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Computer Modeling of Temperature Fields in the Soil and the Bearing Capacity of Pile Foundations of Buildings on Permafrost

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Abstract. Global climate warming challenges the permafrost areas losing the frozen state and stability. Industrial development and human activity in these regions also contributes to the degradation of permafrost. The construction of residential buildings and their operation in these territories mainly involves maintaining the soil under these structures in a frozen state throughout the entire period of their operation. For these purposes, pile foundations and ventilated crawl spaces are used. The basements may also include the devices aiding stabilize the soil. For example, it could be hundreds of the seasonally operating cooling devices. An urgent task is long-term forecasting of the dynamics of changes in the bearing capacity of a pile foundation of a building, considering climatic and technogenic impacts on the surrounding soil. A new model and numerical algorithm were developed to study the dynamics of changes in the bearing capacity of piles during the operation of the building, considering temperature monitoring data from temperature sensors located in thermometric wells. Validation of the developed software package was carried out based on the existing and constantly arriving data on soil temperature monitoring to a depth of 10 meters on the server. A comparison of the obtained monitoring data and the calculated data in thermometric wells showed a significant improvement compared to the previously used model and calculation program for this residential building.

Keywords: mathematical modelling, heat and mass transfer, permafrost.

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Introduction

The territories of Western Siberia and the northern latitudes of Russia, which are covered by permafrost, are extremely important for the Russian economy. These regions are rich in various minerals and have great oil and gas fields. In the development strategy of the northern territories

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of Russia, a significant place is given to the balanced development of the economy, industry, and social infrastructure with the preservation of natural ecosystems. Sustainability of engineering infrastructure in regions occupied by permafrost [1] needs for extra attention due to observed climate warming [2–4]. Experiencing significant changes and degradation of permafrost [5–8] may lead to possible technogenic accidents [9, 10].

In accordance with the Russian Building Code [1], the capital structures and residential buildings require special rules for construction and operation in such territories. In accordance with these rules, the construction should be carried out following two principles. The first principle of construction means the construction and operation of capital structures must keep the foundation soils in a frozen state. The second principle of construction means the permafrost foundation soils should be used in a thawed or thawing state. So, before the construction the thawing layers should be achieved to the expected depth or under the assumption the thawing during the operation. In Russia, more than 75% of all buildings and engineering structures in the permafrost zone were built and operated according to the first principle. Thawing of ice-saturated rocks due to climate change or various technogenic impacts will be accompanied by subsidence of the earth's surface [11] and the development of dangerous frozen geological processes leading to accidents, the possible consequences of which may be the destruction of pile foundations of capital structures and residential buildings [12]. To predict these processes, various methods of monitoring the condition of the foundations of structures are used [13]. The bearing capacity of building foundation piles also depends on the temperature of the surrounding soil, therefore, in the city of Salekhard, employees of the Arctic Research Center of the Yamal-Nenets autonomous district have built and are developing an automatic temperature monitoring (ATM) system for the soil surrounding the pile foundations residential buildings [14, 15]. For this purpose, thermometric wells equipped with temperature sensors were drilled in the ventilated crawl spaces of buildings. Analysis of the temperature data obtained from this system allows us to draw conclusions about the condition of the soil under buildings. However, to model unsteady thermal fields throughout the entire area of a pile foundation, it is necessary to investigate mathematical models based on ATM data. The presence of thermometric wells makes it possible to determine the lithology of the soil and to validate the constructed numerical methods [16]. In accordance with the first principle of construction, it is also necessary to maintain the foundation soils of residential buildings in a frozen state.

Therefore, in the northern regions the pile foundations, ventilated crawl spaces, and various devices for cooling the soil may be used side by side under buildings [17, 18]. The seasonal cooling devices (SCDs) may be mentioned as the most common. The SCD operational principle is based on the physical laws of cooling due to the temperature difference in the soil and in the ventilated crawl space. So, the SCDs are in process only on winter. SCD operation makes significant changes in the surrounding soil and has to be accounted in the mathematical model and is required extra calibration with data from temperature sensors in thermometric wells.

