Modernization of the individual device for temperature stabilization of the soil

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Abstract. The authors of the article developed a finite-element model of a soil with a thermal stabilizer that takes into account the thermal effect from the environment, as well as the temperature of atmospheric air, wind speed, magnitude of the heat flux from solar radiation, albedo of the active surface, magnitude of the heat flux in the infrared, thermal conductivity of the snow cover, thermal conductivity and heat capacity of the soil, which makes it possible to calculate the haloes of freezing the soil. The results of a numerical experiment conducted using the COMSOL Multiphysics software complex showed that using the developed design of the thermal stabilizer allows increasing the zone of soil freezing around the bottom of the cooling device.

1. Introduction

Active reclamation of the regions of the Russian Federation covered with permafrost soils (PFS) requires the application of protection means for rocks that have been in a frozen state for dozens of years. Such rocks have specific physical, mechanical, engineering-geological, filtration properties that are taken into account when designing the bases, foundations for the construction of facilities on the territory of PFS. The permafrost rocks have an upper active layer, which during the year changes its temperature, and the lower one, which has a negative temperature. Because of the abundance of ice, rock characteristics change with temperature. An inadmissible condition for the operation of bases and foundations are deformations that may exceed the limit values for the melting of PFS.

The regulatory document for the construction of buildings and structures on the territory of PFS is the set of rules "Foundations of Buildings and Structures" [5], according to which the projected facilities are built following one of two principles. The first principle involves the use of permafrost soils as bases while maintaining them in the frozen state throughout the life of the facilities. The second principle permits the use of permafrost soils as bases in the thawed state. According to the first principle, constructions are erected with the economic justification and its expediency, the second principle is used when the deformations do not exceed the maximum permissible values for the erected structure.

2. Materials and methods

The applied measures to protect the PFS from thawing are divided into two types [6]: active and passive.

Active measures are ventilated basements, which are used for the bases of buildings and structures. Advantages: possibility to use in combination with other cooling means. Disadvantages: it is not the main method of maintaining negative soil temperatures.

The tubular system for freezing the base soils is divided into a horizontal "HNT" and a vertical "VNT". The operational principle is based on the circulation of refrigerant through the tubes and the heat transfer from the evaporative part to the condenser part, where heat is released into the atmosphere. The HNT system. Advantages: the ability to maintain the temperature in hard-to-reach places. Disadvantages: metal-consuming method, cools the surface of the soil. The VNT system. Vertical cooling pipe system "VNT". Advantages: it freezes the foundation soil faster at the initial stages of construction and operation, and fuses the soil within 12-15 meters depth. Disadvantages: it is used mainly to maintain the temperature of tanks, roads and railways, buildings up to 120 meters wide.

Individual seasonal cooling devices "SCD" - thermal stabilizers. Devices have an individual single-tube design with an all-metal casing, charged with a refrigerant. By design features they are divided into vertical, inclined and slightly inclined. According to the type of refrigerant used: liquid, vapour-liquid, gas and gas-liquid. The vapour-liquid ones have found wide application due to good heat-transferring ability. According to the principle of operation, thermal stabilizers of seasonal and year-round action are distinguished. The principle of the thermal stabilizer is based on the circulation of the refrigerant inside the tube. The lower evaporative part of the SCD is underground. Taking the heat of the soil, the refrigerant inside the structure boils, the vapour of the boiling refrigerant rises, carrying with it heat energy. In the external condenser part, the refrigerant vapour condenses, transferring heat to the outside air. Condensed refrigerant flows down closing the continuous circulation. The refrigerant circulation is only possible if there is a temperature difference in the evaporator and condenser parts. In summer, the temperature of the outside air is much higher than the temperature in the evaporator part and the effect of the heat stabilizer is suspended. Advantages: universality, the method is applicable to any type of object that needs to maintain negative soil temperatures. Disadvantages: the dependence of the duration of the device's active operation on external factors - the ambient temperature. To eliminate the disadvantage, it is necessary to install a greater number of heat stabilizers, to prevent thawing of the soil and deformations of the structures.

