Calculation of foundation platforms on degraded permafrost bases

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Abstract. In connection with degradation of permafrost soils, the issue of designing and building foundations is acutely raised, taking into account the possible thawing of the soil at the base of structures. A spatial foundation platform is less sensitive to deformations of the foundation soil due to the integral work of the structure, compared to other foundations. For this and a number of other reasons, the use of the platform is promising. As the main structural material in spatial foundation platforms, it is advisable to use engineering wood, because of its advantages in comparison with reinforced concrete and metal. The article presents some results of calculations of the foundation platform of the folded type. The COMSOL Multiphysics software package simulates the process of thermal degradation of the soil under the foundation platform caused by an increase in air temperature. As a result, the soil warming zone was established, which is necessary for the design of the foundation platform taking into account changing boundary conditions. Preliminary conclusions are made about the influence of the degradation of the frozen base on the stress-strain state and the structure of the foundation platform of the folded type.

1. Introduction

Modern economy of the Russian Federation is aimed at developing the Arctic regions. The subsoil of cryolithozone hides a lot of minerals, which dictates the need to develop the Arctic territory. The construction of buildings and structures on permafrost is relevant, promising and at the same time problematic not only for Russia, but also for the countries located in Northern latitudes. Taking into account the cryogenic processes of permafrost and predicted global warming, it is important to develop foundation structures that ensure the stability of the structure during the degradation of permafrost strata [1, 2].

According to the authors, the use of various types of spatial foundation platforms [3-5] is clearly appropriate here. Platforms can be made in the form of systems of cross beams or trusses, structural plate, plate-rod structure, as well as in the form of shells and folds [Patent 83520 Russian Federation, Spatial Foundation platform]. Regardless of design solution, the spatial foundation platform must be combined. Modular and versatile spatial foundation platforms improve transportability and allow them to be used for various buildings and structures.
2. Materials and methods
The use of spatial foundation platforms based on timber in Northern latitudes is promising due to the reduction of the risk of base thawing due to the low thermal conductivity of wood [7]. Wood has a low coefficient of thermal conductivity, which significantly increases the energy efficiency of the structure as a whole. The use of wooden structures reduces logistics costs due to their transportability. In addition, due to the increased factory readiness and prefabricated wooden structures, the speed of construction increases. In general, the construction of buildings made of timber in Northern latitudes is a promising direction due to technical, aesthetic and geometric characteristics of the structure [8-10].

The use of reinforced concrete foundations has its significant disadvantages due to their rather large weight, poorly developed logistics of high-latitude construction and seasonality of installation work. Precast concrete is difficult to transport, and cast-in-place concrete significantly slows down the construction process. With all the known advantages, metal structures contribute, in particular, to undesirable heat transfers into the thickness of the base soil [6].

When installing the platform, it is not expected to perform significant amounts of earthwork. The top layer of soil is cut off or an embankment is formed to form the design surface.

During the operation of buildings and structures built on spatial foundation platforms, it is necessary to take into account the possible degradation of the frozen soil of the base. Thermal degradation of soil can be caused by many factors, such as (for the case of Norilsk) [11]:

- heat transfer from buildings and structures;
- technogenic impact;
- global climate change;
- water spillage of engineering networks;
- improper organization of engineering preparation of the territory, as a result of which melt water and precipitation penetrate into the soil under the structure.

Each factor affecting the degradation of permafrost strata, in turn, consists of different physical processes.

3. Results
The following operating conditions of the spatial foundation platform on a frozen base are possible:

- normal;
- normal-probable;
- emergency.

Normal operation of a foundation platform is a complex of natural physical processes that occur during the operation of the spatial foundation platform in accordance with current regulatory and advisory documentation. During normal operation, the calculation modeling takes into account the physical processes of heat transfer to the thickness of the ground base from the thermal contour of the building or structure, convection in the ventilated space of the foundation platform, and climate changes in the environment during the year.

