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Energy efficiency of underground structures in harsh climatic conditions

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Abstract. The object of the study is an underground structure located in a region with a harsh climate. The placement of structures in the underground space solves the urgent problem of reducing the heating cost for buildings and structures in the northern regions. The paper proposes ways to improve the energy efficiency of underground structures through the choice of the structural characteristics of such structures by the criterion of minimum heat loss. The method for calculating heat energy losses through external enclosing structures is based on determining the temperature fields in the ground mass adjacent to the structure throughout the year. The temperature in the ground is determined by solving the non-stationary heat conduction problem. The results of the step-by-step solution of the heat transfer problem in the form of temperature fields are used further to calculate heat losses at specified time intervals. The results of determination of the influence of thermal insulation, the depth of the object relative to the ground surface and the temperature of the internal air on heat loss are presented. The analysis of the presented results makes it possible to make the correct choice of the design parameters of the designed underground facilities in various climatic conditions.

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1. Introduction

Great attention is paid to topical problems of energy and energy efficiency of facilities in the world. One of the directions is the expansion of the use of alternative energy sources. Another effective way can be to reduce the amount of energy consumed for heating the premises or to maintain the required temperature regime in the premises. The enclosing structures of buildings and structures and the surface of the Earth are subject to the effects of cyclical changes in the air temperature. Huge resources are spent on elimination of such influences on indoor temperature. According to [1], about 40 % of the total heat produced is consumed only for heating residential buildings. Currently in the world there is an active development of natural resources in the northern regions with low air temperatures. Energy costs for buildings and structures heating in such regions of the Eurasian and American continents are especially high, and the delivery of energy carriers can be complicated.

At the same time, the average ground temperature at a certain depth is more stable and often exceeds the air temperature in the cold season. In such conditions, the reduction of heat energy losses by structures can be achieved by placing structures underground. At a certain depth, temperature fluctuations remain quite insignificant, and in some cases the ground temperature remains closer to the required indoor air temperature. The use of thermal energy of the near-surface layers of the ground during the warm season can contribute to an increase in the efficiency of underground objects.

The course of air and ground temperature in the regions of the Northern Hemisphere has been studied earlier and allows them to be used as initial data in the study of the problem posed. Areas where the temperature of the near-surface ground layer reaches large negative values are described in [2–5]. Ground temperature and the pattern of its fluctuations at different depths throughout the year in some regions of the northern hemisphere are given in [6–9]. In one of the northern regions of Canada [6], the temperature at a depth of about 10 m remains practically constant and is about –3 °C. At a depth of 4 m it can drop to –3.6 °C, at a depth of 2 m it drops to –4.7 °C, 1 m – up to –6.5 °C. The grounds in the study area are represented by silty clay. On Olkhon Island (on Lake Baikal), a constant temperature of about 0 °C is maintained at a depth of 3.65 m [7]. At the same time, at a depth of 1.5 m, it decreases to –3.75 °C, at a depth of 1 m, it decreases to –7.5 °C. Here, the grounds on the site are represented by sandy loams. In the conditions of the alpine steppe in Tibet [8], a constant temperature of about 0 °C is maintained at a depth of about 10 m. The grounds here are represented by sand and gravel. At a depth of 3 m, in an alpine meadow, the ground temperature drops to –3 °C. The results of the most ambitious studies in the Central Transbaikalia region are presented by N.A. Shpolyanskaya [9]. Here, for one of the wells, it is established that constant temperatures of about 1.3 °C are maintained at a depth of about 13 m. At a depth of 8 m, the temperature drops to 0.8 °C, at a depth of 4 m – to –0.8 °C, at a depth of 2 m – up to –6 °C. Here, sand with grit and sandy loam with grit occur in the near-surface layer. Ground temperature and its fluctuations at depth depend on the composition, moisture, ground structure, on the degree of surface shielding by natural and man-made factors.

Previous studies have shown that, under certain conditions, the costs of heating underground structures are significantly reduced in comparison with similar above-ground structures. For this reason, the interest in underground construction in the world is steadily growing. Prospects are being created for the rational use of underground structures in the northern regions. The energy efficiency of underground structures is confirmed by historical experience, experimental and theoretical studies of a number of authors and is analyzed in a number of works. The efficiency of the underground and semi-underground location of buildings is substantiated in [10]. Here, using the example of refrigerators built in the USA, it is noted that the operating costs of warehouses and refrigerators for underground versions are reduced tenfold. It also shows energy savings for underground industrial buildings in Sweden, Norway and Finland. There are extensive classifications of underground structures according to various characteristics and directions of its use [11, 12].

