

Original article

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Nanotechnology and parameters of permafrost soil thawing in the construction of building foundations and transportation structures

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ABSTRACT

Introduction. The construction of infrastructure facilities, industrial enterprises and residential complexes requires design solutions that ensure the operational reliability of foundations in conditions of degradation of permafrost groundwater. The geological conditions of permafrost soils affect the strength, stability and durability of structures. Construction without taking into account the characteristics of permafrost soils leads to precipitation; deformations of buildings and emergency situations associated with the degradation of the soil mass due to changes in climatic conditions. Existing technologies may not always meet the requirements for the reliability of construction facilities. In order to maintain the durability and stability of structures, it is necessary to take into account risk factors for the northern regions, where climatic conditions are very harsh and construction sites are subjected to significant loads. Rising average annual air temperatures are causing the active layer—the seasonally thawed portion of permafrost soils—to deepen across all affected regions. When designing modern structures, the depth of foundation must be increased, which in turn leads to an increase in construction costs in permafrost zones. Based on the results of the calculation, the required temperature of steam supply to the steam needle, the diameter of the needle, the thickness of its wall, the arrangement of needles, the area of thawing from both one and a complex of steam needles, as well as the time of back-freezing of the soil mass were determined to take into account the possibility of work on their fastening. **Materials and methods.** The article presents the nanotechnology of thawing permafrost soils with steam needles and the calculation justification necessary to take into account the possibility of work on thawing the soil mass and their further consolidation. The calculation justification is based on the example of the construction of a transport facility in Norilsk, Krasnoyarsk Territory, since this region belongs to the regions of the Far North. The calculation was performed in the specialized software package MIDAS GTS NX Thermal analysis. **Discussion.** The following was performed: verification of the calculation models; simulation of the existing range of steam needle wall thicknesses; simulation of the existing range of steam needle diameters; simulation of the existing temperature range of steam supply to the steam needle; modeling of two possible schemes for the placement of steam needles in a soil array; modeling to determine the distance between steam needles when they are installed in an array of soils; modeling to determine the time required for the thawing of the soil mass and their reverse cooling. The analysis of the results is performed for each of the stages of the calculation justification. The optimal design of the steam needle (diameter, wall thickness, steam supply temperature), the arrangement of the needles and the distance between the needles when they are installed in the soil array, the area and volume of the heated soil array, the time of thawing and reverse cooling of the soil array are determined. **Conclusion.** As part of the work performed, the design parameters of the steam needle are justified, including the optimal diameter, wall thickness and temperature of the supplied steam. The optimal location of steam needles and the necessary distances between them have been established, key indicators of the process of thawing permafrost soil have been determined: the timing, volume and area of thawing, as well as the time interval for the return of soils to their original frozen state. The results of the presented article form the basis for the design and construction of reliable foundations of buildings and transport facilities in regions with the spread of permafrost soils.




KEYWORDS: research results of scientists and specialists; nanotechnology in construction; nanotechnology; permafrost; foundation construction; heat engineering; thermal engineering calculations; foundation soils; steam heating; soil thawing

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Нанотехнология и параметры растепления многолетнемерзлых грунтов при строительстве фундаментов зданий и транспортных сооружений

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АННОТАЦИЯ

Введение. До 65% площади Российской Федерации находятся на территориях распространения многолетнемерзлых грунтов, поэтому работы по совершенствованию существующих и развитию новых технологий сооружения фундаментов в таких условиях сохраняют свою актуальность. Северные территории богаты своими природными ресурсами, такими как нефть, газ и полезные ископаемые, поэтому в последние годы наблюдается тенденция их активного развития. Сооружение объектов инфраструктуры, строительство промышленных предприятий и жилых комплексов требует проектных решений, обеспечивающих эксплуатационную надежность фундаментов в условиях деградации грунтовых многолетнемерзлых массивов. Геологические условия многолетнемерзлых грунтов влияют на прочность, устойчивость и долговечность сооружений. Строительство без учета характеристик мерзлотных грунтов приводит к осадкам, деформациям зданий и аварийным ситуациям, связанным с деградацией грунтового массива из-за изменения климатических условий. Существующие на сегодняшний день технологии строительства сооружений различного назначения в данных условиях основываются на первом принципе – опирании оснований фундаментов на толщу многолетнемерзлых грунтов, которая является постоянной и не подвержена влиянию сезонного растепления и остывания грунтов. Существующие технологии не всегда могут удовлетворять требованиям, предъявляемым к надежности строительных объектов. Для поддержания долговечности и устойчивости сооружений необходимо учитывать факторы риска для северных регионов, где климатические условия весьма суровы, а строительные объекты подвергаются значительным нагрузкам. Из-за увеличения среднегодовой температуры атмосферного воздуха, толща сезонно растепляемых многолетнемерзлых грунтов повсеместно увеличивается. При проектировании современных сооружений глубину заложения фундаментов необходимо увеличивать, что в свою очередь ведет к увеличению затрат на строительство в зонах распространения многолетнемерзлых грунтов. По результатам расчетного обоснования определена необходимая температура подачи пара в паровую иглу, диаметр иглы, толщина её стенки, схема расстановки игл, область растепления как от одной, так и от комплекса паровых игл, а также время обратного промерзания массива грунтов для учета возможности последующего повышения их несущей способности. **Материалы и методы.** В статье представлена нанотехнология растепления многолетнемерзлых грунтов паровыми иглами и расчетное обоснование, необходимое для учета возможности работ по растеплению массива грунтов и их дальнейшему закреплению. Расчетное обоснование выполнено на примере строительства транспортного сооружения в г. Норильск, Красноярский край, так как эта область относится к районам Крайнего Севера, где распространенной является проблема повсеместного растепления массива грунтов. Расчетное обоснование выполнено в специализированном программном комплексе MIDAS GTS NX Thermal analysis. **Обсуждение.** В рамках расчетного обоснования была выполнена: верификация расчетных моделей; моделирование существующего диапазона толщин стенок паровой иглы; моделирование существующего диапазона диаметров паровой иглы; моделирование существующего диапазона температур подачи пара в паровую иглу; моделирование двух возможных схем расстановки паровых игл в массиве грунтов; моделирование по определению расстояния между паровыми иглами при их установке в массив грунтов; моделирование по определению времени, необходимого для растепления массива грунтов и их обратного остывания. Выполнен анализ полученных результатов для каждого из этапов расчетного обоснования. Определена оптимальная конструкция паровой иглы (диаметр, толщина стенки, температура подачи пара), схема расстановки игл и расстояние между иглами при их установке в массив грунтов, площадь и объем растепляемого массива грунтов, время растепления и обратного остывания массива грунтов. **Заключение.** В рамках выполненной работы обоснованы конструктивные параметры паровой иглы, включая оптимальный диаметр, толщину стенок и температуру подаваемого пара. Установлено оптимальное взаиморасположение паровых игл и необходимые расстояния между ними для эффективного воздействия на грунт, определены ключевые показатели процесса растепления многолетнемерзлого грунта: сроки, объём и площадь растепления, а также временной интервал возвращения грунтов в исходное мерзлое состояние. Результаты представленной статьи создают основу для проектирования и строительства надежных фундаментов зданий и транспортных сооружений в регионах с распространением многолетнемерзлых грунтов.

КЛЮЧЕВЫЕ СЛОВА: результаты исследований ученых и специалистов; нанотехнологии в строительстве; нанотехнологии; транспортное строительство; многолетнемерзлый грунт; сооружение фундаментов; теплотехника; теплотехнические расчеты; грунты основания; паропрогрев; растепление грунтов

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1. INTRODUCTION

Up to 65% of the area of the Russian Federation is located in permafrost areas, so the work on improving existing and developing new technologies for the construction of foundations in such conditions remains relevant [1].

The northern territories are rich in their natural resources, such as oil, gas and minerals, so in recent years there has been a tendency for their active development. Construction of infrastructure facilities, construction of industrial enterprises and residential complexes requires design solutions that ensure the operational reliability of foundations in the conditions of degradation of permafrost soil massif.

The article presents the nanotechnology of thawing permafrost soils with steam needles for their further consolidation.

Based on the results of the calculation justification, the required temperature of steam supply to the steam needle, the needle diameter, wall thickness, the needle placement scheme, the area of thawing from one and a complex of steam needles, as well as the time of reverse freezing of the soil mass were determined in order to further implement the technology of increasing the bearing capacity of the soil base.

The purpose of the work: to perform a calculation justification of soil thawing with the selection of the necessary design of the steam needle, the scheme of their placement and the time of reverse freezing of the soil mass.

For thawing frozen ground with steam needles, a steam boiler (steam generator), steam pipes, flexible hoses, steam needles with various tips and inventory platforms are used. To produce steam on the construction site, a steam boiler with a capacity of up to 650 kg of steam per 1 hour is installed in a temporary room [9, 11, 12].

To work with steam needles, you should use made of rubber-cloth steam-conducting hoses for supplying saturated steam with a temperature of up to 175°C, designed for working steam pressure up to 800 kPa.

Steam needles are solid-drawn pipes equipped with a tip that is connected to the pipe by a screw thread and has several holes for steam output.

2. REVIEW OF EXISTING AND PROSPECTIVE TECHNOLOGIES FOR FOUNDATION CONSTRUCTION IN PERMAFROST AREAS

Permafrost distribution areas have physical and mechanical properties of the host massif, which significantly differ in a number of characteristics in the frozen and thawed states. Features of the temperature regime and changes in the temperature gradient throughout the year introduce additional requirements to the work production process. This section discusses and analyzes existing and promising technologies for the construction of foundations in the conditions of permafrost distribution.

One of the technologies for constructing foundations on permafrost soils is the construction of deep pile foundations [14].

Foundations constructed according to the second principle are used in areas with a high thickness of the seasonal thawing layer of multi-year permafrost soils. They use driven, drilled and screw piles of various diameters and lengths. They provide the load-bearing capacity of the foundations of buildings and structures due to their support on a rock base located in the thickness of the ground mass. The surrounding frozen ground provides additional friction to the pile surface, which increases the load-bearing capacity. The use of piles as stilts reduces the possibility of deformation of the foundations of structures due to degradation of the surface layers of permafrost soils [2–4].