In this study the new algorithm and software were calibrated for a specific residential building (Building I) in the city of Salekhard. In contrast to [16], the climatic and technogenic factors influencing the temperature fields at the base of the pile foundation of this building were studied in detail. Numerical calculations were performed for the dynamics of changes in the bearing capacity of piles in 2021–2023. The presented data verifies the model and the developed numerical algorithm using data from temperature sensors located in thermometric wells. Additional data is obtained from temperature sensors of four thermometric wells. When carrying out numerical calculations, the concept of average bearing capacity of piles was introduced and the dynamics of its changes until January 2024 are shown. Based on the numerical calculations, the further research direction related to improving and increasing the accuracy of the mathematical models, algorithms and software are discussed.

1. Statement of the problem and pethods

Object of study

The object of study is the pile foundation of a nine-story residential building in the city of Salekhard, which, in accordance with the first principle of construction on permafrost, has a ventilated crawl spaces 1.8 meters high, and 186 SCDs are used to cool the soil around 229 piles. Fig. 1 shows a plan of the pile foundation for Building I.

Each automatic monitoring station (SAM station) collects data from four thermometric wells (SAM wells) equipped with temperature sensors that measure soil temperature to a depth of 10 meters with an accuracy of 0.1°C. The triangles in the Fig. 1 are the SAM wells, the squares are the SAM stations, the dots are the piles. Data from all temperature measurements are transmitted to the server every 3 hours using GSM modules. 186 SCDs are not shown in the Fig. 1, but their exact location coordinates in the ventilated crawl space are used in the model and in computer simulations. These devices are vertical cooling devices, which are two-phase closed thermosiphons with a diameter of 38 mm. The aluminum cooling fins of these devices are of 95 cm and the underground depths are of 10 m. To carry out automatic temperature monitoring of the soil in a ventilated crawl space, 6 stations were equipped.

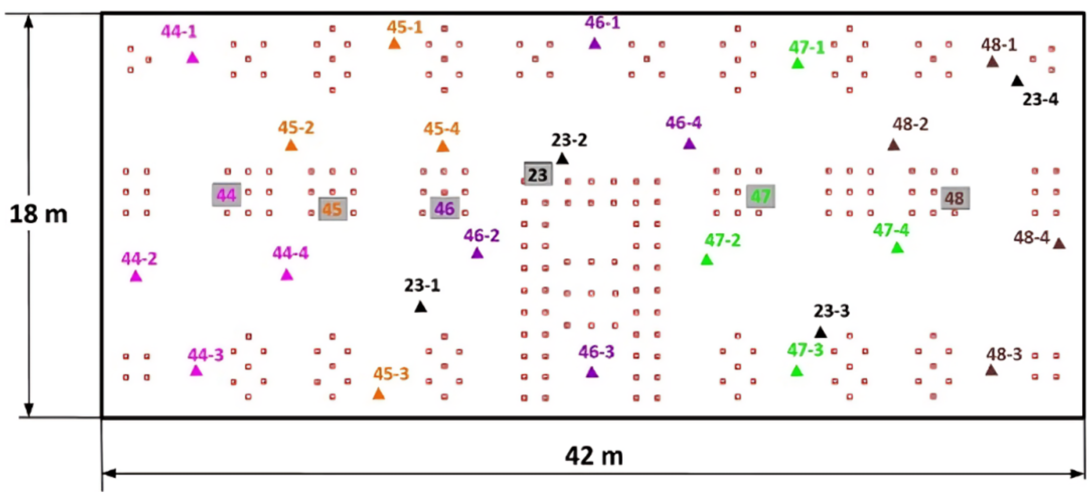


Fig. 1. Scheme of the location of thermometric equipment of the SAMs and the pile foundations under the Building I