The history and examples of the use of underground space, the main directions and a systematic approach to planning this process, a discussion of efficiency criteria are presented in [12–14]. It is noted here that the main advantage of underground structures is provided by the thermal stability of grounds and their thermal insulation capacity. Passive heat supply from the accumulated thermal energy in the ground can occur even in the coldest periods of the year. The advantages and problems of underground construction, as well as the experience of foreign countries in the development of underground space are given in [15]. In the article of V.L. Belyaev [16] notes the presence of large complexes – underground cities – erected in Canada, Finland, Japan, Netherlands, China, Singapore. It also deals with the development of underground space in Moscow. The use of underground space in Helsinki is described in [17]. An example of using the thermal inertia of ground for storing food is given in [18]. Natural smoothing of extreme temperatures due to the thermal insulating properties of ground masses is also used in tunnels [19], underground rooms and shelters [20, 21]. Often, cultural and entertainment, sports objects, production and transport objects are being erected as objects of underground structures in the world. The expediency of using underground space for placing garages, warehouses, archives and other objects is noted.

Criteria and motives for the use of underground space can be associated with the preservation of the environment, with the lack of free space for building, with the smoothing of temperature fluctuations at the surface of the ground massifs, with the need for high sound insulation, the need to increase the energy efficiency of objects, the need to build metro and roads.

Permissible temperature values in rooms, including underground rooms, are established by regulatory documents. For example, according to the requirements of Russian Sanitary Rules and Regulations 2.2.4.548-96 (Industrial premises), the air temperature at production premises should not drop below 16 °C, and sometimes below 13 °C. According to the norms of Russian Construction Rules 113.13330.2012 (Parking of cars), the calculated air temperature in heated rooms is taken not lower than 5 °C.

Along with the general features and directions of the use of underground space, there are also significant differences in its use in the southern and northern regions. In the southern regions, when using underground structures, the problems of smoothing the maximum values of positive temperatures are mainly solved [21, 22]. In the North, an important role is played by smoothing out the impact of extreme values of negative outside air temperatures on structures or maintaining negative ground temperatures. Saving thermal energy in the northern regions during the construction of underground structures is considered in [23, 24], the prospects for the construction of such structures in the North are noted in [25]. The issues of cold accumulation are considered in paper [24], the preservation of permafrost in the foundations of buildings – in article [26].

The use of a large ground layer as a layer of thermal insulation above the structure will require significant costs for earthworks. Therefore, in underground construction, it is necessary to raise the question of the use of artificial effective thermal insulation, which will replace the ground layer around the structure and ensure even greater temperature stabilization at a certain depth and the conservation of thermal energy. Ways of using of thermal insulation in order to maximize the efficient conservation of thermal energy are considered in [27–30]. The influence of the thickness of the thermal insulation on the amount of heat loss for a partially recessed building in Poland is estimated in [27]. The effectiveness of thermal insulation for various climatic conditions of the three US states at three temperature options inside a completely buried and insulated along the entire contour of a warehouse facility is given in [28]. Experimental studies of the efficiency of tunnel insulation in China are presented in [29]. Analysis of the criteria for the effectiveness of thermal insulation of an underground facility using numerical modeling based on simplified techniques is carried out in [30]. In a harsh climate, the issues of using thermal insulation acquire special significance and are considered in [31, 32]. It also solves the actual problem of optimization of ground thermal insulation in the conditions of the Trans-Baikal region [32]. The above studies confirm that the use of thermal insulation reduces the depth at which significant fluctuations in the temperature of the environment occur, and makes it possible to reduce the size of the heat-insulating ground layer above the structure. In the latter case, the structure can be located closer to the surface, which reduces the cost of earthworks.

Various methods are used to calculate the heat loss of underground structures in the design. In most cases, to assess heat loss, separate formulas are used that take into account the difference in temperatures between the outside air and the air in rooms underground [24, 33, 34]. In [35] formulas for calculating heat losses in underground collectors are given, in [24, 33, 34] – formulas for determining heat losses in the buried part of buildings. The disadvantage of the above publications is the incomplete consideration of the influence of the ground massif temperature and the physical properties of the ground changing in different periods of the year.

Another approach to the determination of heat loss by underground objects includes the determination of temperature fields in the ground massif adjacent to the underground structure, taking into account the effect of temperature in room’s underground [20, 36–38]. In [36], the temperature of the adjacent ground is determined by solving a linear problem in a polar coordinate system for an underground potash mine. The problems of heat transfer in the ground massif for slightly buried in the ground structures are solved in [20, 37–38]. This approach, taking into account the physical and mechanical properties of the ground massifs adjacent to the structures, increases the reliability of the results obtained. The results of experimental studies of heat transfer near underground structures, presented in [30, 39–41], confirm the high accuracy of solutions based on the latter approach to the problem. In this case, the calculation of the parameters of heat transfer of underground structures should be carried out on the basis of solving the non-stationary problem of heat transfer.

