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PERMAFROST ENGINEERING

CONSTRUCTION OF BUILDINGS IN THE ARCTIC WITH THE APPLICATION OF GRANULATED FOAM-GLASS CERAMICS IN THEIR BASES

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The construction of heated buildings in the Arctic is considered. To increase the bearing capacity of the foundations via their preservation in the frozen state, an environmentally friendly heat-insulating material obtained from the Arctic raw materials (opal-cristobalite and zeolite rocks) has been proposed. The aim of this work is to evaluate the efficiency of insulation layer made of granular foam-glass ceramic on the basis of numerical modeling of the thermal interaction between the heated building and the frozen base. We have investigated the influence of protective screens, construction parameters of a dome-shaped building, and the thickness of insulation layer on the thermal regime of a frozen base over 30 years in comparison with the option without the use of special engineering measures. Calculations indicate that the safe exploitation of a heated building without traditional seasonal cooling devices and a ventilated underground is only possible with the use of protective screens. The building can have the shape of not only a dome but also an elongated ellipsoid of unlimited length. In this case, for building width of 6–8 m, the thickness of insulation layer should be 1.0–1.4 m. The proposed technology is promising to reduce the cost of low-rise Arctic construction, rational use of mineral resources, and preservation of the permafrost and Arctic landscapes.

Keywords: *Arctic, permafrost, foundations, building construction, heat-insulating material.*

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INTRODUCTION

Natural resources and infrastructure of the Northern Sea Route are among governmental priorities of the future Arctic development [*Fauser, Smirnov, 2018*]. However, such economic and geographical features as remoteness from the developed industrial regions and permafrost conditions hamper construction works and further development of vast Arctic territories. In this regard, improvement of construction technologies in the Arctic is an urgent task.

In Arctic conditions, construction is carried out according to the principle of preserving foundations in a frozen state, which increases the bearing capacity. Therefore, the key feature of construction in the Arctic is the thermal regime of the foundation, whose changes lead to permafrost thawing and may cause accidents [*Melnikov et al., 2019*]. In this regard, while constructing the heated buildings on permafrost, seasonal cooling devices (SCDs) are being applied. These devices support the frozen state of foundations decreasing the ground temperatures in winter despite the emitted heat from buildings. In studies of recent years, the best effect of SCDs coupled with thermal insulation layer has been documented. For example, extruded polystyrene foam boards decrease the heat flux from building to the frozen foundation in summer, when SCDs are out of operation [*Melnikov et al., 2014*].

Ventilated undergrounds are the engineering alternatives for maintaining the frozen state of foundations. For their deployment, pile supports are used with depths exceeding active layer to transfer the load on the frozen ground. Also, the technology of spatial frames (platforms) made of steel or wooden structures maintained directly on the surface is known. Having many points of support, such structures contribute to the uniform distribution of the load on the ground, while at the same time having a ventilated underground [*Vangool, 2018; Inzhutov et al., 2019*].

It is necessary to mention the practice of constructing roads and railways on permafrost with the use of artificial embankments that rise the upper horizon of permafrost (UHP) up to their base. Thanks to this approach, the design standards for construction on permafrost allow the use of peat, subsiding, high-ice, and other grounds as foundations. This ensures high economic efficiency of construction. An additional cooling measure is the use of heat-insulating materials in the body of the embankment and screen structures (canopies) on the slopes of the embankment. Screen structures hinder snow accumulation, promote ventilation and cooling of embankment slopes in winter, and reduce the impact of solar radiation in summer [*Wenjie et al., 2006; Kondratiev et al., 2015; Chen et al., 2020*].

Above mentioned engineering measures to ensure the safe operation of buildings in the Arctic lead to an inevitable increase in construction costs. The remoteness of thousands of kilometers from the developed industrial regions greatly increases the cost of construction materials and structures at the construction site. Therefore, the application of forefront engineering solutions is a necessary condition for Arctic construction from a practical point of view, but insufficient from an economic point of view. Solving the problem of rationalizing construction in the Arctic requires localizing the production of construction materials near objects under construction using local raw materials and energy resources.

