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Thermal Stabilization of Permafrost Using Thermal Coils Inside Foundation Piles

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Abstract

The article deals with the issue of thermal stabilization of soils to preserve the stability of pile foundations in permafrost conditions. The purpose of the work is to develop a technology for year-round freezing of soils by supplying coolant cooled by a refrigeration machine to thermal elements placed inside piles. In this work, the temperature regime of the system "pile foundation – soil" in the stationary formulation of the problem was simulated, and the influence of the depth of placement of thermal elements inside the piles on the soil temperature was investigated. The simulation was performed in the COMSOL software environment, taking into account the heat transfer due to thermal conduction and convection. In the presented model, a platform is fixed on piles, and a heat source is placed on the platform. It is found that an area of thawed soil has formed on the leeward side of the pile foundation. It is concluded that, under certain conditions, deep thermal elements for freezing or keeping the soil frozen should be placed at different depths. Thus, under given conditions, a greater depth of the thermal element placement in the pile, closest to the soil thawing zone, allows to reduce the surface temperature of the pile below ground level and, therefore, increase its bearing capacity. The authors also propose an original unit for soil thermostabilization based on the absorption cooling machine, which can operate at the expense of thermal energy generated by technological sources located on the platform.

Keywords: Frozen Soil; Chiller; Cooling Machine; Refrigerant; Heat Exchanger; Tube; Coolant Circulation; Thawing; Ground.

1. Introduction

The search, extraction, and processing of resources is one of the global tasks that mankind is addressing in the interests of sustainable development [1, 2]. Today and in the coming decades, despite the rapid development of renewable energy [3], it is impossible to meet the energy needs of mankind without fossil fuels [4, 5]. Russia plays one of the leading roles in ensuring the supply of energy resources to world markets, with permafrost occupying about 65% of the country's territory and a significant part of mineral deposits concentrated in the Russian Arctic [6–8]. The integrated development of the Arctic is not an easy task in terms of maintaining the sustainability of infrastructure and the energy costs of economic activity [9–11].

Pile foundations are a reliable solution for construction in permafrost [12–14]. The stability of the pile foundations of buildings and structures resting on permafrost depends on many parameters, the most important of which is the soil temperature [15–17]. The strength of soil decreases as the temperature rises, which leads to a decrease in the bearing capacity of foundations, deformations, and destruction of infrastructure [18–20]. On the contrary, a decrease in the soil temperature leads to an increase in the bearing capacity of foundations, which makes it possible to achieve an economic effect.

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To ensure the stability of structures and the safety of people, various measures for soil thermal stabilization are envisaged. The main method is the construction of a ventilated basement. However, when constructing a ventilated basement in the absence of other thermal stabilization measures, the calculated values of the soil temperature field, at which the transfer of loads to the foundation becomes possible, take up to 5-8 years [21]. Another widely used method of soil cooling is the use of vapor–liquid thermal stabilizers [22–24]. The most widespread in the Russian Arctic are vertical two-phase naturally convective thermosiphons of small diameter (25–40 mm) with an evaporator up to 10-15 m long and a finned condenser, usually up to 1.5 m long. However, the design of thermal stabilizers can be different in both underground and aboveground parts [25, 22]. For example, Figure 1a shows a heat exchanger with a condenser section of six heat exchangers. There are systems with aboveground condensers cooled by fans and more complex systems with horizontal or vertical evaporators in the underground part. However, in the conditions of global climate change [26–28], the development of new technical solutions for soil freezing becomes an urgent task. Such methods include systems with cold air convection in trenches [29] or inside piles [30], systems with convection of other working fluids such as CO_2 [13], thermal insulation or shielding [30–32], and the use of various types of cooling machines, including those powered by renewable energy sources (Figure 1-b) [30–34]. In this connection, the possibility of using absorption cooling machines, which require heat rather than electrical energy, is especially attractive [35, 36]. As a disadvantage of absorption thermal stabilization systems, the need for a pump to supply the absorbent solution can be highlighted, so the need for electricity, although much less, remains [37].

(a) (b)

Figure 1. a) vapor-liquid thermostabilizer recharging with refrigerant [25], b) refrigeration machine connected to soil thermostabilizers [22]

Some studies have been devoted to the thermal stabilization of the soil. For example, Kong et al. [28] present a relatively new method, based on calculating the heat balance at the embankment – soil boundary, which makes it possible to estimate permafrost degradation. The main type of heat transfer was heat conduction. Numerical simulation was performed using the SVHeat geothermal simulation software package. Fontaine et al. [20] present an analytical model for calculating horizontal soil heat exchangers used for simultaneous soil cooling and heat extraction. The model is applicable in cases where there is no seasonal freezing and thawing of the soil due to the nonlinearity introduced by phase transitions. A characteristic feature of the above studies is the absence of sources of thermal pollution, and, therefore, the consideration of heat conductivity as the main type of heat transfer. At the same time, the results of our study showed that the presence of a technological source of thermal energy on the platform leads to the thawing of the upper soil layer as a result of heat transfer due to convection.