The advantages of using such foundations include their high load-bearing capacity, resistance to deformations from degradation of the upper layers of permafrost soils. The disadvantages include high costs for the installation of deep piles, difficulties in carrying out work in remote and hard-to-reach areas, associated with the need to attract heavy large-sized equipment. It is also necessary to take into account the increasing layer of permafrost soils that are subject to degradation during the operation of structures.

Shallow foundations are often used as a foundation structure for buildings and structures [7–8].

Shallow foundations are used in cases of shallow occurrence of permafrost soil thickness and low load on the structure and are classified as structures built according to the first principle. Foundations are arranged so that

their sole is below the mark of seasonal thawing of the soil. Such a foundation design is simple in terms of its execution and has a low cost of implementation.

The main disadvantage of shallow foundations is the possibility of excessive deformations as a result of degradation of permafrost soils and an increase in the thickness of the thawed soil layer of the base.

Thermal stabilization involves the use of special technical solutions aimed at maintaining a constant low temperature of the soil mass around the foundation, by cooling the soil with special heat pumps. This makes it possible to avoid undesirable thermal effects caused by the operation of buildings and structures and the degradation of permafrost.

Thermal stabilization allows you to maintain the frozen state of the soil mass and increases the service life of the structure.

The disadvantages of this method include the need for maintenance of the equipment used, energy consumption for the operation of the cooling system, as well as the possibility of thawing of the soil mass of the base in the event of a prolonged power outage of the cooling system.

The use of waterproofing membranes and modern thermal insulation materials reduces heat transfer to the ground mass, preventing the processes of active ice melting. These measures help to improve the reliability of foundations. The technology does not take into account the influence of changing climatic conditions and soil thawing due to rising ambient temperatures.

Existing methods and methods of foundation construction under permafrost conditions do not take into account permafrost thawing. Foundations constructed according to the first principle have a reduced load-bearing capacity, as well as excessive sedimentary deformations associated with changes in the physical and mechanical characteristics of soils. Foundations based on the second principle provide the necessary load-bearing capacity in the conditions of permafrost degradation, but require high economic costs. It is necessary to improve technologies for building foundations of structures in the conditions of permafrost spreading and their active thawing.

3. ACCEPTED CONDITIONS FOR THE CALCULATION JUSTIFICATION

The calculation justification is based on the example of the construction of a transport structure in Norilsk, Krasnoyarsk District, since this region belongs to the Far North, where the problem of wide spread thawing of the soil masses widespread.

Norilsk is located in a subarctic climate zone, which indicates low temperatures most of the year, frequent exposure to Arctic air masses, little sunlight, and low relative humidity, which increases the perception of cold [6].

The average monthly negative temperature is observed from October to May. The snow cover lasts from 7 to 9 months a year. The temperature is above zero from June to September, the maximum monthly average temperature was observed in July and was +14.3 °C.

The average annual air temperature in Norilsk is –9.6 °C, the annual course of absolute temperatures is 85 °C. The average annual relative humidity is about 76 % (Table 1).

The geological structure of the territory accepted for modeling includes Upper Quaternary and modern soils, lacustrine and alluvial deposits of the Ayakli layer, and igneous rock soils – basalts of the Lower Permian and Upper Triassic, undifferentiated [18–19].

The geocryological conditions of the survey area are characterized by the spread of a continuous permafrost layer with a thickness of more than 100.0 m in the mountainous part and an intermittent permafrost layer with a thickness of more than 50 meters in the flat part of the territory [20–21].

In accordance with the presented initial data, the following arrangement of layers of individual engineering and geological elements is assumed for the object under consideration:

- GE 1. 3.1.1.1/GE 3.2.1.1. – 3 meters*;
- GE 6.1.1.1/GE 6.2.1.1. – 10 meters*;
- GE 7.1.1.1./GE 7.2.1.1. – 4 meters*.

To perform a set of thermal and geotechnical calculations in a specialized software package, the following

Table 1. Accepted ambient air temperatures

Name of the weather station	Month												Year
	1	2	3	4	5	6	7	8	9	10	11	12	
Monthly and annual average air temperature, °C													
Norilsk	–27.0	–26.5	–21.6	–14.1	–5.1	6.2	14.1	10.7	3.7	–8.7	–21.7	–25.2	–9.6
Absolute minimum air temperature, °C													
Norilsk	–53	–52	–46	–37	–25	–11	0	–3	–14	–38	–48	–52	–53
Norilsk	–2	–1	2	9	15	29	32	28	23	12	7	0	32

* The order in which layers are located from the earth's surface and their thickness.

characteristics of the physical and mechanical properties of soils are accepted:

- Soil density ρ , g/sm³;
- Porosity coefficient e , d. units;
- Compression modulus of deformation of frozen ground E_c , MPa;
- Coefficient from Table 5.1 SP22 moed;
- Modulus of deformation E , MPa;
- Coupling With, kPa;
- Internal friction angle ϕ , deg.
- Poisson's ratio ν ;
- The soil model is Mohr-Coulomb.

The accepted design characteristics of soils are presented in Tables 2, 3.

4. ESTIMATED JUSTIFICATION

As part of the work, a design justification was performed, which includes a set of heat engineering calculations, based on the results of which the temperature of steam supply to the steam needle, the needle diameter, its wall thickness, the needle placement scheme, the area of thawing from one and a complex of steam needles, as

well as the time of reverse cooling of the soil mass pinning them.

The mathematical model of heat transfer in freezing-thawing soils should take into account the variability of climatic conditions, soil structure, features of the nanotechnological scheme, thermal properties, etc. [22].

In the presence of a filtration flow, forced convection can be taken into account by numerically solving the energy transfer equation (Fourier-Kirchhoff) or by replacing it with the Fourier equation with an effective thermal conductivity. The temperature field in thawed unfiltered and frozen soils is determined by solving a Stefan-type problem on heat propagation in a region with an upper mobile boundary [23].

All the presented calculations were performed taking into account the time factor and the influence of atmospheric air with a temperature variable by day and month.

The purpose of the first stage of calculation is to determine the volume of soil thawed by a single steam needle, as well as to determine the necessary parameters of steam needles.

For further verification of the models, a simplified version of the model was performed, which assumes the con-

Table 2. Physical and mechanical properties of soils. Frozen state

GE	Name	P g/sm ³	e	E _c MPa	moed	E MPa	C kPa	Φ Deg.	ν
3.1.2.1	Crushed sandy loam, slightly silty, powdery, hard-frozen, layered cryotexture, plastic in the thawed state	20	0.64	17.2	2.5	43	177	25	0.35
6.1.1.1	Pebble sandy loam, highly silty, powdery, plastic-frozen, layered cryotexture, flowing in the thawed state	16.6	0.9	6.438	1.4	6.5	19.3	46.6	0.35
7.1.1.1	Crushed soil with clay placeholder up to 40% (placeholder: non-icy sandy loam, powdery, solid when thawed), brownish-gray, hard-frozen, crusty-crystal	cryotexture 21.1	0.48	35.5	2.8	99.4	72.4	42	0.3

Table 3. Physical and mechanical properties of soils. Thawed state

GE	Name	P g/sm ³	e	E _c MPa	moed	E MPa	S kPa	Φ Deg.	ν
3.1.2.1	Crushed sandy loam, slightly silty, powdery, hard-frozen, layered cryotexture, plastic in the thawed state	20.8	0.67	–	–	53.3	15	37	0.3
6.1.1.1	Pebble sandy loam, highly silty, powdery, plastic-frozen, layered cryotexture, fluid in the thawed state	16.6	1.24	–	–	13.2	9	17	0.35
7.1.1.1	Crushed soil with clay aggregate up to 40% (placeholder: sandy loam non-icy, powdery, solid in the thawed state), brownish-gray, hard-frozen, crusty-crystal	cryotexture 21.1	0.48	–	–	43.5	11	42	0.3

dition of heat transfer and thawing only from the steam needle nozzle, without taking into account the thawing of the soil from heating its walls.

The second developed model is more accurate, as it takes into account the thawing and heat transfer not only through the needle nozzle, but also from its walls.

The appearance of the developed spatial planar models for performing thermal engineering calculations is shown in Fig. 1.

Based on the results of the performed thermal engineering calculations, the area of thawing at the end of the needle from the nozzle is determined, which is shown in Figs. 2, 3.

Based on the presented results, we can conclude that two independent computational models converge.

According to the calculation results, the maximum thawing zone from the nozzle of one steam needle is 0.3×0.3 m (at a depth of 6.0 m).

After verification of the calculation models, we proceed to the selection of the optimal design of the steam needle and the steam supply temperature.

To perform the calculation for selecting the required wall thickness of the steam needle, its diameter and the steam supply temperature, an updated model from the first stage of calculations was adopted.

To perform the calculation, independent thermal engineering models are used, each of which simulates a different wall thickness of the steam needle. The diameter of the steam needle is constant and assumed to be 50 mm. The steam supply temperature is constant and is 170°C . For calculations and subsequent comparison, the following steam needle wall thicknesses are modeled: 1.5 mm, 2.0 mm, 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm, 5.0 mm, 5.5 mm, 6.0 mm.

Based on the results of calculations, similar results were obtained Fig. 3. After analyzing the calculated mod-

els, all the results obtained were summarized in the general Table 4, the summary chart and graph presented in Figs. 4, 5.

Analyzing the results obtained, the above diagram and graph, we can conclude that the wall thickness of the steam needle affects the size (depth) of the steam needle thawing zones from the side surface of the needle. The maximum depth of thawing is achieved when using needles with a wall thickness of 1.5 and 2.0 mm. Of the proposed options, the needle with a wall thickness of 2.0 mm has become the most widely used in practice, since needles with a wall thickness of a smaller value require the use of special equipment on the construction site and additional monitoring of the needle crushing process. Based on this, for further calculations, the wall thickness of the steam needle is assumed to be 2.0 mm.