Mathematical model

Let $T = T(t, x, y, z)$ be the soil temperature at point (x, y, z) for the time t and at the initial time t_0 has a temperature $T_0(x, y, z)$. Following [16, 19], to describe the temperature regime of the soil under the building, we will use the equation taking into account the localized heat of the phase transition:

$$\rho\big(c_\nu(T) + k\delta(T - T^*)\big)\frac{\partial T}{\partial t} = \nabla\,(\lambda(T)\Delta T), \tag{1}$$

where ρ is density [kg/m^3], T^* is temperature of phase transition $[K]$,

$$c_\nu(T) = \left\{\begin{array}{ll} c_1(x,y,z), & T < T^*, \\ c_2(x,y,z), & T > T^* \end{array}\right. \text{ is specific heat [J/(kg}\cdot\text{K)]},$$

$$\lambda(T) = \begin{cases} \lambda_1(x,y,z), & T < T^*, \\ \lambda_2(x,y,z), & T > T^* \end{cases} \text{ is thermal conductivity coefficient [W/(m} \cdot \text{ K)],}$$

$k = k(x,y,z)$ is specific heat of phase transition, δ is Dirac delta function.

This equation allows to solve the problem of Stefan type without the explicit separation of the phase transition [19]. The heat of phase transition is introduced with using Dirac δ-function in the specific heat ratio. The parameters $c(T)$ and $\lambda(T)$ inserted in (1) were determined during laboratory studies of soil from SAM wells drilled in ventilated crawl space. As the initial time moment we take t_0, corresponding to the moment in time 2 years ago and the reconstructed initial distribution of soil temperature at this moment in time $T_0(x,y,z)$ based on ATM data. As studies based on numerical calculations have shown, such a choice is necessary to take into account the operation of all SCDs and their impact on the soil temperature regime for 2 years. Particular attention was paid to modeling the operation of SCDs considering the ATM data. The calculation of the bearing capacity is carried out based on the condition:

$$F \leqslant F_u/\gamma_n,$$

where F is the design load on the foundation, γ_n is the reliability coefficient for the responsibility of the structure, F_u is the bearing capacity of the foundation, determined in accordance with the Russian Building Code and soil temperature data determined during numerical calculations.

Of course, moisture and migration of water should be mentioned in the problem of temperature distribution in soil. When the soil freezes, migration of water contained in the soil is observed [20–23]. This process has a significant impact on the temperature regime of the soil. Indeed, unfrozen water in the soil will migrate from bottom to top into the freezing zone, and latent heat will affect the temperature distribution of frozen soil due to the freezing of replenished water. In the proposed model, SCDs will also be sources of cold in the ground in winter, from which soil freezing will spread in the horizontal direction, and lateral migration above the groundwater level in the case under consideration will be minimal. This study takes into account the latent heat of the initial water content and assumes that the soils in the basements are generally low-moisture, and the soil surface in a ventilated crawl space is insulated with a concrete slab that protects from evaporation and filtration of rain and melted snow water into the soil.

Validation of numerical algorithms

To find the thermal fields in the soil described by (1) in the area of the pile foundation, the finite difference method with splitting into spatial variables is used [19]. The initial equation for each of the spatial directions is approximated by an implicit central-difference three-point scheme, and a system of difference linear algebraic equations having a tridiagonal form is solved by the sweep method. Since thermal fields in the soil have a significant impact on the physical and mechanical properties of frozen soil and the bearing capacity, an important task is to determine the temperature on the surfaces of piles with sufficient accuracy. In order to test the accuracy of the developed algorithm, the numerical results were compared with data from temperature sensors in SAM wells. Figure 2 compares data for SAM well 44–1 during 2023 for various months. In these Figures, the dashed lines correspond to the data of numerical calculations obtained on the basis of the proposed model, and the solid lines indicate ATM data. In general, the agreement of these data is acceptable for engineering calculations.

2. Results of numerical calculation

A large number of works are devoted to development of numerical methods for solving boundary value problems of heat conduction. Basics of finite difference methods are detailed in the