It is noted in Loktionov et al. [33] that much of the research is devoted to refining models for calculating the thermal state of the soil, but another important area of research is the development of new innovative methods of permafrost cooling. For example, in Hu et al. [38], a thermal stabilization method was proposed and investigated that involves the use of a compressor refrigeration machine powered by photovoltaic panels. A small pilot unit was successfully tested, where R600A refrigerant was fed into a spiral heat exchanger from a copper tube enveloping a 3-meter long evaporator section. Like any other method, this one has limitations: despite the creation of an autonomous device, it requires a power source for its operation, and the stability of electricity generation by a photovoltaic panel in the long-term absence of the sun, snowfall, etc. is not guaranteed. In Moiseev et al. [39], it is proposed to use an absorption refrigeration machine for thermal stabilization of the soil, and tanks are provided with heat storage and cold storage material. The entire interior of the piles is also part of a closed cooling circuit. No numerical or in-situ simulation results have been reported to date.

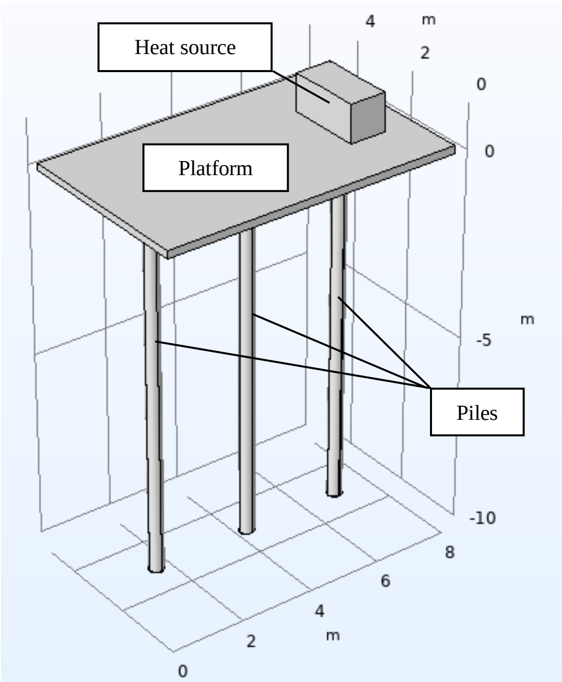
The purpose of this article is to model the process of thermal stabilization of the soil adjacent to the foundation piles by feeding the refrigerant cooled by a refrigeration machine to the thermal elements. In this case, thermal elements are typically located at different depths within the piles. This purpose of this project is to develop a design specification for a low-capacity absorption chiller adapted to soil thermal stabilization tasks.

2. Materials and Methods

The object of the study is the system "pile foundation – soil". The foundation is a platform fixed at a height of 2 m above the ground on three piles located in the same plane. The basic geometric parameters of the pile foundation are shown in Table 1. Thin-walled thermal elements in the form of spirals (thermal coils) are installed inside the piles. The distance between the thermal coils and the inner wall of the pile is 20 mm. The inside of the piles is filled with a liquid agent up to ground level to improve heat transfer. The upper part of the inner space of the piles is occupied by air. The cooled refrigerant is supplied to the thermal coils. The inlet pipes of these coils below ground level (on the vertical part) are covered with tight-fitting thermal insulators. An object with a thermal radiation capacity of 10 kW is installed on the platform. A model of the pile foundation is shown in Figure 2.

Table 1. Parameters of the pile foundation

Element	Parameter	Value
Platform	Dimensions, m	8 / 5 / 0.2
Pile	Length, m	10
	Diameter, m	0.4
	Wall thickness, mm	10
Thermal coil	Diameter of pipe, mm	15
	Number of turns, pcs.	20
	Turn-to-turn distance, m	0.1
	Thickness of thermal insulator, mm	50



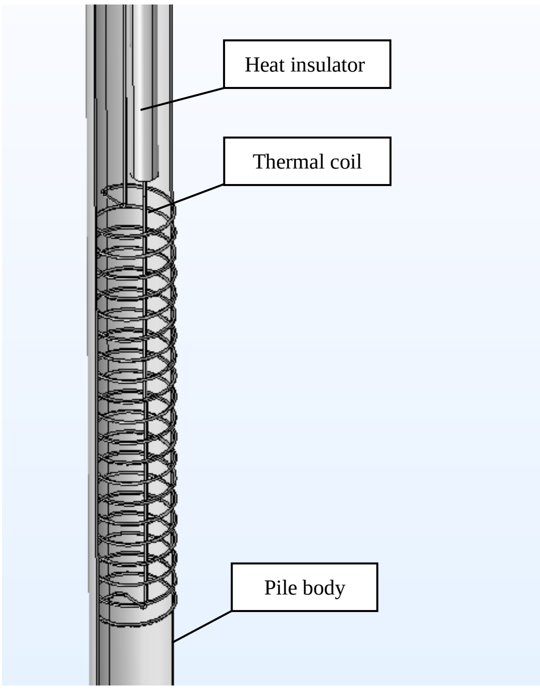


Figure 2. Geometry of a pile foundation model

The heat transfer rate in the air part of the calculation area is 0.05 m/s. Heat transfer is carried out by heat conduction and convection (radiant heat exchange is not modeled). air temperature at the boundaries of the computational domain is set to +8°C (except for the boundary in the heat exchange direction), and soil temperature at the boundaries of the computational domain is set to -2°C. Initial conditions above the ground surface are +8°C, initial conditions below the ground surface are -2°C. In the model it is assumed that refrigerant R134 is supplied from the refrigeration machine, which is not modeled within this work, and the refrigerant temperature at ground level is -3°C. The model uses materials from the standard library of the COMSOL Multiphysics software environment:

- Soil with a density of 1600 kg/m^3;
- Air in the space around the pile foundation, as well as inside the piles above the ground level;

- Steel for pile case, platform and technological heat source;
- Copper for thin-walled thermal coils (including thermal coil input tubes);
- Polyurethane for thermal insulation for thermal coil inlet tubes;
- Kerosene in the space inside the pile body below ground level;
- Refrigerant R134 as the refrigerant supplied to thermal coils.

