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Forecast the Processes of Thawing of Permafrost Soils under the Building with the Large Heat Emission

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Abstract. The paper describes a mathematical model of the soil experiencing freezing and thawing. The mathematical model is realized by the authors with the use of finite element method in the program «Termoground». The results of calculation the processes of the thawing of permafrost soil under the building with the large heat emission with various constructive measures for the conservation of frozen soil structure are given. Taking into account high costs of such measures it is recommended a combination of I and II principles of the design of foundations allowing partial thawing of soil, which requires the ability to predict the deformation of thawing soil.

1 Introduction

The prevalence of the processes of freezing and thawing of soils on the Earth is completely great. These processes are extended especially in the north latitudes on the Eurasian and American continents and also in the countries which are adjacent to the South Pole. Low temperature in winter periods is typical for mountainous areas, for example in Central Europe. Finally, the enormous Siberian spaces of the Russian Federation from the coast of the Arctic Ocean to the border with China composed of permafrost soils. Designing of foundations of buildings and structures on such soils has its special features which are differed significantly from the designing of bases and foundations of buildings on the non-frozen soils.

Besides the regions with the cold climate the problem of freezing and thawing of soils can also be found in the territories with high plus average annual temperatures during the underground works using freezing method. This method for example is widely used in the construction of tunnels especially inclined subway tunnels during the intersection by them the soft water-saturated soils of great thicknesses. The disadvantage of the method of freezing is significant settlement of territory after the degradation of ice-ground cylinders which causes deformations of buildings and structures located in the zone of influence of soil thawing.

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The volumetric strains characteristic for the soils in the process of their freezing and thawing can be up to ten percent or more. In this regard during the solution of this type of problem it is necessary to be able to predict not only temperature fields but also stress-strain state of system "structure – freezing (thawing) soil".

The practice of the construction and operation of buildings and structures when the influence of the processes of freezing and thawing of the soil was ignored has a huge number of negative examples. According to many years of experience of the authors we can mention the formation of lenses of frozen soils up to 6 meters under the buildings of Petersburg refrigerators; freezing of soils under buildings in the winter time, freezing of soils along the contour of pits in winter period, etc. In all these cases with the freezing or subsequent thawing of soil the through cracks were formed in the frameworks of buildings (walls or columns), and the sheet pile walls were deformed with the break of anchors. In the case of occurrence of permafrost soils in the base of foundations their thawing in the process of operation led to the settlements amounts to tens of centimeters which made further functioning of objects impossible [1-12].

2 Solution the problems of freezing and thawing of soils

Thus, the problem of the calculation of freezing and thawing of the soils – of base or medium, which contains construction, are extremely urgent. However, in these cases it is required to take into account the interaction between foundations and structures. Moreover the calculation of such interaction in connection with the development of computer calculations is possible only with the use of numerical methods which makes it possible to solve problems, also, for the three-dimensional conditions.

The calculation of the influence of freezing and thawing of soils assumes two-step solution of problems – first calculation of temperature fields and then the determination of the stress-strain state of the soil and the structure. Let us note that the Stephen solution for the solution of temperature problem cannot directly be used because in the cohesive soils the transition of water into ice and back occurs not at a zero temperature but in the range of negative temperatures. The freezing of the cohesive soils in most cases is accompanied by the migration of pore water to the front of freezing. In connection with this, the correct calculation of temperature fields requires taking into account the influence of the additionally entering water, which is essential for the balance of the entire heat exchange. Therefore the first step of calculations is calculation of temperature fields as a result of solution of hygrothermal problem.

The question about the lawfulness of using one or other expression for the thermal conductivity arises in solving the problem of hydrothermal problem.

The well-known equation for conductive heat transfer for the media with phase transitions is written as follows [1, 2]:

$$C_{th(f)}\rho_d \frac{\partial T}{\partial t} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}(\lambda_{th(f)} \frac{\partial T}{\partial x_i}) + q_v \tag{1}$$

where $C_{th(f)}$ – specific heat of soils (frozen or thawed); ρd – soil skeleton density; T – temperature, t – time; $\lambda_{th(f)}$ – thermal conductivity of soil (frozen and thawed); x, y, z – coordinates; q_v – internal heat source capacity.