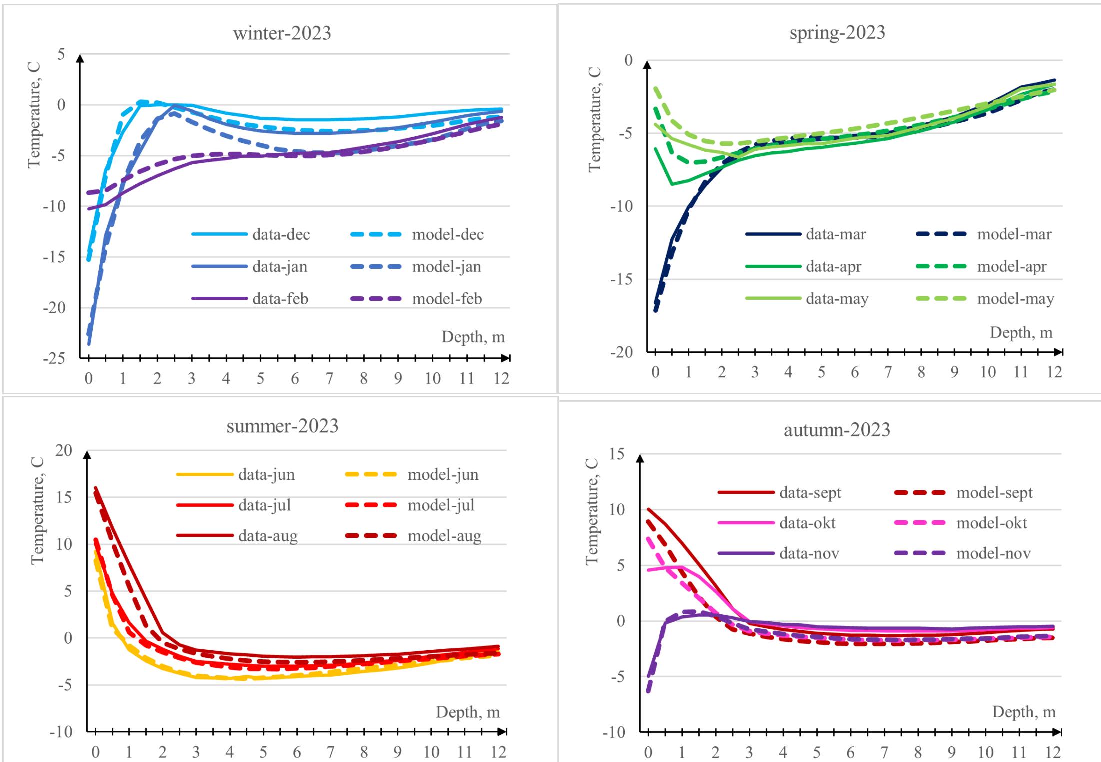


Fig. 2. Comparison of temperature sensor data in well 44–1 with numerical calculation data in the seasons 2023

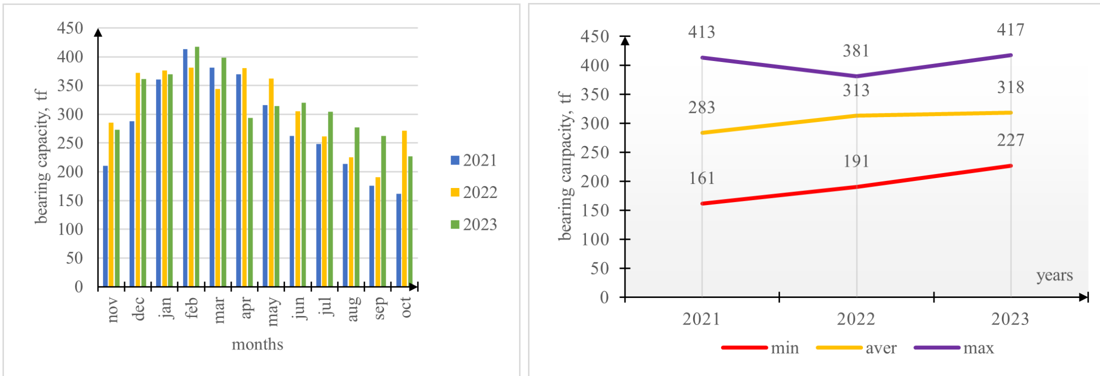
works [24, 25]. To solve the Stefan problem for the equation (1), the finite difference method using the method of splitting in spatial variables has proven itself well [19].