In this study the temperature distribution of the soil and the pile body was evaluated. The calculations were performed using the COMSOL Multiphysics program, which implements the finite element method for calculations. The problem was solved in a stationary formulation, i.e., dynamics was not investigated. At first, simulations were performed in the absence of ground thermal stabilization (no refrigerant was fed to the thermal coils). Then the simulation was conducted with ground thermal stabilization, and the possibility of placing the thermal coils at different depths inside the piles was investigated. A block diagram of the methodology for this study is shown in Figure 3.

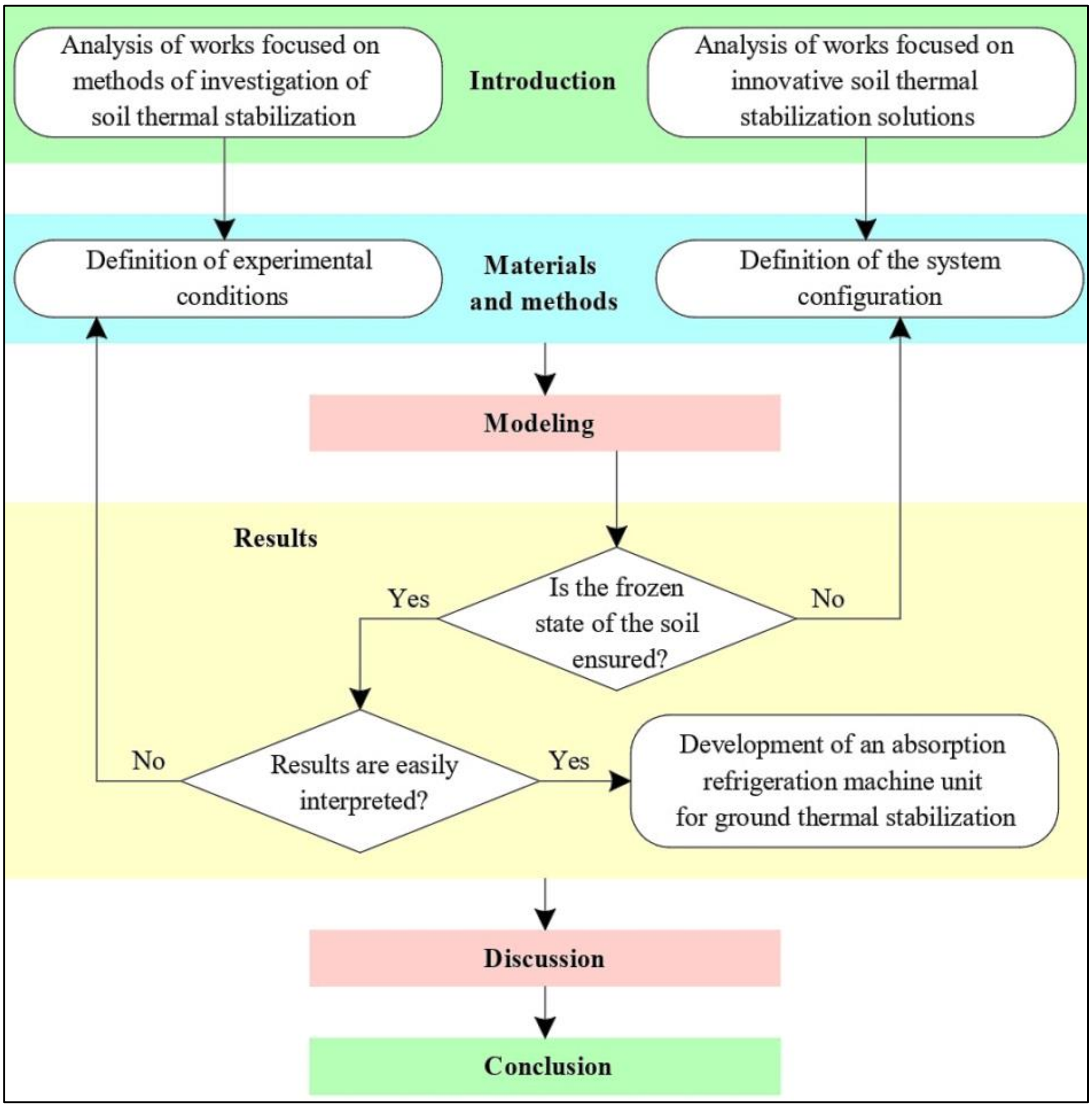


Figure 3. Block diagram of the methodology of this study

3. Results

3.1. Simulation of the Case without Thermal Stabilization

At the first stage, a simulation of the thermal regime of the "pile foundation– soil" system was carried out in the absence of thermal stabilization of the soil. Refrigerant was not supplied to the thermal coils. The results of the simulation are shown in Figure 4.