The complete differential equation of thermal conductivity takes the form:

$$\rho_d (C_{th(f)} + L_0 \frac{\partial W_w}{\partial T}) \frac{\partial T}{\partial t} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}(\lambda_{th(f)} \frac{\partial T}{\partial x_i}) + q_v \tag{2}$$

where L_0 – water-ice latent heat of transition; W_w – water content of unfrozen water.

The calculation of temperature fields with the use of the expression (2) provides for the calculation of the heat transfer only by the mechanism of conduction. However as already mentioned the certain quantity water migrates to the front and into the frozen zone. In this regard the question appears what amount of heat the migrating water brings and whether it is necessary to take this heat delivered to the front due to convection into account in the heat equation.

The question about the relative influence of conductive and convective heat transfer in freezing soils studied R.L.Harlan and J.F.Nixon [3]. They have shown that the convective component should be considered only at high rates of mass transfer. However in the case of the migration of water in the relatively low-permeable cohesive soils the contribution of convective component of heat flux can be disregarded.

The similar conclusion can be approached on the other hand comparing the rate of freezing and water migration. In most cases the rate of the water migration is not more than ten percent of the rate of freezing, which makes it possible not to take into account the contribution of the heat delivered into the frozen zone by the migrating water. Thus, the use of expressions (1) and (2) for calculating the temperature fields in the freezing soils of low permeability is justifiable.

The use of rigorous theoretical solutions is thus far impossible for the forecast of an increase of the water content in the freezing zone due to the water migration. The authors of the article developed the «Termoground» program based on the well-known computer complex FEM models [8, 9] where the amount of inflowing water in the frozen zone is established on the basis of processing of experimental works of L.V.Chistotinov [4] and G.M.Feldman [5]. This amount of inflowing water depends on the type of soil, rate of its freezing as well as the distance between the front of the freezing and the groundwater level.

For the calculation the stress-strain state of the freezing soil it is necessary to assign the law of the soil deformation during the freezing depending on different factors. The calculated temperature fields can come out as this factor; however, similar solutions are applicable only for the closed systems [6]. More correct are established during the first step of calculations the fields of the water content of soil, an increase in volume of which during transition of water into ice will make it possible to estimate increase in the volume of soil with the freezing. An additional factor in increasing the soil volume during freezing is the growth of frost cracks. Finally, according to our experience in the majority of cases in the calculations of frost heave such the influence of factors as stresses in soil, etc. can be neglected.

For the solution of the problems of thawing there are different ways – from taking into account only the physical characteristics of frozen soil to the direct use “thermal” and “load” component of the standard characteristics of thawing placed in the Russian standards.

3 Numerical modeling of degradation of permafrost soil under the building with large heat emission

In this paper we consider a specific example of building with large heat emission on permafrost soil – the boiler house. Construction of the building is assumed according to the first principle, i.e., with the preservation of the frozen state of the soil. Foundations under the external walls of boiler house and under the boilers piled with piles length of 10 m. The cross section of building is shown in Fig. 1. The three-dimensional numerical model which includes soil, foundations and building is given in Fig. 2.

The temperature on the outer contour of the boiler is +55°C. It is assumed that the work of the boiler in the annual cycle is carried out from the middle of October before the middle of July. For a number of design considerations aired underground under the building is impossible.

First of all let us consider the solution of the problem without the use of additional measures for the conservation of frozen soil structure. This problem is solved for an example, since it is obvious that the construction of building with the large heat emission without such measures even on the little icy soil does not have a sense.

Fig. 3 shows the area of soil thaw in cross-section after 50 years of operation of a building. Estimated depth of thawing is about 16 m.

