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METHODOLOGY FOR CALIBRATION OF SOIL HEAT TRANSFER MODEL IN ACCORDANCE WITH RESULTS OF MEASUREMENTS

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ABSTRACT

Thermal calculation of specific soils (heaving or permafrost soils) is an important design stage. Heaving soils can significantly increase in volume during freezing, causing local uplifts of structures. Permafrost soils during thawing give significant subsidence. Uneven vertical movement of soils leads to deformation of pipelines, formation of cracks and dips in the roads, building tilt and the jamming of communications in building. The importance of taking these processes into account is difficult to overestimate in the design of structures.

Thermal calculation of soils consists of two main stages. The first stage is a retrospective simulation or calibration of a thermal model. The task of the first stage is to reproduce the thermal conditions that were in the soil in the last decade. The second step is the thermal calculation with taking into account new constructions. This article describes the features of the first stage - calibration of soil models.

The classical approach to calibrating the soil model is one-dimensional modeling based on the results of temperature measurements in wells. This approach works good if the wells are located at a considerable distance from each other. However, if the wells are located closely, then the temperature adjustment in one well may influence the temperature in the other. The authors have developed and tested a method for calibrating the thermal model of the soil, which takes into account this effect. To solve the problem, an influence matrix is compiled. Then new values of changed variables are calculated and the model is checked. This process can be repeated several times to achieve the required accuracy.

Keywords: calibration, heat transfer in soil, snow thickness

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1. INTRODUCTION

The problem of thermal calculation of soils exists in different sections of engineering. Basically, this is construction in specific soil conditions, when a change in the temperature of the soil leads to a corresponding change in their properties. Heaving soils can freeze and increase in volume. Permafrost soils that can thaw and give subsidence. An important stage in the design of any structures (roads, pipelines, buildings) is checking of the thermal regime of the soil and determining its effect on the structure [1 - 6].

Thermal calculation consists of two stages [7-8]. First, a thermal model of the soil is calibrated, which allows to reproduce the real soil and climatic conditions that were at the construction site for the last 50-60 years. At the next stage, the soil is being calculated taking into account new (designed) structures.

The calibration stage (first stage) of the thermal model of the soil is one of the most difficult and time consuming. From the point of view of physics, the soil model is described by a huge number of different variables that can influence each other. Therefore, when calibrating, it is important to choose the variable parameter correctly, determine the limits of its changes, and try to calibrate the model so that the calculation results match the measurements.

There are two main parameters, which must be calibrated - average annual temperature of the soil and the temperature of the soil at a particular time. The several basic parameters of the mathematical model is used to calibrate these values - the thermal conductivity of the soil in the thawed and frozen state, the thickness of the snow cover, the coefficient of heat transfer on the soil surface (or snow). Calibration based on the volumetric heat capacity of the soil is also possible; however, it requires the calculation of water transfer in the soil and additional equations in the model. Here it will not be considered.

One of the most volatile heat transfer parameters is the thickness of the snow cover. It can vary significantly depending on the terrain, the presence of buildings, vegetation, or random climatic factors. This parameter is fundamental when calibrating a model based on the ground temperature at a depth of zero annual amplitudes, because another parameters are functionally related to each other or require additional calculation of the moisture regime of the soil. Therefore, we will further consider the method of calibrating the soil model by changing the thickness of the snow cover to change the average soil temperature. Results can be generalized to any number of variable parameters in 3D space and any number of measured values.

2. MATERIAL AND METHODS

To calculate the temperature in the frost mound authors used the classical heat equation [9]:

$$\left(\boldsymbol{\rho_{soil} C_{soil}} + \boldsymbol{L}\frac{\partial \rho_{liq}}{\partial T}\right)\frac{\partial T}{\partial t} = \boldsymbol{\nabla} \cdot (\boldsymbol{\lambda_{soil} \nabla T}), \qquad 1$$

where $\boldsymbol{C_{soil}}$ – isobaric heat capacity of material, J/(kg·K); $\boldsymbol{\rho_{soil}}$ – soil density, kg/m^3; $\boldsymbol{L}$ – latent heat capacity of material, J/kg; $\boldsymbol{\rho_{liq}}$ – content of liquid phase of material, kg/m^3; $\boldsymbol{\lambda_{soil}}$ – thermal conductivity of material, W/(m·K).

