RESEARCH PAPER

AUTOMATED MONITORING THE TEMPERATURE UNDER BUILDINGS WITH PILE FOUNDATIONS IN SALEKHARD

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ABSTRACT. In the paper, we consider a method of ground temperature monitoring using the thermometric boreholes and computer modeling the residential buildings with the pile foundation in the city of Salekhard; note that it is located in the permafrost zone. Construction of the residential buildings and industrial structures in the permafrost zone and their operation is carried out according to the principle of preserving the frozen state of foundations. For ground temperature monitoring, thermometric boreholes are used. In a given time period, the measured temperatures are transferred to a server for further processing. Information about the temperature is an important factor for the safety of the buildings and it can be used to evaluate the piles bearing capacity. It allows to propose options for the soil thermal stabilization or to eliminate the detected technogenic heat sources. An approach of mathematical modeling to reconstruct the temperature fields in the pile foundation base of a building is discussed taking into account the data of temperature monitoring. 24 boreholes were equipped with more than 400 in-borehole thermal sensors for testing the method under the residential building I. The preliminary modeling is carried out for December and January 2020 for the contact thermal conductivity model with phase transition with the upper part of the geological section typical for Salekhard (the sandy soils). The modeling describes the freezing processes during the months in detail. The thermal monitoring allows to say that the ground in the base of the Residential building I is stable. But there are detected heat transfers near the borehole T1 at the depth of 12–14 m. The combination of monitoring and computer modeling makes it possible to assess the safety of the operation of the residential buildings in cities located in the permafrost zones.

KEYWORDS: permafrost, remote monitoring, thermometry, computer modelling, climate warming

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INTRODUCTION

The cryolithozone covers 35 million km^2, which are more than a quarter of the Earth's land. The part of cryolithozone is the permafrost soils that are found not only in the Arctic, but, also, outside it; for example, in the highlands (Anisimov et. al 1996; Nelson et. al 2002; Zhang et. al 1999). Russia is directly related to the cryolithozone where permafrost occupies 60-65% of the territory or 11 million km^2 (Brown et al. 1997, 2002). It is most widespread in the Eastern Siberia and Transbaikalia. There are different types of the permafrost distribution (continuous, sporadic, isolated), different types of cryogenic structures (massive, layered, mesh form), and different temperature conditions. The different features, physical and chemical properties of the permafrost soils are taken into account in the construction of various engineering structures and residential buildings in the cryolithozone.

Today, the Russian Arctic is developing rapidly; the planning, construction, and exploitation of facilities in the cryolithozone are accompanied by a number of problems. Those are caused not only by the complex structure of the soils, but, also, by the processes of permafrost degradation that is accelerated due to the climate warming. Therefore, newer scientific investigations are in progress. They are aimed on researching the current state of the cryolithozone and assessing the impact of climate change on the permafrost (Nelson et. al 2001; Romanovsky et al, 2001; Zhang et. al. 2003; Streletskiy et al. 2012, 2019; Hjort et al. 2018; Aalto et al. 2018). In particular, assessments of the sustainability of the existing and planning infrastructure are carried out in the Arctic and Sub Arctic territories. A series of works is devoted to the assessment of the bearing capacity of the permafrost soils (Streletskiy et al. 2012, 2019; Hjort et al. 2018). These works indicate the permafrost temperature increasing in the period over 30 years (1960–1990) related to the climate warming. The investigations pointed out up to 45% foundations bearing capacity decreasing in certain areas and that this tendency will entail another 25% decreasing by 2050. The various countries budget's losses (due to possible destructions) are estimated as hundreds of billions of dollars (Streletskiy et al. 2019, Luis Suter et al. 2019). At present, for the Russian Federation, the annual losses related to the operation of infrastructure and the residential buildings on the permafrost reach up to $2 billion. In the future, according to the above predictions, the amount of damage will only grow.

Such predictions and assessments seem quite realistic when considering the current situation (Grebenets et al. 2012; Shein et al. 2020), since the number of disasters and damages to the infrastructure facilities in the cryolithozone has significantly increased recently (BBC News. Russian Arctic… 2020; BBC News. Norway landslide… 2020; The Siberian Times. Two-storey residential… 2020). The current trend of the climate warming leads to the temperature of the permafrost increasing that directly affects the bearing capacity of the soils. The human influences on the state of permafrost are stipulated by development and operation of objects (Filimonov et al. 2017; Kiselyov et al. 2020; Vaganova et al. 2017, 2019).