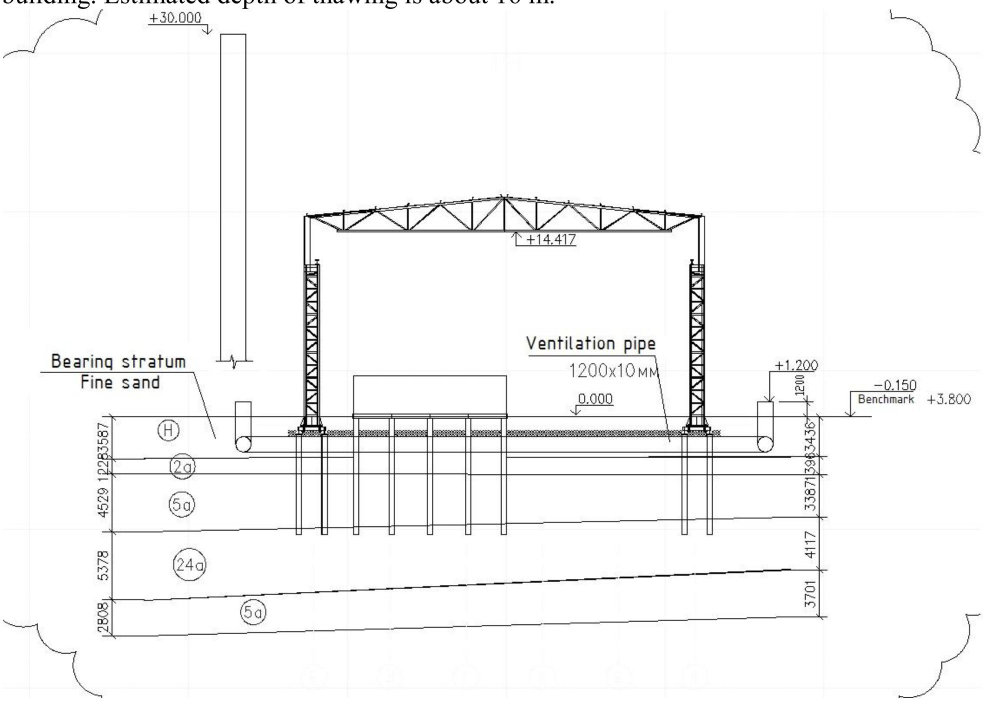

Fig. 1. Cross section of boiler house.

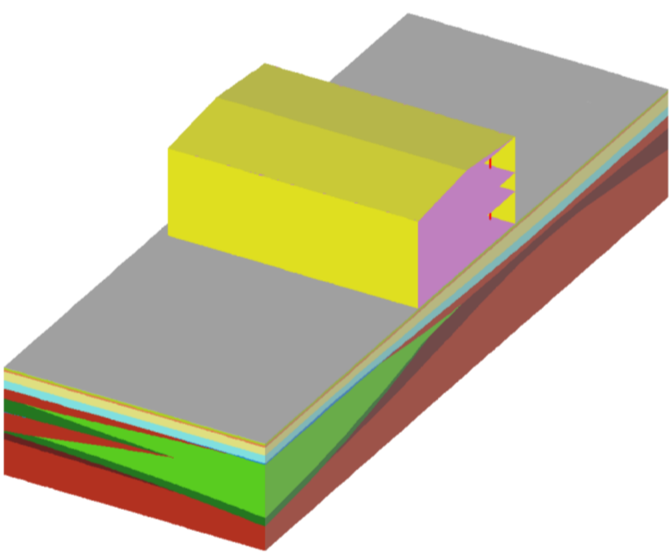

Fig. 2. Numerical models of building and soil.

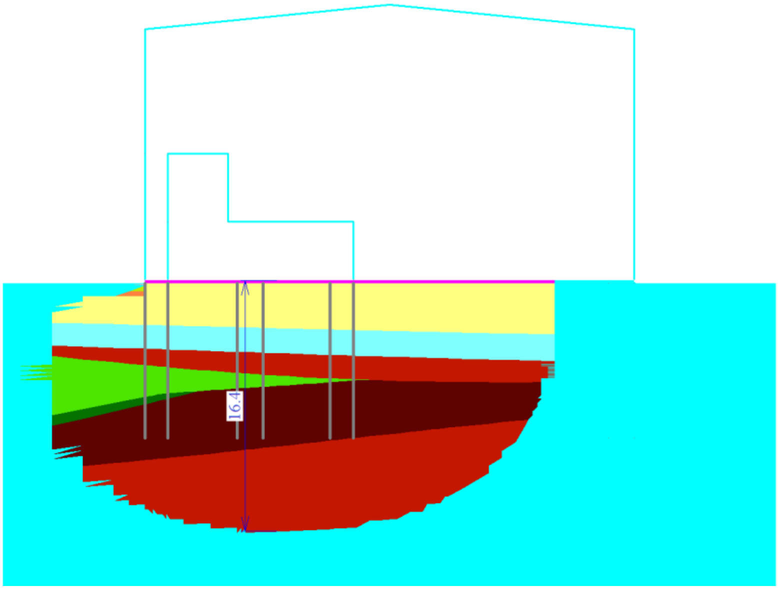

Fig. 3. The area of ground thaw under the building in the absence of measures for the conservation of frozen soil.

