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Analysis of the causes of engineering structures deformations at gas industry facilities in the permafrost zone

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Abstract. Construction of oil and gas infrastructure facilities on permafrost soils is the most important task of increasing the raw material base of the entire fuel and energy industry in Russia. Permafrost soil is a complex, multicomponent system, state of which depends on many factors. Buildings and structures built under such conditions, on the one hand, have a complex thermal effect on permafrost soils, and on the other hand, they perceive the consequences of changes in the characteristics of such soils. This situation leads to the fact that buildings and structures on permafrost soil during their life cycle are subject to complex and poorly predictable deformations. Article presents the results of a study for various degradation processes of permafrost soils that can be implemented at construction sites of industrial facilities. Analysis of the deformations causes for engineering structures at the gas industry in the permafrost zone is carried out. Series of reasons causing such deformations have been investigated. Comprehensive criterion for assessing changes in permafrost-geological conditions of industrial sites is proposed. It is suggested to apply the method of calculating the individual characteristics for the temperature regime of the territory to monitor and assess the conditions of heat exchange and predict changes in the geocryological conditions of permafrost soil.

***Key words*:** permafrost soil; deformations; deformation monitoring; construction in permafrost zone; thermokarst; frost heaving

Introduction. Several dozens of hydrocarbon fields are exploited in the permafrost zone of the Far North, but the main volume of natural gas production falls on the Urengoyskoye, Yamburgskoye, Medvezhye, Yubileinoye, Yamsoveyskoye and Bovanenkovskoye fields. Permafrost soils are widespread in their geological section. For example, the Yamal Peninsula is characterized by continuous distribution of permafrost soils with thick inclusions of formation and wedge ice, widespread dangerous exogenous permafrost-geological processes, which sometimes develop at an extremely high rate.

Frozen state of such soils is characterized by high durability, almost complete absence of compressibility, as well as the presence of a high bearing capacity. At the same time, when such soils thaw and pass into a plastic or fluid state, they almost completely lose their bearing capacity. Investigations of various characteristics for frozen soil are presented in [18, 27], including taking into account the processes of phase transitions [19].

Figure 1 shows an example of erosional destruction of permafrost soil typical for the anthropogenic landscape.

The implementation of various anthropogenic processes during the operation of facilities built on permafrost soils can cause the a ctual temperature regime to deviate from the design values. This can potentially lead, and in some cases even leads, to the occurrence of emergency failures at such facilities. Study of the deformations dynamics for aboveground pipelines in permafrost conditions is presented in [4]; investigations [16, 29] are devoted to



Fig.1. Erosional destruction of permafrost soil

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the analysis of the causes for deformations of underground pipelines; causes and consequences of foundations deformations for buildings and structures of site facilities on permafrost are investigated in works [1, 12]; consequences of deformations directly for the foundations of oil pumping stations of at trunk oil pipelines are shown in [15].

A wide range of works is devoted to the analysis of the practice of operating objects in the oil and gas industry under conditions of permafrost soils degradation. They consider an increase in average annual temperatures and their thawing from the surface, which is typical for the construction practice in the Arctic. The authors' integrated approaches to geotechnical monitoring of buildings in the permafrost zone are presented in [2, 7, 14]; separate works [5, 9] are devoted to the analysis of the practice of operating buildings and structures directly in the field conditions, including the designing stage [28]. The most effective structural solutions for foundations of buildings and structures in the permafrost zone are found in [3, 13]; optimal design of the reservoir foundation is investigated in [8]; design of communication corridors is presented in [20]. Specific investigations [21, 25] are devoted to the issue of preserving the permafrost state of the soil, modeling [6] and maintaining [11] the design temperature regime, including with the use of thermal stabilization systems [10, 22]. Methods of control and assessment of subsidence and deformations of buildings and structures [17, 23] and pipelines [26, 29] at facilities in the permafrost zone are considered, as well as methods of control and observation, including those with control elements for this process [24].