Boundary conditions on the surface of the soil [10]:

$$-\boldsymbol{\lambda_{soil}}\vec{\boldsymbol{\nabla}}\boldsymbol{T} \cdot \left(-\vec{\boldsymbol{n}}_{surf}\right) = \vec{\boldsymbol{Q}}_i, \qquad 2$$

For surface without snow cover inward heat flux:

$$\vec{\boldsymbol{Q}}_i = \boldsymbol{a_{surf}}(\boldsymbol{T_{air}} - \boldsymbol{T}) + (\boldsymbol{1} - \boldsymbol{A})\boldsymbol{q_{sun}} + \varepsilon_i \sigma_0 \left(\boldsymbol{b_{air} T_{air}}^{\boldsymbol{4}} - \boldsymbol{T^4}\right), \qquad 3$$

For surface with snow cover inward heat flux:

$$\vec{Q}_i = \frac{\lambda_{sn}}{c_{sn}\delta_{sn}}\left(T_{surf} - T\right), \qquad 4$$

$$a_{surf}\left(T_{surf} - T_{air}\right) - (1 - A)q_{sun} + \varepsilon_i\sigma_0\left({T_{surf}}^4 - b_{air}{T_{air}}^4\right) = \frac{\lambda_{sn}}{c_{sn}\delta_{sn}}\left(T - T_{surf}\right) \qquad 5$$

where $\vec{Q}_i$ – inward heat flux, W/m^2; $\vec{n}_{surf}$ – normal vector to soil surface; a_{surf} – convective heat transfer coefficient, W/(m^2·K); q_{sun} – sun radiation, W/m^2; T_{air} – air temperature, K; T_{surf} – temperature of snow cover surface, K; ε_i – blackness of soil surface, u.f.; σ_0 – Stefan-Boltzmann constant, W/(m^2·K^4); b_{air} – coefficient of atmospheric counter-radiation, u.f.; A – albedo, u.f.; λ_{sn} – thermal conductivity of snow cover, W/(m·K); δ_{sn} – thickness of snow cover in open field, m; c_{sn} – correcting coefficient of the snow cover thickness, u.f.

Thermophysical characteristics of soil in the mathematical model is described in the table 1.

Table 1 The thermophysical characteristics of soil

Soil	**Name**	C_{soil}^{th}	C_{soil}^{fr}	λ_{soil}^{th}	λ_{soil}^{fr}	ρ_{soil}	T_{soil}^{bf}	T_{soil}^{int}	$\rho_{w,tot}$
		(J/(kg·K))		**(W/(m·K))**		**(kg/m^3)**	**(°C)**	**(°C)**	**(kg/m^3)**
1	Clay loam	1630	1365	1,48	1,69	2000	-0,22	0,60	400
2	Clay loam	1457	1286	1,49	1,69	2000	-0,20	0,60	400
3	Sandstone	750	750	2,80	2,80	2830	-0,00	0,00	0

It the table 1 was used the next conventions: C_{soil}^{fr}, C_{soil}^{fr} – isobaric heat capacity of frozen and thawed soil, J/(kg·K); λ_{soil}^{fr}, λ_{soil}^{th} – thermal conductivity of thawed and frozen soil, W/(m·K); T_{soil}^{bf} – the temperature of the beginning of freezing of soil, ºC; T_{soil}^{int} – temperature interval of freezing, ºC; $\rho_{w,tot}$ is the liquid water content per unit volume of the soil, kg/m3.

An example of the design scheme is shown in Fig. 1. The design scheme is the soil with uneven terrain.

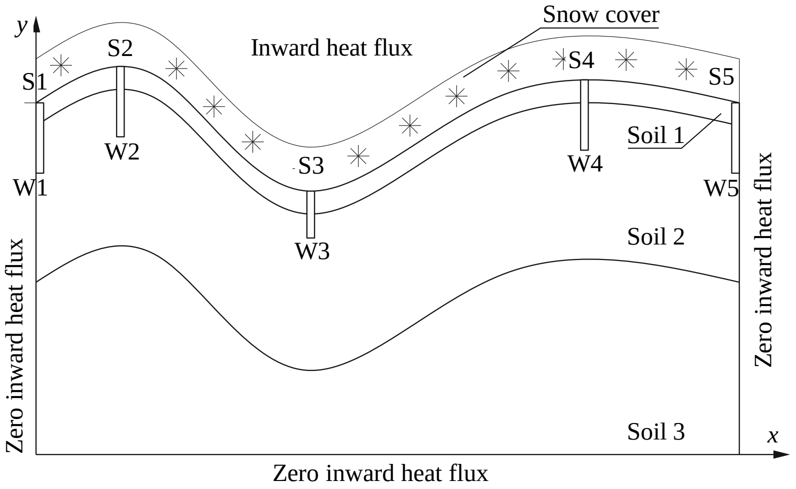

Figure 1 Calculation scheme. Thickness: soil 1 – 1.3m, soil 2 – 8.9m; soil 3 – 29.8m.