Most of all buildings and structures in the cryolithozone of Russia are built and operated on the principle of the preservation of the frozen ground foundation. However, outdated norms and rules are used in the building and further operation of the facilities (SP 25.13330.2012, 2012; Resolution of the State Construction Committee of the Russian Federation of 27.09.2003 N 170, 2003). Note that the existing documents indicate the necessity of geotechnical monitoring of all types of the buildings and structures in the permafrost zone during both the construction and operation. It is necessary to «ensure that stakeholders are informed in a proper time about the detected deviations of the controlled parameters ... from the project values and the results of the thermal and geotechnical prediction» (SP 25.13330.2012, 2012). First of all, this relates to the temperature, the control of which is necessary to confirm the bearing capacity of the foundation soil and to prevent the dangerous permafrost geological processes (thermokarst, subsidence, frost heaving, etc.). Therefore, monitoring and modeling (predicting) the changes in the temperature fields in the site of pile foundations of buildings will increase the operational reliability of engineering structures and residential buildings. Note that in addition to the temperature, to evaluate the bearing capacity of the foundation soil, it is necessary to know other characteristics of the soil, such as wetness, granular mineralogical composition, etc.

Beginning from 2018, for the safe operation of the buildings and structures in the permafrost zone in the Yamal-Nenets Autonomous District, a methodology of automated temperature monitoring is developed (Gromadsky et al. 2019). It includes a program for calculating non-stationary thermal fields under buildings with the pile foundations. In the future, it is planned to expand the functionality of the program and add the ability to recalculate the obtained temperature values into the bearing capacity of the soil for the current state and for the prognosis. In 2020, to test the methodology, the administration of the Salekhard city provided four capital buildings where about 80 boreholes were drilled and equipped with the thermometric equipment.

According to (Kuzin 1963) the territory of the modern development of the city of Salekhard and the surrounding area is located on the V sea terrace (Q1) and on the I and II alluvial terraces of the Ob and Polui rivers (Q3-Q4). The average depth of the active layer is 1.5-2 m and has recently been increasing. The thickness of the permafrost reaches 150 m, and its temperature within the depth of the zero annual amplitude varies from -0.5 to -2ºC. The upper part of the section is dominated by sandy. With depth, sandy loam and loam appear, and clay is less common. Salekhard is located near the border, where the continuous permafrost turns into intermittent. Therefore, the monitoring of the permafrost under the objects is particularly relevant here.

This paper focuses on monitoring and studying the processes of propagation of the thermal fields in the site of the pile foundation of the residential building in the city of Salekhard using the thermometric boreholes.

The paper presents and analyzes the preliminary temperature data obtained for the foundation of the residential building in the city of Salekhard, Zoya Kosmodemyanskaya str. 68 (hereinafter referred to as the Residential building I). An enough dense grid of the borehole thermal sensors allows us to obtain unique data that can be used for the numerical modeling and prediction of the permafrost soil temperature in the entire area of the pile foundation.

In combination with temperature monitoring of the soil in the area of the pile foundation the possibility and the promises of the method of mathematical modeling application are discussed. It is suggested that the combination of the methods allows one to analyze, predict and prevent the destructive tendencies in the permafrost foundations.

METHODOLOGY OF REMOTE MONITORING THE GROUND TEMPERATURE

Automated monitoring of the temperature of the soil demands thermometric boreholes arrangement in a ventilated basement to a depth of at least the actual length of the pile under residential building (10 meters or more). The drilled boreholes are equipped with the systems of automatic monitoring of the permafrost temperature SAM-Permafrost (Kurakov Sergey Anatolyevich, Tomsk) that are designed for the remote autonomous registration and data transmission from the connected thermometric cables (maximum 4 cables and 1 air temperature thermistor) in a single database and, further, to the remote server using the GSM module. The client software allows one to configure controllers, read, export, and visualize the data. Error of calibration of the sensors of temperature measurement is ±0.1°C. The resolution of the temperature measurement is 0.07°C. Such characteristics of the thermometric equipment correspond to modern developments in the field of geotechnical monitoring (kriolab.ru, 2021; msu-geophysics.ru/uslugi/geotexnicheskij-monitoring, 2021; rgtekh.ru, 2021).