Researchers note the joint negative impact of both climatic factors (long-term growth trend of average annual temperatures), and factors of technogenic and anthropogenic nature on the frozen state of the soil. Combined effect of these factors becomes the cause of the occurrence and development of deformation processes and deviations from the design position of buildings and structures in the Far North. It also leads to the introduction of solutions for deep or surface freezing of soils in the design and construction processes, including the use of systems that maintain temperature conditions of soil throughout the entire life cycle of the object.

System of production, transportation and storage of hydrocarbons in the areas of permafrost distribution includes areal and linear engineering structures for various purposes. Forced-ventilated soil foundations, on which buildings and structures of frame-panel type are located, ventilated underfloors with natural ventilation under reservoirs, placement of pipelines and other linear structures in thermal insulation on overpasses can be seen as examples of design solutions developed for objects on permafrost soils. Figure 2 shows an example for the implementation of such solutions.



Fig.2. Buildings and structures at the field with naturally ventilated underfloor

Methodology. In practice the use of areas with continuous distribution of permafrost soils as bases is carried out according to the first principle of construction (methodological foundations for establishing the principles of permafrost soils operation are set out in SP 25.13330.2012), which provides for their preservation in a frozen state for the entire period of operation. For example, the first principle of using soils in a frozen state was adopted for buildings and structures during construction and during the operation of facilities, taking into account the permafrost conditions and the temperature state of the soils of the foundation of objects throughout the territory of the Bovanenkovskoe oil and gas condensate field.

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When using permafrost soils according to the first principle, the vertical planning of the territory is solved by arranging a general-planning earth fill for all structures of the object. Earth fill serves as an artificial foundation for buildings and structures and prevents technogenic impact on structurally unstable permafrost soils. Earth fill is used to organize the relief and surface drainage of sites.

The second principle of using frozen soils as a foundation assumes their partial or complete thawing. Application of this principle is possible, for example, in the conditions of sites, on which an extensive distribution of thawed rocks is revealed, or in the case of a significant thickness of the frozen rock roof (at least 5-7 m) even with small-scale permafrost lenses. By the nature of the thermal interaction of engineering structures with the soil of the foundations, they are distinguished as follows:

• objects, which design provides for the presence of technological elements that make it possible to forcibly maintain the established design principle of using the foundation soil. This is done by cooling the soil during construction according to the first principle, or by regulating the heat flow during construction according to the second principle (Fig.3, *a*);

• objects, which design does not provide for the presence of structural elements that ensure the maintenance of the temperature regime of soils, actually determined by the average statistical realization of factors that form the conditions of heat transfer on the surface (Fig.3, *b*).

The main cryogenic processes and phenomena that cause deformations of engineering structures of gas industry facilities in the permafrost zone are: thermokarst, slope processes (solifluction, soil creeps), cryogenic heaving, thermal erosion, cryogenic cracking. When the ground vegetation is destroyed, all these processes develop at a high rate.

Phenomenon of thermokarst is realized during construction under conditions of changes in the heat exchange of permafrost soil with the atmosphere and the surrounding soil. Reasons for such violation can be both natural degradation processes of surface soil layers during climatic changes, and anthropogenic processes of soil destruction during the construction of engineering facilities. Consequence of violations is the process of intensive thawing of ice-saturated soils or ice lenses in the soil mass. Practice shows that the destruction of the soil cover, excessive watering of the surface, as well as a change in the configuration of snow deposits in 4-5 years can lead to an increase in the average annual temperature of the soil by 1 degree and an increase in the area of seasonal soil thawing by 30-50 %. As a result of these processes, local areas of thermal subsidence with a depth of 0.3 to 0.5 m appear on the soil surface.

Formation of thermokarst subsidence leads to settlement for the foundations of buildings and structures and the appearance of deformed sections of pipelines, which in turn leads to the appearance



Fig.3. Examples for the implementation of the thermal interaction mechanisms of engineering structures with the soil using seasonal cooling devices (*a*); without structural elements providing artificial maintenance of soil temperature regimes (*b*)

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and growth of bending stresses in the wall. Observation of thermo-crust processes at the Medvezhye field shows that local thermal subsidence is in a very wide range from several centimeters to 1.5-2.0 m. Intensity of soils subsidence under engineering structures can increase in the presence of plastic-frozen and thawed soils with low bearing capacity, especially when such soils are exposed to vibration loads from equipment with dynamic characteristics.