At the same time, the results of calculations, taking into account the thermal inertia of the ground, given in the publications presented above, assess the effectiveness of underground structures in the southern regions. The energy efficiency of underground construction in harsh climatic conditions, taking into account the choice of the necessary technical parameters of structures, has not been studied enough. This circumstance required an assessment in this article of the effectiveness and the feasibility of using underground structures in regions with severe climatic conditions.

The object of research is underground structures in the northern regions. The subject of research is the magnitude of the loss of thermal energy through the external enclosing structures of structures when they are underground. The purpose of the work is a numerical analysis of the loss of thermal energy and an increase in the energy efficiency of underground structures in harsh climatic conditions. To achieve the purpose, it is necessary to solve the following tasks: formation of a method for determining the heat loss of a structure, taking into account non-stationary heat transfer in the ground, temperature fields in the ground massif and heat loss at specified time intervals; determination of quantitative indicators that assess the advantages of the underground layout based on the clarification of the temperature and properties of the surrounding ground; assessment of the degree of influence on the energy efficiency of underground structures of such factors as the depth of the object from the day surface, the thickness of the thermal insulation layer, the temperature in the premises.

2. Methods

A ground massif subject to continuous temperature changes at each point associated with temperature changes on the day's surface during the year is considered. The nature of temperature changes over time is determined by the climatic parameters of the region. An underground structure is located at some depth from the earth's surface. A ground massif with structural elements of the structure and thermal insulation form the design model shown in Fig. 1. The structural elements of the structure's cross-section are highlighted in blue, and the elements of thermal insulation are highlighted in orange. The variable parameters of the computational model are the distance from the structure to the day surface, the thickness of the thermal insulation, and the air temperature in the premises.

The problem is solved by the finite element method using the LIRA CAD software package. The design model of structures and ground is divided into finite elements. Finite elements of thermal conductivity and convective heat transfer are used. In the vertical direction, the ground massif, reinforced concrete structures and layers of thermal insulation are divided into finite elements with a step of 0.25 m, in the horizontal direction – with a step of 0.25 and 0.5 m. The temperature change in the ground massif and in structures is determined by a software package based on the theory of unsteady heat transfer. The phase transition under the influence of seasonal freezing and thawing of the soil is taken into account by stepwise adjustment of the parameters during the iterative process. The course of the outside air temperature and convective heat transfer are taken into account. The initial and boundary conditions on the contour of the ground massif model, on the day surface and in the ground massif are set on the basis of long-term observations. Numerous studies show that the obtained temperature fields at individual internal points of the computational model after repeated cyclic calculations do not depend on the initial temperature in the massif and are completely determined by the boundary conditions of the problem. The air temperature in the premises during the calculations is assumed to be constant. Energy costs for ventilation, water supply and sanitation depend on the purpose of the facilities. They are supposed to be taken into account when continuing research.

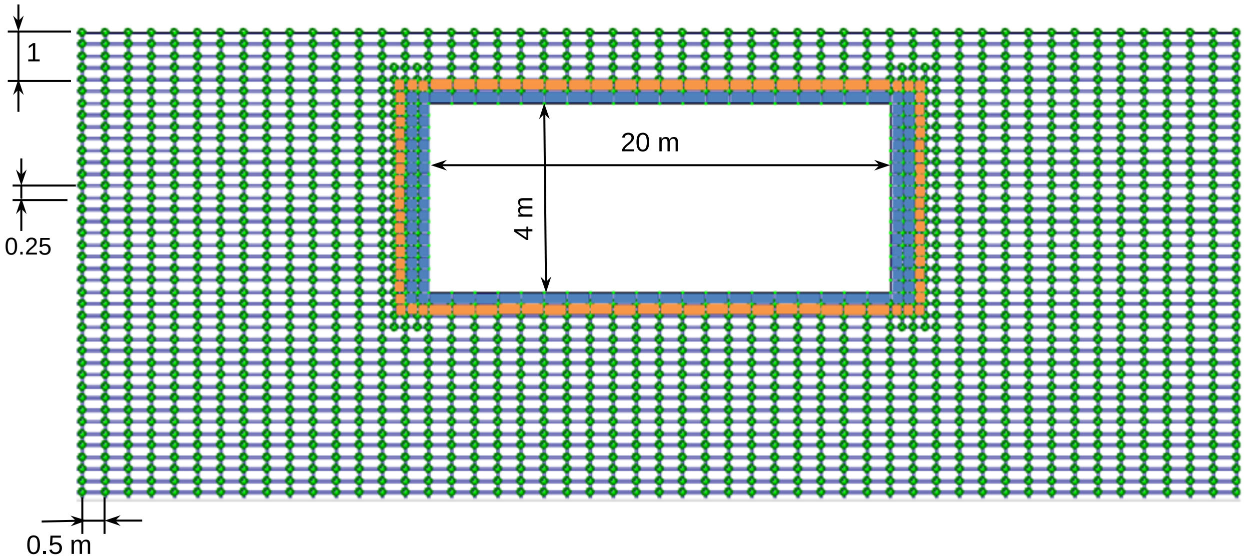

Figure 1. Cross-section of an underground structure.