In numerical calculations, an orthogonal condensed mesh is used. In the $\{x, y\}$-plane, the computational grid is condensed around the elements of the pile foundation (piles and SCDs) and thermometric wells, which are used to set the initial temperature distribution in the three-dimensional computational domain, as well as to test the developed software.

Calculations show that we can use as a computational grid consisting of $331 \times 154 \times 39 = 1987986$ nodes. The calculations were carried out on the supercomputer Uran in N. N. Krasovskii Institute of Mathematics and Mechanics (Yekaterinburg). The time step during the numerical experiments was chosen to be 1 day.

Let us consider the dynamics of changes in the bearing capacity of the pile foundation from 2021 to 2023. To do this, using the developed software, we will determine the bearing capacity of each of the 229 piles. Let us introduce the concept of the average bearing capacity of all piles, equal to the sum of the bearing capacities of all piles on the first day of each month, divided by the number of piles. Fig. 3 shows the change in this characteristic from November 2021 to October 2023. The bearing capacity of all piles is measured in tf. Note that $1tf = 9806,65N$.

To study the bearing capacity of piles, it is also useful to consider the minimum annual average bearing capacity, the average annual average bearing capacity, and the maximum annual average bearing capacity. Fig. 3(b) shows these characteristics. It can be noted that in 2022 there was a noticeable decrease in the maximum average annual bearing capacity, which is explained by a warmer winter period compared to the winter period in 2021 (Fig. 4). In 2023, the winter period became colder than in 2021. In 2022 the maximum average annual bearing capacity increased.



(a) (b)

Fig. 3. Average bearing capacity (a) and minimum, average and maximum bearing capacities (b) in 2021, 2022, 2023

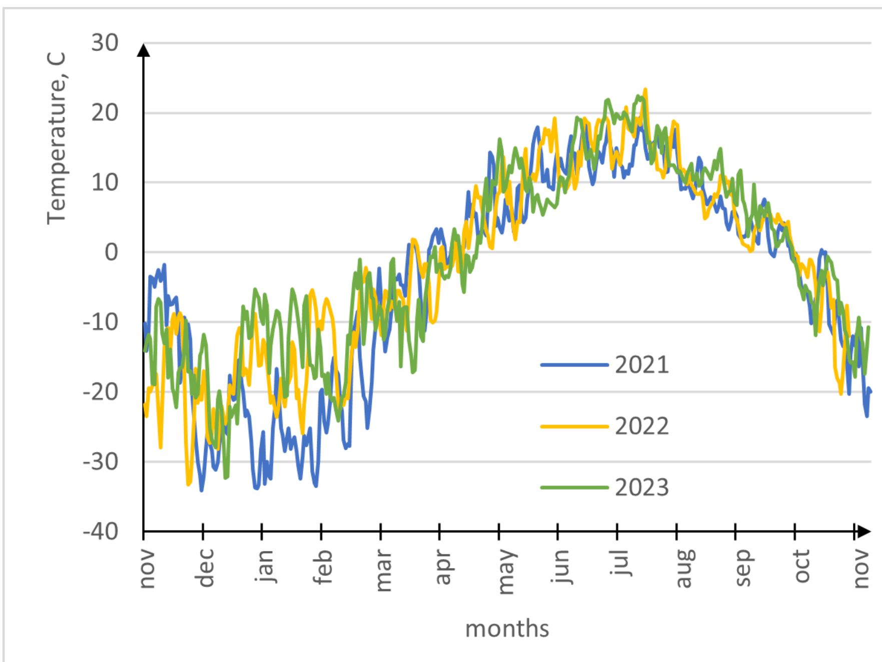


Fig. 4. Air temperature in a ventilated crawl space in 2021, 2022, 2023

For the practical use of the obtained average characteristics, the minimum annual average characteristic is of particular interest, which must be considered when designing and operating residential buildings in regions with permafrost. Numerical calculations did not record a critical change in the bearing capacity of the piles for Building I.

3. Discussions and conclusions

To assess the bearing capacity of piles for residential buildings in permafrost regions, a new model was developed that considers the accumulated ATM data, and a new method for simulating the operation of SCDs, which made it possible to evaluate the various characteristics of the bearing capacity of a specific pile foundation of a residential building. An important point of this study was the detailed validation of the developed numerical methodology on data obtained from temperature sensors placed in SAM wells.