Cryogenic landslides and creeps may develop in the presence of slopes and pronounced relief in areas where permafrost soils are spread. This leads to the movement of watered and thawed soil along the surface of the frozen mass down the slope. Gravity of the soil mass and the intensity of solar insolation are among the main factors influencing the occurrence and development of cryogenic landslides. Anthropogenic processes of changes in the water balance of territories, disturbance of the vegetation layer of the surface and the appearance of increased loads on the slope also lead to an increase in the risk of a cryogenic landslide. Areas with the risk of cryogenic landslides include slopes with a steepness of 1 to 10 degrees and a length from 100 to 1500 m. To assess the danger of landslides, their conditional classification is distinguished by size into small, medium, large and very large. Assessment criterion is the landslide area, not exceeding for small – 0.2-0.3 hectares; for medium – 1-2.5 hectares, for large – 3-5 hectares, for very large – more than 5 hectares. Mass thickness of the sliding soil in such cases is determined by the value of the depth for seasonal thawing and ranges from 0.4 to 0.8 m. For fluid-plastic soils, the thickness is significantly less and usually has a value of no more than 0.2-0.4 m.

Movement rate of landslides usually depends on the inclination angle of the slope, intensity of insolation, ice content of the soil, fractional composition of the soil and has a value from fractions of a meter to several meters per day.

Unfavorable conditions for moisture migration in the soil mass during thawing and freezing processes can cause the processes of cryogenic heaving of the soil.

Cryogenic heaving can have both significant and minor negative impacts on engineering structures, since the thickness for the layer of heaving-hazardous soils is limited by the depth of seasonal thawing. Long-term mounds of heaving reach heights of up to 8 m, in cross-section area – several tens of meters. Figure 4 shows a typical example of the heaving mound formation on the territory of an on-site facility of the oil and gas industry.

Practical experience in the operation of buildings and structures at the Medvezhye field shows that the most common cause for deformation of foundations and structures is the process of cryogenic heaving of the soil. Seasonal movement of piles in such conditions can reach 100-150 mm. Characteristic effect of constantly increasing heaving, which leads to the fact that every year, after the winter cycle, the piles do not have time to return to their original position, causes deformations up to 200-300 mm, at local points – up to 1 m.



Fig.4. Example for a heaving mound of permafrost soil

Surface waters, including those resulting from anthropogenic activity, can negatively affect permafrost dispersed rocks, destroying them and forming new types of relief. These processes are known as thermal erosion and thermal abrasion. Process of thermal erosion goes intensively in the conditions of lacustrine-alluvial soils or icy alluvial soils in the presence of drain along the slope of the terrain. This leads to the formation of characteristic ravines, incisions and gullies. Thermal abrasion process goes along the banks of water bodies in the form of surf niches, which, in the process of development, lead to the collapse and retreat of the coastline.

Stresses increase in the surface layer of the soil can lead to the formation of a network of cracks and the phenomenon of cryogenic cracking. Common cause of cryogenic cracking is an increase in stresses during the freezing of seasonally thawed soil and subsequent cooling of the frozen soil. This process is especially intensive in areas with a small thickness of snow cover. Cracks initially appear on the surface and grow in depth throughout the freezing season, the depth of cracks can reach 3-4 m, and the width lies in a wide range from several centimeters to several meters.

Discussion. Causes of deformations during construction and operation of areal and linear objects, resulted from the development of cryogenic processes, have been well studied by design, construction and specialized scientific organizations. Integrated engineering and geological surveys are carried out in practice for the design of areal and linear objects in the permafrost zone, which allow the following:

- assessing the complexity of the engineering and geocryological conditions for the construction and operation of areal and linear objects; nature and distribution of permafrost; depth of seasonal thawing; water saturation for the layer of seasonal thawing of soils in summer; thickness of the water-saturated layer; average annual soil temperatures; ice content of sediments; soil salinity; presence of saline negative-temperature pressure waters and the chemical composition of salts in brines; development of wedge ice and ice formation deposits; presence of frost cracking and heaving of soils; manifestation of slope processes; presence of interpermafrost and subpermafrost waters;
- assessing the risk of dangerous cryogenic processes manifestation during construction and operation of areal and linear facilities;
- determining the boundary conditions for permissible technogenic violations;
- substantiating the measures to protect territories and structures from hazardous cryogenic processes;
- selecting design solutions for the construction of facilities on frozen soils;
- predicting the development of dangerous cryogenic processes;
- creating a geotechnical monitoring network, which, as a rule, includes ground benchmarks, deformation marks, thermometric and hydrogeological wells.

As an example, it is necessary to consider the regular and systemic monitoring of subsidence carried out at the Medvezhye field within the framework of regime leveling. It covers the facilities of nine GTF and nine BCS, including interfield pipelines. Total number of observed deformation marks exceeds 5500. Observations have shown that about 20 % of the monitored piles or pile clusters were subject to various deformations. It was revealed that 12 % of the total number of piles are subject to deformations exceeding the permissible values adopted in the project. This leads to the need for early unscheduled overhauls, reconstructions, and, in certain situations, the shutdown of the fields.

The most common reason for the appearance of deformations in buildings, structures and pipelines in the fields of the Far North in the initial periods of their operation is the underestimation of the permafrost soils properties in the process of design and construction of facilities. This results in the process of heat transfer disruption in the "structure – foundation soils" system.

Projects drawn up taking into account the results of a preliminary comprehensive geocryological survey of the construction site and in compliance with the existing norms and rules for construction on frozen grounds should not be accompanied by deformations of engineering structures during their operation and should ensure the successful long-term trouble-free operation of facilities. Experience in the construction and operation of oil and gas structures in the permafrost zone shows that there are a number of difficulties associated with ensuring the stability of structures when the conditions of heat exchange between permafrost soils and the atmosphere change and, as a consequence, occurrence and increase of deformation amplitudes, such as distortions for the frames of buildings and equipment, pipe bends, increased vibration of units. The main reasons for the development of such deformations, if the errors in survey and design are excluded, are changes in the permafrost-geological

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conditions that occur after the completion of construction due to a change in the composition of the soils of the active layer, amount of snow cover, possibility of direct and scattered solar radiation, disturbance or elimination of ground covers, an increase in soil moisture, deviation of the temperature regime of the foundation soils from design solutions and, as a result, changes in the conditions of heat transfer on the surface.

Changes in the conditions of heat transfer on the surface can transform the direction of the permafrost process, which can go either in the same direction as the climatic trend, intensifying it, or in the opposite direction, weakening the climatic trend, and lead to the development or degradation of frozen layers. Due to its low thermal conductivity, snow acts as a heat-insulating layer and therefore reduces both the depth of freezing during winter and the depth of thawing in summer. Snow cover also reduces the amount of solar radiation received by the earth's surface, thereby affecting the difference between the average annual air temperature and the temperature of the earth's surface.

Disturbances of the surface organic layer and vegetation cover in the area of permafrost soils distribution, regardless of whether they are associated with natural or technogenic causes, usually leads to an increase in the thickness of the active layer. Changes in the permafrost-geological conditions of industrial sites are observed after the creation of the earth fill. Position of buildings and structures in the relief can change the nature of snow accumulation and spatial solar exposure and determine the spatial differentiation of the temperature field. Degradation of frozen rocks leads to dramatic changes in the conditions of the functioning for foundations since the durability and deformation properties of soils directly depend on temperature. As a result, the uncertainty in the properties of the foundation soils gives rise to the possibility of exceeding the calculated deformations and stresses in the foundation, as well as the occurrence of emergency situations. Therefore, for the entire technological equipment in the system of production and transportation of natural gas at the fields in the Arctic regions, one of the most important problems is the problem of finding and implementing the most effective technical solutions to prevent the loss of operational reliability of buildings, structures and pipelines due to deformations arising from the violation of properties and the nature of the interaction for permafrost soil with the surrounding natural and anthropogenic environment.