Construction technologies in permafrost areas indicate the high efficiency and attest to the high demand for thermal insulation materials [*Melnikov et al., 2014, 2019, 2021; Chen et al., 2020; Niu et al., 2021*]. Meanwhile, the Arctic territory has the largest raw material potential for their production in Russia – the deposits of opal-cristobalite rocks of the Yamalo-Nenets Autonomous Okrug [*Smirnov, Ivanov, 2015*] and zeolite rocks of Yakutia [*Ivanov, 2021*]. Publications of recent years indicate promising technologies for the synthesis of inorganic heat-insulating materials with a cellular structure called foam glass ceramics produced from these rocks [*Erofeev et al., 2018; Goltsman et al., 2020; da Silva et al., 2021; Konovalova et al., 2021*]. Due to its closed-porous structure, the material has low water absorption, retains thermal insulation properties in the ground, and has the required strength for use in the foundations of buildings and structures in granular form [*Ivanov, 2021; Melnikov et al., 2021*].

Further economic development of the Arctic will require hundreds of thousands of cubic meters of thermal insulation materials, where granular glass-ceramic foam can find wide practical application. Instead of traditional SCD and ventilated underground, in this work authors propose an alternative design solution in the form of a thermal insulation layer (TIL) insulating the building from the frozen foundation. Since the design standards for the permafrost require a rationale for the temperature regime for the entire period of operation, the purpose of this research is to evaluate the efficiency of using a proposed layer made of granular foam glass ceramics by numerical modeling of the thermal interaction between a heated building with a frozen foundation.

MATERIALS AND METHODS

Modelling site is located in permafrost area in Novy Urengoy, Yamalo-Nenets Autonomous Okrug, Tyumen Region. The choice is determined by the corresponding climatic characteristics, the availability of the required calculated data from engineering-geological surveys, and raw material reserves in the form of nearby large deposits of opal-cristobalite rocks for producing granular foam glass ceramics [*Smirnov, Ivanov, 2015*].

Table 1 shows the climatic characteristics averaged for 2006–2020 according to the Urengoy weather station (no. 23453). The total solar radiation is given according to reference values [*SP 131.13330.2012, 2015*] reduced by considering average cloud conditions for the city of Tarko-Sale [*Scientific..., 1998*]. Mean annual ground temperature is −1.2°C at the lower boundary of zero annual amplitude depth (15 m), and active layer depth is 1.5 m. Base of the construction site is composed of fine slightly heaving sand with a low ice content (type 1) to a depth of 0.2 m and weakly decomposed peat with a low ice content (type 2) (0.2–5.5 m). The remaining section (5.5–15 m) consists of type 1 sediment.

Table 1. **Climatic characteristic of the construction area**

Characteristic	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Air temperature, °C	−23.8	−20.8	−14.7	−5.7	−0.2	12.2	16.3	12.0	6.2	−3.5	−16.6	−20.9
Wind speed, m/s	2.9	2.7	3.2	3.6	3.6	3.3	3.1	2.8	3.0	3.2	2.6	2.8
Total solar radiation, W/m^2	2	15	44	74	105	111	113	82	49	19	6	0
Snow depth, m	0.64	0.73	0.80	0.75	0.42	0.07	–	–	–	0.10	0.23	0.48

Table 2. **Calculation ground characteristics**

Ground type	Wetness, %	Temperature of freezing onset, °C	Thermal conductivity, W/(m·°C)		Specific heat capacity, kJ/(m^3·°C)		Heat of phase change, MJ/m^3
			thawed	frozen	thawed	frozen	
1	22	−0.28	1.85	2.18	2784	2120	108
2	124	−0.40	0.94	1.41	3444	2762	174

The calculated characteristics of the foundation grounds are presented in Table 2. The regime of groundwater found at a depth of up to 3.8 m depends on the infiltration of atmospheric precipitation and has fluctuations of up to 1.0 m.

As the study object, we have chosen a dome-shaped residential heated building with a minimum surface area of contact with the environment, which reduces heat loss through the walls. Technical ideas for the construction of energy-efficient residential architecturally expressive structures of aerodynamic shapes in the form of a sphere, dome, ellipsoid, lens, or cone are especially relevant in the climatic conditions of the Arctic and can be implemented in the near future [*Inzhutov et al., 2019*].

