Geotechnical Monitoring of Pipeline Systems Operating Under Conditions of Permafrost (Yakutia)

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Abstract. Life safety on the territory of the Republic of Sakha (Yakutia) is directly related to the uninterrupted supply of energy and heat, which is caused by low climatic temperatures. Even in Central Yakutia, the average period of temperatures below 0 °C is about 210 days, below –20 °C - 138 days. The minimum temperature is distributed in the range from –47.8 °C to –60.3 °C. Under such natural conditions, the release of any object in gas and heat supply chain leads to disastrous consequences. In the year at gas and heat supply facilities, several dozen emergencies of varying severity are recorded, mainly in winter period. The system of oil and gas pipelines laid on the territory of the Republic of Sakha (Yakutia), mostly located in the permafrost zone, is affected by dangerous geological processes, which significantly affects its reliability and safety. For stable operation of oil and gas complex (OGC) of the Republic, an assessment of pipeline state system, based on geotechnical monitoring, is necessary. The monitoring system provides heterogeneous data, the analysis of which helps to clarify the interaction between pipeline and permafrost in various geological conditions, and allows you to evaluate and predict the condition of objects and environment.

1. Introduction
Huge reserves of gas and oil are concentrated on the territory of the Republic, which make up on an equal basis with the Irkutsk region the majority of oil and gas reserves of Eastern Siberia and the Far East. Natural gas by consumers of Central Yakut Energy District has been used since 1967, and West Yakut - since 1983. Three fields are in development: Sredneviluisky and Mastakhsky Gas Condensate Fields, as well as Srednebotuobinsky Oil and Gas Condensate Fields located in Western Yakutia [1, 2].

On the territory of the region the construction and operation of section of the main oil pipeline Eastern Siberia-Pacific Ocean (VSTO) is under way. Pipeline system VSTO includes the construction of oil pipeline with a length of 2757 km and a diameter of 1067/1220 mm [1, 2].

It has been established that the construction of pipeline route leads to a sharp activation of exogenous processes on the territory of technological corridor. Logging during corridor construction, disruption of vegetation cover during trench digging, disruption of natural drainage of water bodies during construction of parable road and pipeline logging are the main potentially dangerous geotechnical processes, during which it is necessary to adhere to the principle of “prevention of impact” on frozen landscapes [2,3]. The main reasons mentioned above, which cause the possibility of creating emergency situations on the main pipeline (MT), create the following factors of influence on the technical condition of pipeline system: creation of stresses in the structure body related to mechanical movement of the pipe due to the change of trench profile (cleaning and washing of soils,
bare sections of the route, freezing of water-saturated soils); cyclic seasonal freezing processes cause soil emptying during freezing and precipitation during thawing, which leads to creation of a complicated deformed state of the structure and causes its possible destruction [2,3]. Geotechnical monitoring makes it possible to detect initial forms of dangerous natural and man-made processes and to predict the occurrence of accidents [4,5].

The information obtained as a result of geotechnical monitoring presents various data. The analysis of these data helps to clarify the mechanisms of interaction between a pipeline and the permafrost under various geological conditions, as well as allows evaluating and predicting the state of objects and the environment. One of the most effective ways to develop the oil and gas pipeline maintenance system in the study area is the use of GIS technologies that allow modeling the positive and negative consequences of various situations under certain initial scenarios.

The analysis of works on the development of information support for solving the problems of oil and gas pipeline safety has shown that the main principles in the construction are: a systematic approach to the composition and method of data storage; updating; data fusion; modularity and orientation to modern software products [6], the ability to correct information from users without changing the composition and content of databases. Openness for the purpose of possible replenishment of databases and their expansion, blocking artifacts; interconnectedness of blocks through the transit area; unity in the use of programming languages, data sampling tools, and information flow management tools [6]; the ability to search when entering basic and additional parameters of objects, synchronization of data selection in maps, processing routes, profiles [3]. The complex problem of life safety and life support is based on the interaction of socio-natural and technogenic spheres [7]. The problems of ensuring the reliability and safety of hazardous industrial facilities which undoubtedly include pipeline systems can be solved only by using heuristic, mathematical and experimental methods and taking into account the maximum number of factors, including insufficiently defined and their specific interaction with each other during the operation of extended technical systems [8].

### 2. Methods and materials

Elements of the pipeline system interact with the geological environment, and under certain operating conditions they can have a noticeable effect on changing the rate of dangerous geological processes development.

The study on the assessment of the interaction of the environment and the main pipeline includes the following stages: analysis of the state of a territory where the PTS is located; assessment of mutual impacts of PTS and their consequences; identification of measures that mitigate or prevent negative interactions.