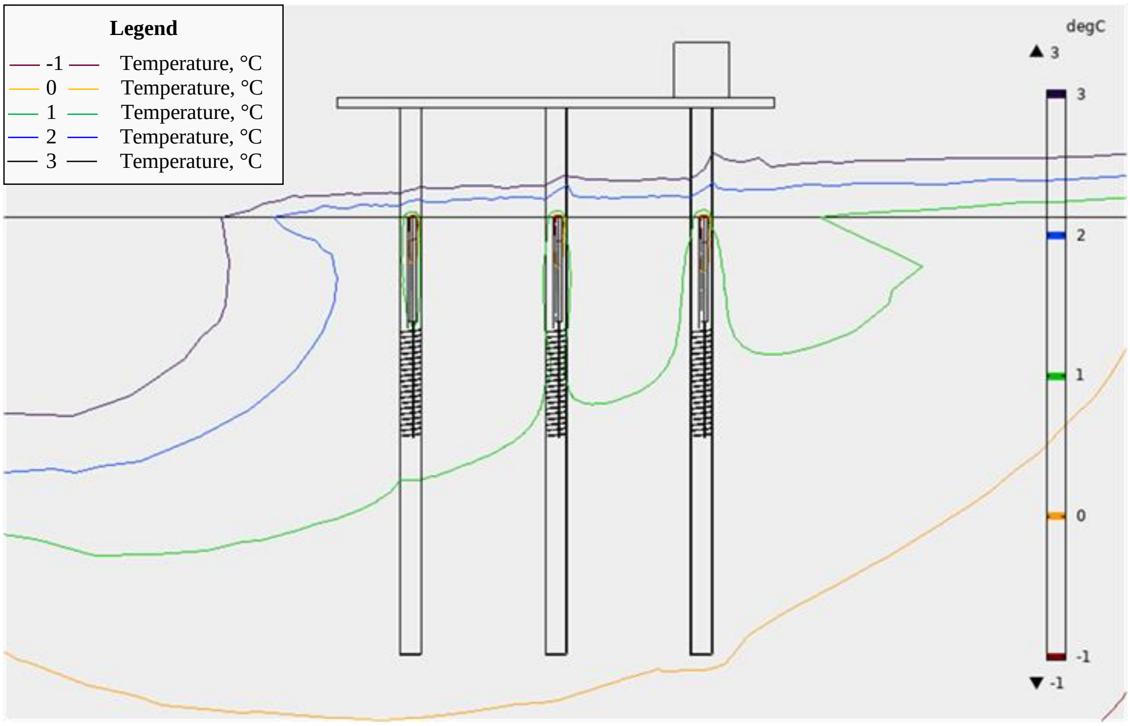


Figure 4. Soil isotherms in the model without soil thermal stabilization

Figure 4 shows that the soil around the piles has a temperature above 0°C, and a significant part of the surface of the piles is in contact with the soil, which has a temperature even above +1°C. Obviously, the steady state of the pile foundation in this case is not ensured. The temperature distribution for this case is given in the following section in Table 2.

Table 2. Pile surface and soil temperature data for different thermal coil placement options inside the piles

N	Depth of the upper part of the thermal coil relative to the ground level (m)			Average surface temperature of the pile (°C)			Average soil temperature in the calculation (°C)	
	Pile 1	Pile 2	Pile 3	Pile 1	Pile 2	Pile 3	in cross section	in volume
1		No thermal stabilization		1.01	0.79	0.54	-0.46	-0.81
2		1		-0.87	-1.05	-1.12	-0.58	-0.84
3		1.5		-0.90	-1.06	-1.13	-0.64	-0.82
4		2		-0.81	-1.00	-1.08	-0.62	-0.88
5		3		-0.84	-0.97	-1.02	-0.61	-0.85
6	1.5	1	1	-0.88	-1.10	-1.19	-0.68	-0.90
7	2	1	1	-0.85	-1.13	-1.22	-0.68	-0.92
8	3	1	1	-1.02	-1.24	-1.31	-0.72	-0.91
9	4	1	1	-0.68	-1.09	-1.14	-0.62	-0.86

3.2. Simulation of the Case with Thermal Stabilization

At the next stage, a simulation of the thermal regime of the system "pile foundation – soil" during thermal stabilization of the soil by feeding the refrigerant cooled to a negative temperature into the thermal coils was carried out. The thermal coils are placed inside the piles at the same depth: the distance from the thermal coil helix to the ground level is 2 meters. obtained isotherms in the cross section of the model are shown in Figure 5.