The thermistors are installed in boreholes on the thermometric cables with the step of 0.5 m until the depth of 5 m, and with the step of 1 m in the tail. To exclude the influence of the air temperature, the thermometric boreholes are covered with a wooden box with the proper insulation. Four air temperature thermistor are installed in different parts of the ventilated basement at a height of 1-1.5 m. The results of temperature measurements are automatically collected on the server and duplicated on a specially developed web resource (https://monitoring.arctic.yanao.ru) where it is possible to analyze, visualize, and export the data about the temperature of the soil. Now this site is running in a test mode and only the specialists have the access. In addition to the automated data collecting, there is a mode of importing data from files; the mode allows one download files from the SAM-Permafrost terminals without the built-in GSM module. The full access to the web-resource is provided for specialists and all

stakeholders. There, the following options are provided:
- display the monitoring the objects on the map with the ability to view advanced information (number of boreholes, installation time, etc.);
- display the scheme of the set of thermometric boreholes for the monitoring objects with the ability to view information on each of the boreholes;
- visualization of data in the form of tables and graphs and export of data for the selected thermometric boreholes.

RESULTS OF REMOTE MONITORING THE GROUND TEMPERATURE (07.2018 – 12.2020) UNDER RESIDENTIAL BUILDING I

In the city of Salekhard, the municipality provided four capital buildings to test the automated temperature monitoring methodology. In 2018, four thermometric boreholes were equipped by the thermometric cables (Fig. 1, red dots) in the ventilated basement of the Residential building I. These boreholes were projected according to the standards of construction and operation (SP 25.13330.2012, 2012; and Resolution of the State Construction Committee of the Russian Federation of 27.09.2003 N 170, 2003). In 2020, 20 additional boreholes were drilled and equipped with the thermometric cables (Fig. 1, black dots). The thermometric boreholes were drilled in the ventilated basement under the existing objects with the drilling equipment UKB 12/25 (the height of the ventilated basement is 120-170 cm). Drilling was carried out with the selection of soil samples and a detailed description of the geological section. The upper part of the section is dominated by sandy. With depth, sandy loam and loam appear. According to (Kuzin 1963) is a typical geological section for Salekhard. The boreholes were cased with the solid polyethylene pipe with a diameter of 40 mm. The upper part of the casing pipe was covered with the heat-insulating box.

Thus, 24 boreholes were equipped for testing the method under the Residential building I (Fig. 1). The enough dense grid of the boreholes is installed due to necessity to develop and to verify the methodology and serves to solution of a number of scientific problems. The aim of this project is, in particular, testing the developed program of calculating of the non-stationary thermal fields and to determine the optimal distance between the boreholes. The first task is partially solved in this work, the second one will be solved in the future. The temperature is measured every 3 hours (synchronized with the nearest weather station at the airport of the Salekhard). The accumulated data is transferred to the server every 12 hours.

Figure 2 (a, b c, d) shows the average monthly ground temperatures for the October 2018, 2019, and 2020. The comparison of the data of the soil temperatures in the boreholes in different years shows the temperature decreased in all boreholes at the depth of 9–11 m. This tendency is presumably caused by reaching the projected influence of the seasonal cooling devices (SCDs). Note that they are inserted into the foundation construction. Undoubtedly, it is worth to highlight the temperature change at the depths of 12–14 m in the borehole T1. Here, the temperature in 2020 has increased by 2.5°C. This indicates unwanted effects (possibly, permafrost thawing) below the project depth of the foundation. To find out the reason of this temperature behavior in 2020, it is necessary to carry out additional investigations using, for example, the geophysical methods. In general, the situation with the permafrost in the base of the foundation of the Residential building I can be described as stable, since the soils at the base of the pile foundation are in frozen state.