There is 5 wells in which temperatures were measured (Table 2). The task of calibration is to provide the set temperature in 5 wells (W1-W5) with the measured annual average temperature by adjusting the thickness of the snow cover.

Table 2 Average annual temperature in points W1-W5

Well	Point coordinate (x,y)	Surface	Point coordinate (x,y)	Average annual temperature in Well, T_m, °C
W1	(0,-6)	S1	(0,0)	-0.20
W2	(5,-4)	S2	(5,2)	-0.25
W3	(15.75,-9)	S3	(15.75,-5)	0.10
W4	(31.2,-5)	S4	(31.2,1.3)	-0.20
W5	(40,-6)	S5	(40,0)	-0.18

The methodology of calibration consists of 3 stages.

Stage I "1D Pre-Calibration". Pre-calibration allows determining the order of the changing magnitude. Here, the values of the coefficients to the thickness of the snow cover are selected in the standard way [10] for each well, like if there are no other wells. The tasks of the stage are to create an initial temperature distribution in the ground, which will be corrected later.

The results of pre-calibration 1D give us values of the coefficients to the thickness of the snow cover c_{sn} at points W1-W5 (table 3).

Table 3 The calculated values of the coefficients c_{sn} in points W1-W5

Well	Point coordinate (x,y)	c_{sn} calculated on stage I	$\Delta T/\Delta c_{sn}$
W1	(0,-6)	1,071	6.10
W2	(5,-4)	1,062	6.10
W3	(15.75,-9)	1,132	5.25
W4	(31.2,-5)	1,071	5.10
W5	(40,-6)	1,075	6.10

Stage II "Checking of calibration in 2D".

The obtained values of c_{sn} from the previous stage are transferred to the 2D model and the temperature in the soil is calculated. The calculation stops when the temperature of the soil stops to change. The values of the coefficients c_{sn} between the wells are calculated by linear interpolation. It should be noted that if the wells are located far from each other, then the mutual influence of changes in the thickness of snow on the surface on the temperature in the side of wells will be small and the distribution will be close to the 1D model in sections with wells.

According to the results of the calculation in the second stage, the following temperatures were obtained at points W1-W5 (table 4).

Table 4 Calculated average annual temperature in points W1-W5 on stage II

Well	**Average annual temperature of soil (measured), T_m, ºC**	**Average annual temperature of soil (calculated on stage I) , T_I, ºC**	**Average annual temperature of soil (calculated on stage II on first iteration) , T_{II}, ºC**
W1	-0.20	-0.20	-0.10
W2	-0.25	-0.25	-0.17
W3	0.10	0.10	0.17
W4	-0.20	-0.20	-0.14
W5	-0.18	-0.18	-0.10

From the results at the second stage, it is clear that the calculated values of temperatures differ significantly from measured and obtained at the first stage. Thus, calibration must take into account the mutual influence of conditions on the soil surface at all points.

Stage III "Calculation of influence factors and recalculation of snow cover thickness". If the results of calibration at stage II do not correspond to the specified accuracy of calculation, then coefficients of mutual influence is calculated. In each well the coefficient to the thickness of the snow changes slightly and the temperature change in other wells is calculated. Then a matrix of mutual influence coefficients and a column of the required temperature change are compiled.

For the simulated case matrix in the table 5.

Table 5 Interaction matrix $[\mathbf{A}] = \Delta T/\Delta c_{sn}$ in points W1-W5 on stage III (first iteration)

Well		$[\mathbf{A}] = \Delta T/\Delta c_{sn}$					$\mathbf{B} = T_m - T_{II}$
		$\Delta c_{1,sn}$	$\Delta c_{2,sn}$	$\Delta c_{3,sn}$	$\Delta c_{4,sn}$	$\Delta c_{5,sn}$	
W1	ΔT_1	0,550	2,075	1,250	0,250	0,000	-0,098
W2	ΔT_2	0,700	1,825	1,350	0,200	0,000	-0,079
W3	ΔT_3	0,000	0,600	3,900	0,600	0,150	-0,074
W4	ΔT_4	0,000	0,200	1,075	2,000	0,650	-0,061
W5	ΔT_5	0,000	0,200	0,900	1,625	1,325	-0,080

Calculating the inverse matrix of the influence coefficients and multiplying the temperature changes by a column, we obtain a change in the coefficients to the thickness of the snow cover. The results are transmitted to stage II and the calculation is repeated.