It is obvious that with this large depth of the soil thawing the development of catastrophic settlements should be expected. Fig. 4 shows a diagram of settlements of the building after 50 years of its operation in the construction of buildings on the shallow foundations.

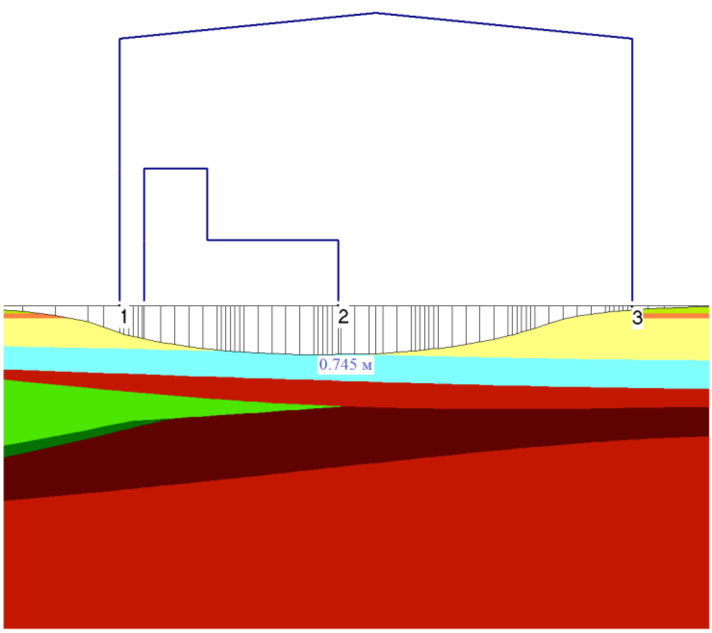

Fig. 4. Plot of ground settlements under the building in the absence of measures for the conservation of frozen soil structure and the construction of buildings on the shallow foundations

Diagram does not include the settlements of building due to its own loads. After 50 years the estimated settlement of the building is 75 cm. Fig. 5 shows the graphs of the

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development of settlements of building in the time for three characteristic points – two points (№1 also №3) along the edges of building, one point (№2) – under the center of building.

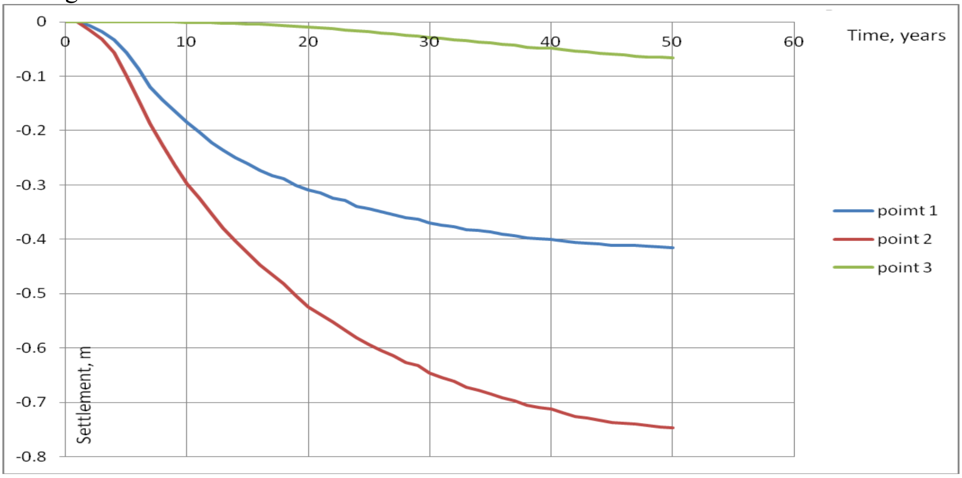

Fig. 5. Graph of settlements of building in the time.