The dome-shaped building is mounted on a pre-prepared layer made of granulated glass-ceramic foam laid in a geosynthetic shell. The material is produced in industrial quantities and has the following characteristics: fraction 5–20 mm, calculated coefficient of effective thermal conductivity 0.09 W/(m·°C), bulk density 280 kg/m^3, compressive strength 1.8 MPa, specific heat capacity 260 kJ/(m·°C) [*Melnikov et al., 2021*].

The proposed design solution has multifunctionality and the following practical advantages:

1. Acting as a load-bearing element, the layer evenly transfers the load from the building without requiring special preparation of the natural base surface.

2. The layer is an artificial embankment that insulates a heated building from the frozen foundation by heat-insulating material.

3. The floor covering in the room is arranged over the surface of the layer, so there is no need for its thermal insulation, unlike a ventilated underground.

A cross section of the dome-shaped building is shown schematically in Fig. 1. The internal radius of the dome is accepted to be 4 m, taking into account the living area of the room equal to 50 m^2. The thickness of the thermal insulation layer is taken to be 1 m; in terms of thermal resistance, this is equivalent to a 0.3-m-thick layer of extruded polystyrene foam traditionally used in the construction on permafrost [*Melnikov et al., 2014, 2019*]. The material used for wall enclosing structures was lightweight concrete based on granulated glass-ceramic foam aggregate with a thermal conductivity of 0.12 W/(m·°C) and a heat capacity of 720 kJ/(m^3·°C).

Predictive calculation of the frozen base temperature field was carried out using a modern numerical method for solving the equation of non-stationary thermal conductivity, considering phase transitions and the amount of unfrozen water in the ground [*Melnikov et al., 2014, 2019*]. In solving the plane axisymmetric problem of finding the temperature field of the dome-shaped building base, its right half-plane was considered (Fig. 1) so that the left boundary of the calculation area adjoins the axis of the building.

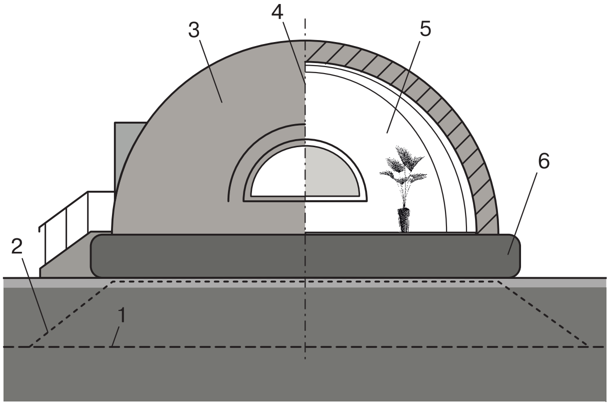

Fig. 1. Cross-section of dome-shaped building:

1 – natural location of UHP; 2 – normative location of UHP; 3 – enclosing structure made from lightweight concrete 0.5 m thick; 4 – building's axis of symmetry; 5 – inner living space; 6 – layer of granular ceramic foam in a geosynthetic shell.

The width of the calculation area was three times the internal radius of the dome in order to take into account the lateral temperature effect exerted by the surface. The vertical size of the calculation area corresponded to the depth of the lower boundary of the zero annual amplitude layer. In this regard, at the lower boundary of the calculation area, boundary conditions of the first kind were accepted with a constant temperature of −1.2°C, equal to the mean annual ground temperature. At the lateral boundaries of the computational domain, the condition of heat flux being equal to zero was accepted, which corresponds to boundary conditions of the second kind.

Boundary conditions of the third kind corresponded to the upper boundary of calculation area, including building and surface. Air temperature inside the building was accepted to be 23°C annually. For the surface, the mean monthly air temperature, total solar radiation, thermal resistance of the snow cover in winter (Table 1) and of the 0.1-m-thick surface turf with a thermal conductivity of 0.52 W/(m·°C) were specified. The heat transfer coefficient on the surface was calculated depending on the wind speed and the presence of snow cover (Table 1) according to the method [*Vabishchevich et al., 2017*].