Normal-probable operation of a spatial foundation platform is a complex of physical processes that include processes during normal operation, as well as probable changes in weather and climate conditions during the entire period of operation. In normal-probable operation, together with physical processes corresponding to normal operation, the processes of snowdrifts, changes in natural mode of movement of surface and ground water, as well as global climate change are taken into account. In turn, global climate change affects the temperature of frozen soil and the amount of wind loads. In this regard, the zones of soil thawing under the spatial foundation platform will have their own character.

Emergency operation of a spatial foundation platform is a stochastic system of physical processes that includes processes during normal operation (including violation of physical processes related to
normal operation) and normal-probable operation, as well as processes that have a harmful anthropogenic origin. Emergency operation involves various physical processes, such as:

1) anthropogenic change of natural landscapes;
2) anthropogenic environmental pollution;
3) violation of the natural regime, conditions of movement and composition of surface and ground water;
4) operational leaks from communications;
5) mechanized redistribution of snow deposits with annual storage of powerful snow dumps in courtyards;
6) improper organization of engineering training of nearby territories.

When designing spatial foundation platforms, in our opinion, six types of boundary conditions for thawing the frozen base under the foundation platform are to be considered (table 1).

**Table 1. Boundary conditions for the thawing of the ground base.**

| Type of boundary condition | The nature of soil thawing under the platform. Operation condition. The physical process that caused thawing. | A schematic image of a thawed (degraded) zone of permafrost under the spatial foundation platform (shaded in black) |
|---------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| 1 Base thawing is not available. Normal operation of the platform. | | |
| 2 Thawed base under the center of the platform. In normal-probable operation, such a thawing pattern is possible when the natural regime of groundwater movement changes. In case of emergency operation of the platform, a similar zone of thawing may be caused by significant heat transfers from the overlying structures, or by spillage of water from engineering networks | | |
| Type of a boundary condition | The nature of soil thawing under the platform. Operation condition. The physical process that caused thawing. | A schematic image of a thawed (degraded) zone of permafrost under the spatial foundation platform (shaded in black) |
|-----------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| 3                           | Thawed base around the perimeter of the platform. It is possible with normal-probable operation in snow-drifts and global climate change. In the event of an emergency operating condition, it may be caused by a violation of physical processes during normal operation. Less than 1/2 of the thawed base (the platform works as a console). In case of emergency operation of the platform, a similar thawing zone may be caused by improper engineering preparation of the surrounding area. As a result, surface wastewater enters the base under the platform Local thawing zones (the location of thermal degradation zones in this diagram is shown conditionally). Possible in case of emergency operation of the foundation platform, as a result of local temperature increases and water spills of engineering networks. Base thawing over the entire area. Such a pattern of thawing is possible under normal-probable operation in the case of changes in the natural flow of surface and ground water, as well as in the case of global climate change. In case of emergency operation, it is possible as a result of any physical processes. | ![Thawed base](image1)  
![Local thawing zones](image2)  
![Base thawing over the entire area](image3) |
| 4                           | ![A schematic image](image4)  
| 5                           | ![A schematic image](image5)  
| 6                           | ![A schematic image](image6)  

The second column (table 1) shows the most likely causes of the formation of the corresponding thawing zones. As, for example, in the case of the 3rd boundary condition, thawing along the perimeter of the foundation platform is also possible, if the engineering preparation of the nearby territory is not properly organized; as a result, surface wastewater enters the base along the perimeter.
of the platform. This reason is unlikely in relation to other reasons, but it is possible. In fact, depending on the initial data, the consequence of any physical process can be expressed by any zone of thawing of the frozen base under the foundation platform.

When operating a spatial foundation platform it is worth considering four types of limiting states:

1) The thawed base under the centre of the platform. The causes of this limiting state are described in Table 1 for the second type of boundary condition;
2) The thawed base along the perimeter of the platform. The causes of this limiting state are described in Table 1 for the third type of boundary condition;
3) Less than 1/2 of the thawed base (the platform works as a console). The causes of this limiting state are described in Table 1 for the fourth type of boundary condition;
4) Local thawing zones under the platform. A description of the causes of this limiting state is given in Table 1 for the fifth type of boundary condition.

Each boundary condition describes the behavior of the platform when the load-bearing capacity of the base is exhausted, and the platform cannot be operated.