To determine the moment of the beginning of the permafrost thawing in the borehole T1, the results of the temperature measurements at the depths of 11, 12, 13, and 14 meters for the two-year monitoring period were analyzed (Fig. 2e). The measurement results show that the depth of zero annual amplitude under Residential building I and on this type of the landscape is more than 10 meters. We can assume that at the depths greater than 10 m, the SCDs reached its projected power only in 2019, because the temperature in the borehole T1 at a depth of 11 m was close to zero in 2018 (Fig. 2e, gray curve), and since the winter 2019, the thermistors showed a stable negative temperature. The moment of the beginning of the permafrost thawing is clearly defined. In the borehole T1, the temperature at the depth of 13–14 m began to increase in early summer, 10.06.2020. Apparently, it is due to the spring melt water, which initiated the process of thawing. The further temperature monitoring is necessary to determine the power of the heat source and to predict the state of the permafrost. In addition, it is necessary to identify the nature and issue of the heat source. If our assumptions are correct and the permafrost thawing is caused by the groundwater, then the underground leakage can be determined using the electrical resistivity tomography (ERT). The ERT method is successfully used to solve the problems of mapping permafrost, determining the depth of the active layer and tails (You et al. 2013; McClymont et al. 2013; Yeltsov et al. 2017; Olenchenko et al. 2019).

In 2020, for further testing of the automated temperature monitoring methodology, 20 more boreholes were drilled and equipped with the thermometric cables (Fig. 1, black dots). Note that the automatic transmission of temperature

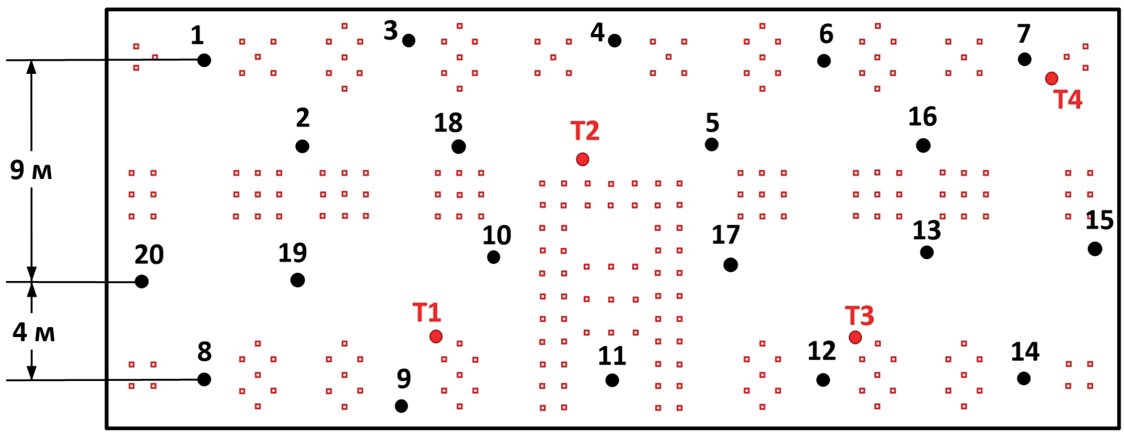

Fig. 1. Scheme of the pile base (red squares) and the location of the thermometric boreholes (black and red circles) under the Residential building I in the horizontal plane