In the all-year-round SCD, the Peltier effect is realized. The Peltier effect is a thermoelectric phenomenon, which is accompanied by the release or absorption of heat as electric current passes through the contact point of two different conductors. The amount of heat produced depends on the properties of the conductors, the direction of the current flow and its force. When installing the module realizing the Peltier effect in summer, the necessary temperature difference will be created for the continuous operation of the heat stabilizer. Advantages: the lack of dependence of the thermal stabilizer on weather conditions. Disadvantages: the need to provide a source of electricity for each thermal stabilizer.

Passive protection refers to the thermal insulation of the object with the contacting soil. For pipelines laid underground, additional means can be the use of a factory circular heat insulation pipeline, which significantly reduces the thermal load on permafrost soils, reducing halos of thawing. Also, additional heat-shielding screens and replacement of icy subsidence grounds in the bases of projected objects are used, which will reduce the drawdown and will not exceed the permissible values of deformations.

At present, the most demanded technical solution capable of compensating for man-made impacts on the bearing capacity of permafrost soils is the use of soil thermal stabilizers. After analysing the long-term Russian and foreign experience of using soil thermal stabilizers, several of them can be distinguished.

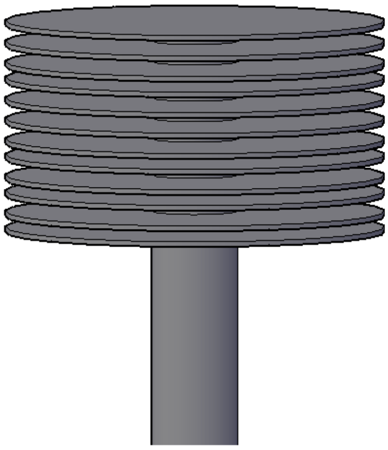

Figure 1. Transversely finned thermal stabilizer.

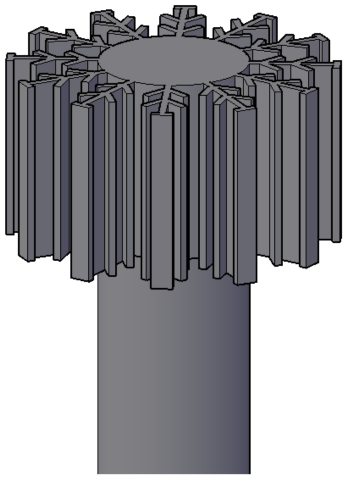

Figure 2. Longitudinally finned thermal stabilizer.

A transversely finned thermal stabilizer, shown in Figure 1, has a clear advantage in production, transportation and operation due to the simple construction of the condenser part. The main way to increase the heat transfer of the condenser part is to increase the finning area. If applying this method, metal costs increase, and with an increase in the finning coefficient, the relative depth of the intercostal gap increases, at which the root zone is gradually eliminated from heat transfer, which leads to a slowdown in heat transfer.

Longitudinally finned thermal stabilizer (Figure 2) has an increased capacity of freezing and has a greater heat dissipation capacity due to the presence of additional ribs. The design is not widely used in the industry due to the technologically complex manufacturing process and the high costs of metal production.

3. Solution procedures

The authors proposed the construction of the condenser part of the thermal stabilizer in Figure 3, which allows eliminating the identified shortcomings. It is proposed to weld tubes of a smaller diameter along the perimeter of the cylindrical surface in parallel to the base direction, which resemble the needles of a hedgehog. The ribs in the transverse plane are located at an angle to each other and as the length of the rib increases the intercostal distance between them increases either. The design features of the developed thermal stabilizer exclude the formation of stagnant zones with an increase in the finning area.

To test the advantages of the developed design of the thermal stabilizer, we will perform the numerical experiment. For this purpose, the design scheme in Figure 4 is: soil model that takes into account thermal effects from the environment, air temperature, wind speed, heat flux from solar radiation, albedo of the active surface, heat flux in the infrared part of spectrum, thickness and thermal conductivity of the snow cover, thermal conductivity and heat capacity of the soil.

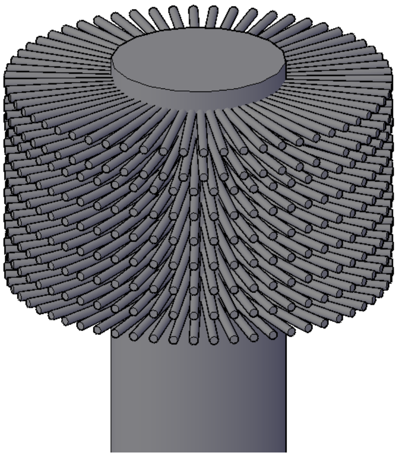

Figure 3. “Hedgehog”.