To perform calculations for selecting the required steam needle diameter, separate heat engineering models are used, each of which simulates a steam needle of a certain diameter. Based on the results of the calculations, the optimal wall thickness of the steam needle is assumed to be 2.0 mm, and the steam supply temperature remains constant – 170°C . For calculations and subsequent comparison, steam needles of the following diameters are modeled: 20.0 mm, 30.0 mm, 40.0 mm, 50.0 mm, 60.0 mm.

Based on the results of calculations, the results obtained were summarized in Table 5, and a diagram and graph of the distribution of thawing parameters were constructed, presented in Figs. 6, 7.

The maximum thawing zone from the needle nozzle is achieved when using a steam needle of the largest diameter – 60.0 mm. Therefore, for further calculations, the steam needle diameter is assumed to be 60.0 mm.

To perform calculations for determining the required temperature of steam supply to the steam needle, a previ-

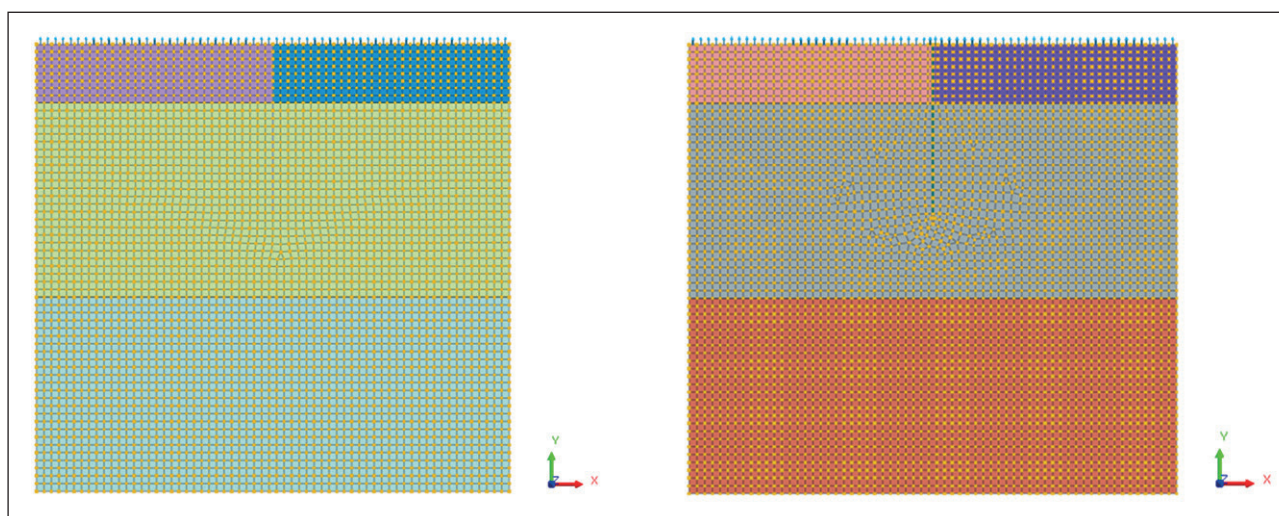


Fig. 1. Simplified finite element model (left) and refined finite element model (right)

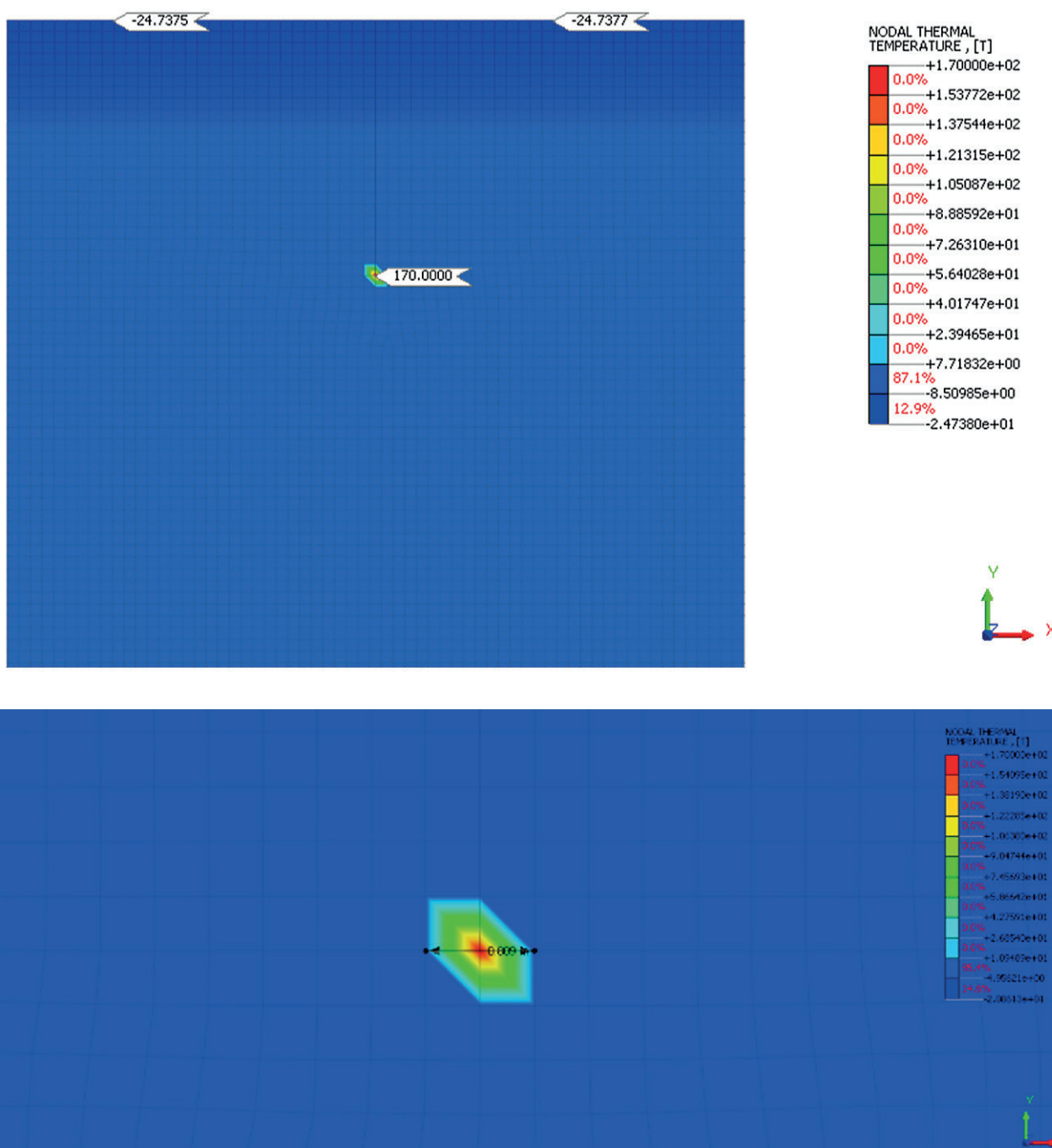


Fig. 2. Simplified model. The stage after installing the needle and thawing the soil. The first 30 days of well operation. Winter period

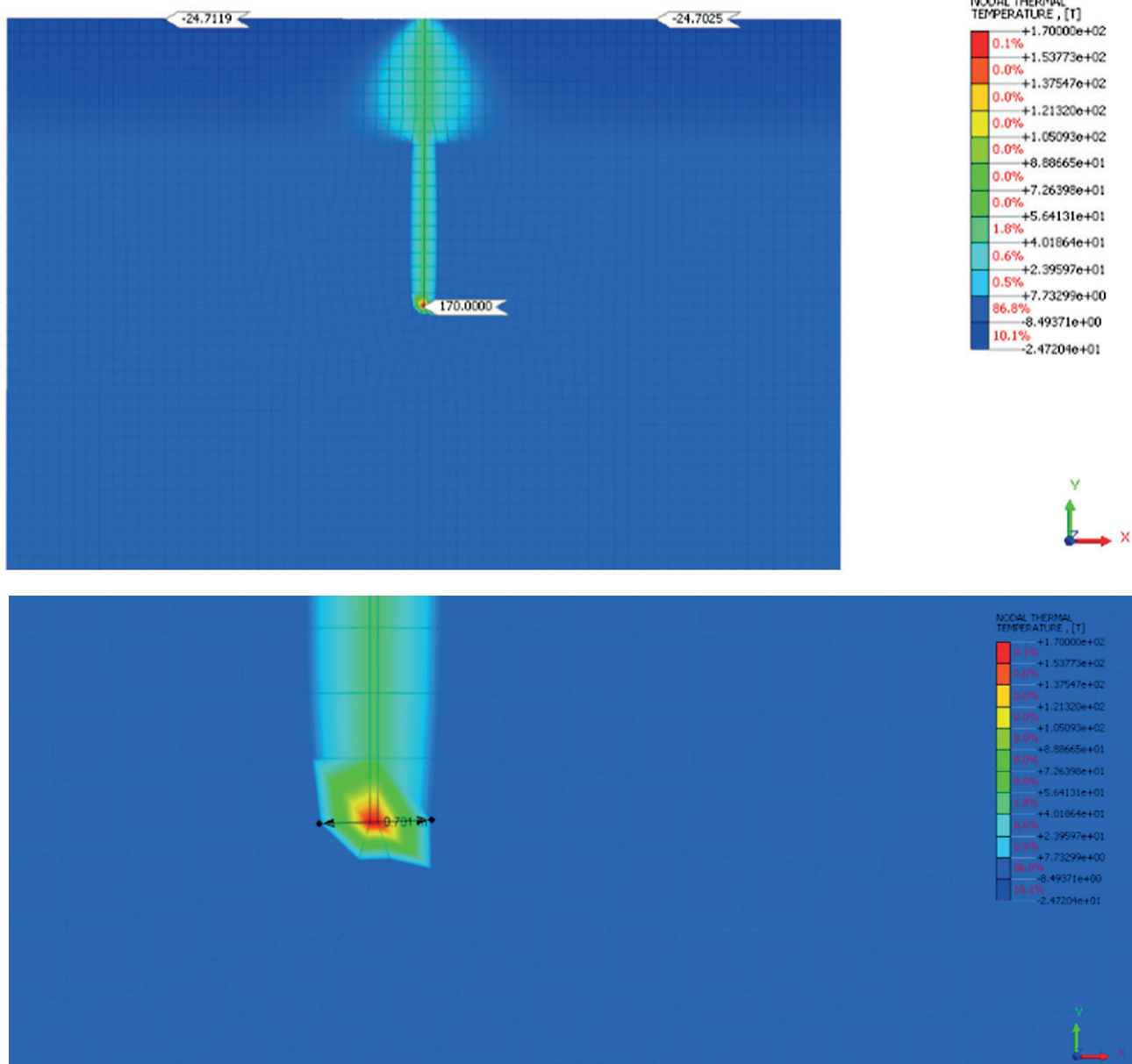


Fig. 3. Updated model. The stage after installing the needle and thawing the soil. The first 30 days of well operation. Winter period

