Assessment of compliance of foreign geotechnical complexes for calculations of freezing-thawing of soils with Russian legal normatives

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Abstract. The design of construction objects in the conditions of the far north relates to changes in the temperature regime of the soil mass. In this regard, to choose the right design, it is necessary to be able to predict the change in the temperature field over time. Taking into account that heat release or absorption occurs when passing through the freezing onset temperature, the thermal conductivity equation, even for the one-dimensional case, becomes non-linear. Several software packages have been developed to solve heat conduction problems. Meanwhile, theoretical assumptions concerning the assignment of heat capacity and heat conductivity coefficients may differ. It is of interest to assess the compliance of the results of calculations of freezing and thawing issues with Russian norms.

1 Introduction

Under the conditions of active development of the Far North regions, the issue of modeling the processes occurring in the soils while freezing and thawing becomes extremely relevant. The program "Termoground" was developed with the participation of specialists of St.-Petersburg transport university [1-3] as part of the FEM Models software package, which allows analyzing freezing and thawing processes, as well as frost heave and thawing deformations using the calculated temperature and water content fields. The Term-ground package has a long experience of successful use in the practice of calculations and design, the theoretical assumptions implemented in it are verified and fully meet the requirements of domestic codes. FEM Models is widely used in the design in civil and transportation engineering [5-6] including thermothyphone for termally-stabilized bases [4].

Nowadays, more and more often specialists are faced with the problem of assessing the reliability of the initial data and results of thermophysical modeling, performed in foreign geotechnical software packages, for example, such as Midas GTS NX. This requires a certain

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verification of these programs in terms of their theoretical assumptions, as well as compliance with domestic regulatory documents.

Evaluation of the heat capacity parameter

Algorithms of numerical calculations of thermal conductivity issues are well worked out and known, so the occurrence of errors at this stage is extremely unlikely. In this connection, the main issue is the question of initial data and theoretical assumptions of calculations. Let's consider the methodology for determining the basic thermophysical characteristics of soils. In general, the first component of the specific heat capacity of thawed or frozen soil can be calculated knowing the ratio of soil components (phases)

$$c = (c_s m_s + c_w m_w + c_i m_i)/m$$

Where c_s, c_w, c_i–the specific heat capacity of solid particles, water, and ice, respectively, m–mass of the allocated volume of soil. The Midas software package uses the expression for the volumetric heat capacity (assuming complete water saturation of the soil pores S=1) are presented as:

$$c\rho = (1-n)\rho_s c_s + n[(1-f_u)\rho_i c_i + f_u \rho_w c_w], \quad (1)$$

Where ρ_s, ρ_w, ρ_i–the densities of solid particles, water, and ice, respectively, f_u–function of the relative unfrozen water content as a function of temperature, n–soil porosity.

By means of simple transformations, formula 1 can be reduced to the form used in domestic codes [7]:

$$c = c_s + \rho_w w_w + c_i(w_{tot} - w_w)]\rho_{d,f}, \quad (2)$$

Where $\rho_{d,f}$–density of dry frozen or thawed soil; w_{tot}-total water content of frozen soil; w_w – water content of frozen soil due to unfrozen water, determined based on the dependence

$$w_w = k_w w_p,$$

Where k_w–coefficient, taken for clay soils depending on the plasticity index and temperature of the soil according to [1]; w_p– water content at the plasticity limit.

The second determining component of the heat capacity of thawed or frozen soil is the heat of phase transformations-the latent heat of phase transitions in the negative temperature range, absorbed or given back by the ground due to changes in the groundwater phase, represented in the form:

$$L_0 \frac{\partial w_w}{\partial T}$$

Where L_0 =335x10^6 J/m^3=335x10^3 kJ/m^3=8975 Btu/ft^3=79760 kcal/m^3–heat of phase transformation of water-ice;

In the Midas GTS NX software suite, the dependency has a slightly different entry

$$L_0 w_{tot} \frac{\partial f_u}{\partial T}.$$

Analysis of dependences (1) and (2) demonstrates that the same assumptions are used in determining heat capacity. The main issue is to find the function of relative unfrozen water content f_u. To find it, numerous empirical relationships can be used to determine the water content due to unfrozen water as a function of temperature. From the point of view of compliance with domestic codes, the function f_u is determined by the values of the coefficient k_w.