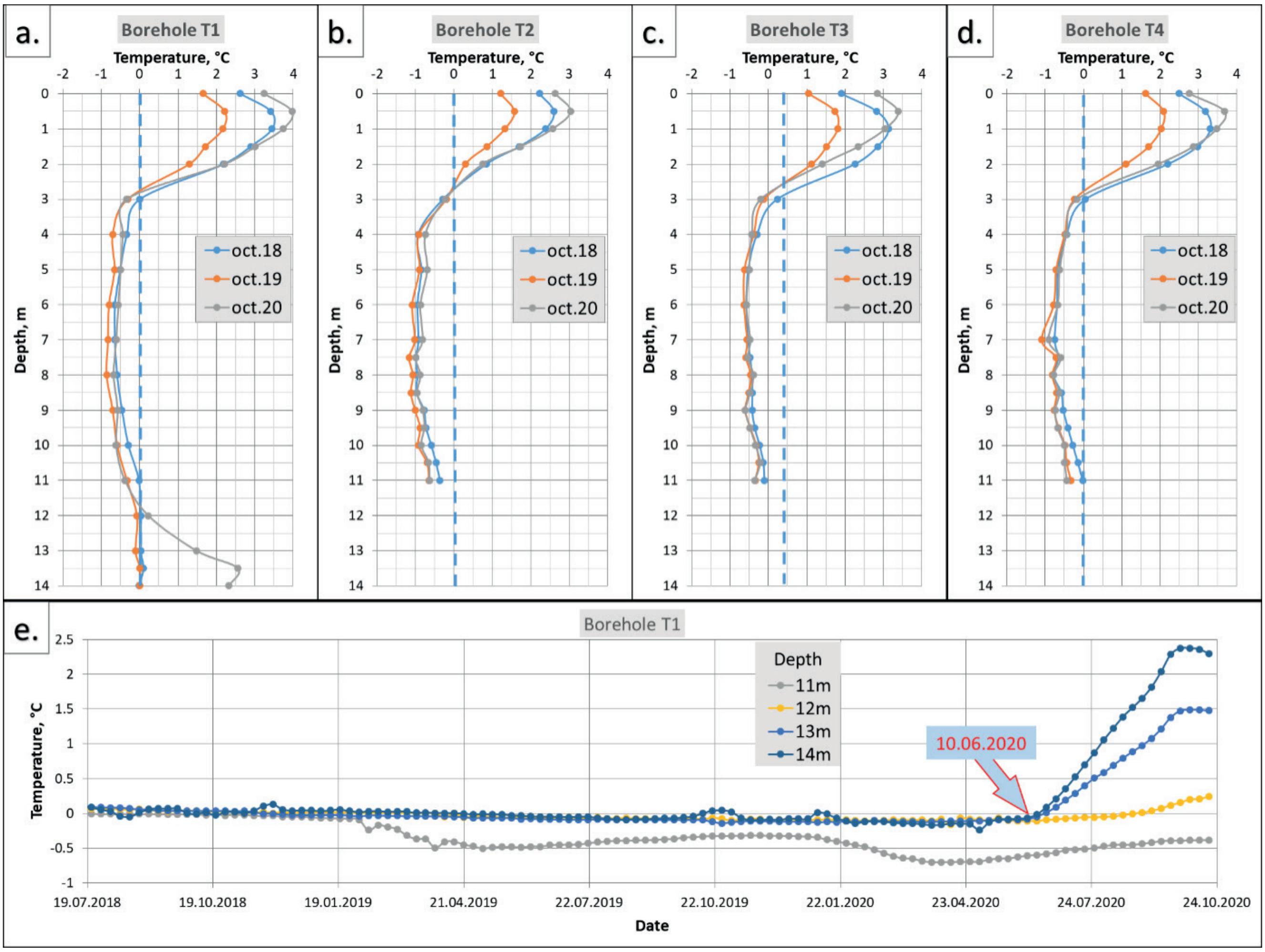

Fig. 2. The results of measuring the temperature of soils under the Residential building I: monthly average temperature for the October 2018-2020 in the boreholes T1-T4 (a, b c, d); (e) is the temperature in the borehole T1 for 19.07.2018-24.10.2020 at depths 11, 12, 13, and 14 meters

to the server from boreholes T1-T4 was interrupted on 23.10.2020 due to the technical difficulties and at the time of writing, the data received after 23.10.2020 has not been processed. Therefore, for three-dimensional analysis (interpolation) and modeling, only the wells 1-20, equipped at the end of 2020, are used.

The first temperature monitoring data transferred to the server from the new 20 wells allowed us to visualize the three-dimensional distribution of the temperature field under the Residential building I by the interpolation at different time points up to the depth of 12m (Fig. 3). The interpolation was carried out without taking into account geology, using the tools of programs designed to visualize geodata. We considered two cases: the weekly average temperature (30.11.2020–06.12.2020) at the beginning of monitoring (Fig. 3a) and the weekly average temperature (11.01.2021–17.01.2021) at the beginning of 2021. As a result, it was found that there is a zone of thawing under Residential building I (Fig. 3, shaded in of red), which is probably caused by leaks from the water lines. The pipes go into the ground directly above the thawing zone. Moreover, the location of the detected thawing coincides with the T1 borehole where, at the depth of 12–14 m, the permafrost thawing began in the summer of 2020 (according to the temperature observations). These two temperature anomalies are highly likely related due to their localization. The further monitoring will possibly predict the impact of these anomalies on the permafrost under the building.