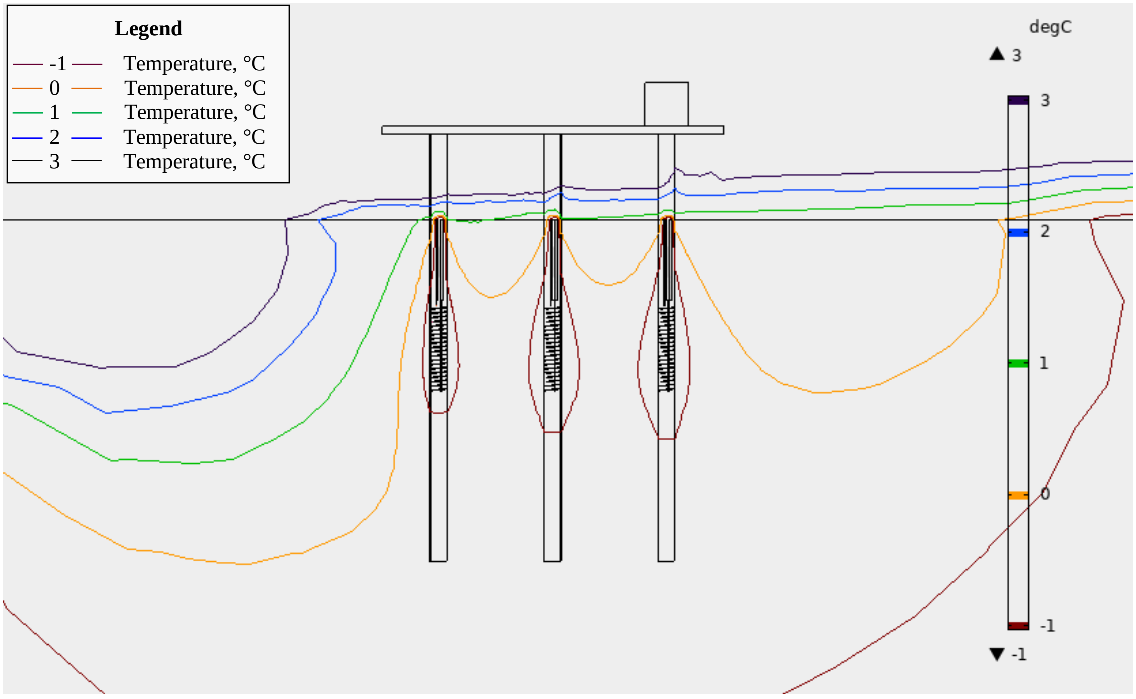


Figure 5. Soil isotherms in the model with soil thermal stabilization when the thermal coils are placed inside the piles at the same depth

Figure 5 shows that under these conditions the frozen state of the soil around the piles is ensured. It should be noted that on the leeward side, due to the air flow heated by the heat source, a significant thawing area is formed, the parameters of which significantly depend on the wind parameters. In Figure 5, the thawing depth is 8.3 m. Data on temperature distribution for this case are also shown in Table 2. The piles are numbered from left to right.

One of the objectives of the study was to determine the feasibility of placing the thermal coils inside the piles at different depths. For this reason, the depth of the thermal coils inside the piles was changed. The results of simulation of the temperature field of the soil adjacent to the piles for some options of thermal coil placement inside the piles are shown in Table 2. analysis of the results shows that under these simulation conditions, different depths of thermal coil placement inside the piles result in lower temperatures of the cooled soil. Figure 6 shows soil isotherms for option 8 (as the most optimal) from Table 2. The depth of the thermal coils N 1/2/3 (distance from ground level to the helix of the thermal coil) is 3/1/1 meter, respectively. A comparison of the isotherms in Figures 5 and 6 also clearly shows that it is reasonable to place the thermal coils at different depths under these conditions. Thus, a greater depth of the thermal coil placement in the pile, closest to the soil thawing zone makes it possible to reduce the surface temperature of the pile below the ground level, and, therefore, to increase its bearing capacity.

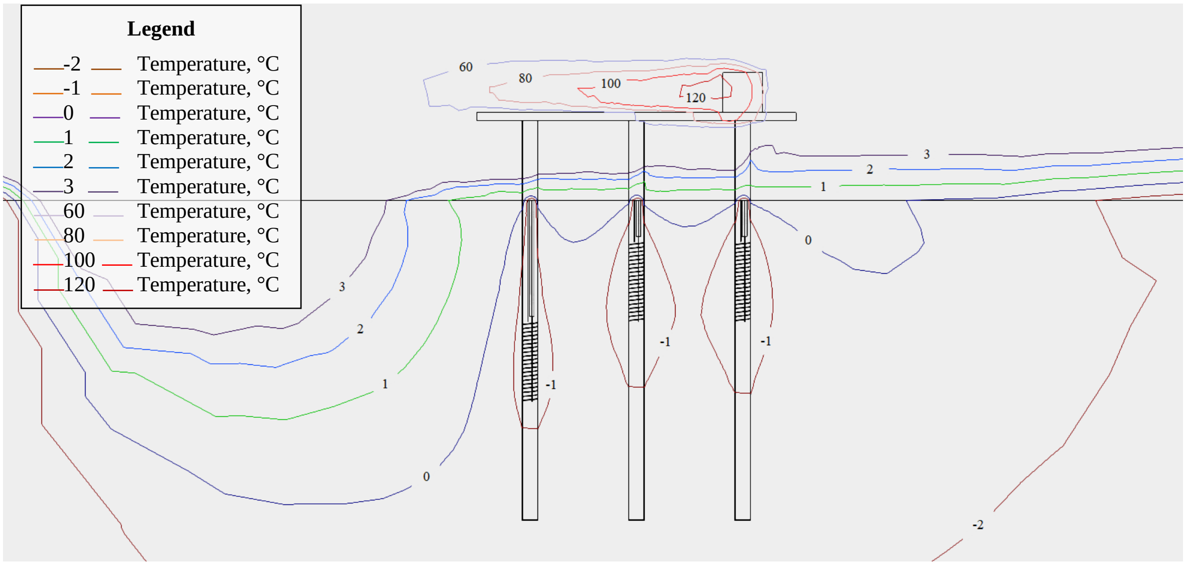


Figure 6. Soil isotherms in the model with soil thermal stabilization when placing thermal coils inside the piles at different depths