Results. Since the parameters of freezing and thawing depend on the magnitude and duration of the effect of positive or negative temperatures, the freezing and thawing indices can be used as indicators to control changes and predict the development of deviations in the temperature regime of the foundation soils from design solutions.

Temperature fluctuations can be estimated by the number of degrees of air temperature or soil surface temperature above or below 0 °C, and the duration of this deviation is expressed in units of time. Indices of freezing I_f and thawing I_t are expressed as the sum of degree-days for the freezing or thawing season. For a specific day, the value of a degree-day is directly equivalent to the average daily temperature, expressed in degrees Celsius. Freezing index is represented by the area of the temperature distribution curve below 0 °C line (Fig.5). Thawing index is represented by the area

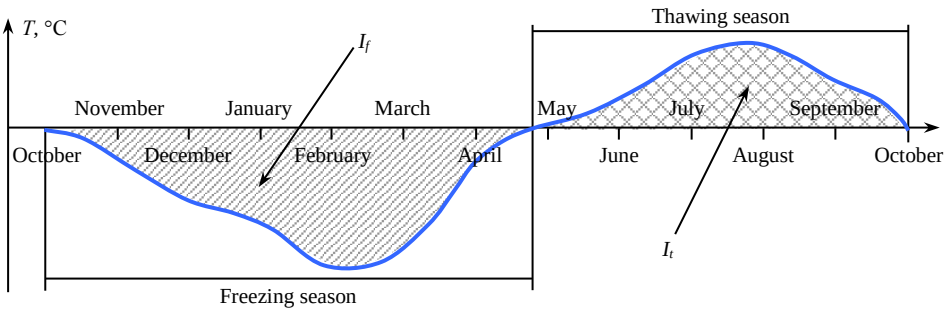


Fig.5. Graph for dependence of soil temperature throughout the year

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determined by the part located above the 0 °C line for a time equal to the duration of the corresponding season (Fig.5). Figure 6 shows an example of actual soil temperatures and the dynamics of their change throughout the year for Yakutsk. A feature of calculating the freezing and thawing indices is the need to solve the problem of determining the optimal measurement depth. When the measuring point is located at a large depth (Fig.6, curve for 1.6 m) or when the measuring point is too close to the surface (Fig.6, curve for 0.8 m), values of freezing indices can vary significantly from season to season even in the absence of anthropogenic factors.

Ratio of the of freezing I_f and thawing I_t indices forms an individual characteristic of the temperature regime of the territory T_t:

$$T_t = \frac{I_f}{I_t} = \frac{\sum_{i=1}^{n} |t_i| z_i}{\sum_{j=1}^{m} t_j z_j},$$

$$I_f = \int_0^{-\infty} f(t)\, dt = \sum_{i=1}^{n} |t_i| z_i,$$

$$I_t = \int_0^{+\infty} f(t)\, dt = \sum_{j=1}^{m} t_j z_j .$$

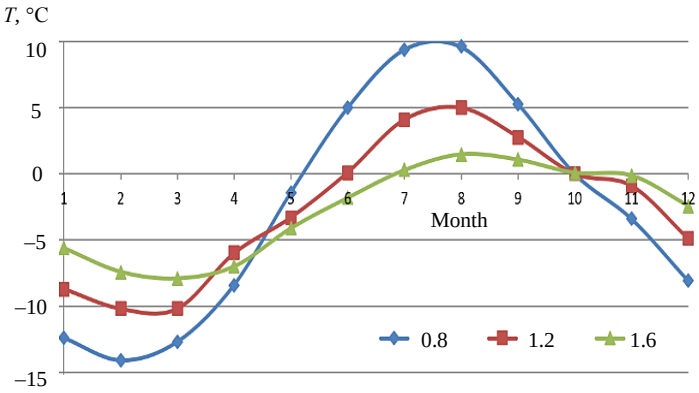


Fig.6. Actual soil temperatures throughout the year at various depths, m: 0.8 (T_t = 2.1); 1.2 (T_t = 3.61); 1.6 (T_t = 11.9)