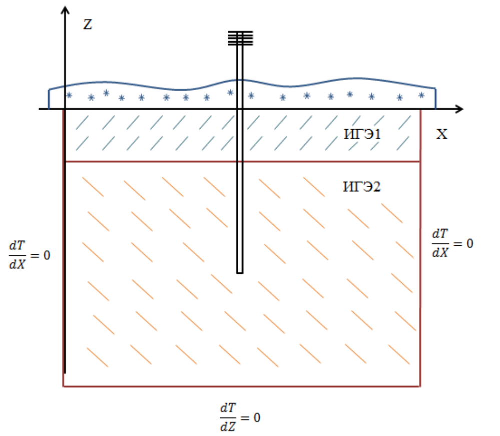

Figure 4. Calculation scheme.

Modelling of the temperature mode is performed in the Comsol Multiphysics software package. The determination of the temperature field in the computational domain requires the solution of the differential heat equation [6]:

$$\frac{\partial T}{\partial \tau} = Q\nabla^2 T + \frac{q_v}{\rho c} \quad (1)$$

Taking into account the factors considered in the developed model, we obtain:

$$p_{sk}\left(c_{p,sk} + W\left(c_{p,w} + \left(c_{p,l} - c_{p,w}\right)\theta(T)\right) - L_{melt}W\frac{d\theta}{dT}\right)\frac{dT}{d\tau} = \overline{\nabla}\cdot\left(\lambda\overline{\nabla}(T)\right) \quad (2)$$

where ρ_{sk} is the density of the skeleton of the soil;
$c_{\rho,sk}$ is the heat capacity of the soil skeleton at constant pressure;
$c_{\rho,w}$ is the heat capacity of water at constant pressure;
$c_{\rho,i}$ is the heat capacity of ice at constant pressure;
L_{melt}- heat of the ice-water phase transition;
λ is the thermal conductivity of the soil;
θ is the ratio of the mass of ice to the mass of all water at a given temperature;
W is the mass moisture content of the soil;
T is the temperature at the point under consideration.

To solve the equation, the boundary conditions "zero heat flow" are set on the lower and lateral surfaces of the modelled soil massif and on the soil surface, according to [3]:

$$Q = Q_c - Q_s + Q_r = \\ = a_i\left(T_{pov} - T_{v,i}\right) - (1 - A)q + \varepsilon_i\sigma_0\left(T_{pov}^4 - T_{v,i}^4\right) + \varepsilon_i\sigma_0\eta T_{v,i}^4 \quad (3)$$

where Q is the heat flux from the ground to the atmosphere;
Q_c is the convective heat flux;
Q_s - heat flux from solar radiation;
Q_r is the radiative heat flux in the IR region of the spectrum;
α is the convective heat transfer coefficient of the underlying surface of the soil;
q - direct and diffuse heat flux of solar radiation to the horizontal surface;
ε - the degree of blackness of the underlying surface of the soil;
σ_0 is the Stefan-Boltzmann constant;
η - coefficient of atmospheric radiation;
i - the index refers to the i^{th} month of the year.

The boundary conditions at the boundary of the SCD-atmosphere:

$$Q_v = \alpha_k (F_r E_r \mu + F_{tr})(T_0 - T_g) \quad (4)$$

where α_k - convective heat transfer coefficient;
F_r and $F_{\tau r}$ - the surface area of the ribs and intercostal space;
E_r - edge efficiency coefficient;
μ is the correction factor for changing the thickness of the cross section of the rib.

The boundary conditions at the boundary of the SCD are:

$$Q_g = \alpha_v \frac{F_c}{F_e}(T - T_v) \quad (5)$$

where F_c and F_e- the area of the condenser and evaporator;
$\alpha_{v\_\text{в}}$ is the heat transfer coefficient of the above-ground condenser part of the SCD [7].

4. Results of simulation

Figures 5-7 show halos of soil freezing.