The 1st and 6th boundary conditions are not limiting states. The case of no thawing under the foundation platform is favorable. In the case of thawing over the entire area, the performance characteristics of the platform depend on the loads and properties of the base. Boundary condition 6 is similar to boundary condition 1, except that the load-bearing capacity of the base is reduced, and platform operation might be impossible.

In accordance with the identified limiting states, the corresponding calculation schemes can be identified (table 2).

Table 2. Calculation schemes for various limiting states.

| Type of limiting state | Design scheme |
|------------------------|---------------|
| 1. Thawed base under the center of the platform | 1 state (reduced load-bearing capacity) |
| 2. Thawed base along the perimeter of the platform | 2 State (soil subsidence) |
| 3. Less than 1/2 of the thawed base (the platform works as a console) | |
| 4. Local thawing zones under the platform | |

The thawed base support of the foundation platform can be considered in 2 states:

1) Reduced load capacity of the thawed zone;
2) Subsidence of soil as a result of thermal degradation.

In the first state, the base has sufficient load-bearing capacity and increased pliability. There is contact between the platform and the base. Loads from overlying structures continue to be transferred to the weakened base. The 1st state of the thawed base support of the foundation platform is more typical for large-block soils, large and gravelly sands. When thawing, soil deformations are
insignificant. Ice particles, passing into a liquid aggregate state, do not destroy the structure of the soil, thereby providing sufficient load-bearing capacity. The ice that fills the pores between the soil particles, when thawing, does not subject the solid particles of the soil to significant movement. Before thawing, the bearing capacity of the soil was higher, since the particles of soil and ice worked as one whole. Thawing increased the porosity of the soil, hence compressibility characteristics.

In the second state, as a result of subsidence, there is no contact between the platform and the base. Operation of the platform is carried out due to the spatial work of the structure.

The authors have calculated the spatial foundation platform made of wooden elements, for the building of lenticular form (figures 1, 2). The structural solution of the spatial foundation platform is proposed in the form of folds.

The folds are formed by two plates installed with an angle of inclination of 37° with respect to the vertical; the folds are installed with overlapping seams to ensure the spatial operation of the structure. The interface of the slab of folds at the top is hinged.

On the tops of the folds, in the direction perpendicular to their direction, the foundation slabs are laid. The interface of slabs with folds and the interface of slabs with each other on the side faces are hinged.

At the base of the foundation, in the direction perpendicular to the folds, the base slabs are arranged. The interface of slabs with folds and the interface of slabs with each other on the side faces are hinged.

The frame of the lenticular building is formed by sixteen semi-arches in the amount of 18 pieces of 160×693 mm cross-section with a step of 5.209 m in the greatest 30 m diameter of the building. The lens base diameter - 16 m. Building height is 13 m. From the largest diameter of the building, the semi-arches are located down to the base and up to the support ring that unites the columns, with a diameter of 6 m. The columns with a cross section of 235×660 mm are arranged in a circle in the amount of 9 pieces. The bearing structures are made of glued wood of 2 grades (pine).
A close analog of the spatial foundation platform considered by the authors in the form of wood-based folds is the spatial foundations of Yu. M. Goncharov and A. P. Popovich, designed and implemented in experimental construction from reinforced concrete.

The spatial foundation platform in the form of folds is designed from CLT plates [12-15] arranged obliquely to each other, forming a spatial folded surface of the billowed type.

The space between the CLT plates and the base soil (in the form of a triangular prism) can be filled with low-compressible soil and insulation (figure 3). The space between the CLT plates and the first storey floor (in the form of a triangular prism) is ventilated and can be used for the location of communications.

The device of triangular prisms from low-compressible soil is a labor-intensive process, depending on the time of year and on the properties of the soil. It is advisable to consider a variant of the device of a folded foundation, in the lower belt of which CLT plates are located (figure 4).

To implement the principle of building closure and spatial operation of the platform, it is advisable to place CLT plates in the upper belt (figure 5).