Note that when providing the bearing capacity of pile 1 in option 7, it should also be taken into account that even though the average temperature of each pile and the average soil temperature in the model area are slightly higher, the average soil temperature in the volume of the computational domain is lower. this value is too small in these conditions (0.01°C), but under other circumstances they can show similar results. The primary factor is the bearing capacity of the pile under these conditions. Thus, the actual task of future research is to determine the optimality criteria for selecting the depth of placement of thermal coils and to create a methodology for selecting the optimal depth of their placement.

3.3. Absorption Chiller Concept for Soil Thermal Stabilization

With an absorption chiller, it is possible to provide cooling of the refrigerant supplied to the thermal coils placed inside the piles to a small negative temperature. This is especially relevant for process plants that are a source of waste heat, such as internal combustion engines or gas turbines. The advantage of absorption chillers over compressor chillers is their ability to run on thermal energy. This reduces the load on the power supply system of the pile foundation. The most common types of absorption chillers used in industry are lithium bromide and ammonia absorption chillers. The principle of operation of the absorption chiller is illustrated by the scheme shown in Figure 7.

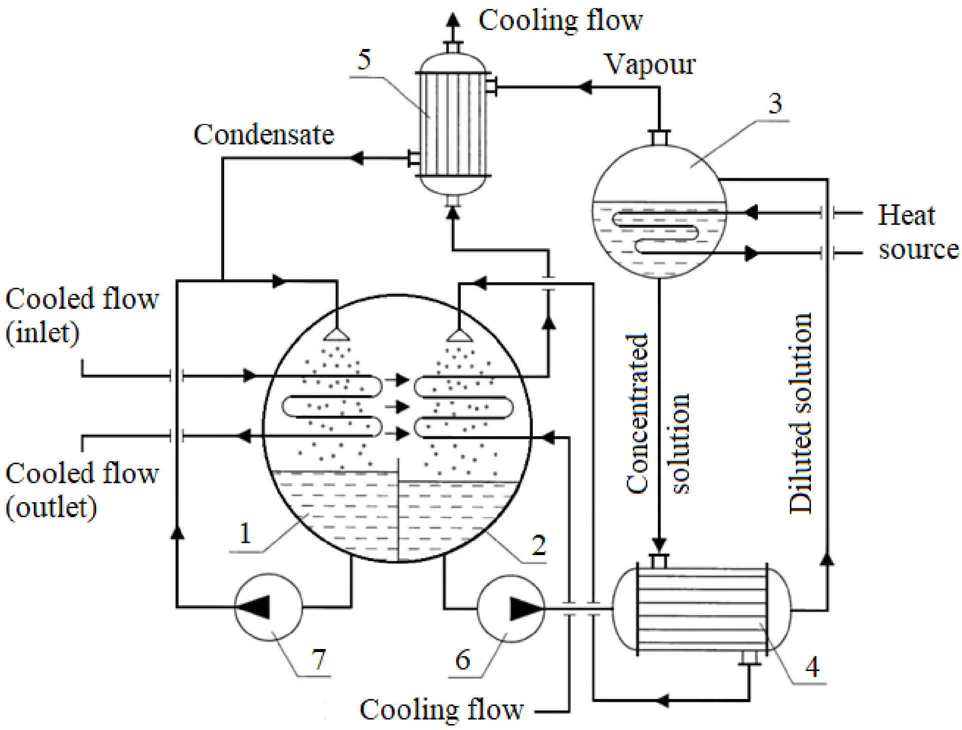


Figure 7. Schematic explaining the principle of operation of absorption chiller: 1 – evaporator, 2 – absorber, 3 – steam generator, 4 – heat exchanger, 5 – condenser, 6 – absorbent supply pump, 7 – refrigerant supply pump

Water is used as a refrigerant in the absorption chiller, and water-ammonia solution or lithium bromide solution is used as an absorbent [40]. The refrigerant evaporates at temperatures below +5°C in evaporator 1, due to vacuum created in the absorption chiller (about 6 mm Hg). The refrigerant cools the flow circulating through the tubular coil. The heated concentrated absorbent solution is supplied by pump 6 from steam generator 3 through heat exchanger 4 to irrigate the tubular coil into absorber 2. There the absorbent absorbs refrigerant vapor coming from evaporator 1. The diluted absorbent solution is pumped by pump 6 through heat exchanger 4, where it is heated, to steam generator 3. In the steam generator 3, as a result of heat input from an external source, the refrigerant evaporates and enters condenser 5. the liquid refrigerant is then fed to the evaporator 1 for irrigation. The concentrated absorbent is returned to the absorber. Since the absorption of refrigerant vapors is an exothermic reaction, the cooling stream (water or air) enters the absorption chiller at a temperature not usually higher than +30°C, which is easily feasible under permafrost conditions.