The organization of geotechnical monitoring of main pipelines is carried out in several consecutive stages. Each stage is characterized by specific tasks, equipment, methods, and resulting research materials. Based on the analysis of materials of each stage, the object and tasks of the study of each subsequent stage are determined.

The organization of network for monitoring of various dangerous geological processes (thermokarst, landslides, frost) at different stages considerably differ by a technique, amount of works, used equipment, devices and obtained information. For example, at the initial stage of observation of deposits drones are used, at the following stage thermal imaging aerial collection with the use of “Geoskan-401” complex which allows obtaining a thermal imaging plan and orthophotoplans of investigated area in one flight. Electromethods of deposits is performed by “Scala-48” electric exploration station, Slumberger set. Georadiolocation studies are performed by the set of equipment “ОКО-2” manufactured by NPP “Logis”. The organization of network for monitoring of various dangerous geological processes (thermokarst, landslides, frost) at different stages considerably differs by a technique, amount of works, used equipment, devices and obtained information. For example, at the initial stage of observation the drone aircrafts are used, at the following stage the thermal imaging aerial photography with the use of “Geoskan-401” complex which allows obtaining a thermal imaging.
plan and orthophotoplans of investigated area in one flight. Electrotomography of deposits is performed by “Scala-48” electric exploration station, Slumberger set. Georadiolocation studies are performed by a set of equipment “OKO-2” manufactured by “Logis” Research and Production Enterprise. In the structure of geotechnical monitoring network (GMN) of sites equipped with special equipment that allows carrying out control by instrumental methods using such means as thermometric and hydrogeological wells; depth benchmarks which serve as initial altitude base, relative to which measurements of planned and altitude position of pipeline are carried out at control points on sections with difficult geological conditions and determination of displacements relative to previous measurement cycle. Natural cryogenic processes and phenomena are characteristic of pipeline route section: cryogenic soil heaving which is common in almost the entire territory of allocated geocryological route sections; formation that develops mainly in the northern part of the studied area within the permafrost development area; erosion and thermal erosion processes developed to varying degrees at a number of geocryological sites and causing processes of sedimentation, collapse, sedimentation, landslides and others; solifluctional and landslide formation, the thermokarst of which is formed in connection with thawing of ice-saturated soils and extraction of underground ice leading to seeding of ground surface, emergence of negative forms of relief and their waterlogging.

Dangerous geological processes caused by the anthropogenic impact differ from the natural ones by their location, directly related to engineering structure, great intensity of symptoms, more rapid time course; direction, different from the characteristic of similar natural phenomena in the area, and often opposite to it.

Heaving. The forms of its development are different. It depends on the specific hydrogeological conditions of the territory. It is most intensively developed in the swamped bottoms of folds and creek valleys, low terraces above the floodplain, and solifluxion-proluvial plumes. Morphologically, the process is expressed in the development of a small bumpiness that covers the entire floodplain part of the valley bottoms. Larger forms of seasonal heaving up to 1-3 m high can be observed along the rear parts of floodplains and bottoms of folds in the valley of rivers. The freezing of interpermafrost taliks is under-explored hazards. This phenomenon is caused by the existence of a thawing site around the pipeline. Under these conditions, sandy soils will almost everywhere have a moisture content equal to full moisture content, and in the places where the pipeline passes through the valleys in the autumn period will be induced by comprehensive freezing, especially by combination of severe frost and lack of snow. The consequences of this process are poorly understood but it is often developed in the form of powerful seasonal permafrost mounds.

Thermokarst. Its physiographic trait is diverse and depends on the nature of subterrenean ice, the area captured by the process. Thermokarst is dangerous for linear objects by subsidence of the base soil, the speed of which decreases with the growth of the ice content of rocks, and the value, on the contrary, increases with the increase in ice content. It should be noted that thermal subsidence is possible even in rocky soils, because the upper part of their section is strongly fractured.

Thermoerosion develops on icy dispersed soils or on monomineral ice on slopes of any steepness. Since the subterrenean ice masses are not delineated on the results of surveys, the position of areas with a thermal erosion hazard can only be given with some probability. Thermoerosion and thermosuffusion are very dangerous (category 3) in areas where there are thermoerosion ravines or suffusion funnels. The dangerous category of the process is assigned for slopes with a steepness of more than 5°, composed of any soil, except rock, large-block or clay with a volume ice content of more than 0.45 or having a fluid consistency under straight-thawing.

Corroms. Morphologically, corroms on slopes appear in the form of so-called "stone seas" and "stone rivers". The composition of a clastic material is small and large. The mechanism of action of corroms differs by considerable complexity.