The position of the points is shown in Fig. 4. As it can be seen from the graphs without any measures to preserve the frozen soil structure during the entire 50-year of operation of the building it will undergo settlements. Thus, it is necessary to find the solution to reduce the sizes of the area of thawing of the soil, since the thaw trough seizes foundations under the walls (left part of the section in Fig. 3).

Construction of buildings on the designed 10-meter length piles reduces the estimated settlements of the building almost in 2 time (Fig. 6), especially in the locations of the piles (to 47 cm in 50 years of operation of the building). However, in the span areas the settlements reduce insignificantly (to 62 cm).

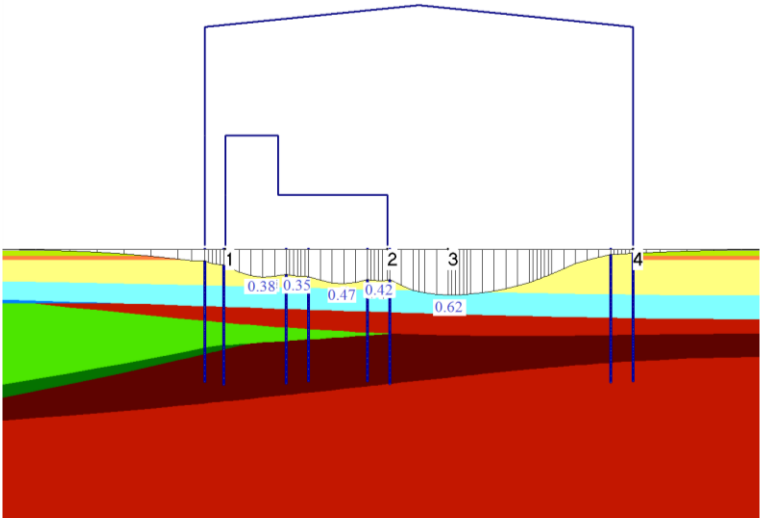

Fig.6. Plot of ground settlements under the building in the absence of measures for the conservation of frozen soil structure and the construction of buildings on the 10-meter length piles.

Graphs of the development of settlements in the time in Fig. 7 are shown for the same points under the building as on the graphs Fig. 5. Graph for the intermediate point (№3) with the greatest absolute value of settlement is additionally shown. The graphs show that the deformation of the soil appears almost immediately at the beginning of the thawing of the soil which is associated with the development of negative skin friction on the piles with the subsidence of soil thawing.

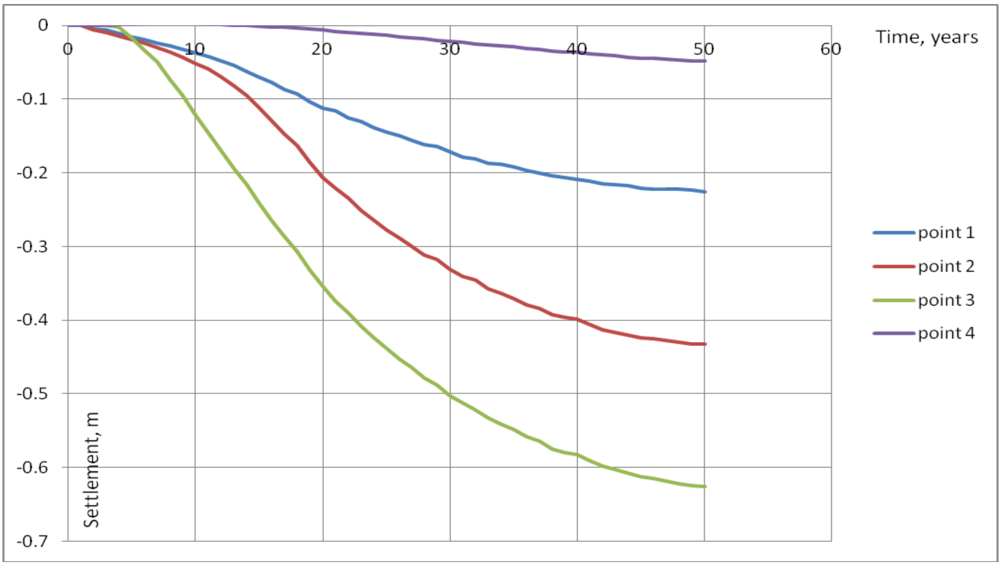

Fig. 7. Graph of settlements of building on piles in the time.