Water-ammonia absorption coolers are used to achieve negative cooling temperatures (up to -70°C), lithium bromide absorption refrigerators are used to achieve positive cooling temperatures [41]. In multistage absorption chillers, negative temperatures are achievable even when lithium bromide solution is used as the absorbent. This paper proposes an improved design of an absorption chiller to provide year-round soil freezing. The functional diagram of the absorption chiller with an air cooler is shown in Figure 8.

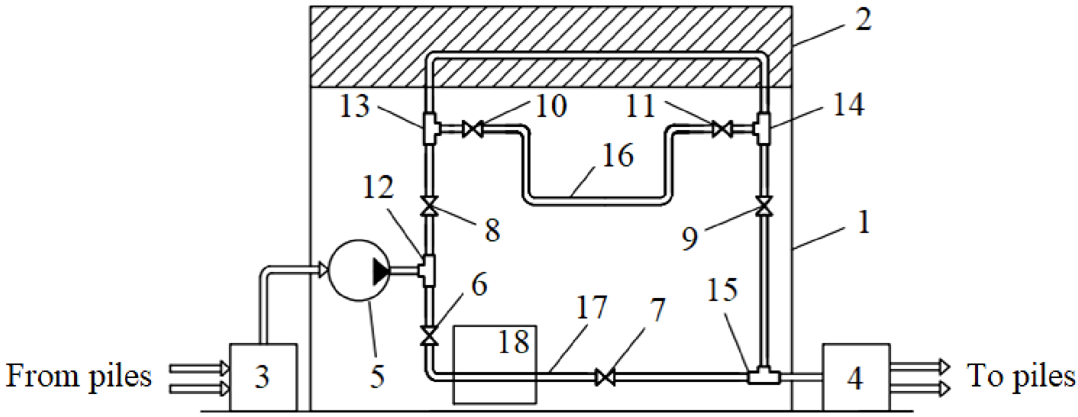


Figure 8. Absorption chiller with air cooler for year-round soil thermal stabilization: 1 – absorption chiller, 2 – air cooler, 3 – collector of heated refrigerant, 4 – collector of cooled refrigerant, 5 – pump, 6–11 – valves, 12–15 – tees, 16 and 17 – lines, 18 – evaporator of absorption chiller.

The proposed absorption chiller works as follows. refrigerant cooled to negative temperature is supplied from collector 4 by pipelines into piles. The heated refrigerant is supplied to collector 3 by pipelines from the piles. Then refrigerant is pumped by pump 5 to tee 12.

During operation of absorption chiller 1, mainly in warm seasons, valves 6, 7, 10 and 11 are open, and valves 8 and 9 are closed. In this case, the heated coolant enters line 17, passing through evaporator 18 of the absorption chiller 1. evaporator 18 cools the refrigerant. The refrigerant cooled to negative temperature enters collector 4 through open valve 7. the absorber and condenser (positions 2 and 5 in Figure 7, not shown in Figure 8) are cooled by air cooler 2. For this purpose, the coolant circulates in a closed circuit formed by pipeline 16 and air cooler 2.

If it is required to freeze the soil at negative ambient temperature, valves 8 and 9 are in open state, and valves 6, 7, 10 and 11 are in closed state. In this case the heated refrigerant supplied by pump 5 flows through the open valve 8 to the inlet of the air cooler 2. The cooled refrigerant from the outlet of air cooler 2 through the open valve 9 enters collector 4, where it is distributed through the pipelines leading to the piles. Thus, soil cooling at negative ambient temperatures can be performed without turning on the absorption chiller 1.

As part of the continuing research, it is planned to refine the "pile foundation – soil" model in terms of the design of the pile foundation, as well as the structure and initial temperature field of the soil. This will make it possible to optimize the system and obtain more accurate results of simulation of the process of thermal stabilization of the soil. The choice of the optimal refrigerant will also be carried out, taking into account the current environmental and climatic requirements.

4. Discussion

Thus, the supply of cooled to a small negative Celsius temperature (-3 °C at ground level) coolant to the deep thermal coils made it possible to reduce the average soil temperature in the computational area. In Hu et al. [38], the outer wall of the evaporator, represented by a copper tube twisted into a spiral, was cooled to a temperature of -15°C, but there a compressor refrigerating machine was used. Obtaining such temperatures in absorption chillers is difficult and requires expensive multistage units, so calculations with lower coolant temperature were not performed.

The proven effectiveness of the individual approach to the choice of the depth of placement of the thermal coil inside the pile as a whole allows to improve the design of various devices, including those not related to the use of refrigeration machines. for example, there are known designs of thermosiphons, the evaporating part of which is immersed inside the pile. The evaporators of such thermosiphons may be set once at different depths based on multi-year air and soil temperature data. Alternatively, a system for adjusting the depth of placement of thermal coils inside the pile can be provided.

In terms of practical application, the results obtained in this work may be useful on point and linear objects located in permafrost. For example, thermal elements can be placed inside piles during the construction of modular pile structures, the concept of which was developed earlier (Figure 9) [42]. A favourable concomitant factor in this case is the presence of technological heat sources on the platforms: diesel generators, electric motors, etc., which opens up the possibility of using absorption refrigeration machines for the purpose of soil thermal stabilization. As for the application of refrigeration machines, their use on linear facilities located in the permafrost zone, such as pipelines, power lines, roads, etc. is not feasible, but it is possible on the objects of local infrastructure.