As a result of the non-stationary problem of heat transfer solving, temperature fields are obtained in the ground and in structures. The loss of heat energy is determined by the solution of a quasi-stationary problem on specified time intervals of one month. Taking into account the temperature distribution in the ground massif, in the structures and in the premises, the heat flux from the structure through the ground massif is determined. The heat flux is calculated based on the average temperature fields for each month. Heat loss per year is obtained by summing heat fluxes for each month. Heat loss to the ground for a period equal to one month is [35]

$$Q = z \cdot F \cdot K \cdot \left(t_v - t_s\right), \tag{1}$$

where z is the heat transfer time, hour; F is area, m^2; K is calculated heat transfer coefficient, (W / m^2 · °C); t_y is internal air temperature, °C; t_s is the temperature of the adjacent ground, °C.

Formula (1) defines the heat loss through a selected area with a given area. Redistribution of heat fluxes in the ground massif and its accumulation for discrete time intervals is determined at each step of solving the non-stationary heat transfer problem. The technique used differs by taking into account the change in the temperature fields in the ground adjacent to the structure.

3. Results and Discussion

A ground massif, which lies to a depth of 14 m from the day surface with an underground structure located in it, is considered. In the horizontal direction, the computational model includes a ground massif at a distance of 20 m from the outer contour of the structure. Fig. 1 and the following figures show fragments of sections along the massif, which are necessary for an objective illustration of the studied parameters. The cross-section of the underground structure has dimensions of 20 and 4 m (see Fig. 1). The length of the structure is taken to be 100 m. The thickness of the bearing enclosing structures of the walls made of reinforced concrete is 0.5 m. The floor structures and covering constructions are 0.25 m thick. Structural elements inside the structure (columns and internal walls) are not shown in Fig. 1. The depth of the structure from the surface is taken equal to 1 and 2 m, the temperature in the rooms is 8 °C or 20 °C, the thickness of the thermal insulation layers of the enclosing structures along the outer contour for different options is 0.25 or 0.5 meters.

Boundary and initial conditions on the bottom and side faces of the ground massif correspond to the temperature values in the massif in natural conditions. The boundary conditions on the upper edge are determined by the course of the outside air temperature. The facility is located in one of the regions of the Trans-Baikal Territory. Average monthly and annual air temperature according to Russian Construction Rules 131.13330.2012 (Construction climatology) is given in Table 1.

Table 1. Average monthly and average annual air temperature, °C.

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
–25.0	–20.2	–9.6	1	9.2	16.2	18.5	15.7	8.4	–0.8	–13.1	–22.6	–1.9

A homogeneous ground massif in the model is formed from loams with the following characteristics: dry ground density γ = 1.8 g/cm^3, moisture content W = 20 %, thermal conductivity coefficient of frozen and thawed ground λ_f = 2.0 W / (m °C) and λ_{th} = 1.6 W/(m °C), heat capacity of frozen and thawed ground C_f = 2.41 J / (m^3 °C) 10^{-6} and C_{th} = 3.17 J / (m^3 °C) 10^{-6}, freezing start temperature T_{bf} = –0.2 °C. Thermal conductivity and heat capacity of concrete λ = 1.69 W / (m · °C), c = 0.84 kJ / (kg · °C), density of concrete – γ = 2.5 g / cm^3. Thermal conductivity and heat capacity of a polystyrene foam heat insulator λ = 0.03 W / (m · °C), c = 1.34 kJ / (kg · °C), density γ = 0.035 g / cm^3.

To assess the energy efficiency of an underground object, the temperature fields in the massif and the loss of thermal energy through the enclosing structures are determined. Temperature values in the middle of each month in typical cross-sections for the considered basic ("basic") variant of the structure, buried by 1 m, when the temperature in the premises is taken equal to +8 °C, with a thermal insulation thickness of 0.25 m are given in Table 2. The distribution of temperature fields around the structure in mid-July and mid-February is shown in Fig. 2 and 3.