The calculation start date of January 15, 2020 met the condition of installing a layer in winter in order to reduce the thermal impact in summer, when the dome construction was performed. The initial temperature distribution at the base corresponded to the borehole thermometry data on the start date of the calculation: from −6 to −4°C at a depth of 0–0.3 m, from −4 to −0.8°C at a depth of 0.3–3 m, and from −0.8 to −1.2°C at depths 3–15 m. Predictive calculation of the temperature field of the base was carried out for the long operation of the building: up to 30 years and 8 months, given the high rate of climate warming with an annual increase in the mean air temperature by 0.08°C [*Pavlov et al., 2010*]. The final calculated date of September 15 corresponded to the maximum active layer depth at the base.

RESULTS AND DISCUSSION

The results of calculating the thermal interaction of a building with a frozen foundation at the required time are the temperature field consisting of a set of temperature values of ground blocks 0.05 × 0.05 m in size, into which the calculation area is divided. The position of the UHP at the base changes under the influence of the building, which characterizes the boundary between frozen and thawed ground. Thus, knowing the temperature field at the base, it is possible to visualize the UHP using an isotherm characterizing the temperature at which the ground begins to freeze (Table 2).

Figure 2 shows a reduced fragment of the calculation area reflecting the dynamics of the position of the UHP directly under the dome-shaped building on a thermal insulation layer in comparison with a traditional 1-m-high embankment composed of the local ground type 1. In the second case, the calculation considered the thermal resistance of the floor inside the building, which corresponded to the territorial standard value of 5.5 m·°C/W for floors above unheated undergrounds of residential buildings.

The results of predictive calculation indicate significant dynamics of thawing at the frozen base. As a result, active layer depth under the central part of the building by September 2030 reaches 2.6 and 4.8 m for buildings on a thermal insulation layer and a traditional ground embankment, respectively (right and left in Fig. 2). The significantly greater thaw depth of a building on an embankment confirms the efficiency of a heat-insulating layer. However, in the proposed form, the design solution does not allow achieving the normative (close to the thermal insulation layer) position of the UHP (Fig. 1), which requires additional cooling measures.

In this regard, further calculations considered the year-round impact of screen structures installed along the perimeter of buildings. In winter, snow accumulation occurs on the surface of the structure, so the thermal resistance of snow on the ground surface has not been taken into account.

It should be emphasized that screen structures and their supports must remain stable under the standard snow load reaching 4 kPa for Arctic territories, according to [*SP 20.13330.2016, 2018*]. Taking this into account, their dimensions were limited to a 2.5-m distance from the building wall, as shown in Fig. 3, where the screen structures are shown schematically. The design features of screen structures in the construction of transportation structures on permafrost are covered in more detail in Russian and foreign literature [*Wenjie et al., 2006; Kondratiev et al., 2015; Chen et al., 2020*].

We considered the reflective effect of screen structures in the calculation from May to September by zeroing the values of total solar radiation (Table 1) when setting boundary conditions on the ground surface under the screens, which corresponds to the natural and numerical experiments of the authors [*Wenjie et al., 2006*]. The dimensions of the dome, embankment, and layer were preserved. The results of modeling the impact of screen structures are presented in Fig. 3.

The additional cooling measure taken into account in the calculation contributes to a significant cooling of the base under the building-enclosing structures, which is characterized by a rise of the

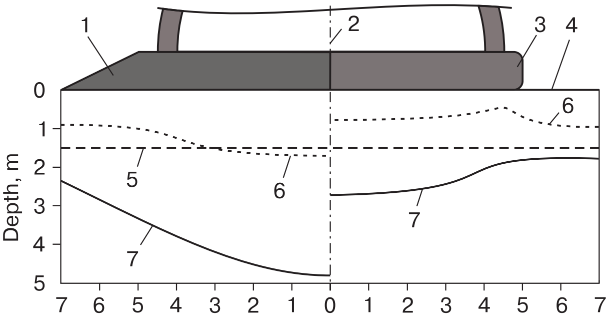

Fig. 2. Impact of ground embarkment (*left*) and thermal insulation layer (*right*) on the change of UHP:

1 – artificial embarkment; 2 – building's axis of symmetry; 3 – thermal insulation layer; 4 – base surface; 5 – natural location of UHP; 6 – September 2022; 7 – September 2030.