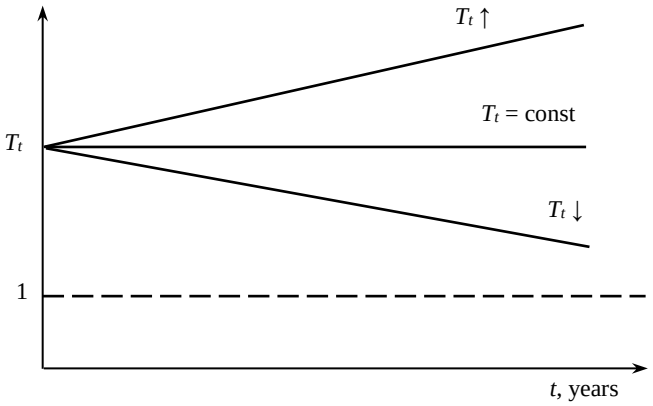


Fig.7. Models of changes in the individual characteristics for the temperature regime of the territory T_t

where $f(t)$ – time dependence of soil on temperature; n – number of days with temperature below 0 °C; m – number of days with temperature above 0 °C; t_i – temperature below 0 °C in i day; z_i – number of days with temperature t_i; t_j – temperature above 0 °C in j day; z_j – number of days with temperature t_j.

Individual characteristic of the temperature regime for the territory T_t lies in the range from 0 to +∞. Zero value corresponds to soil, temperature regime of which does not imply freezing, and the value +∞ to soil, temperature regime of which does not imply unfreezing – permafrost (an example is shown in Fig.7). For seasonally frozen soils with an average annual temperature (at the measurement depth) below 0 °C, the T_t value is greater than 1, for seasonally frozen soils with an average annual temperature (at the measurement depth) above 0 °C, the T_t value is less than 1. Optimal measurement point is such a depth, where the average annual ground temperature is close to or equal to 0 °C, at the established thermal regime for a given depth, the value of T_t is close to 1.

With a stationary thermal engineering state of soils, the value of T_t remains almost constant every season (T_t = const). Minor fluctuations occur from year to year, if the value of T_t grows (T_t ↑), this signals that the soil begins to accumulate cold and freeze, depth of thawing will decrease, as will temperature of the frozen soil. If the value of T_t decreases (T_t ↓), the process of thawing occurs in the soil, the temperature of the frozen soil decreases, and the depth of annual thawing increases.

Since the collection of data on air temperature is usually carried out at all meteorological stations, and measurements of the temperature state for the foundation soils of objects throughout the territory

are an integral part of geotechnical monitoring, formation of the freezing index I_f and thawing I_t in the context of the territory within the annual cycle is not very difficult. Models of changes in the individual characteristics for the temperature regime of the territory are shown in Fig.7. Direct algorithm for implementing the methodology for making management decisions based on models of changing the individual characteristics for the temperature regime of the territory will be presented in subsequent works.

Conclusion. Changes in the permafrost characteristics for the permafrost soil of a technogenic nature is the most important factor in the accident-free operation of engineering structures of the gas industry in the permafrost zone. Operating organizations face the tasks of efficient and timely detection of prerequisites for the occurrence of these processes, tracking the intensity and forecasting development in the near future. Analysis of freezing and thawing indices can be used as a comprehensive criterion for assessing changes in the permafrost-geological conditions of industrial sites. Analysis of the numerical values of the freezing and thawing indices allows assessing the final impact of the entire spectrum of technogenic and natural factors on the state of permafrost soil.

Numerical values of the freezing and thawing index, expressed by calculating the individual characteristics for the temperature regime of the territory, should be used as signal criteria for the beginning of of changing the permafrost state of the soil under structures and for making decisions on changing the level of control, introducing one or another thermal stabilization system or other methods of stabilizing permafrost processes. Observations of the freezing and thawing indices allow defining the moment for manifestation of trends in the processes of gradual change in the conditions of heat transfer between permafrost soils and the atmosphere and in the temperature regime of the foundations soils of engineering structures in gas industry facilities in the permafrost zone. Such information allows timely planning of measures for deformation monitoring of buildings and equipment in order to exclude the possibility of their failures.