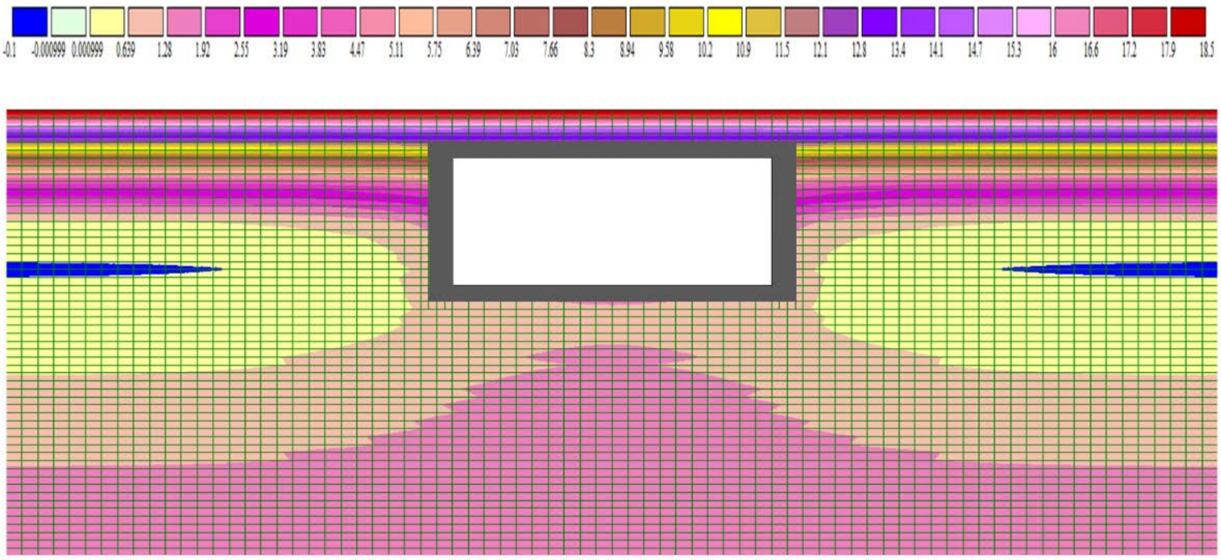

Figure 2. Distribution of temperature in the massif in July
(The numerical values on the color scale are given in °C).

As can be seen from the presented results, the temperature of the ground near the surface of the covering structures during the year fluctuates in the range from 12.3 °C in July to –11.5 °C in February. The change in ground temperature above the covering structure with an increase and decrease in air temperature is more significant than a change in ground temperature in its natural state. This is due to the limitation of the heated zone with a layer of thermal insulation and the accumulation of thermal energy above the covering constructions. The maximum ground temperature under the floor structure is 3.3 °C in February, the minimum is 0.9 °C in June. The ground temperature remains practically the same in the middle sections of the floor and the covering constructions and changes slightly as the corners are approached.

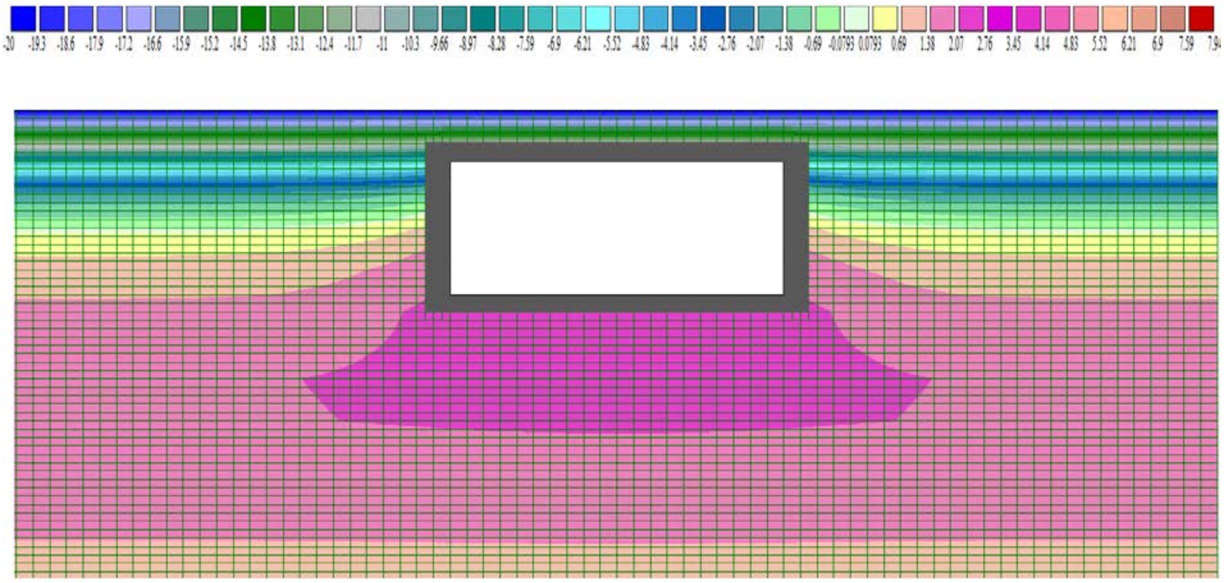

Figure 3. Temperature distribution in the massif in February (The numerical values on the color scale are given in °C).