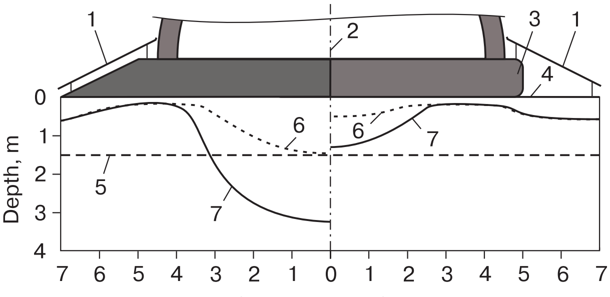

Fig. 3. Impact of screen structures on the UHP for buildings on ground embarkment (*left*) and thermal insulation layer (*right*):

1 – screen structure (shown schematically); 2 – building's axis of symmetry; 3 – thermal insulation layer; 4 – base surface; 5 – natural location of UHP; 6 – September 2022; 7 – September 2030.

UHP to the base of the embankment and the heat-insulating layer (left and right in Fig. 3). In the case of the ground embankment, however, the formation of a 3.4-m-deep talik under the center of the building (by September 2030) requires the use of alternative measures: deployment of horizontal or inclined SCDs under the building or replacing the embankment with a ventilated underground. Due to its low efficiency, the embankment was not considered in further calculations.

The efficiency of screen structures is noted when comparing the positions of the UHP in Fig. 2 and Fig. 3 (right) in the case of building a dome on a thermal insulation layer. Nevertheless, the dynamics of the talik formation under the center of the building with a depth of 1.4 m by September 2030 (Fig. 3, right) indicates that the UHP is not sufficiently close to the normative (Fig. 1). In order to minimize or completely eliminate the talik development at the base, authors changed the design parameters of the building in further predictive calculations: the dimensions of the dome and the thickness of the heat-insulating layer.

In the first case, we have reduced the internal radius of the dome by 1.3 times (to 3 m). In order to maintain the accepted area of the room, the building took therefore an elongated ellipsoid shape. With a fixed width of the ellipsoid, the area of the room will depend on its length, which does not affect changes in the UHP in the cross-profile of the base, as well as in the case of linear engineering structures (roads, pipelines, etc). Thus, the area of the room can significantly exceed the accepted one and is only limited by the constructive length of the ellipsoidal building. In the second case, the thickness of the thermal insulation layer was increased to 1.4 m (approximately by a factor of decreasing the radius of the dome) while maintaining the initial internal radius of the dome.

The results of modeling the thermal impact of buildings with structural changes made for the first and second cases are presented in Fig. 4 to the left and right of the axis of symmetry of buildings. It can be seen that the position of the talik by September 2030 in both cases reaches the boundary of the frozen foundation at a depth of 0.2 m, i.e., weak-bearing ground of type 2 remains frozen. The position of the talik by September 2050 characterizes the insignificant dynamics of thawing at the base to a depth of 0.4 m only under the center of buildings. The remaining part of the base is characterized by the constant position of the UHP throughout 30 years of building operation and its almost complete approach to the base of the thermal insulation layer, i.e. to the normative position in Fig. 1.

As seen from Fig. 4, safe operation of a heated dome-shaped building on a thermal insulation layer is possible only with the use of additional cooling measures and considering the design parameters of the building. This is achieved, for example, by reducing the width of the building, or increasing the thickness of the layer; it is possible to completely prevent the thawing of weak-bearing ground at the base without removal, and also without the use of SCD and a ventilated underground.