Fig. 5 shows the air temperature in a ventilated crawl space in January 2024 from the temperature sensors at SAM station 44 (orange). If the air temperatures in different parts of the ventilated crawl space generally differ little from each other, then the temperatures on the surface $z = 0$, which is a concrete covering, can already differ significantly. For example, a comparison of surface temperatures at SAM well 44–1 (blue) and at the surface at SAM well 48–2 (yellow) shows that the difference on some days can reach 15°C (Fig. 5).

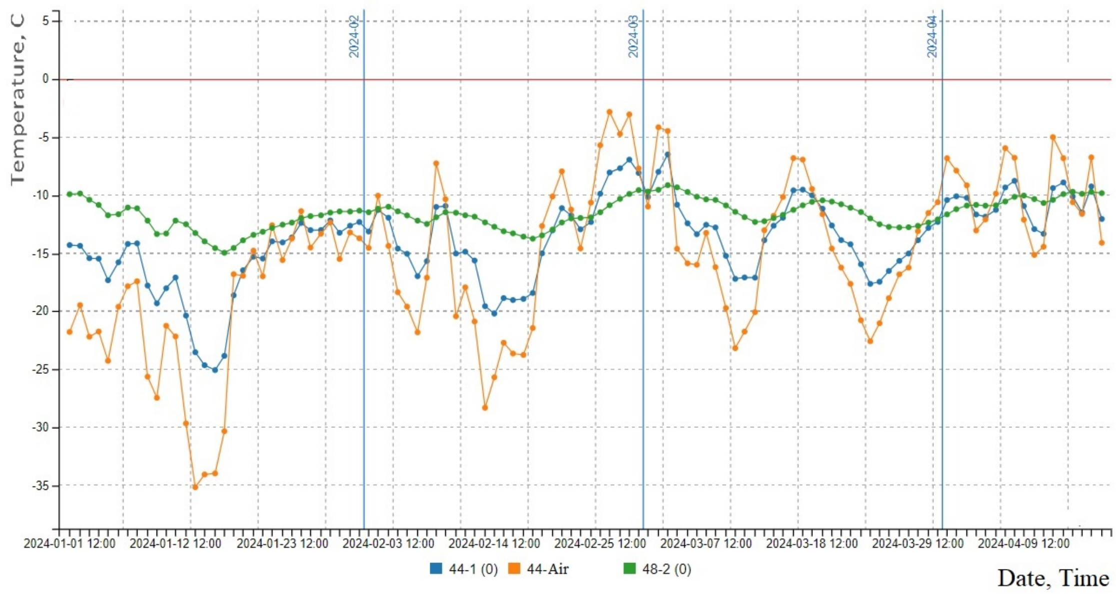


Fig. 5. Air temperature in a ventilated crawl space and surface temperature $z = 0$ at two points in January 2024

A similar situation with a significant difference in temperature on the surface $z = 0$ exists at other points. Fig. 6 shows changes in surface temperature in January 2024 near SAM well 45–1, which has a minimum average temperature at point 45–1(0), and near well 48–2, which has a maximum average temperature at point 48–2(0).

Such differences in surface temperatures can be associated with several factors: utility failures, snow falling into the ventilated crawl space from outside, different operating efficiency of the SCDs, and the presence of utilities, which, despite the necessary thermal insulation, can be additional sources of heat. In any case, to more adequately describe the dynamics of changes in the temperature regime of the soil around the foundation piles, it is advisable to use a two-dimensional approximation of surface temperatures, taking into account the accumulated ATM data and the correct setting of the SCD operation. This approach will also make it possible to carry out numerical calculations in the event of utility accidents, when the surface temperature can increase significantly in winter, first due to the influx of water, and then due to its freezing and the formation of additional thermal insulation of the surface, when a local thermal anomaly occurs that changes the bearing capacity of the soil. Based on a new algorithm for taking into account the influence of SCDs and ATM data on the temperature regime of the soil around foundation piles, software was developed, the validation of which was tested on the available