Table 4. Calculation results for determining the optimal wall thickness of a steam needle

Parameter name	Wall thickness, mm									
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Size of the heated area from the needle nozzle, m	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3	0.3×0.3
Depth of thawing from the side surface of the pile, MMG zone, m	0.405	0.405	0.404	0.404	0.403	0.403	0.403	0.402	0.402	0.402
Size of the thawed zone in the area of annually thawed-frozen soils, m	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41

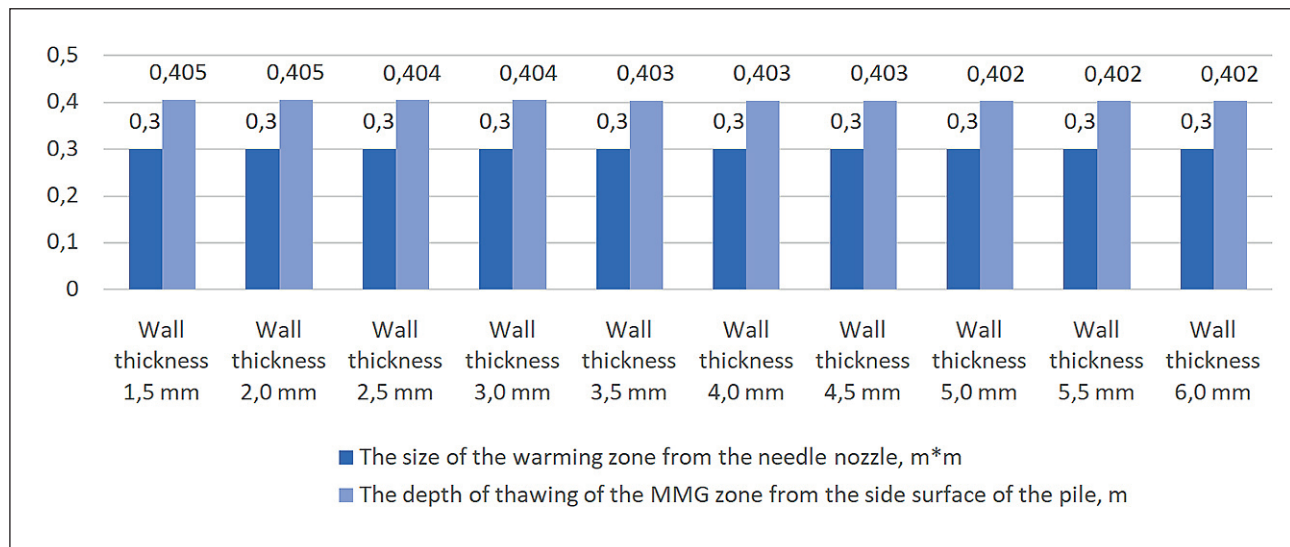


Fig. 4. Diagram of the distribution of thawing parameters depending on the wall thickness of the steam needle

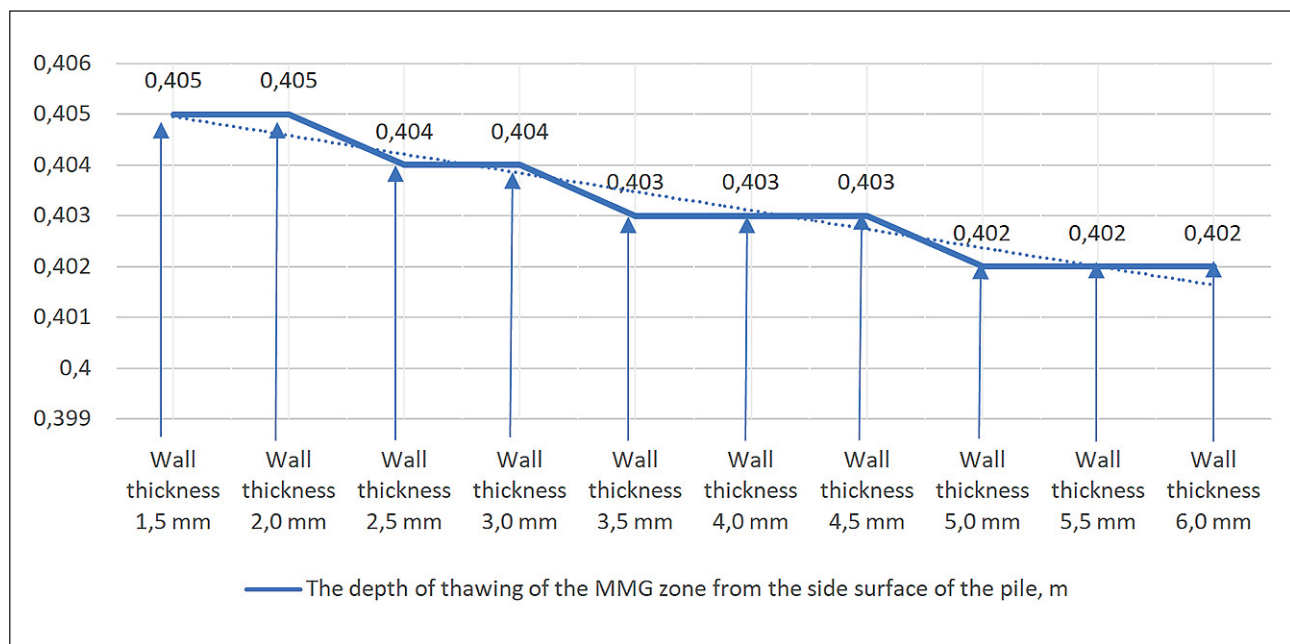


Fig. 5. Graph of the dependence of the frost zone thawing depth on the wall thickness of the steam needle

Table 5. Calculation results for determining the optimal steam needle diameter

Parameter name	Needle diameter, mm				
	20.0	30.0	40.0	50.0	60.0
Size of the heating zone from the needle nozzle, m	0,193×0,193	0,206×0,206	0,218×0,218	0,238×0,238	0,250×0,250
Depth of thawing from the side surface of the pile, MMG zone, m	0.1	0.1	0.1	0.1	0.1
Size of the thawing zone in the area of annually thawed-frozen soils, m	1.32	1.32	1.32	1.32	1.32

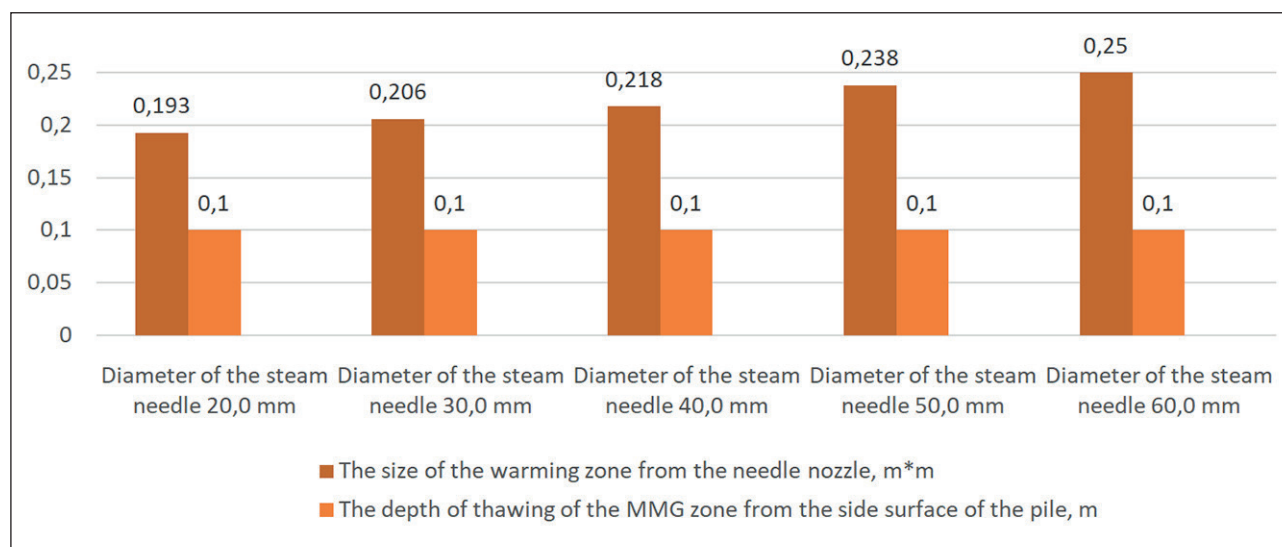


Fig. 6. Diagram of the distribution of thawing parameters depending on the diameter of the steam needle