REFERENCES

1. Babello V.A., Smolich S.V. Estimating causes of railway terminal deformations on permafrost soils. *Geotechnics*. 2011. N 2, p. 42-48 (in Russian).

2. Bereznyakov A.I. Scientific substantiation and industrial implementation of integrated geotechnological monitoring of gas production systems at fields in the north of Western Siberia: Avtoref. dis. ... d-ra tekhn. nauk: Moscow: Institut problem nefti i gaza RAN, 2005, p. 48 (in Russian).

3. Botvineva N.Yu., Burakova I.S., Fomenko O.G. Foundations for structural unstable soils. *Sovremennaa nauka i innovacii*. 2016. N 2 (14), p. 133-139 (in Russian).

4. Vitchenko A.S. Control of the deformed state for aboveground pipelines in the permafrost zone: Avtoref. dis. ... kand. tekhn. nauk. Moscow: Nauchno-issledovatelskii institut prirodnykh gazov i gazovykh tekhnologii, 2008, p. 22 (in Russian).

5. Baltabaev Sh.G., Serebryakov E.P., Lebedev M.S., Lebedeva E.T. Geotechnical monitoring of the yamburg oil and gas condensate field in the conditions of continuous distribution of permafrost soils. *Engineering survey*. 2015. N 1, p. 64-69 (in Russian).

6. Golubin S.I. Mathematical modeling of the thermal interaction for an underground gas pipeline with permafrost soils on the Yamal Peninsula. *Inzhenernaya geologiya*. 2009. N 4, p. 20-27 (in Russian).

7. Griva G.I. Geoecological conditions for the development of gas fields on the Yamal Peninsula: Avtoref. dis. ... d-ra geol.-mineral. nauk: Tomsk: Tomckii gosudarstvennyi arkhitekturno-stroitelnyi universitet, 2006, p. 46 (in Russian).

8. Ibragimov E.V.1, Kronik Ya.A. Optimization arrangement of bases and foundations in permafrost (by example of a vertical steel tank VST-20000 m^3). *Geotechnics*. 2018. Vol. 10, N 5-6, p. 52-61 (in Russian).

9. Menshikov S.N., Morozov I.S., Melnikov I.V. et al. Engineering protection of the objects at the Bovanenkovskoe oil and gas condensate field from the impact of hazardous exogenous processes. *Nauka i tekhnika v gazovoi promyshlennosti*. 2014. N 2 (58), p. 14-22 (in Russian).

10. Koloskov G.V., Ibragimov E.V., Gamzaev R.G. On the problem of choosing optimal systems of soil temperature stabilization for construction in the cryolithozone. *Geotechnics*. 2015. N 6, p. 4-11 (in Russian).

11. Krylov D.A., Fedotov A.A. Temperature regime of permafrost soil under the building with pile foundation. *Herald of the Bauman Moscow State Technical University. Series Natural Sciences*. 2013. N 3 (50), p. 106-116 (in Russian).

12. Naberezhnyi A.D., Kuzmin G.P., Poselskyi F.F. Analysis of bearing capacity reduction of soils and foundations under geocryological conditions of the republic of Sakha (Yakutia). *Industrial and Civil Engineering*. 2016. N 8, p. 64-69 (in Russian).

13. Osokin A.B., Smolov G.K. Modern technologies for the construction of bases and foundations for the development of oil and gas fields in the permafrost zone. *Nauka i tekhnika v gazovoi promyshlennosti*. 2015. N 4 (62), p. 89-96 (in Russian).

14. Popov A.P. Management of geotechnical systems of gas industry in the permafrost zone: state forecast and reliability ensurance: Avtoref. dis. ... d-ra tekhn. nauk. Tyumen: Institut kriosfery Zemli Sibirskogo otdeleniya Rossiiskoi akademii nauk, 2005, p. 48 (in Russian).

15. Kosheleva L.I., Miusov S.P., Ryazantsev D.G., Kovyrshin S.S. Reasons for disclosure of deformation seams of foundations at the NPS-2 station of the Kuyumba – Tayshet oil pipeline. *Stroitelnye Materialy*. 2018. N 12, p. 55-60. DOI: 10.31659/0585-430X-2018-766-12-55-60 (in Russian).