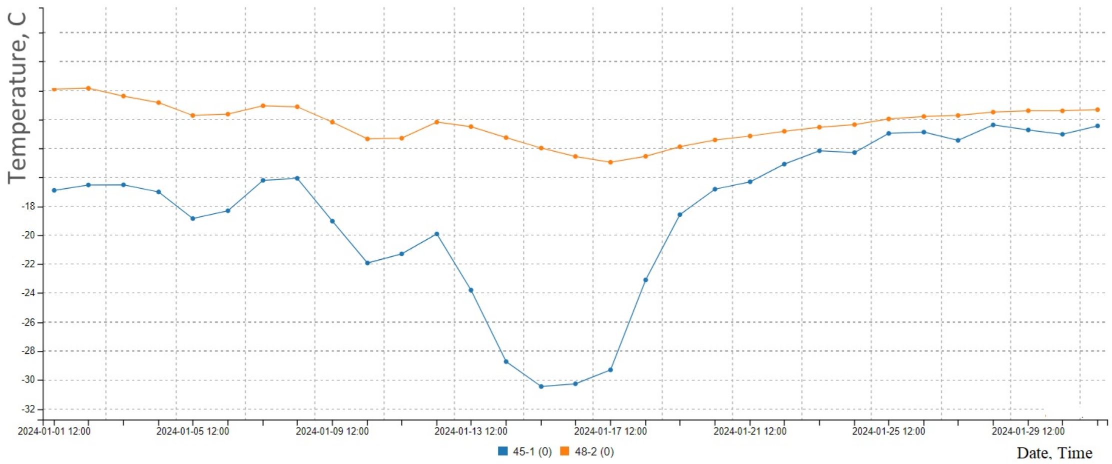


Fig. 6. Surface temperature in a ventilated crawl space of Building I in January 2024

data from temperature sensors from SAM wells. A good agreement between the ATM data and the obtained numerical calculation data was obtained. The greatest difference between the calculated data and the ATM temperature data was observed in the winter months when the bearing capacity of the piles is maximum. This difference may be associated with the need to use the above-described method for setting the temperature on the surface, as well as with the Gibbs-Thomson effect, which is associated with the presence of unfrozen water in the soil, which leads to a change in the shape of the interphase boundary and a decrease in the freezing point of the soil. It was noted in [26] that the deviation of the calculation results from the experimental data gradually increases with decreasing temperature. In our case, comparison of numerical calculations and ATM data in September and October (Fig. 2) showed good agreement. During these months, the soil is the warmest after the summer season, and therefore has a minimum bearing capacity, which is most often used when assessing the reliability of a pile foundation.

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Компьютерное моделирование температурных полей в грунте и несущей способности свайных фундаментов зданий на вечной мерзлоте

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Аннотация. Освоение обширных регионов, занятых вечной мерзлотой, сталкивается с проблемами, связанными с потеплением климата, которое способствует деградации вечной мерзлоты. Строительство жилых домов и их эксплуатация на этих территориях в основном предполагает поддержание грунта под этими сооружениями в мерзлом состоянии на протяжении всего периода их эксплуатации. Для этих целей используются свайные фундаменты и вентилируемые подполья. Сложность компьютерного моделирования возникает из-за учета сезонно действующих охлаждающих устройств, количество которых в конструкции современного здания определяется его размерами и в среднем может достигать 200 штук. Актуальной задачей является долгосрочное прогнозирование динамики изменения несущей способности свайного фундамента здания с учетом климатических и техногенных воздействий на окружающий грунт. Для этих целей были разработаны новая модель и численный алгоритм исследования динамики изменения несущей способности свай в процессе эксплуатации здания с учетом данных температурного мониторинга с датчиков температуры, расположенных в термометрических скважинах. Валидация разработанного программного комплекса проводилась на основе существующих и постоянно поступающих данных мониторинга температуры грунта до глубины до 10 метров. Сравнение полученных данных мониторинга и расчетных данных в термометрических скважинах показало значительное улучшение по сравнению с ранее использованной моделью и программой расчета для данного жилого дома.

Ключевые слова: математическое моделирование, тепломассоперенос, вечная мерзлота.