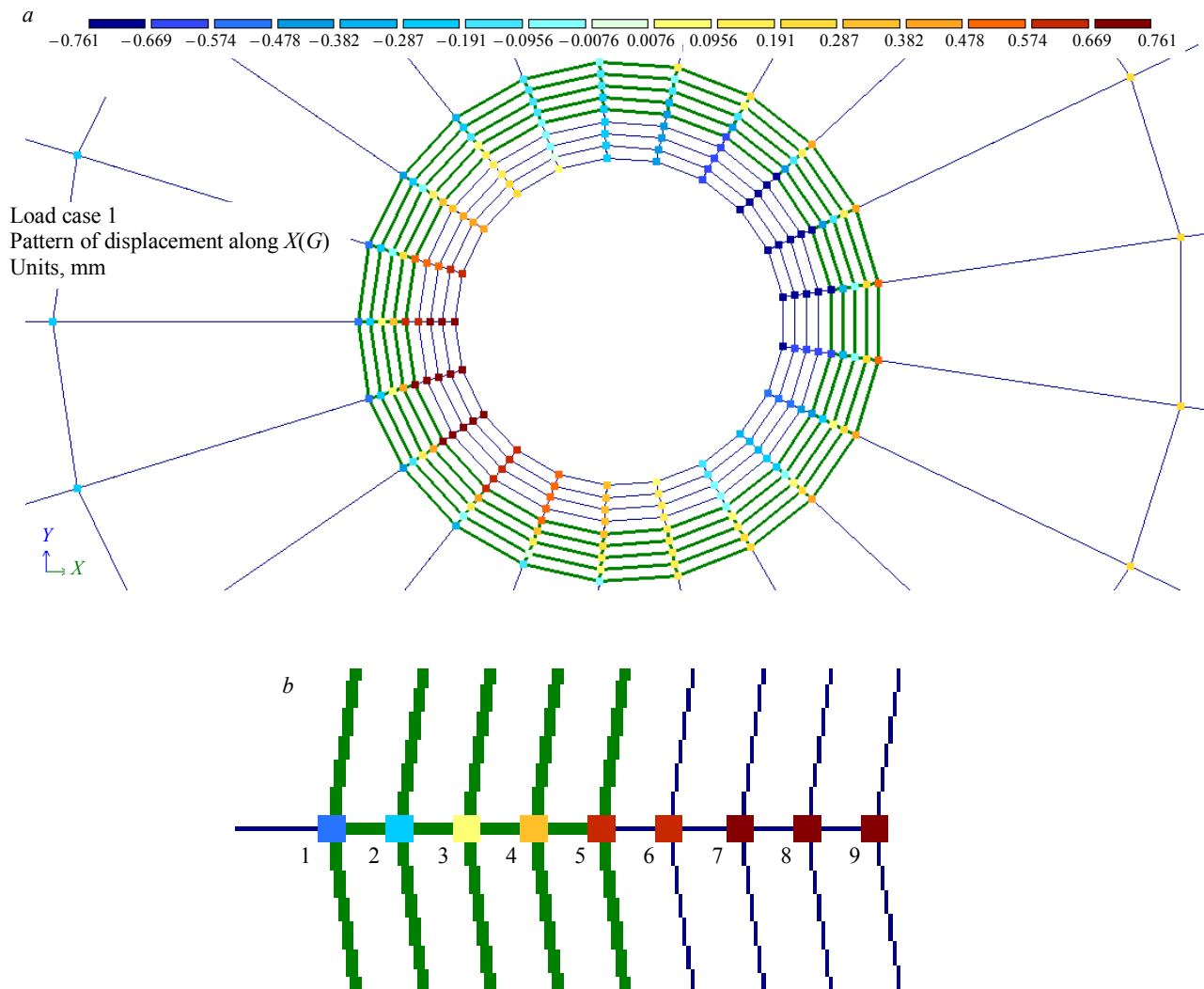


Fig.2. Pattern of displacement of nodes in the finite element model: *a* – arbitrary cross-section displacements; *b* – a section of displacements of casing and ice nodes.
Displacements: node 1 – minus 0.57 mm; node 2 – minus 0.29 mm; node 3 – 0.19 mm; node 4 – 0.38 mm; nodes 5-6 – 0.67 mm, nodes 7-9 – 0.766 mm

used under the conditions indicated in the table (permafrost sand, gap – 15.25 mm). The casing with a wall thickness of 16 mm is affected by ice pressure slightly exceeding the critical pressure. The string with a wall thickness of 18 mm ensures a safe operation under the above-mentioned conditions.