Table 2. Temperature values at different time periods.

Time period	Temperature values at characteristic points of the outer surface of structures, °C						
	Covering construction points		Floor construction points		Wall construction points		
	Medial	Angled	Medial	Angled	Upper	Medial	Bottom
January	–8.4	–8.5	2.8	2.7	–3.4	1.6	2.4
February	–11.3	–11.5	2.5	2.4	–7.4	0.8	2.0
March	–2.7	–2.8	1.6	1.4	–2.7	–0.6	1.1
April	–1.1	–1.1	1.6	1.3	–1.5	–0.2	1.0
May	0.7	0.7	1.4	1.1	–0.1	0	0.7
June	9.3	9.3	1.2	0.9	5.5	0.5	0.7
July	12.2	12.3	1.3	1.0	8.5	1.4	0.8
August	11.4	11.5	1.9	1.6	9.5	4.2	1.5
September	8.3	8.3	3.2	2.9	8.3	5.5	3.1
October	4.1	4.0	3.3	3.2	5.4	5.4	3.5
November	0.8	0.8	3.1	2.9	1.9	3.3	2.6
December	–4.5	–4.6	3.0	2.8	–0.5	2.4	2.7

The nature of the change in ground temperature at the outer surface of the enclosing structures of the walls is more complex. At the top of the wall, temperature fluctuations are maximum. They vary in the range from –7.4 °C to 9.5 °C. The maximum and minimum ground temperatures at the base of the wall are 3.5 and 0.7 °C, respectively. The maximum and minimum temperatures at the middle of the wall and at the bottom of the wall are reached with a noticeable phase shift in relation to the extreme outside temperatures. It depends on changes in ground temperature at depth in natural conditions. Graphs of ground temperature changes at a depth of 3.5 and 6 meters in natural conditions are shown in Fig. 4. The upper part of the ground massif surrounding the structure, saturated with heat in summer, gives off thermal energy to the layers of ground located below. In the cold period of the year, the wave of a decrease in temperature spreads downward. The positive temperatures around the structure delays the penetration of extreme negative temperatures in depth for 2 months (until March) at a depth of 3.5 meters and for 5 months (until June) at a depth of 6 meters. The penetration into the depth of extreme positive temperatures occurs with a shift of 3 months (until October) at a depth of 3.5 and 6 meters. Such a phase shift distinguishes underground structures located in harsh climates from regions with high air temperatures [37], where there is a slight phase shift between ground and air temperatures. Wave-like changes in temperature in the ground massif adjacent to the structure affect the loss of thermal energy by the structure during the year. Thus, the inertia of the ground around the underground structure smooths out extreme fluctuations in the temperature of the outside air. As a result, the influence of ground inertia is a positive factor for stabilizing the temperature of the grounds adjacent to the structure.

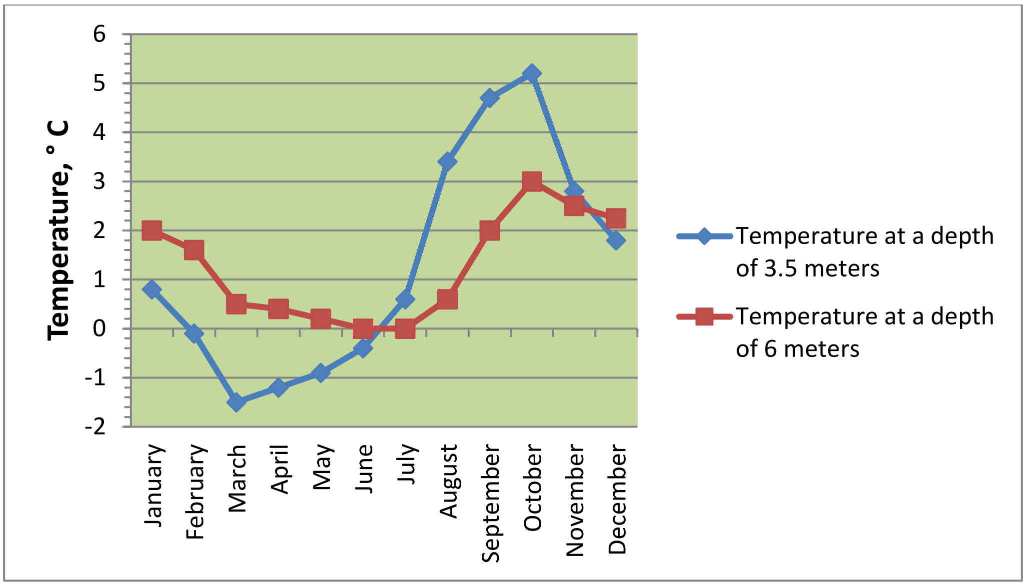

Figure 4. Annual variation of ground temperature at a depth of 3.5 m and 6 m in natural conditions.