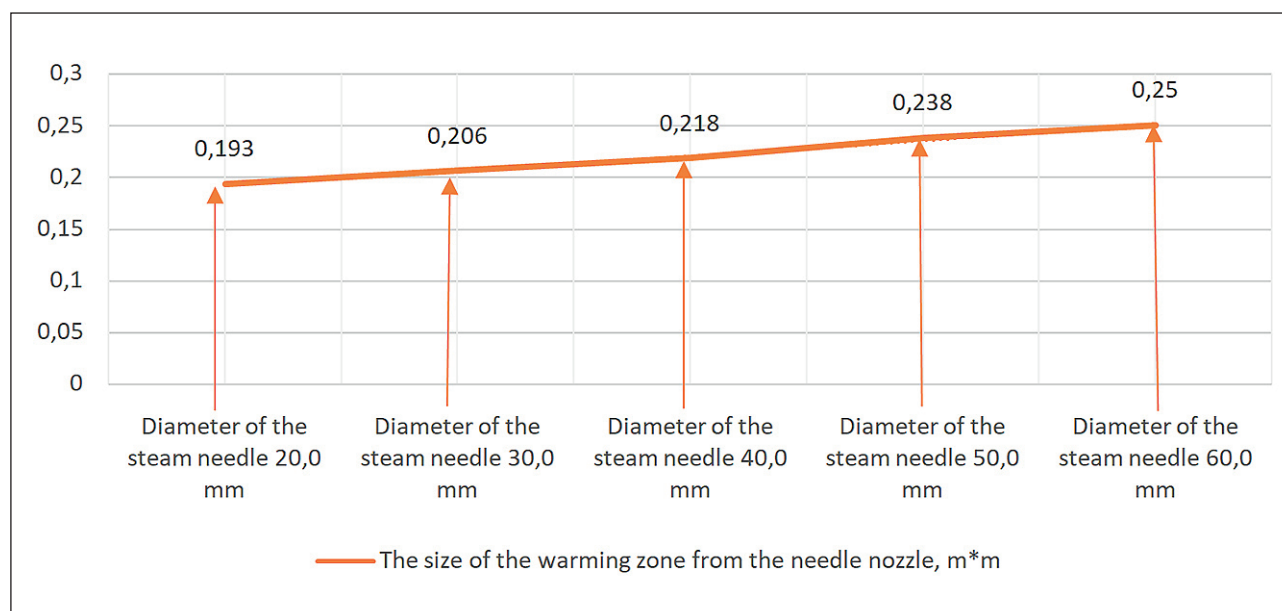


Fig. 7. Graph of the dependence of the size of the thawed zone on the diameter of the steam needle

ously developed heat engineering model is used, in which a certain temperature of steam supply is set for each of the considered cases.

The following design of the steam needle is accepted: diameter – 60.0 mm, wall thickness – 2.0 mm. For calculations and subsequent comparison, the initial steam temperatures are modeled: 100, 120, 140, 160, 170 °C.

Based on the results of calculations performed for each of the heat engineering models, the results were obtained, which are presented in general form in Table 6, as well as a diagram and graph of the distribution of the main parameters of thawing, presented in Figs. 8, 9.

The maximum melting zone of the array from the steam needle nozzle is reached at a steam supply temperature of 160–170 °C. However, an analysis of the practice of soil thawing shows that the use of the maximum possible steam temperature of 170 °C requires the use of high-precision equipment, complete elimination of possible steam leakage and shortcomings in the insulation of steam pipelines. When the temperature decreases to 160 °C, the melting zone of the soil mass does not change and is 0.250 m at a steam temperature of 170 °C to 0.247 m at a steam temperature of 160 °C.

For further calculations, the following design of the steam needle is accepted: the diameter of the steam needle

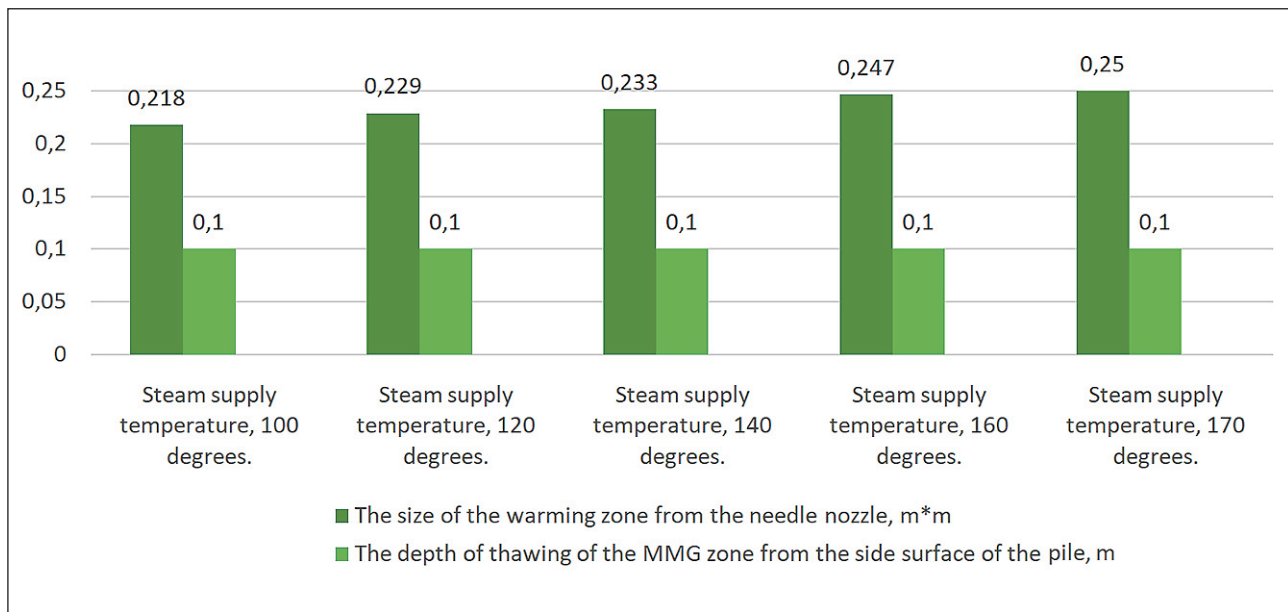


Fig. 8. Diagram of the distribution of thawing parameters depending on the steam supply temperature

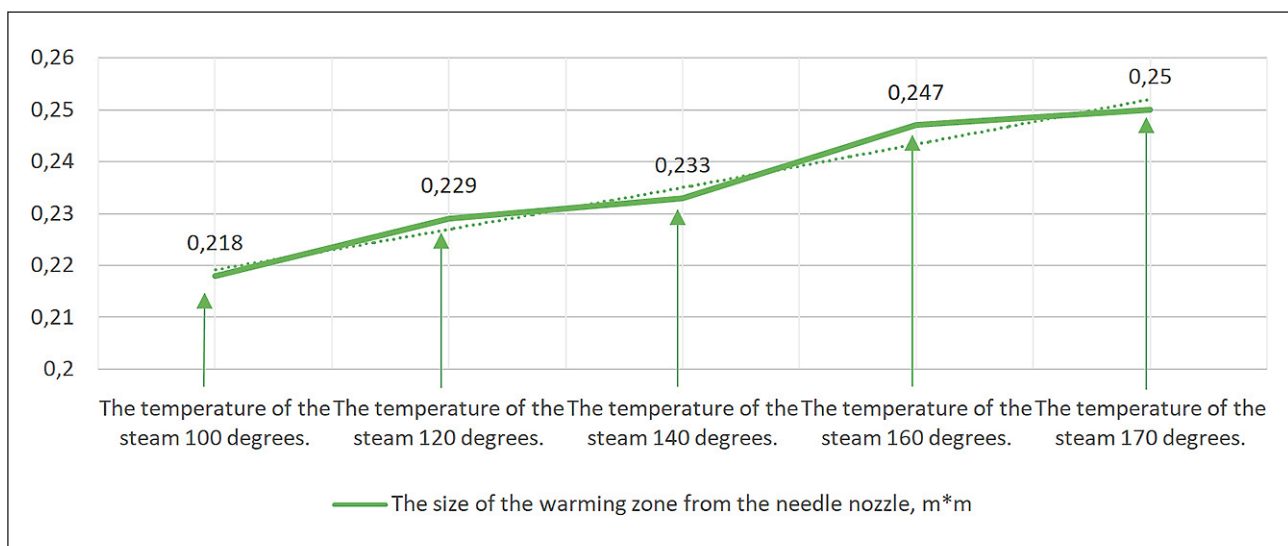


Fig. 9. Graph of the dependence of the size of the heating zone on the temperature of the steam supply to the steam needle

Table 6. Calculation results for determining the optimal steam supply temperature

Parameter name	Steam supply temperature, °C				
	100	120	140	160	170
Size of the heating zone at the end of the needle from the nozzle, m	0.218×0.218	0.229×0.229	0.233×0.233	0.247×0.247	0.250×0.250
Depth of thawing from the side surface of the pile, MMG zone, m	0.1	0.1	0.1	0.1	0.1
Size of the thawing zone in the area annually thawing-freezing soils, m	1.32	1.32	1.32	1.32	1.32

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is 60.0 mm, the wall thickness is 2.0 mm; the steam supply temperatures are 160 °C, the distance between the steam needles is 0.5 m, and two heat engineering models are used:

- with a rectangular arrangement of needles.
- with a “checkerboard” arrangement of needles – with the displacement of one row of needles relative to another.

The appearance of the developed heat engineering models is shown in Figs. 10–13.