2 Evaluation of the thermal conductivity parameter

The Midas GTX NX software package uses formulas based on the ground component ratio similar to (1) to find the ground heat transfer coefficient:

$$\lambda_{fT} = (1-n)\lambda_s + nS[(1-f_u)\lambda_i + f_u\lambda_w] + n(1-S)\lambda_v, \quad (3)$$

Where $\lambda_s, \lambda_w, \lambda_i, \lambda_v$–the thermal conductivity coefficient of solid particles, water, ice and steam, respectively.

The calculation of thermal conductivity by the ratio of soil components is not quite correct in terms of physics, because in addition to the percentage composition of the soil, its structure and texture affect the heat transfer. Convection and radiation in addition to conductive transfer take place in the soil mass, so the real dependencies are very complicated. By domestic codes determination of the thermal conductivity, the coefficient is carried out depending on the density of dry soil and its water content based on special tables [7]. a fragment of the specified table is presented below (Table 1). It should be noted that in the previous edition of this norms, volumetric heat capacity is also allowed to be taken according to the table

Table. 1. Thermophysical characteristics of dry frozen or thawed soil (issue of 1988).

Density of dry frozen or thawed soil $\rho_{d.f}$ · ton/m^3	**Total water content w_{tot}**	**Heat transfer coefficient. W/(m×°C). [kkal/(m×hour×°C)]**						**Volumetric heat capacity. kJ/(m^3×°C)10^{-6} [kkal/(m^3×°C)]**	
		Sand and gravel		**Silty sand**		**Loam and clay**			
		λ_{th}	λ_f	λ_{th}	λ_f	λ_{th}	λ_f	C_{th}	C_f
0.1	9.00	-	-	-	-	-	-	4.00 (950)	2.31 (550)
0.1	6.00	-	-	-	-	-	-	2.73 (650)	1.68 (400)
0.1	4.00	-	-	-	-	-	-	1.88 (450)	1.26 (300)
0.1	2.00	-	-	-	-	-	-	1.05 (250)	0.64 (200)
0.2	4.00	-	-	-	-	-	-	3.78 (900)	2.40 (570)
0.2	2.00	-	-	-	-	-	-	2.10 (500)	1.47 (350)
0.3	3.00	-	-	-	-	-	-	4.15 (990)	2.40 (570)
0.3	2.00	-	-	-	-	-	-	3.32 (750)	2.10 (500)
0.4	2.00	-	-	-	2.10 (1.80)	-	2.10 (1.80)	3.78 (900)	2.73 (650)
0.7	1.00	-	-	-	2.10 (1.80)	-	2.00 (1.75)	3.60 (855)	2.10 (500)

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1.0	0.60	-	-	-	2.00 (1.75)	-	1.90 (1.65)	3.44 (820)	2.18 (520)

Below (see Fig. 1) we present the results of the comparison of the value of thermal conductivity of soil in thawed λ_{th} and frozen λ_f state, taken by the tables [7] and calculated by the formula (3), taking in this expression two extreme values for the function f_u, corresponding to fully thawed and frozen ground.

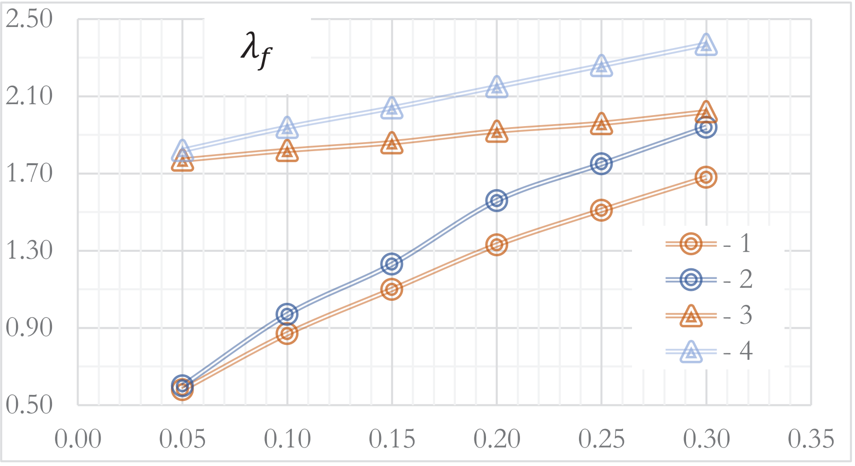

Fig. 2. Thermal conductivity coefficients of frozen and thawed soils (W/m*⁰C). 1-tabular values λ_{th}; 2-tabular values λ_f; 3–λ_{th} calculated by formula (3); 4–λ_f calculated by formula (3).