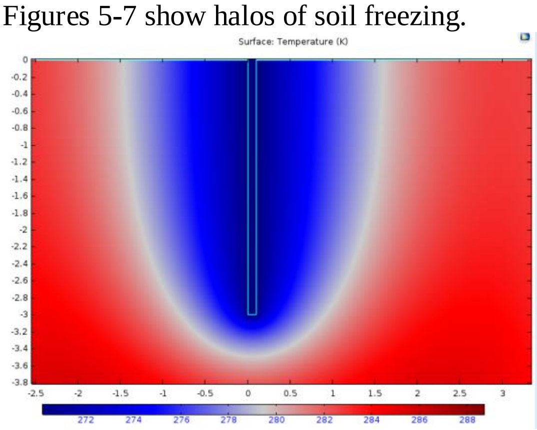

Figure 5. Transversely finned thermal stabilizer.

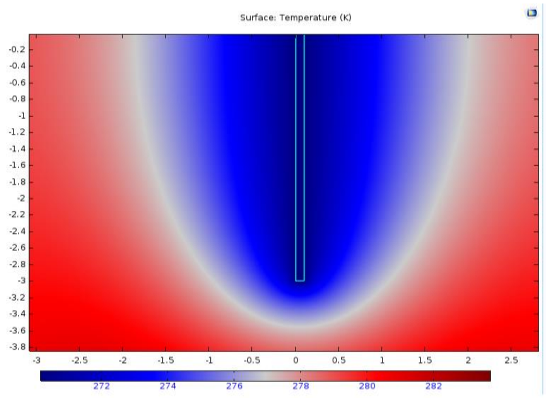

Figure 6. Longitudinally finned thermal stabilizer.

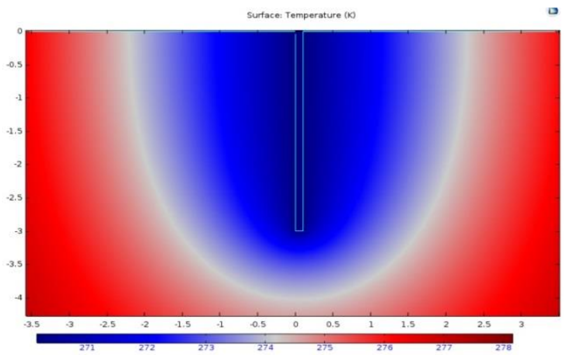

Figure 7. "Hedgehog".

In the constructions considered, Figures 1-3, the distribution of temperatures in the soil and the radius of the freezing zone around the SCD have different values. Based on the results of the numerical experiment, the halo of the freezing of the soil of the transversely finned thermal stabilizer in the radius has a maximum value of 1.5 meters, in the longitudinally finned 1.9 meters; the developed thermal stabilizer construction has 2.2 meters. The change in the shape of the ribs of the capacitor part of the SDA led to an increase in the heat transfer rate of the "heat stabilizer-atmosphere," which in turn led to an increase in the freezing halo of the soil.

Table 1. Values of the temperature distribution of the freezing halo of a transversely finned SCD.

		axis X									
		0.25	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**	**2.5**
axis Y	**-0.4**	270.56	272.91	274.79	276.30	277.95	279.09	280.16	281.22	281.86	282.35
	-0.8	271.49	272.9	274.7	276.44	277.92	279.27	280.35	281.26	282.00	282.46
	-1.2	271.64	273.33	274.99	276.71	278.32	279.43	280.58	281.54	282.19	282.63
	-1.6	271.54	273.31	275.28	276.93	278.79	279.76	280.89	281.79	282.42	282.77
	-2	271.61	273.85	275.45	277.45	279.02	280.29	281.13	282.04	282.63	283.07
	-2.4	271.71	274.06	275.84	278.22	279.57	280.75	281.83	282.57	283.24	283.05
	-2.8	272.77	275.24	277.32	279.17	280.61	281.63	282.69	283.23	283.65	283.91
	-3.2	276.33	278.06	279.33	280.67	281.79	282.76	283.46	284.02	284.26	284.40
	-3.6	280.51	281.07	281.93	282.55	283.29	283.90	284.43	284.75	284.93	284.96
	-4	283.44	283.51	283.98	284.34	284.78	285.08	285.40	285.55	285.57	285.47

Table 2. Values of temperature distribution of the freezing halo of the developed design of the SCD.