The calculation by expression $\Delta c_{sn} = [\mathbf{A}]^{-1}\mathbf{B}$ and the results of second iteration on stage II is in the table 6.

Table 6 Calculated average annual temperature in points W1-W5 on stage III→II (second iteration)

Well	**Point coordinate (x,y)**	**Average annual temperature of soil (measured), T_m, ºC**	**c_{sn} calculated on stage III**	**Average annual temperature of soil (calculated on stage II on second iteration) , T_{II}, ºC**
W1	(0,-6)	-0.20	1,113	-0.17
W2	(5,-4)	-0.25	1,009	-0.25
W3	(15.75,-9)	0.10	1,124	0.10
W4	(0,-5)	-0.20	1,062	-0.21
W5	(0,-6)	-0.18	1,039	-0.18

Analysis of the results in table 6 shows that the temperature difference at the second iteration was significantly reduced compared with the first iteration. After 2-3 iterations the temperature difference will be close to zero.

3. RESULT AND DISSCUSION

First, we analyze tables 3 and 5. The first thing we see is a significant difference in the results of calculating the $\Delta T/\Delta c_{sn}$. The difference is almost up to 12 times! Also, non-diagonal coefficients have a significant value, which coincide in order with the diagonal coefficients in neighboring wells. This suggests that the mutual influence should be taken into account in the calibration methodology of the soil model.

Further we compare the temperature distribution in the soil at the first iteration and the second iteration. The calculation results are presented in Fig. 2 and 3.

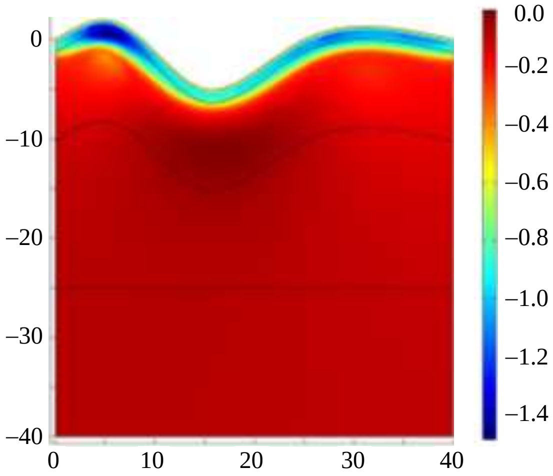

Figure 2 The distribution of temperatures in the soil for second iteration

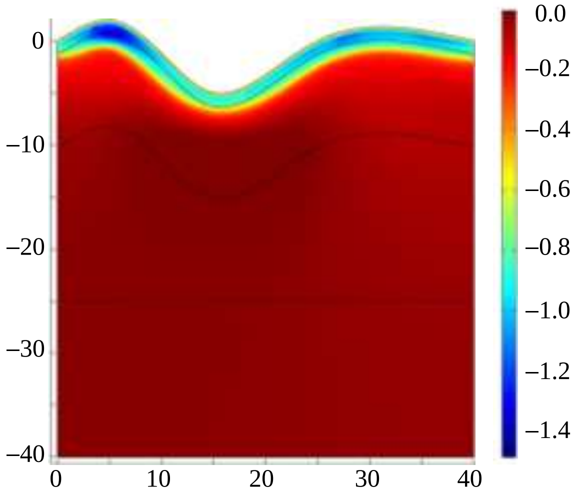

Figure 3 The distribution of temperatures in the soil for first iteration

The calculation results show that the using of authors' algorithm approach the temperature regime of soil to the measured value fast. In wells W2-W5, the calculated temperature values approached with sufficient accuracy. In the well W1, the difference decreased twice. Repeating of stage II-III several times improves accuracy after each iteration.

4. CONCLUSION

The authors developed the method for calibration of the thermal model of the soil, which allows eliminating the difference between the calculated temperature and measured. The method takes into account closely located temperature measurement points and, accordingly, the effect of parameter correction in one well on the temperature regime to another well.

As an example, the authors considered the adjustment of the average annual temperature in the well by changing the thickness of snow cover on the surface. The results indicate that good convergence between the calculated and actually measured average annual temperatures is achieved. Repeated iterations allow to achieve the required convergence.

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