In turn, the air temperature in the underground structure also affects the temperature of the adjacent ground massif. The influence of the structure under consideration on the ground temperature in the horizontal direction is about 8 meters. The zone of influence of a buried structure in the horizontal direction coincides with the result given in [37]. The effect on the ground temperature below the floor level is about 7.5 meters. This limited impact is due to the use of thermal insulation. The results of determining heat energy losses through the enclosing structures are presented in Table 3.

Table 3. Loss of heat energy by the structure.

Time period	Energy loss, kWh			
	Through covering construction	Through floor structures	Through wall structures	Total
January	2740	868	576	4184
February	3223	918	674	4815
March	1788	1068	685	3541
April	1520	1068	649	3237
May	1220	1102	622	2944
June	-218	1136	521	1439
July	-702	1120	410	828
August	-568	1018	268	718
September	-50	802	433	1185
October	652	786	236	1674
November	1202	902	410	2514
December	2088	836	473	3397
In just one year	12895	11624	5957	30476

The analysis of the heat losses presented in Table 3 indicates the highest total amount of losses through the ceiling (42.4 %) and floor (38.1 %) and less heat loss through the walls (19.5 %). This is due to the multiple difference in the areas of these surfaces, as well as year-round heat loss through a significant area of the floor surface. At the same time, in terms of the intensity of heat loss through a unit of area in the cold season, heat flow through the ceiling and walls prevails. As can be seen from Table 3, in the period from October to May there are significant losses of thermal energy through the ceiling, in the period from June to September, heat energy enters the ceiling (the energy values are marked in the table with a "-" sign). In regions with a warm climate the heat flux through the floor remains insignificant [20]. In our case the significant heat flux from the floor is due to the low positive ground temperatures under the floor structure throughout the year. At the same time, positive summer heat impulses do not have a significant effect on ground temperature below floor level. The ground temperature here is significantly different from the indoor temperature.

When comparing the underground and aboveground options for structures, it was found that at the design temperature of the internal air +8 °C and the above design parameters, the heat loss for the underground structure was 1.5 times lower compared to a similar above-ground structure. A structure without thermal insulation is not considered, since this option will lead to freezing of structures and a decrease in the temperature of their inner surface below the dew point.

To assess the effectiveness of individual constructive measures, the temperature distribution on the contour of the structure and the corresponding heat energy losses in the most energy-intensive periods of the year (in January and February) are determined. The calculation results are presented in tables 4 and 5. Heat losses during this period fully reflect the influence of the investigated factors on the efficiency of underground structures. When the structure is deepened to 2 meters from the outer contour of the structure, the ground temperature near the outer contour of the covering construction in January and February becomes significantly higher due to the increase in the insulating function of the ground layer. At the same time, the temperature of the ground under the floor structure and in the zone of the lower part of the walls changes insignificantly due to its greater stability with increasing depth. An increase in the temperature of the internal air in the premises up to 20 °C have an insignificant effect on the temperature of the ground on the contour of the structure. The indicated increase in the air temperature leads to an increase in the temperature of the ground at the surface of the enclosing covering construction by 1.6–1.8 degrees. The ground temperature under the floor structure and at the bottom of the walls also increases in 2 winter months by 1.2–1.4 degrees. An increase in the size of the thermal insulation layer to 0.5 meters, regardless of the considered depth of the structure, limits the heating of the ground massifs adjacent to the structure and significantly reduces the temperature at the outer contour of the object (see Table 4).

Table 4. Temperature values on the contour of the structure for different design features.

Time period and technical features	Temperature values at characteristic points of the outer surface of structures, °C						
	Covering construction points		Floor construction points		Wall construction points		
	Medial	Angled	Medial	Angled	Upper	Medial	Bottom
January, basic version	–8.4	–8.5	2.8	2.7	–3.4	1.6	2.4
February, basic version	–11.3	–11.5	2.5	2.4	–7.4	0.8	2.0
January, depth 2 m	–0.6	–1.0	3.0	2.8	–0.1	2.4	2.8
February, depth 2 m	–3.1	–3.5	2.6	2.4	–1.3	1.6	2.3
January, indoor temperature is 20 °C	–7.8	–7.9	4.4	3.9	–2.6	2.8	3.5
February, indoor temperature is 20 °C	–10.7	–10.8	4.3	3.7	–6.4	2.2	3.2
February, insulation 0.5 m, deepening 1.25 m from the roof supporting structure	–13.7	–13.8	2.1	2.0	–7.7	0.4	1.7
February, insulation 0.5 m, deepening 2.25 m from the roof supporting structure	–5.2	–5.4	2.3	2.2	–1.6	1.2	2.0

Table 5. Loss of thermal energy by the structure at different design features.