		axis X									
		0.25	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**	**2.5**
axis Y	**-0.4**	270.56	270.92	271.41	271.89	272.36	272.82	273.25	273.71	274.12	274.53
	-0.8	270.56	270.93	271.46	271.93	272.42	272.83	273.30	273.73	274.17	274.55
	-1.2	270.59	270.97	271.50	271.97	272.44	272.94	273.42	273.80	274.21	274.62
	-1.6	270.60	271.01	271.56	272.06	272.59	273.04	273.48	273.90	274.32	274.74
	-2	270.64	271.13	271.71	272.24	272.75	273.20	273.67	274.06	274.46	274.86
	-2.4	270.73	271.28	271.92	272.45	272.99	273.42	273.90	274.25	274.63	275.02
	-2.8	270.97	271.66	272.32	272.85	273.32	273.73	274.16	274.51	274.89	275.21
	-3.2	272.05	272.51	273.00	273.40	273.82	274.13	274.50	274.84	275.13	275.45
	-3.6	273.26	273.44	273.72	273.98	274.28	274.56	274.84	275.14	275.41	275.69
	-4	274.11	274.21	274.37	274.56	274.77	274.99	275.24	275.47	275.69	275.93

To find the average value of the temperature, a double integral was used in the region of the ground freezing halve, the obtained values of the temperatures of the freezing halo of the considered designs of thermal stabilizers were approximated using a polynomial. We took the double integral from the resulting function divided by the halo area and obtained the average temperature. To solve the integral, we used the mathematical simulation program Matlab.

$$\bar{T} = \frac{1}{S}\iint_S f(x,y)dA \qquad (6)$$

$$T = \int_0^{2.5}\left(\int_{-4}^{0}(267.6 + 7.67\cdot \mathrm{x} - 4.627\cdot \mathrm{y} + 4.235\cdot \mathrm{x}^2 + 7.061\cdot \mathrm{x}\cdot \mathrm{y} -\right.$$

$$-1.637\cdot \mathrm{y}^2 - 4.305\cdot \mathrm{x}^3 - 0.468\cdot \mathrm{x}^2\cdot \mathrm{y} + 6.813\cdot \mathrm{x} * \mathrm{y}^2 + 1.487\cdot \mathrm{y}^3 +$$

$$+ 1.463\cdot \mathrm{x}^4 - 0.1925\cdot \mathrm{x}^3\cdot \mathrm{y} - 0.8448\cdot \mathrm{x}^2\cdot \mathrm{y}^2 + 1.934\cdot \mathrm{x}\cdot \mathrm{y}^3 +$$

$$+ 0.8976\cdot \mathrm{y}^4 - 0.1956\cdot \mathrm{x}^5 - 0.001187\cdot \mathrm{x}^4\cdot \mathrm{x} - 0.05467\cdot \mathrm{x}^3\cdot \mathrm{y}^2 -$$

$$-0.2146 \cdot x^2 \cdot y^3 + 0.1266 \cdot x \cdot y^4 + 0.1079 \cdot y^5)dy)\, dx$$

The calculation is made for SCD with different types of fins of the condenser part. Estimated area of the ground frost halo 5x4 m. The difference in the average temperatures of the crosswise finned and designed thermal stabilizer is 6.63 degrees.

The results of a numerical experiment conducted using the COMSOL Multiphysics software complex showed that using the developed design of the thermal stabilizer allows increasing the zone of soil freezing zone around the bottom of the cooling device.

5. Conclusions

1. The authors of the article developed a finite-element model of a soil with a thermal stabilizer that takes into account the thermal effect from the environment, as well as the temperature of atmospheric air, wind speed, the magnitude of the heat flux from solar radiation, the albedo of the active surface, the magnitude of the heat flux in the infrared, the thermal conductivity of the snow cover, the thermal conductivity and heat capacity of the soil, which makes it possible to calculate the haloes of freezing the soil.
2. It has been revealed that the average temperature of the ground freezing halo of the developed structure is 6.63 °C lower than that of the cross-finned thermal stabilizer.
3. Modernization of the condenser part of an individual seasonal device resulted in a reduction of metal costs for its production, with an increase in the heat transfer intensity, which will have a positive impact on their payback.

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