In the temperature range from the freezing start temperature T_{bf} to a temperature of minus 15^0C on the basis of formula (3) the value of λ_{fT} is calculated automatically. In accordance with the codes, the thermal conductivity coefficient can be determined by the expression

$$\lambda_{fT} = \lambda_{fT} - (\lambda_f - \lambda_{th}) \frac{w_w - w_{w(-15)}}{w_{tot} - w_{w(-15)}},$$

Where $w_{w(-15)}$–the water content of frozen soil due to unfrozen water at minus 15°C. This dependence is laid down in the "Termoground" software.

The comparison shows that the values of the thermal conductivity coefficient calculated by the formula (3) are somewhat higher than the tabulated values; however, to date, there is no complete theory allowing to consider and evaluate the contribution of each of the factors that affect the thermal conductivity of soil, we can assume that some differences in determining the thermal conductivity of frozen soil will not greatly affect the results of calculating the temperature fields in the ground.

3 Solving the one-dimensional thawing issue

For the final evaluation, we compare the results for the following one-dimensional model issue based on the remarks above. A 10 m thick soil massive, to which a temperature of $+20^0$C is applied at the upper surface, has an initial temperature of -10^0C. The soil has the following physical characteristics: freezing start temperature $T_{bf}=0^0$C, the thermal conductivity of thawed and frozen ground 175 kJ/(day*m*^{0}C); heat capacity of thawed and frozen soil 1700 kJ/(m^3*^{0}C). Dry soil density 1 g/cm^3, water content w_{tot}=0.4, plasticity limit

w_p=0.25, plasticity index I_p=0.2, density of solid particles 26.6 kN/m^3. Fig. 2 shows good convergence of the results.

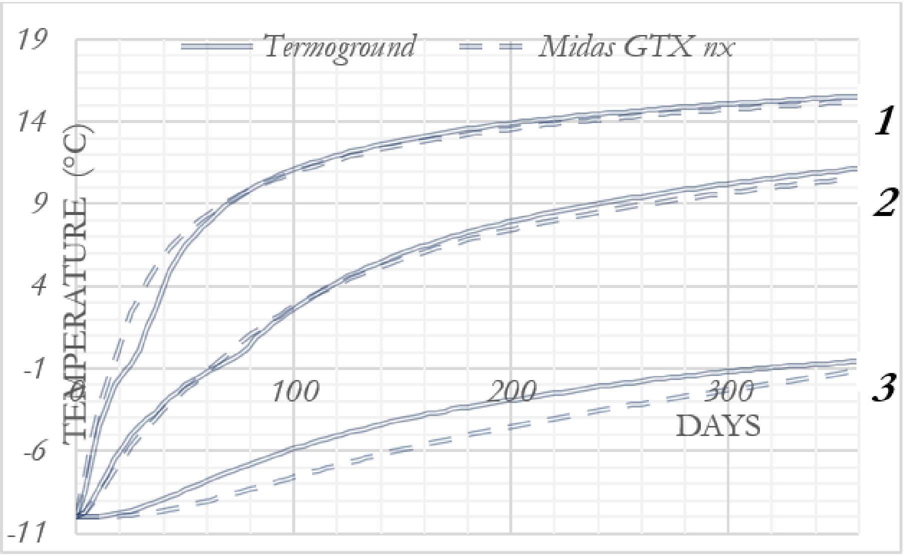

Fig. 2. Graphs of changes in the soil temperature at different depths using the tabulated values of the thermal conductivity coefficient (solid line) and calculated by the formula (3) (dashed line). 1-1 m depth; 2-2 m depth; 5 m depth.

4 Conclusion

Thus, we can conclude that the general theoretical assumptions used in calculations of freezing-thawing of soils are very similar, so foreign geotechnical software packages programs are applicable for modeling temperature problems in frozen soils.

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