Both calculation models are performed in the spatial formulation of the problem, taking into account the effect of atmospheric air with a temperature variable by day and month. The calculations were performed taking into account the time iteration with the results recorded

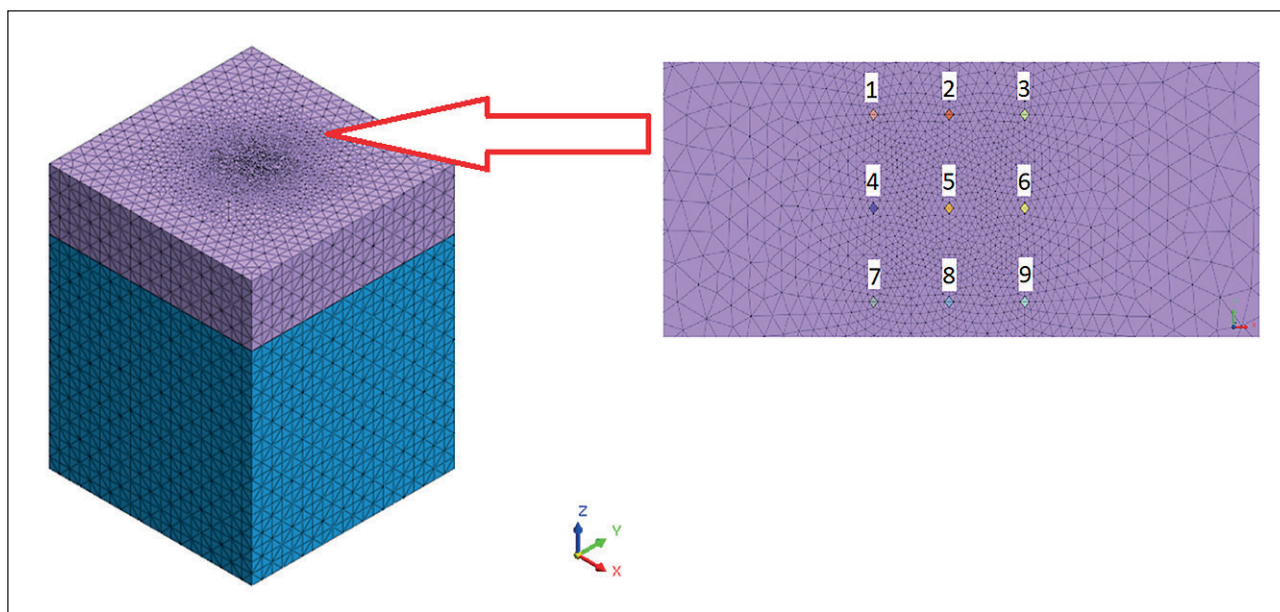


Fig. 10. A finite element model with a rectangular arrangement of needles without their displacement

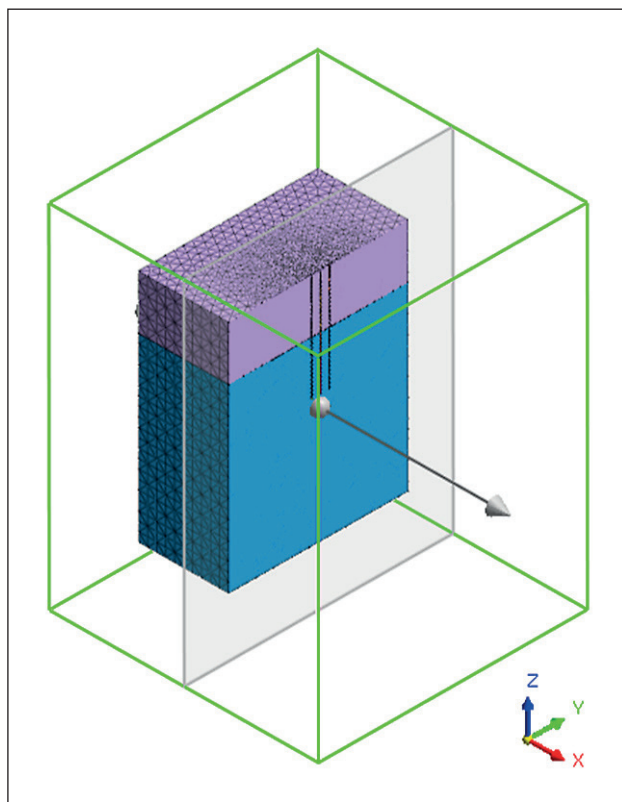


Fig. 11. Finite element model with a rectangular arrangement of needles without their displacement with a depth of 6 m

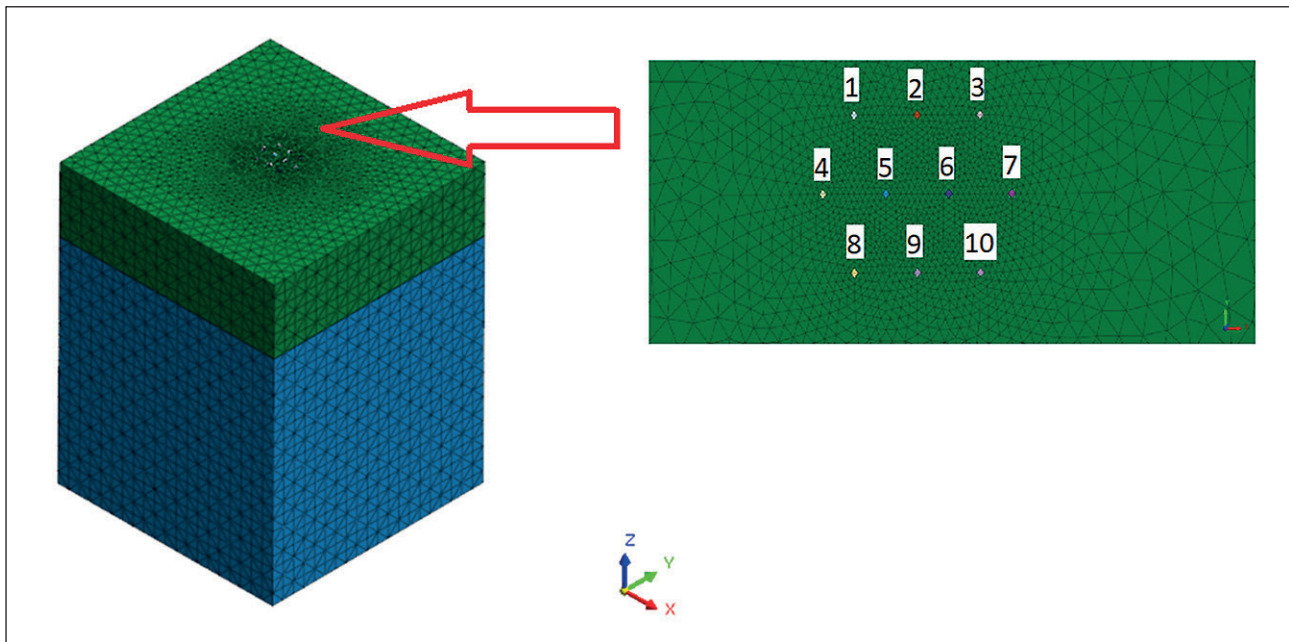


Fig. 12. A finite element model with a “checkerboard” arrangement of needles with the displacement of one row of needles relative to another

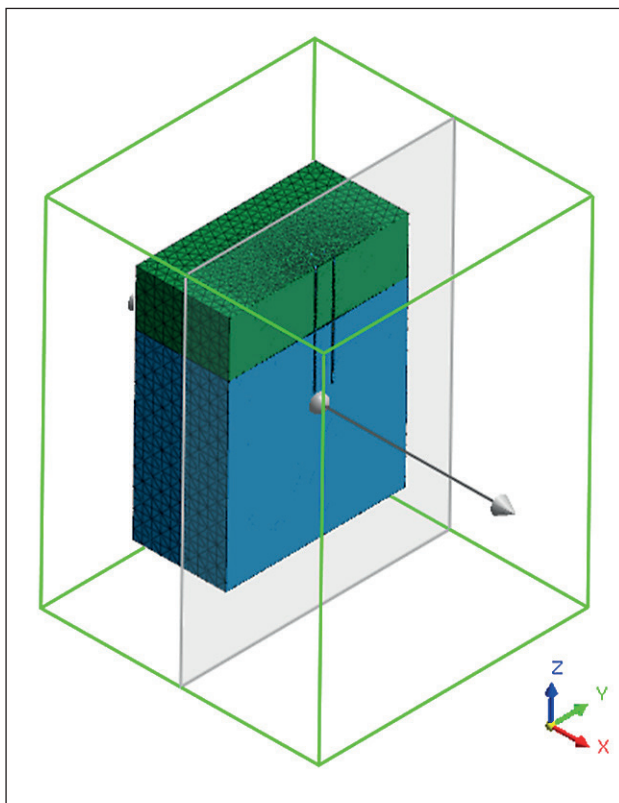


Fig. 13. Finite element model with a “checkerboard” pattern of needle placement with a displacement of one row of needles relative to another with a depth of 6 m

for each day. The results of the calculations are shown in Figs. 14, 15.

To compare the calculation results obtained, we will determine the size of the thawed soil zone at the level of – 6.0 m from the earth’s surface (Figs. 16, 17).

The area of soil thawed by a single steam needle for a model with a “staggered” needle arrangement (with one row of needles shifted relative to another):

$$2.43 \text{ m}^2 / 10 \text{ pieces} = 0.243 \text{ m}^2.$$

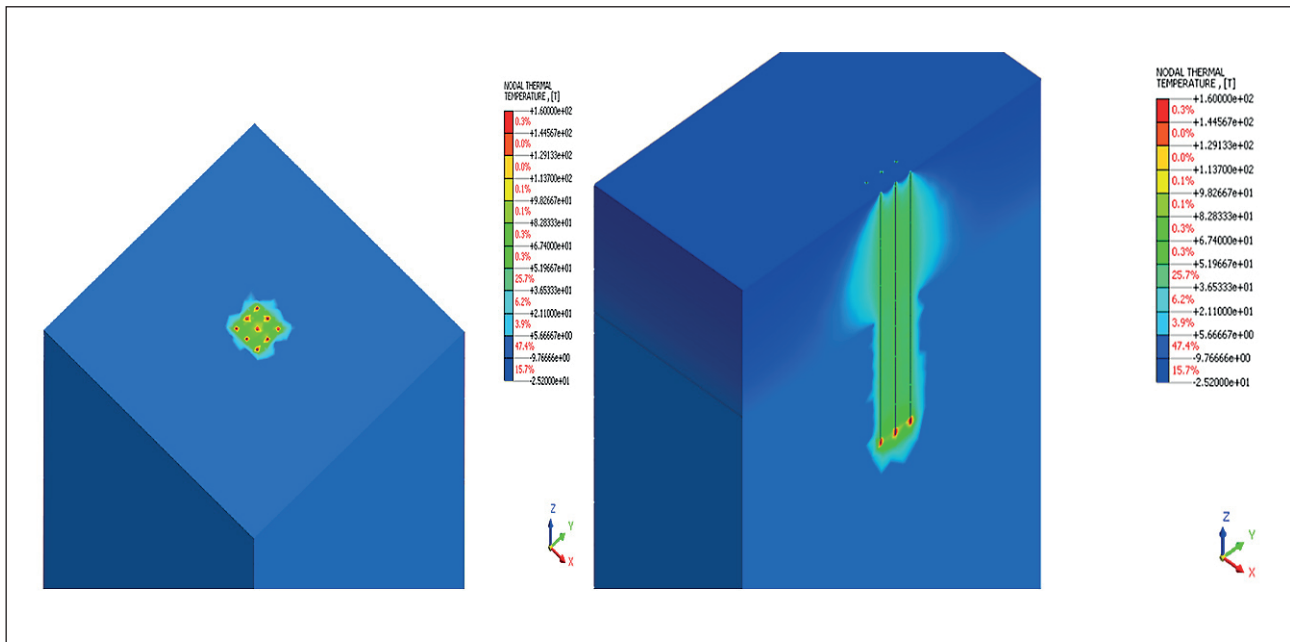


Fig. 14. A model with a rectangular needle arrangement (no offset). Stage – 10 days of steam needle operation