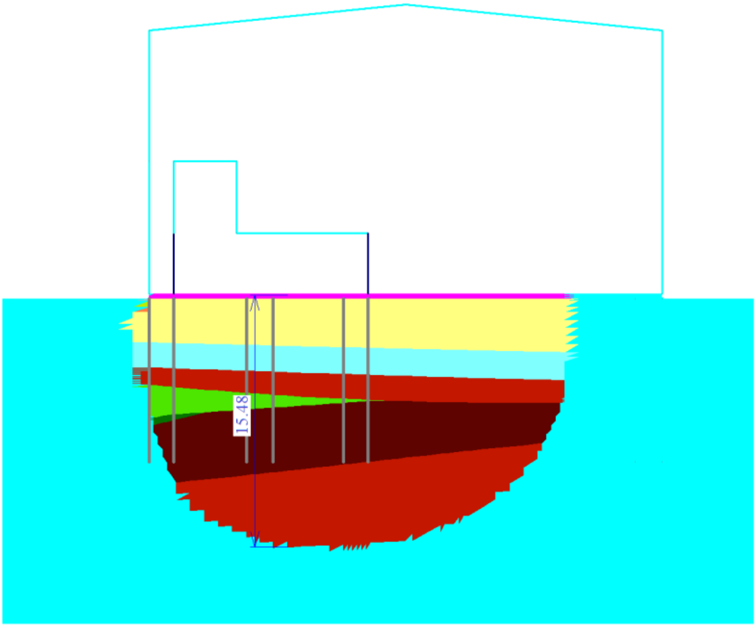

Fig. 8. The area of ground thaw under the building with the vertical thermal stabilizers on the outer contour of the building.

Let us estimate the effectiveness of the work of the vertical seasonal-cooling devices (SCD) for the case in question. Since the building does not have the aired underground, the installation of thermal stabilizers is possible only near the outer side of the building. The depth of the SCD was taken equal to the depth of piles. The work of SCD is accepted to evaluate by the effectiveness ratio of cooling. AS one of the most effective the thermal stabilizers of the type TMD-5 is considered with the anticorrosive aluminum alloy with the ratio of cooling efficiency to 0.75 developed be “Inter Heat Pipe” company. In our calculations we assumed the most common and cheap SCD made of steel with a diameter 54 of mm irrespectively of the type of thermal stabilizer with the effectiveness ratio of the cooling 0.5.

With the simulation of work of the SCD near the foundations of the building of boiler house the thermal stabilizers were arranged next to each pile of external rows. It is evident from Fig. 8 that the SCD eliminate the heat propagation in the ground outside of the building dimensions, actually ensures the work of the external piles, near which the SCD are installed, however the internal piles are located in the zone of thawing. These heat stabilizers do not affect the depth of thawing of the soil under the boilers.

One of the most effective for reducing of the soil thaw depth is often assumed the insulation between the ground floors of the building and the ground. Let us consider the case of 30-centimeters heat insulation made of polyfoam under the ground floor of the building in combination with the vertical SCD installed at the outer contour of the building.

It is evident from Fig. 9 that under these conditions the depth of thawing is reduced to 11.3 m. The internal piles are located completely in the zone of the thawing of soil. According to the experience of our calculations, the thermal properties of the 10-centimeter layer of polyfoam are equivalent to the 1-meter layer of soil. Thus to exclude the thawing of soil it will be required the 1-1.5-meter layer of thermal insulation.