Figure 2 shows the pattern of the displacements of the nodes of the finite element model resulting from the freezing of water in the annulus space and the subsequent increase in ice volume for the variant shown in row 6 of Table 1. It has the node number and their displacement in relation to the global coordinate system along the *x*-axis. The movements of the nodes are indicated relative to their initial position before the application of the load. The maximum horizontal movements of the nodes relative to their initial position before the load are applied in the casing elements.

From the analysis of the results presented in Figure 2 and Table 2, it follows that the total deformation of the ice layer, taking into account its compression, is 1.24 mm for the considered option. The movement of the outer edge of the casing wall as a result of its compression by ice is 0.67 mm. The displacement of the borehole wall under ice pressure is 0.57 mm. Thus, the fraction of rock deformations for the considered option is about half of the total deformation of the ice layer. The fraction of permafrost sand deformations is two times less. In general, this indicates the need to consider the deformation of the borehole wall during the formation of calculated models.



Table 2

Displacement of nodes of a calculated model

Item N	Option parameters, rock	Casing wall displacement, mm	Casing surface displacement, mm	Ice deformation, mm	Ice layer increase during water freezing, mm
1	Casing according to GOST, sand, $\delta = 10.3$ mm, gap 15.7 mm	0.14	1.10	0.17	1.41
2	Casing with thickened wall, sand, $\delta = 15$ mm, gap 15.7 mm	0.24	0.96	0.21	1.41
3	Casing with thickened wall, sand, $\delta = 16$ mm, gap 15.7 mm	0.24	0.95	0.22	1.41
4	Casing with thickened wall, clay soil, $\delta = 16$ mm, gap 15.7 mm	0.57	0.67	0.17	1.41
5	Casing with increased gap, sand, $\delta = 16$ mm, gap 28.5 mm	0.39	0.58	0.59	2.56

The increase in Young's modulus of any of the model elements of the “casing – rock mass” system leads to an increase in internal forces and pressure on the operating string and vice versa. The solution of the multifactor problem using volumetric finite elements ensures the account of the interdependence of deformations and the mutual influence of the elements of the calculation model on each other. Stresses in the casing wall do not exceed the yield strength of the material (GOST R 51613-2000) and a possible threat to the operating well is the loss of stability and collapse of a polymer casing under pressure during ice compression.

Conclusion. The suggested method for determining the stress-strain state of operating wells made of polymer material and adjacent rock masses using spatial finite elements allows us to evaluate the ability of the strings to withstand the load from ice pressure when water freezes in annular space. The calculations established the necessary geometric parameters (wall thickness and diameter) of a polymer casing, ensuring its stability under the influence of radial load. The degree of distribution of ice deformations between elements of the design scheme is determined. It is established that rock masses should be included in the design scheme since their deformations are comparable in magnitude with the string deformations. The presented calculation method for casing can also be applied to other operation conditions, different from those described in this article.