Let analyze the ground temperature at the base of the foundation of the Residential building I in the early December 2020 (Fig. 3a) and in the January 2021 (Fig. 3b). We can say that during a month and the half of the monitoring, the temperature of the detected anomaly (Fig. 3a, shaded in red) dropped to zero (Fig. 3a, white-red color). This means that the thawed soils almost froze during this period of the winter. This is provided by the norms for building on the principle of preserving permafrost. Obviously, the analysis of the current temperature field allows one to detect the zones with anomalous temperatures, which highly likely means the weakening of the bearing capacity of the soil. This information can prevent possible accidents in time by a proper plan of actions.

In addition, to control the temperature of the permafrost at the base of the foundation, the dense enough grid of in-borehole thermal sensors and a measurement period (every 3 hours) will allow one to promptly respond to water lines breakdowns (pipe breaks). Note that these will be detected by an unexpected temperature jump in data of near-surface (at the zero depth) sensors.

The further temperature monitoring under the buildings in the city of Salekhard will provide data that will be used to the numerical modelling of the non-stationary thermal field and to calculate the bearing capacity of the foundations of the monitored buildings for the forthcoming years. The numerical calculations will be carried out using the program developed by specialists of the N.N. Krasovskii Institute of Mathematics and Mechanics, Ural Branch of RAS together with the Arctic Research Center of the Yamal-Nenets autonomous district. In this paper, the algorithm of the program and the first calculations using the real data are presented.

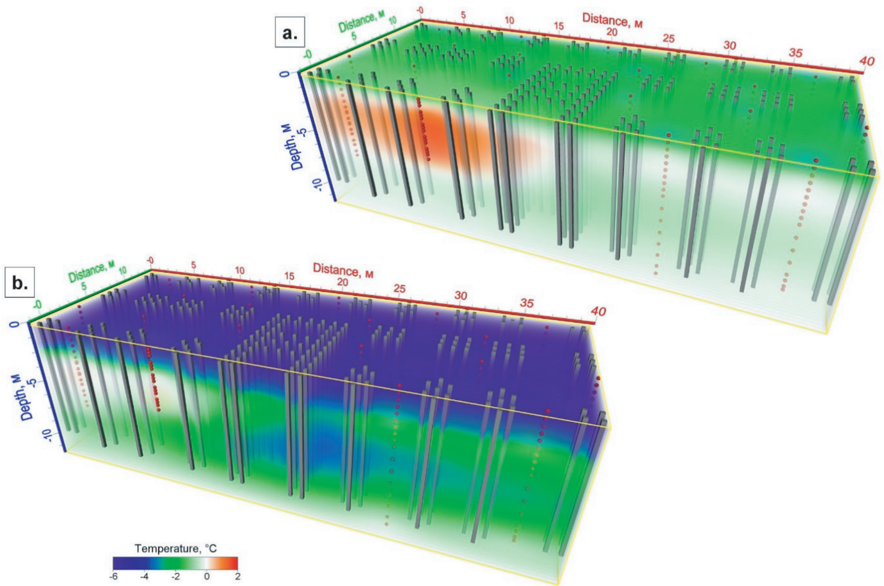

Fig. 3. Scheme of the pile base (grey piles) and the location of thermistors (red spheres) and 3D interpolation of weekly average temperature of soils that measured at the base of the foundation of the Residential building I: (a) – 30.11.2020–06.12.2020; (b) – 11.01.2021–17.01.2021

DISCUSSION

It is easy to imagine that if not to make a minimal effort for the geotechnical monitoring of the soils of buildings foundation in the future, the young cities located in the permafrost zones will inevitably repeat the history of older ones. Investigation of the rate of permafrost degradation in the natural and anthropogenic conditions will improve the construction norms and regulations. The infrastructure and residential buildings should be built already taking into account the predictions of the future permafrost changes obtained using real thermometry data.