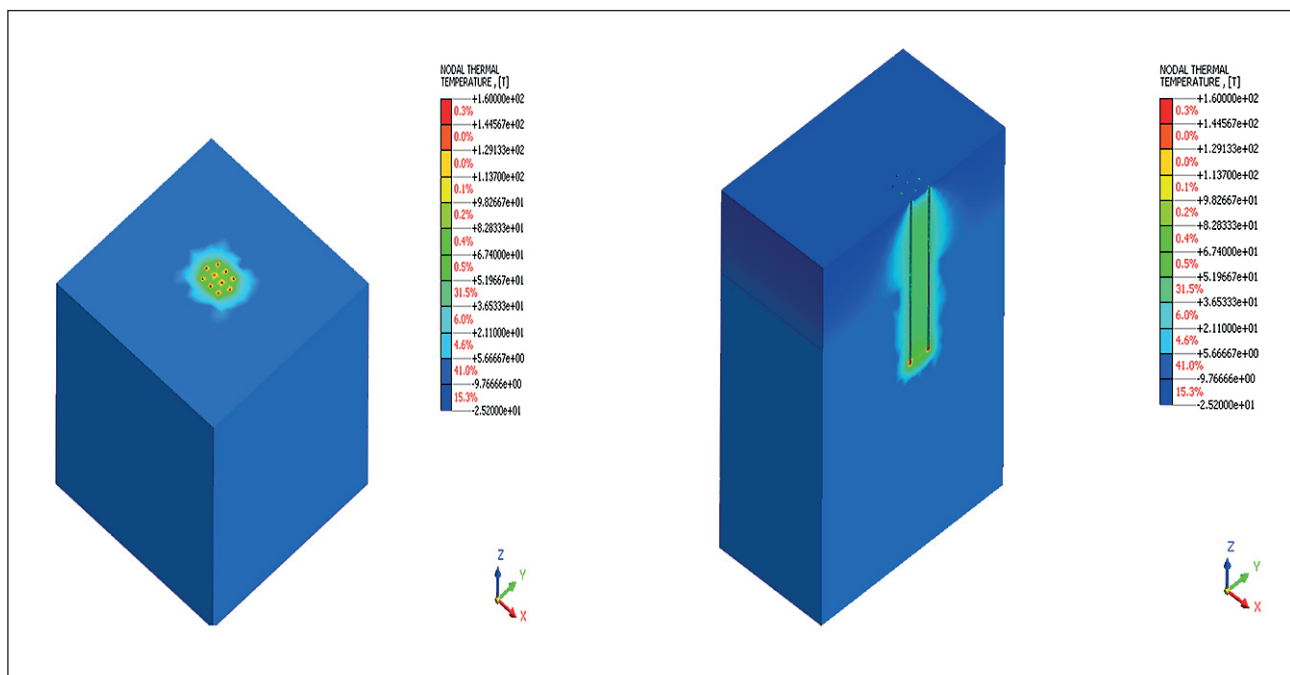


Fig. 15. A model with a “staggered” needle arrangement (with one row of needles shifted relative to another). Stage – 10 days of steam needle operation

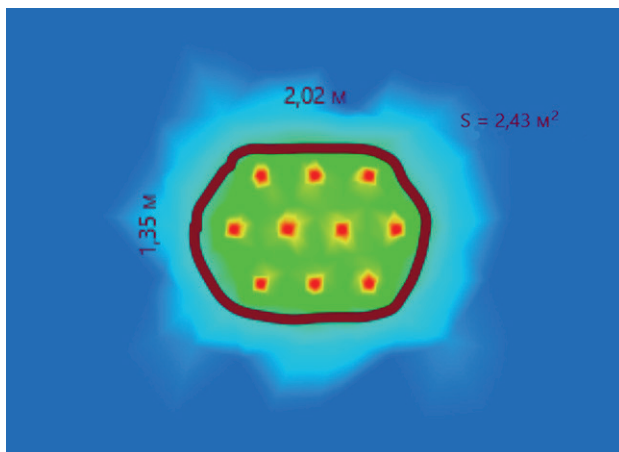


Fig. 16. A model with a “staggered” needle arrangement with one row of needles shifted relative to another. The soil thawing zone is 2.02×1.35 m. The area of the thawing zones 2.43 m²

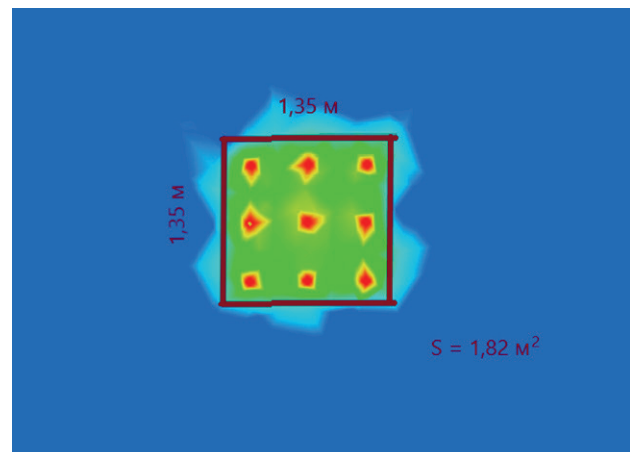


Fig. 17. A model with a rectangular arrangement of needles. The soil thawing zone is 1.35×1.35 m. The area of the soil thawing zone is 1.82 m²

Table 7. Results of calculations performed for selecting the optimal distance between steam needles and comparing the placement schemes of steam needles

Layout of steam needles	Number of steam needles in the model, pcs	Area of thawed soil, m ²	Area of thawed soil per steam needle, m ² /pc.	Depth of thawed soil below the steam needle mark, m
Model with a rectangular needle arrangement (without displacement)	9	1.82	0.202	0.37
Model with a «staggered» needle arrangement (with displacement of one row of needles relative to another)	10	2.43	0.243	0.36

Model with a rectangular needle arrangement (no offset):

$$1.82 \text{ m}^2 / 9 \text{ pieces} = 0.202 \text{ m}^2.$$

The results obtained show that the mass of thawed soil remains undisturbed, and there are no inclusions of frozen soil. The time required for thawing the soil mass is 10 days from the moment the steam needles are put into operation.

To perform the calculation for determining the time of return to the initial frozen state, a heat engineering model with a “checkerboard” arrangement of needles is used.

Modeling of ground cooling was performed after the stage-by-stage installation of steam needles, their work on soil thawing and disconnecting the needles with subsequent removal from the array. The results of the calculations are shown in Figs. 18–21.

Table 8. Results of calculations for reverse freezing of the soil mass

Stage	Maximum temperature, °C	Size of the thawed zone, m	Thawing contour
Stage after switching off the steam needles (ground freezing). 10 days after switching off the needles	25.98	1.7×1.3	Contour is not broken
Stage after switching off the steam needles (ground freezing). 20 days after switching off the needles	11.59	1.5×1.2	Contour is not broken
Stage after switching off the steam needles (ground freezing). 30 days after switching off the needles	3.62	1.2×1.0	Contour is not broken
Stage after switching off the steam needles (ground freezing). 40 days after switching off the needles	-0.97	-	No contour, complete freezing

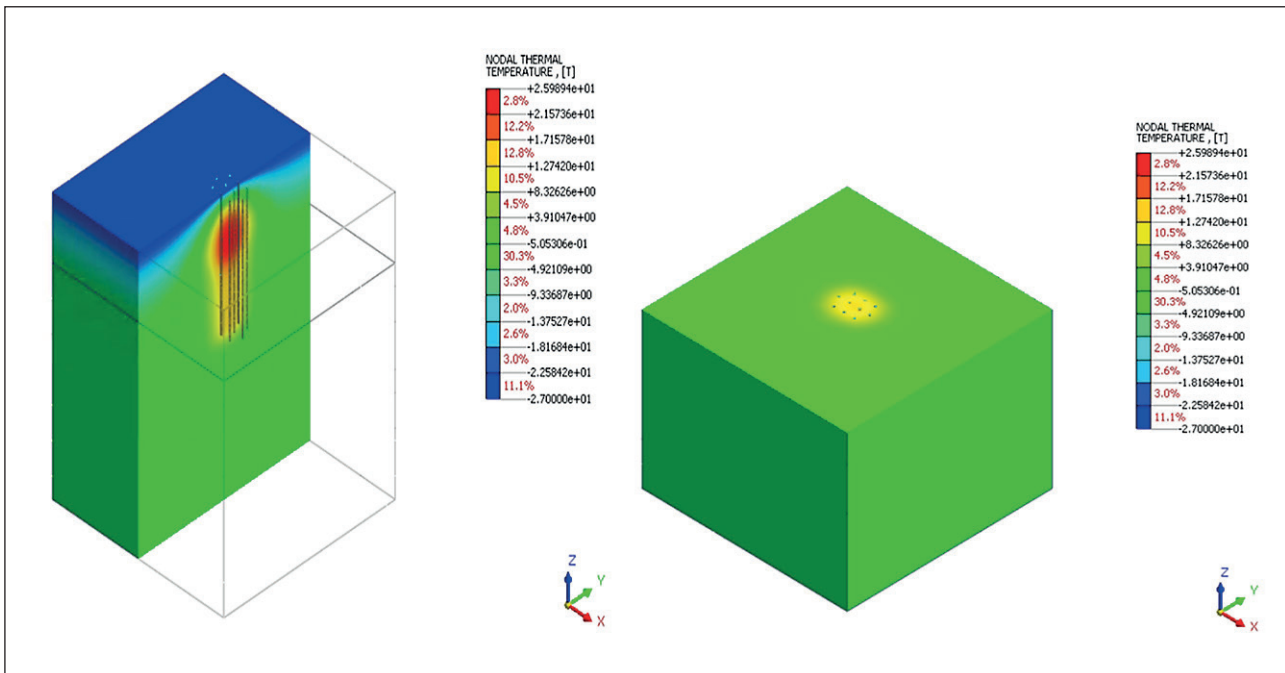


Fig. 18. A model with a “checkerboard” arrangement of needles with their displacement. Stage – 10 days from the moment of switching off the steam needles