REFERENCES

1. Bychkovskii N.N., Guryanov Yu.A. Ice construction sites, roads and crossings; Saratovskii gosudarstvennyi tekhnicheskii universitet. Saratov, 2005, p. 260 (in Russian).
2. Zheleznyak I.I., Stetyuha V.A. Calculation of a polymer pipe on the effect of an external load in the well located in permafrost rock. *Izvestiya Uralskogo gosudarstvennogo gornogo universiteta*. 2018. Iss. 3 (51), p. 113-117. DOI 10.21440/2307-2091-2018-3-121-125 (in Russian).
3. Zverev G.V., Tarasov A.Yu. Calculation and analysis of the impact of permafrost on the fastening of well N 338 of the Vankorskoe field during operation. *Vestnik Permskogo natsionalnogo issledovatel'skogo politekhnicheskogo universiteta. Geologiya. Neftegazovoe i gornoe delo*. 2013. N 8, p. 41-51 (in Russian).
4. Ivanov A.G., Solodov I.N. The choice of casing material for the equipment of production wells for underground leaching. *Gornyi zhurnal*. 2018. N 7, p. 81-85. DOI: 10.17580/gzh.2018.07.16 (in Russian).
5. Kuznetsov V.G. Technique and technology for increasing the life cycle of well support in the permafrost zone (Problems and solutions): Avtoref. dis. ... d-ra tekhn. nauk. Tyumenskii gosudarstvennyi neftegazovyi universitet. Tyumen, 2004, p. 50 (in Russian).
6. Leonov E.G., Zaitsev O.Yu. Calculation of phase and pressure contents during freezing of water-containing media in borehole annulus and interstring space during freezing. *Stroitel'stvo neftyanykh i gazovykh skvazhin na sushe i na more*. 2005. N 1, p. 10-16 (in Russian).
7. Makarev L.B., Tsaruk I.I. Mineral resources base of uranium in the southern outskirts of the Siberian formation. *Materialy Chetvertogo mezhdunarodnogo simpoziuma "Uran: geologiya, resursy, proizvodstvo"*, 28-30 noyabrya 2017. Vserossiiskii nauchno-issledovatel'skii institut mineralnogo syrya. Moscow, 2017, p. 60-61 (in Russian).
8. Rudov S.E., Shapiro V.Ya., Grigorev I.V., Kunitskaya O.A., Grigoreva O.I. Mathematical modeling of the compaction of frozen ground under the influence of forestry machines and skidding systems. *Sistemy. Metody. Tekhnologii*. 2018. N 3 (39), p. 73-78. DOI: 10.18324/2077-5415-2018-3-73-78 (in Russian).
9. Medvedskii R.I. Construction and operation of oil and gas wells in permafrost. Moscow: Nedra. 1987, p. 230 (in Russian).



10. Arsentev Yu.A., Nazarov A.P., Zabaikin Yu.V., Ivanov A.G. On the calculation of production casing made of polymer materials for permafrost. *Aktualnye problemy i perspektivy razvitiya ekonomiki: Rossiiskii i zarubezhnyi opyt.* 2019. N 21, p. 27-32 (in Russian).
11. Polozkov A.V. Peculiarities of calculating permafrost hydraulic fracturing pressures and abnormal pressures affecting well support during refreezing. *Stroitelstvo neftyanykh i gazovykh skvazhin na sushe i na more.* 2000. N 4, p. 14-22 (in Russian).
12. Shesternev D.M. D, Verkhoturov A.G. Mining and geological environment of mineral deposits of Transbaikalie under climate change. Zabaikalskii gosudarstvennyi universitet. Chita, 2014, p. 227 (in Russian).
13. Westermann S., Ostby T.I., Gisasnas K., Schuler T.V., Etzelmüller B. A ground temperature map of the North Atlantic permafrost region based on remote sensing and reanalysis data. *The Cryosphere.* 2015. Vol. 9, p. 1303-1319. DOI: org/10.5194/tc-9-1303-2015
14. Huang A., Su R., Liu Y. Effects of a coupling agent on the mechanical and thermal properties of ultrahigh molecular weight polyethylene/nanosilicon carbide composites. *Journal of Applied Polymer Science.* 2013. Vol. 129. Iss. 3, p. 1218-1222.
15. Kamarainen J. Studies in Ice Mechanics. Helsinki University of Technology. Helsinki, 1993, p. 182.
16. Khademi Zahedi R., Shishesaz M. Application of a finite element method to stress distribution in burried patch repaired polyethylene gas pipes. *Underground Space.* 2019. Vol. 4 (1), p. 48-58. DOI: org/10.1016/j.undsp.2018.05.001
17. Wang F., Song Z., Cheng X., Ma H. Patterns and Features of Global Uranium Resources and Production. IOP Conf. Ser.: Earth and Environmental Science. Institute of Physics Publishing (UK). 2017. Vol. 94, p. 1-7.
18. Saunders J.A., Pivetz B.E., Voorhies N., Wilkin R.T. Potential aquifer vulnerability in regions down-gradient from uranium in situ recovery (ISR) sites. *Journal of Environmental Management.* 2016. Vol. 183, p. 67-83. DOI: 10.1016/j.jenvman.2016.08.049
19. Zirakian T., Riahi F., Boyajian D., Mohammadi M., Behraves A. Stability Performance Assessment of Pipelines under Hydrostatic Pressure. *Current Trends in Civil & Structural Engineering.* 2019. Vol. 1 (5), p. 1-9. DOI: 0.33552/CTCSE.2019.01.000524
20. World distribution of uranium deposits (UDEPO) with uranium deposit classification. International Atomic Energy Agency (IAEA), Austria. Vienna, 2009, p.126.

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