Polygonal soils are developed within depressions, confined mainly to complexes of alluvial, lake-alluvial, defluxion-deluvial-proluvial deposits. From the point of view of engineering geology, the process of frost cracking sharply worsens the strength properties of soils, causes deformation of engineering structures, so it must be taken into account when designing and building.
Based on the results obtained at the initial stages of geotechnical monitoring, a map of the development of dangerous for MP geological processes is created in GIS. To collect, store and use information obtained as a result of geotechnical monitoring, a geo-information database is created. Then, based on the geo-information database, a network of ground-based observation sites for the development of dangerous geological processes of MP is created, where monitoring equipment is placed. According to the data obtained during geotechnical monitoring, MP sites are ranked according to the degree of danger of activation of dangerous geological processes. At the same time, first of all, the equipment is installed on the most dangerous sections of the MP route. In GIS, thematic layers of ground observation sites and hazard ranks are created accordingly.

As a result of processes monitoring on the linear part of the main pipeline, which is organized on dangerous sections of the route, dynamic, time-varying indicators of the state of the natural and technical system are identified, a comprehensive analysis of which is used to assess and forecast the development of dangerous processes. Indicators of ground-based observations taken at sites with dangerous geological processes correspond to the specifics of an impact of the geological hazards (GH) on the design elements of the main pipeline. Using these complex heterogeneous indicators, we evaluate the prevalence of dangerous processes along the MP route, the large scale of their development; evaluation of the speed of dangerous processes development, the forecast of activation and development of dangerous processes.

Geoinformation technologies allow providing access to a database (DB) of heterogeneous spatially linked information for solving problems of assessing the state of extended technical systems (ETS) and visualizing the result.

When developing methodological principles for creating a database of geoinformation data for the integrated use of aerial photo- and aerial videography, space images and ground survey data of extended linear natural and technical systems, it was taken into account that it should:

- perform information and reference functions with the ability to serve simultaneously a certain number of users;
- allow analyzing the state of natural-technical system (NTS);
- ensure the formation of initial data when solving various tasks to assess the condition of a pipeline.

The database is structured in such a way as to provide information support for the operation of functionally different modules of the geoinformation system: a reference information module, a module for preparing and exporting data to solve problems of evaluating parameters, sizes of dangerous zones, ranking pipeline sections by hazard level; other tasks for assessing the state of a long linear NTS.

3. Results and discussion
A network of geotechnical monitoring of the main pipeline was created with the participation of the Institute of Physical and Technical Problems of the North to solve the problems of monitoring and ensuring the safe operation of oil and gas facilities connected with exogenous processes. To collect, store and analyze heterogeneous information assigned in the issuance of the GTM, a geo-information database was formed. The information in database is presented in the form of an array: numerical data; coordinate data; tables; test records; audio-, photo-, aero-, space-photography; cartographic data.

As basic data for work the following complex of materials served: materials of archival space shooting of high and average resolution; field geological, hydro-geological, geodesic survey materials; air visual survey materials; engineering survey materials.

The list of map database objects (spatial data) of GIS contains the following sections: hydrographic network; terrain; human settlements; vegetation; roads. They can be used to frame an image of the area that gives a spatial reference to the elements of a pipeline system.

To describe the elements of an oil and gas pipeline, the following are used: a pipeline axis; a locking equipment; pickets; pipeline service roads and access routes; buildings and assets of the MPS.
The list of characteristics of these objects includes: the name of an object in accordance with the specifications of the operational documentation; the main parameters of an object according to the operational documentation; the state of an object at the time of inspection (observation).

In order to display the results of analysis of the state of extended linear natural and technical systems in the territory where there is mutual influence of pipeline system elements and geological environment, zones with time-varying boundaries and parameters are identified based on monitoring results. Zoning defines the boundaries of areas with homogeneous features and is carried out according to the type of geological hazards and the degree of danger. Zones are formed on the basis of decryption and determination of indicators from materials of aero- and space surveys, clarification of parameters of exogenous geological processes during field survey; Measurements of coordinates of sedimentary marks by geodetic methods.

The list of zone characteristics includes: a name; numerical and textual parameters of a zone; the area; a total perimeter, the length of a process development section along a pipeline; planned and high-altitude position of the upper pipeline forming part; the length and width of the watered section of ditch bight.

To evaluate the parameters of hazardous processes that disrupt the equilibrium state of geological environment, the following digital models are created: relief; water currents; vegetation; thermal field forming around the pipeline; change of pipeline spatial position over time is estimated for further ranking.