In the last decade, the development of the Arctic regions by oil and gas companies has given the instrumental, scientific, methodological, and technological impetus to the system of geotechnical monitoring. This system has recently outlined, the needs and abilities are determined. It is necessary to have the real-time monitoring system as an enough dense grid of the in-borehole thermal sensors, which have to be examined and justified by specialists of the geocryology. Such systems are already developing, but mainly for the oil and gas infrastructure (Arhgeo.com 2020; Permafrost-engineering.com 2021; Pugach V.N. et al. 2019). The idea of automated monitoring in the urban environment has been conceiving for more than three years by the Arctic Research Center of the Yamal-Nenets Autonomous District together with colleagues of the Moscow State University (Gromadsky et al. 2019; Shein et al. 2020) and is currently being tested in Salekhard.

A combination of temperature monitoring in the pile foundation area of the residential buildings together with mathematical modeling methods that use data from the grid of the in-borehole thermal sensors is a promising direction. It will cumulate the advantages of these approaches. The thorough monitoring will allow one to quickly respond to technogenic and natural factors affecting on the bearing capacity of the soil, but, in addition, the computer modelling will allow one to make prognosis of the observed tendencies. Moreover, in contrast to the three-dimensional interpolation of the average soil temperature, reconstructed from the data of thermometric boreholes, the zones of influence of SCDs are clearly visible in the temperature fields obtained by the numerical simulation (Fig. 4). The mathematical modeling in the evaluation of the thermometry data will allow one both to test hypotheses about the detected anomalies and to predict the long-term impact of climatic and anthropogenic factors.

The models developed earlier for the processes of thawing of permafrost (Filimonov et al. 2013; Vaganova N.A. et al. 2017, 2019) are easily transferred to the modeling of processes in pile foundations. To complete the model for simulating thermal fields in the ground with a pile base, it is necessary to take into account the position of the piles, dimensions, as well as the SCDs and possible sources of heat in the ground that may be detected by thermistors.

Mathematical modeling is a convenient forecasting tool that makes it possible to assess not only the current temperature regime of the foundation, but also to test hypotheses of the causes of possible deviations in planned regimes, as well as to highlight trends of different scenarios. The main areas of application of modeling in the monitoring system may be considered as follows:

• creation of a foundation model for the buildings pointing out the essential parameters;
• assignment or correction of the parameters necessary for calculations in conditions of incomplete data and possible assumptions;
• comparison of the calculated data with the monitoring data;
• updating the model in real time, for example, when weather conditions change;
• formulation of criteria for evaluating various modeled states of the system;
• ability to respond to observed deviations in real time.

A preliminary numerical simulation of the Residential building I is carried out for December and January in 2020–2021 season of the monitoring. A geometric model of the building is suggested, the data of thermometric boreholes (Fig. 3a) are taken as the initial data.

The following parameters typical for the sandy soils like in the base are used in the calculations: the thermal conductivity of frozen/thawed soil is 1.89/1.74 W/(m K), the volumetric heat capacity of frozen/thawed soil is 2.17/2.42 10^3 kJ/(m^3 K), the phase transition heat is 6.699 10^4 kJ/(m^3 K), phase transition temperature is -0.1°C.

The preliminary modeling is carried out for December (average air temperature is -15.3°C) and January (average air temperature is -21.2°C). The data were obtained from