The authors have calculated the spatial foundation platform in the COMSOL Multiphysics software package in order to determine the parameters of soil thawing under the lower belt. The 2nd limiting state of operation of the foundation platform-thawing along the perimeter of the platform was studied.
In this case, the physical process of heat transfer from the lens-shaped building under operation was considered, without taking into account the convection and air flow of the ventilated space of the spatial foundation platform. This combination of physical processes is possible in the normal-probable operation of the spatial foundation platform, for example, in the processes of snow drifts of the platform's vented blowouts. The spatial foundation platform rests directly on the soil without bedding. The problem is solved with boundary conditions of the third kind. When calculating, the heat transfer coefficient is assumed to be constant and equal to 23 W/(m²·°C) in accordance with Russian State Standard SP 50.13330.2012. The surface temperature is assumed to be equal to the average monthly outdoor air temperature for the city of Norilsk (table 3) according to Russian State Standard SP 131.13330.2012. At the lower boundary of the calculated area, at a depth of 10 meters, based on the literature and calculated data, a heat flux of 2.72 W/m² was set. The indoor temperature is assumed to be constant and equal to 20° C, the heat transfer coefficient is 8.7 W/(m²·°C) according to Russian State Standard SP 50.13330.2012.

### Table 3. Temperature for the city of Norilsk.

| Month  | January | February | March | April | May | June | July | August | September | October | November | December |
|--------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Soil temperature | -27.3 | -25.3 | -20.2 | -14.7 | -5.2 | 5.2 | 14.4 | 10.7 | 1.8 | -11.2 | -21.8 | -26 |

During the calculation, the soil temperatures under the foundation folded platform were determined for 4 years. It was found that in the hottest month of the year, the temperature in the central part of the platform under the lower belt of the platform has a negative value, and along the perimeter of the platform, the base is thawed along the soil surface by 1.5 meters from the edge of the platform (figure 6).

The SCAD software package (SCAD PC) was used to determine the stresses acting in CLT slabs of foundation structures. The foundation structures were modeled with shell elements (41-rectangular shell element).

The elastic base coefficients are assigned as the boundary conditions of the base under the platform. The foundation is based on frozen soil with an elastic modulus of 50 MPa and a Poisson's ratio of 0.4.

To evaluate the design performance, two calculation options were performed. The first option provides for solid support of the base of the spatial foundation on the frozen soil, which corresponds to the boundary condition of type 1. While the second option provided for soil thawing along the perimeter of the foundation by an amount of 1.5 meters, which corresponds to the boundary condition of type 3. Thermal degradation in this case was modeled by assigning elastic base coefficients equal to zero to the elements of the slab based on the thawed soil.
4. Discussion
As a result of static calculation, deflections of structures and stresses in the foundation slabs were determined for two variants. The cross sections of major structural elements were calculated: CLT folds slabs – 165 mm thick; the upper belt CLT slabs – 301 mm thick; CLT slabs of the lower belt of the platform – 165 mm thick.

As a result of static calculation, it was found that during thermal degradation of the soil along the perimeter of the platform at a distance of 1.5 meters, the maximum vertical movement of the lower slab structures increased by 2.3 mm. The maximum resulting stresses in the foundation elements increased by 0.13 MPa.

Based on the above, it can be concluded that when the soil is thawed under the spatial foundation at a distance of 1.5 meters, the forces and movements increase slightly, which makes it possible to continue normal operation of the lenticular building, installed on the spatial foundation platform in the form of folds.

5. Conclusion
1. For the first time, variants of operating conditions of a spatial foundation platform on a frozen base are formulated.
2. Six boundary conditions of thawing of the frozen base under the spatial foundation platform are determined.
3. Four limiting states of operation of the spatial foundation platform are revealed.
4. Two states of support of the spatial foundation platform on the thawed base are considered.
5. A thermophysical calculation of the spatial foundation platform in the form of folds for the case of the 2nd limiting state (thawing along the perimeter of the platform) is performed.
6. Static calculations have shown that during thawing of the soil under spatial foundations at a distance of 1.5 meters, further normal operation of the building of lenticular shape, mounted on a
spatial foundation platform in the form of folds is possible.

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