When listing the properties of database objects, the attention is paid to those that are of particular importance for solving problems related to the assessment of the state of extended linear natural-technical systems. Spatial reference of the boundaries of zones and NTS objects is performed using KP, kilometer markers, fundamental geodetic points, and log markers.

To determine the boundaries of indicators of geological hazard, images obtained by high-and ultra-high-resolution space survey systems are used; digital aerial photographs; materials of continuous digital photography from a helicopter or an aircraft; digital photos of various objects taken during their survey.

When placing digital photographic materials in the database, they are accompanied by a set of attributes: time of shooting; coordinates of a shooting point; technical characteristics of a camera; the description of a shooting object.

To fix the route of a camera movement from aircrafts during aerial photography and aerial visual inspection, the database uses tracks. Tracks are sequences of spatial coordinates and time markers for forming nodal points on a route. The distance between nodes can be constant or variable.

Attributes of tracks are: a name; time of formation beginning; operator's IDs; sampling interval; description of the measuring coordinate system; description of the coordinate system and time reference.

All listed objects, including the map base, piping system parts, monitoring tools, zones, and digital models, are DB content elements. The developed database nicely connects to ArcGIS.

The GIS reference and information module includes: a set of databases on technical and structural characteristics of objects of the Republic's oil and gas complex, statistics on accidents that occurred at objects; natural and climatic characteristics of a region where an object is located, characteristics of dangerous geological sites; reference data that contains a list and summary of national regulations for the design and construction of OGC facilities, industry sector codes and rules for the construction and operation of facilities, as well as instructions for conducting various studies at industry facilities.

All listed objects, including the map base, piping system parts, monitoring tools, zones, and digital models, are DB content elements. As an example of integrated use of the database and mathematical modeling, result of ranking the sections of the main pipeline according to the degree of danger of developing the thermowell is given. Fig. 1
4. Conclusions
One of the methods for state value of the main pipeline (MP) operating under difficult climatic conditions, and timely detection of dangerous pre-emergency situations is geotechnical monitoring (GM). GM is organized in several successive stages resulting in a set of indicators determined by various surveys. Indicators of observations taken at sites with dangerous geological processes correspond to the specifics of an impact of GH on the elements of the main pipeline structure. Using these complex and heterogeneous indicators, we assess the abundance of dangerous processes along the MP route, the scale of their development; assess the speed of development of dangerous processes, and forecast the activation and development of dangerous processes.

The information obtained as a result of geotechnical monitoring provides heterogeneous data. To collect, store and use it a database of geoinformation data is set up. Using this database and GIS, it is possible to assess the state of extended PTS, visualize the result, rank MP sites according to the degree of a risk of GH development, and model the positive and negative consequences of various situations under certain initial scenarios, predict the possibility of emergency situations and their consequences depending on environmental conditions, determine measures to mitigate or prevent negative interactions.

5. References
[1] Information material Interregional meeting in the Republic of Sakha (Yakutia) "Prospects of development of hydrocarbon deposits in Eastern Siberia and the Far East" (Yakutsk Sakhapoligrafizdat) 30 p
[2] Tikhonova S A, Kapitonova T A, Struchkova G P 2019 Safety assessment of oil and gas pipelines using satellite information Procedia Structural Integrity Vol. 20 pp 230-235 https://doi.org/10.1016/j.prostr.2019.12.144
[3] Kapitonova T A, Struchkova G P, Levin A I 2018 Risk assessment Analysis of the Mastakh-Berge-Yakutsk main gas pipeline laid in the cryolithzone Problems of safety and emergency situations 6 pp 34-43
[4] Bolshakov A M 2010 Analysis of damage and defects in the main gas pipelines and tanks North of the Gas industry 5 pp 52-53
[5] Hongwei Li, Yuanming Lai, Lizhong Wang, Xiaosong Yang, Ningshan Jiang, Liang Li, Cheng Wang, BaocunYang 2019 Overview of the current state: interactions between buried pipeline and frozen soil Science and technology of cold regions
[6] Fei Wang, Guoyu Li, Wei Ma, Qingbai Wu, Mihaela Serban, Samsonova Vera, Fedorov Alexandr, Ningshan Jiang, Bo Wang 2019 Production–permafrost interaction monitoring system along the Sino-Russian oil pipeline Engineering Geology Vol. 254 pp 113-125
[7] Makhutov N A, Makosko A A 2018 Scientific bases on the analysis of mutually coordinated problems of industrial and ecological safety Safety and emergencies problems 6 pp 3-11
[8] Berman A F, Nikolaychuk O A 2018 Model of transdisciplinary problems for substantiation of the technogenic safety properties *Safety and emergencies problems* 6 pp 21-34