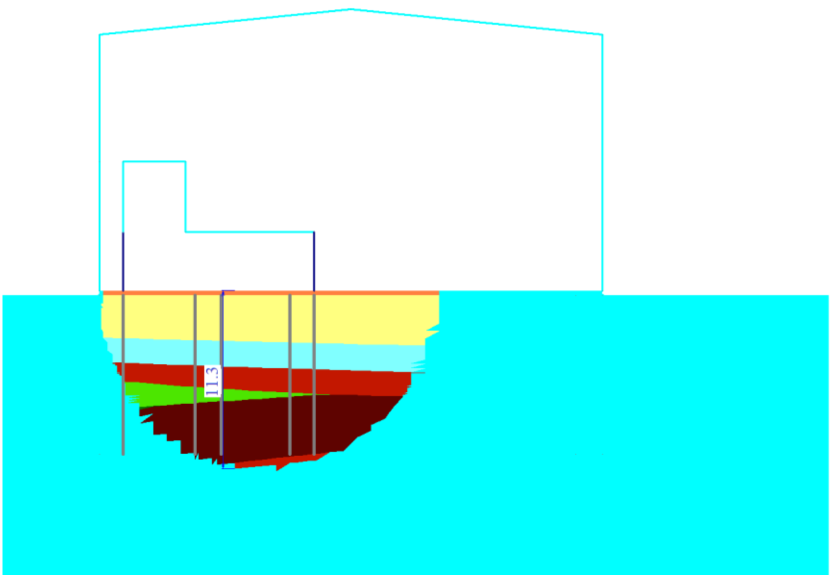

Fig. 9. The area of ground thaw under the building with the vertical thermal stabilizers on the outer contour of the building and 30-centimeters layer of heat insulation.

The horizontal ventilated channels under the building in combination with the 30-centimeter layer of heat insulation prove to be most effective for the building with the large heat emission. Under the conditions in question this version makes it possible to practically completely exclude the thawing of soil under the building. According to the calculations the maximum depth of thawing is fallen for the warm period, when the ventilated channels are turned off while the boiler is not working. This depth is 1.1 m (Fig. 10) that is almost equal to the depth of seasonal freezing and thawing of the soil.

Thus, for a satisfactory solution of the problem of minimization of soil thawing the ventilated channels are effective for a satisfactory solution of the problem of minimization of soil thawing.

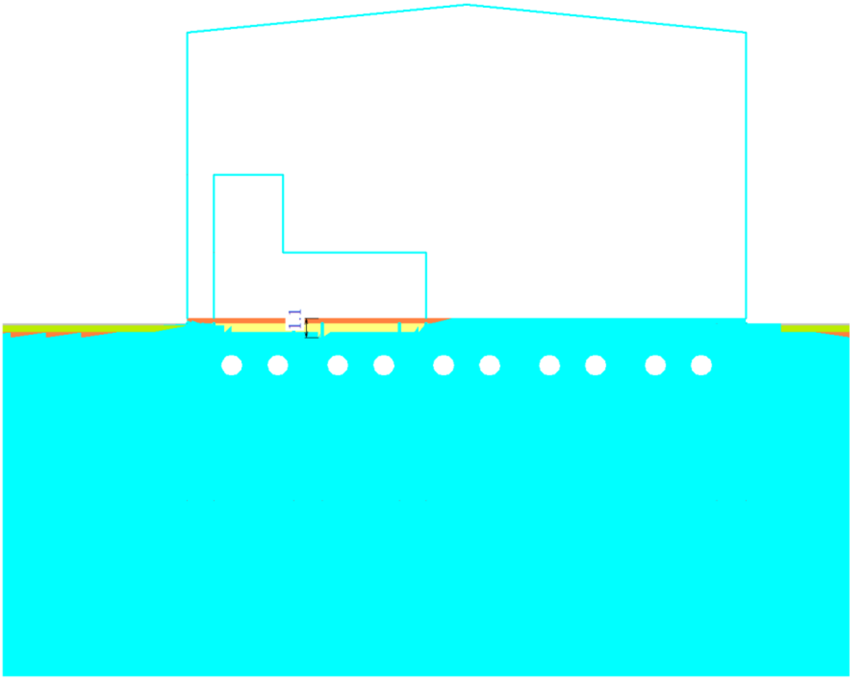

Fig. 10. The area of ground thaw under the building with the horizontal ventilated channels and 30-centimeters layer of heat insulation**.**

Conclusion

During construction of buildings with a large heat emission on the permafrost soils the dimensions of the area of soil thawing in both the horizontal and vertical directions can be tens of meters.

According to the results of calculations, ventilation channels under the building in combination with the horizontal heat insulation of relatively small thickness are one of the most effective measures.

The measures for conservation of frozen soil structure are quite expensive and energy intensive. In such conditions the combination of I and II principles of the design of foundations allowing partial thawing of soil seems appropriate. However, the possibility of a combination of these principles is not enough just only on the base of prediction of the temperature fields in soils. The correct solution of problems should include an assessment of the evolution of temperature fields and stress-strain state of the system "construction - freeze (thawed) soil" for the entire period of operation of the building.

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