16. Gulin D.A., Faizullina E.V., Sharipova E.I. et al. The problem of soil heaving in pipeline construction and methods for its elimination. *Problemy sbora, podgotovki i transporta nefti i nefteproduktov*. 2020. N 4 (126), p. 60-72. DOI: 10.17122/ntj-oil-2020-4-60-72 (in Russian).

17. Menshikov S.N., Dzhaljabov A.A., Vasiliev G.G. et al. Spatial Models Developed Using Laser Scanning at Gas Condensate Fields in the Northern Construction-Climatic Zone. *Journal of Mining Institute*. 2019. Vol. 238, p. 430-437. DOI: 10.31897/pmi.2019.4.430

18. Sannikov G.S. Changes in morphometric parameters of thermokarst lakes in western Yamal as an indicator for the dynamics of the geological environment and its response to technogenic impact (on example of the Bovanenkovskoe field): Avtoref. dis. ... kand. geol.-mineral. nauk. Tyumen: Institut kriosfery Zemli Sibirskogo otdeleniya Rossiiskoi akademii nauk, 2016, p. 25 (in Russian).

19. Skapintsev A.E. Geoecological substantiation of engineering protection and geotechnical monitoring of pipeline construction in the permafrost zone: Avtoref. dis. ... kand. tekhn. nauk. Moscow: Moskovskii gosudarstvennyi stroitelnyi universitet, 2013, p. 20 (in Russian).

20. Sokolov S.M., Kisev S.V. Designing of field pipelines in the communication corridors under difficult conditions. *Oil and gas studies*. 2014. N 4, p. 77-79 (in Russian).

21. Skvortsov D.S., Kraev A.N., Kraev A.N., Zhaisambaev E.A. Ways to combat frost heaving of seasonally freezing soils in the foundations of buildings and structures. *The Eurasian Scientific Journal*. 2019. Vol. 11. N 5, p. 1-12 (in Russian).

22. Gorkov V.A., Korkishko A.N., Nabokov A.V. Stabilization of soils by the method of "cold rescycling" in conditions of permafrost soils for the infrastructure development of oil-and-gas field. *Fundamental research*. 2017. N 7, p. 20-24 (in Russian).

23. Strizhkov S.N. Reducing the anthropogenic influence of buildings and structures on soil bases and their geomonitoring in permafrost. *Industrial and Civil Engineering*. 2013. N 11, p. 8-12 (in Russian).

24. Baltabaev S.G., Serebryakov E.P., Lebedeva E.T., Lebedev M.S. Controlling the hydrogeological regime in order to prevent deformations of pile foundations as a result of frost heaving of soils (by the example of the Yamburg oil and gas condensate field). *Geotechnics*. 2015. N 6, p. 24-33 (in Russian).

25. Huijun J. Design and construction of a large-diameter crude oil pipeline in Northeastern China: A special issue on permafrost pipeline. *Cold Regions Science and Technology*. 2010. Vol. 64. Iss. 3, p. 209-212. DOI: 10.1016/j.coldregions.2010.04.016

26. Wang F., Li G., Wei M. et al. Pipeline – permafrost interaction monitoring system along the China – Russia crude oil pipeline. *Engineering Geology*. 2019. Vol. 254, p. 113-125. DOI: 10.1016/j.enggeo.2019.03.013

27. Shur Y., Goering D. Climate Change and Foundations of Buildings in Permafrost Regions. *Permafrost Soils*. 2009. Vol. 16, p. 251-260. DOI: 10.1007/978-3-540-69371-0_17

28. Utkin V.S., Sushev L.A. The reliability analysis of existing reinforced concrete piles in permafrost regions. *International Journal for Computational Civil and Structural Engineering*. 2017. Vol. 13. N 2, p. 64-72. DOI: 10.22337/2587-9618-2017-13-2-64-72

29. Wilkie S.A., Doblanko R.M., Fladager S.J. Northern Canadian pipeline deals with effects of soil movement. *Oil & Gas Journal*. 2001. Vol. 99. N 20, p. 62-66.

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