Time period and technical features	Energy loss, kWh			
	Through covering construction	Through floor structures	Through wall structures	Total
January, basic version	2740	868	576	4184
February, basic version	3223	918	674	4815
January, indoor temperature is 20 °C	4640	2600	1354	8594
February, indoor temperature is 20 °C	5120	2620	1747	9487
January, depth 2 m	1440	840	442	2722
February, depth 2 m	1860	900	509	3269
February, insulation 0.5 m, deepening 1.25 m from the roof supporting structure	1840	500	310	2650
February, insulation 0.5 m, deepening 2.25 m from the roof supporting structure	1120	480	278	1878

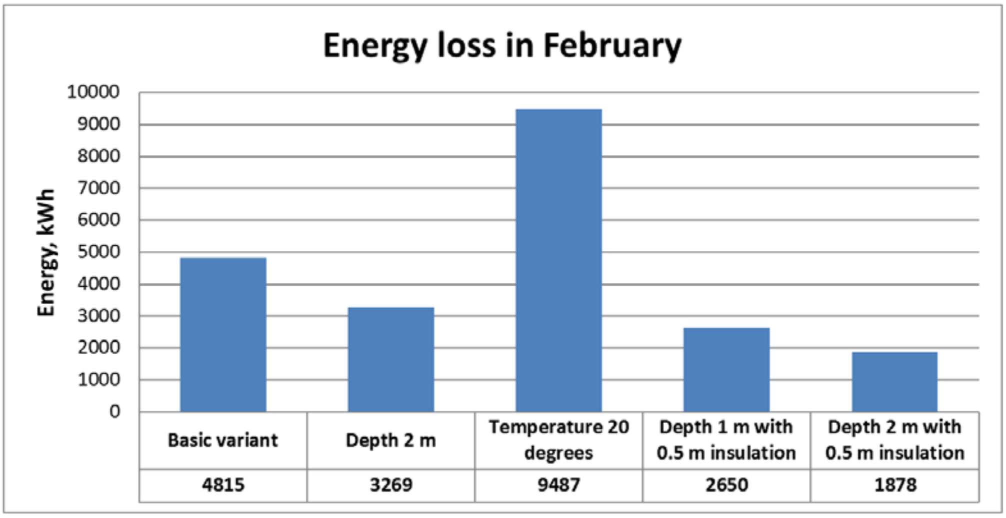

Figure 5. Energy losses of an underground structure in February.

As follows from the results presented in Table 5, moving the structure to a depth of up to 2 meters from the surface of the outer contour of the structure reduces heat losses by a third in two months compared to the base case. An increase in the temperature of the indoor air in an underground room up to 20 °C doubles the heat loss in the two coldest months. An increase in the thickness of thermal insulation from 0.25 to 0.5 meters for a structure located at a depth of 1.25 meters from the supporting structure of the coating reduces heat loss by 1.82 times. For a structure located at a depth of 2.25 meters, heat losses are reduced by 1.74 times. Increasing the insulation layer turns out to be more effective than increasing the depth of the structure and less costly in terms of the amount of work. The effectiveness of constructive measures on the example of heat losses in February, characterized by the highest heat losses for the year, is clearly shown in Fig. 5.

4. Conclusions

1. A method for determining heat losses in underground structures in a harsh climate, based on determining the temperature fields in the adjacent ground massifs by solving the non-stationary problem of heat conduction is presented. The technique is distinguished by taking into account the thermal inertia of the ground mass with significant fluctuations in the outside air temperature.

2. The degree of energy efficiency of underground construction objects in harsh climatic conditions was determined by the criterion of reducing the loss of thermal energy by the structure. Energy losses by an underground object in the considered climatic conditions and with the used design parameters are reduced by 1.5 times in comparison with a similar above-ground structure.

3. The effectiveness of individual design measures to reduce heat energy losses for underground structures has been established. Deepening a structure to 2 meters from the surface reduces heat energy losses by a third in the coldest months compared to a structure buried by 1 meter. The energy efficiency of

underground structures in the northern regions increases with the indoor temperature approaching the temperature of the ground in its natural state, as well as with the use of large layers of effective thermal insulation materials at the outer contour of the structures.

4. The problem to be solved is of great practical importance for assessing the feasibility of using underground construction facilities in harsh climatic conditions and for choosing the design parameters of underground facilities.

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