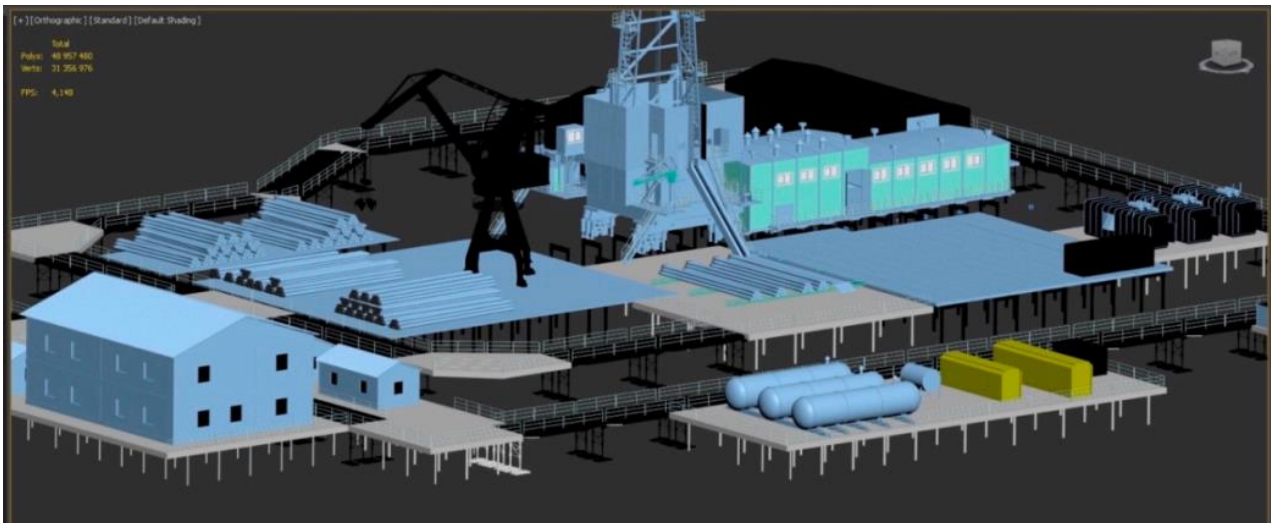


Figure 9. The concept of modular pile structures for the Arctic

The paper shows that heat transfer by convection can have a significant effect on permafrost thawing in the presence of heat sources. Implementation of numerical simulation in software systems such as COMSOL [20, 43] or ANSYS [44] opens up wide opportunities for modeling thermal processes in the "pile foundation – soil" system and developing new technical devices for soil thermal stabilization. These capabilities are usually not available in highly specialized programs for calculating the thermal stabilization of soils, designed mainly for the calculation of ventilated basements, the configuration of thermosiphons, etc. However, some assumptions and limitations are adopted in this paper. In particular, the computational problem is solved in the stationary formulation, i.e., the dynamics of soil freezing are not taken into account, which is very important in conditions of constantly changing meteorological conditions. In addition, the presence of water or ice in the ground was not modeled, which does not correspond to the real conditions of foundation operation. These and other assumptions will be taken into account in the further development of the work.

5. Conclusions

Thermal stabilization of permafrost to prevent its thawing is an important scientific and technical problem, which in most cases is solved by passive cooling methods such as constructing ventilated basements and using vapor-liquid thermal stabilization systems. However, in the context of global climate change, the development of new methods of thermal stabilization, which include systems with refrigeration machines, becomes urgent. The main results obtained in this study substantiate the expediency of improving various devices for soil thermostabilization. The results of the work can be used, among others, in devices that do not have in their composition a refrigeration machine, since thermal elements inside piles can be, for example, thermosiphon evaporators.

- The frozen state of the soil around the piles can be achieved by supplying the thermal coils located inside the piles with a coolant cooled to a slightly negative temperature.
- The presence of a heat source on the platform mounted on the piles can result in a significant near-surface thaw zone through heat transfer by convection.
- Depth thermal coils for freezing or keeping the soil frozen are advisable to be placed at different depths in general.
- An original scheme for the unit, including an absorption chiller and air cooler, was proposed to ensure year-round cooling of the soil in the permafrost zone.

At the first stage of the study, assumptions and limitations were made: for example, there is no water in the simulated soil, and the process of thermal stabilization was simulated in the stationary formulation of the problem. These factors will be taken into account in future research, which also involves the creation of a laboratory stand and the verification of the developed model. Another area of work is the refinement of the pile foundation design and an extended mechanical calculation of the bearing capacity of the foundation. The implementation of this work and the planned research on the subject of the project will make it possible to justify the required capacity of the prospective absorption refrigeration machine for the needs of thermal stabilization of the soil adjacent to the pile foundation.

6. Declarations

6.1. Author Contributions

Conceptualization, L.A. and B.G.; methodology, B.G.; software, L.A.; validation, D.M. and G.B.; formal analysis, D.M.; investigation, L.A.; resources, B.G.; data curation, B.G.; writing—original draft preparation, L.A.; writing—review and editing, D.M.; visualization, L.A.; supervision, G.B.; project administration, D.M.; funding acquisition, D.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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