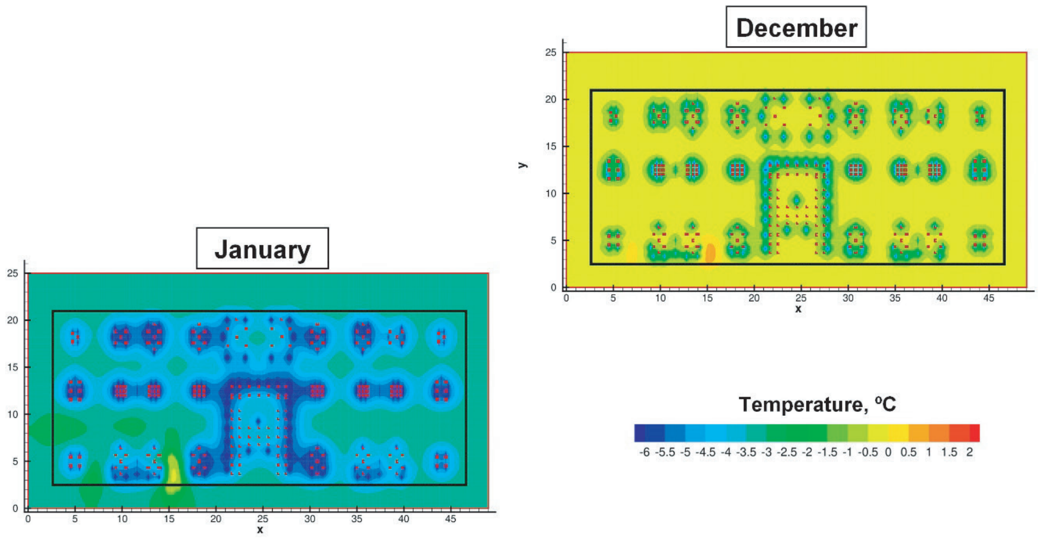

Fig. 4. The computed temperature at the deep of 2.3 m under the Residential building I in December and January

four air temperature thermistors installed in different parts of the ventilated basement at a height of 1-1.5 m. The ventilated basement area is shaded, so the solar radiation can be neglected. The square concrete piles at the base have dimensions of 0.3m×0.3m×10m, with the thermal conductivity is 1.74 W/(m K), the volumetric heat capacity is 2.42 10^3 kJ/(m^3 K). SCDs are the metal tubes with the diameter of 0.02 m and the depth of 10 m and are considered as the internal sources of cold, and the temperature on which depends on the difference of air temperatures on the surface and the soil temperature (Vaganova N.A. et al. 2019). In Fig. 4, the temperature at the deep of 2.3 m is shown in (x,y) plane for December and January. The SCDs work and the resulting freezing is stronger in January. The warmer area in the soil (detected in the previous stage, Fig. 3) became cooler and freezes due to the SCDs influence. This is observed by the following monitoring of the ground. In the future development, the authors plan to analyze the calculated temperature fields and compare it with the temperatures recorded by the thermistors. The model should be verified with using of the data of one-year period at least.

A complex approach to the geotechnical monitoring of the buildings and structures located in the permafrost areas will allow one to link the data obtained with the mathematical modeling of the thermal processes and to reach the accurate (as far as numerical calculations will allow) assessment of the bearing capacity of the foundation. But «this system itself will be effective if it will be based both on the results of the engineering surveys and project design, and on the information about the conditions for their implementation (construction). That is, on the balanced system: survey – project design – construction (building) – operation (monitoring)» (Rivkin 2020).

The projects of creation of the monitoring systems in the permafrost zones are necessary to be supported by all stakeholders, executive and legislative authorities, construction organizations, management companies, etc. At the same time, it is necessary to develop appropriate laws and legal norms. The complex geotechnical monitoring systems are directly related to sustainable development of Northern cities and apply to the modern technical and the informational technologies.

CONCLUSIONS

The thermal monitoring in the boreholes T1–T4 started from summer of 2018 and allows one to say that the ground in the base of the Residential building I is stable. We have to note that the temperature increased by 2.5°C in the borehole T1 at the depth of 12–14 m. It points out the detrimental effects (permafrost thawing) and detects the heat transfers in this zone. The scope of the detected thawing and the source of heat (presumably groundwater) are advisable to be investigated with using the geophysical methods, for example, the electrotomography.

The reconstruction of the full-scale thermal fields by the monitoring data will allow one to detect the zones of possible weakening of the bearing capacity of the soils or thawing zones. This information sharing can prevent in time possible accidents by a proper plan of actions.

The enough dense grid of the in-borehole thermal sensors will allow one to promptly respond to utility breakdowns (pipe breaks), which will be detected by an unexpected temperature jump in the data of the near-surface (at the zero depth) sensors. The full-scale reconstruction of temperature in the ground with using the numerical simulation of the inserted devices will clarify the temperature in the soil in the zones out of reach of the thermistors, in particular, on the pile surfaces. In contrast to the thermal monitoring, the data of the computer simulations can predict the development of various temperature processes depending on the changes in the climatic parameters. Moreover, including technogenic heat sources into the model may be detected with delay or too lately to prevent destructive processes. But accumulation and analysis of the data of the long-time observation can make contribution to the refinement and adjustment of the model and computer simulation program in order to obtain more thorough results.

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