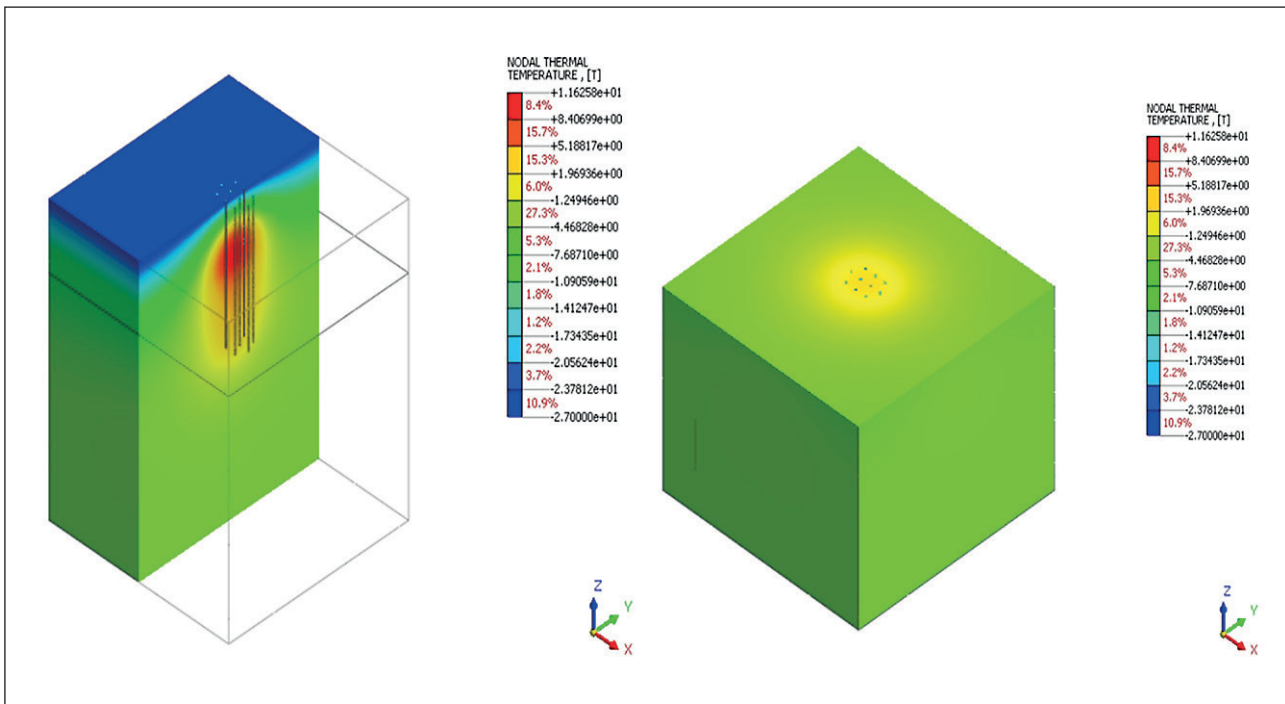


Fig. 19. A model with a “checkerboard” arrangement of needles (with an offset). Stage – 20 days from the moment of switching off the steam needles

The result of calculations for determining the time of soil return to its original frozen state shows that complete freezing of pre-thawed soils occurs 30 days after the steam needles are turned off and removed.

5. CONCLUSION

1. As a result of the calculation, the optimal design of the steam needle, its diameter, wall thickness and steam supply temperature were determined.

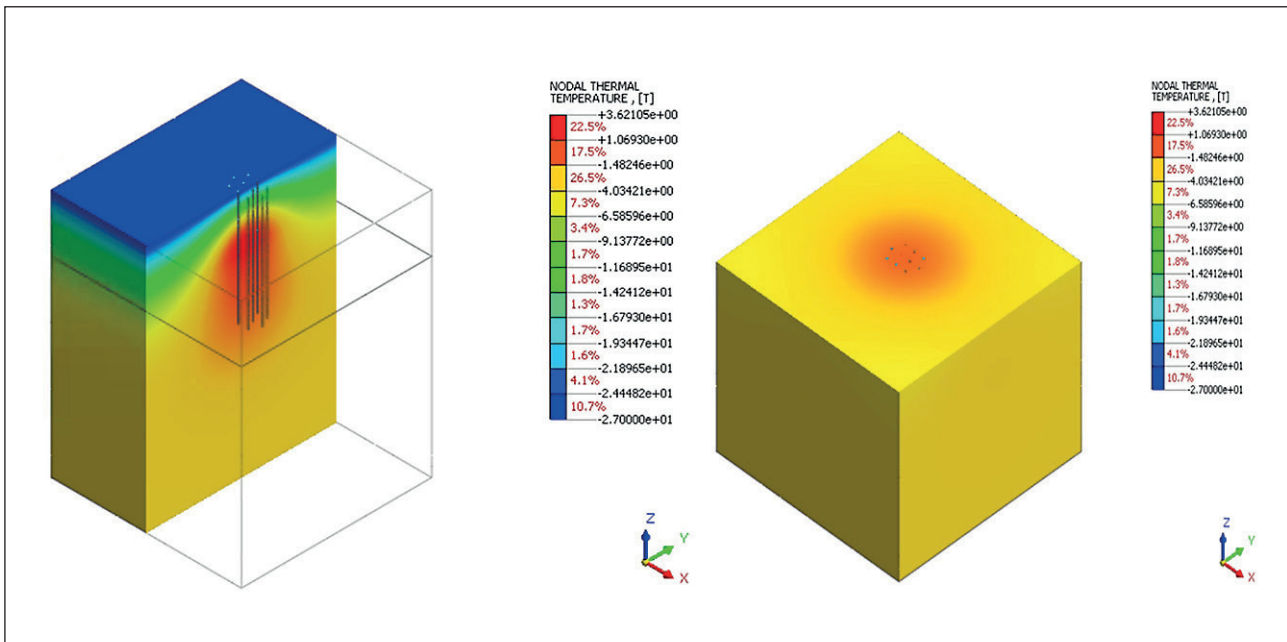


Fig. 20. A model with a “checkerboard” arrangement of needles (with an offset). Stage - 30 days from the moment of switching off the steam needles. Section along the Y-axis

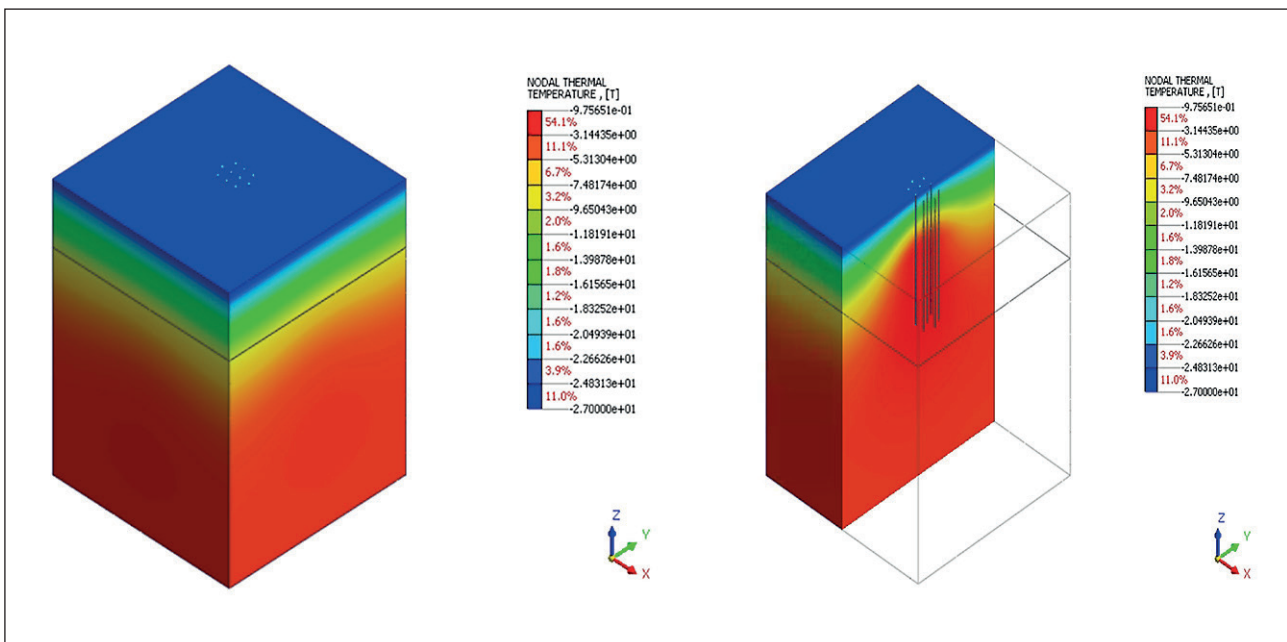


Fig. 21. A model with a “checkerboard” arrangement of needles with their displacement. Stage – 40 days from the moment of switching off the steam needles. Section along the Y-axis

2. The required distance between the steam needles and their placement is determined.

3. The term, area, volume of permafrost to be thawed and the time for the soil to return to its original frozen state have been determined.

4. The results of the work performed will allow us to consider the possibility of constructing foundations of buildings and transport structures in permafrost conditions using the proposed nanotechnology.

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ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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A.I. Panchenko – idea; scientific guidance; research concept; final conclusions.

I.A. Galaburda – search for material; processing of source materials; revision of the text.

A.V. Kendyuk – processing of source materials; scientific text editing.

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