The economic efficiency of a thermal insulation layer made of granular ceramic foam with a thickness of 1.4 m in comparison with the installation of a pile foundation with a ventilated underground is an almost threefold reduction in cost per unit area. Based on the well-known practice of reducing costs by 30% when using horizontal SCD instead of a ventilated underground [*Melnikov et al., 2014, 2019*], savings in comparison with SCD reach a double value.

An additional economic effect is possible due to a reduction in transportation costs in the case of the production of granular glass-ceramic foam near Arctic construction sites using mobile complexes based on a railway platform [*Melnikov et al., 2021*]. The material is applicable as a filler in lightweight concrete used in the form of monolithic enclosing structures (domes, shells, etc.), blocks, wall panels, floor screeds, etc. Thus, granular glass-ceramic foam can replace traditional heat insulators (for example, polystyrene foam), whose transportation to the Arctic is unprofitable.

A disadvantage of the proposed construction technology is the limitation of the width of an ellipsoid building (6 or 8 m in size), while the width of buildings supported by horizontal SCDs reaches 100 m. In this regard, the construction zone will increase due to the additional area between buildings required for communications, passages, technical and economic needs, fire safety purposes, etc. Herewith, an ellipsoid building can have an unlimited length and area, and its plan configuration can differ from linear, taking the form of an arc, circle, torus, spiral, etc, despite the fixed width. Consequently, the location of ellipsoidal buildings in the built-up area

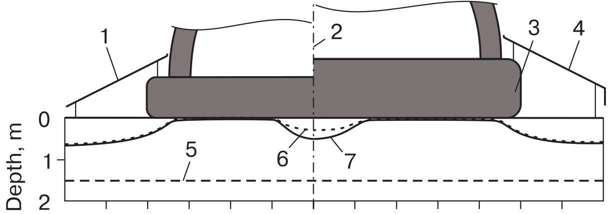

Fig. 4. Impact of reduced (up to 3 m) inner radii of the dome (*left*) and increased (up to 1.4 m) thermal insulation layer (*right*) on the position of UHP:

1 – screen structure (shown schematically); 2 – building's axis of symmetry; 3 – thermal insulation layer; 4 – base surface; 5 – natural location of UHP; 6 – September, 2022; 7 – September, 2030.

Fig. 5. Dome-shaped building made of granulated foam glass ceramics.

should be linked to their configuration in plan, considering the possible thermal interaction of adjacent buildings.

Currently, there is practical experience in the use of granulated foam glass ceramics in the construction of a dome-shaped building in the Natural Rehabilitation Complex "GNEZDO" in Tyumen, Fig. 5. The building was built on a 0.4-m-thick thermal insulation layer, which eliminated frost heaving under conditions of deep (up to 2 m) seasonal freezing of the base, as well as reduced heat loss through the floor. Wall blocks made of granulated glass-ceramic foam laid on the concrete load-bearing shell of the dome were used in the building enclosing structures.

The modeling results indicate broad prospects for such construction in the Arctic. The high strength, hydrophobicity, low thermal conductivity, flowability, and fire safety of granular foam glass ceramics allow the construction of dome-shaped and ellipsoidal buildings, which are not only an object of Arctic infrastructure, but also an element of landscape design, as follows from Fig. 5. Thus, the proposed technical solution can ensure the safety of not only permafrost proper but also the entire natural landscape, a part of the Arctic ecosystem.

CONCLUSIONS

A technology for the Arctic construction of heated low-rise dome-shaped buildings on a thermal insulation layer made of granular glass-ceramic foam is proposed. Mathematical modeling of the thermal interaction of a building with a frozen base made it possible to estimate the influence of cooling measures and design parameters of buildings on the temperature regime of the frozen base. Buildings on an ellipsoidal shape with a width of 6–8 m on a thermal insulation layer of 1.0–1.4 m in thickness meet the condition for preserving the foundation in a frozen state. The cost of the ow-rise construction on permafrost is reduced because of the exclusion of seasonal cooling devices and ventilated undergrounds; localization of the the production of granular foam glass ceramics from local sources in remote Arctic territories also reduces the cost of construction. The use of granular foam glass ceramics in the proposed design solutions contributes to the rational use of mineral resources and preservation of permafrost, Arctic landscapes, and ecosystems.

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