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DEVELOPING AN INTELLIGENT INFORMATION SYSTEM TO SOLVE THE TASKS OF HEAT AND MASS TRANSFER PROCESSES IN SOILS IN THE DESIGN OF LOGGING ROADS

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ABSTRACT

The durability, reliability, and longevity of the roadway and surface of logging roads, as well as the quality and efficiency of their construction, largely depend on the heat and mass transfer processes, which occur inevitably during their construction and operation. The depth of theoretical research on heat and mass transfer processes and the degree of its practical utilization in road construction are determined mainly by the reliability of methods of determination and knowledge of thermal and moisture properties of highway soils and surface layers. In this connection, substantiation of methods for the assessment and study of the thermal and moisture characteristics of soils is a relevant task in the construction of roads in general and logging roads in particular. Thus, the study aims to develop an intelligent information system to address the processes of heat and mass transfer processes in soils for different calculation schemes in computer-aided design systems for logging roads. The developed heat and mass transfer calculation schemes enable the analysis of heat diffusion and moisture migration, as well as their mutual impact on each other. Based on the analysis of the considered physical nature of heat and mass exchange processes, the study offers a hypothesis on the heat and mass transfer processes occurring in the construction and operation of roads that can be studied via samples in compliance with the conditions of unambiguity, which allows determining the heat and mass transfer processes in soils. A general structural scheme for the study of heat and mass transfer properties of soils is developed, which makes it possible to substantiate the most rational methods of measuring moisture, thermal fluxes, coefficients of heat and temperature conductivity, moisture conductivity, and the thermogradient coefficient.

Keywords: *Soil, Moisture, Heat Flux, Thermal Conductivity, Moisture Conductivity.*

1. INTRODUCTION

Heat and mass transfer that occurs in roadbeds or highway soils during the performance of technological operations has a significant impact on the efficiency and quality of road construction processes and the durability, longevity, and performance parameters of logging roads of various categories.

Under the effects of mechanical and natural factors in the processed layers of soil or roadbed, complex interrelated physical processes occur: heating – cooling, moistening – drying, freezing – thawing, decompression – compression, heaving – sludge.

Roadway soils are complex dynamic disperse systems. During the construction and operation of a logging road, irreversible thermodynamic processes take place in the soils, accompanied by phase transformations and heat and moisture transfer. The intensity of these processes is conditioned by a variety of factors, including the presence and capacity of moisture sources, air temperature fluctuations, wind speed, air moisture, and the physical and mechanical properties of soils [1]. Soils can be moistened by precipitation, groundwater, water vapor contained in the pores of soils, or water from side ditches. Roadway soils can be considered water-saturated capillary-porous bodies. The properties of water in soils and its phase composition depend on the amount of water, its temperature, and the granulometric composition of the soils.

When modeling and forecasting energy and mass transfer, as a rule, numerical integration of the partial differential equations describing these processes is performed [2-4]. The solution to these problems is associated with the study of the dynamics of heat and moisture transfer, as well as salt transfer, coupled with heat and moisture transfer in the soil, the surface air, etc. To perform the respective calculations, it is necessary to set several constants characterizing the architectonics of the crop and soil or their physical parameters, as well as the initial state of the system – temperature and moisture profile, salt concentration profile, etc. [5-7].

Direct measurement of most of these values in laboratory or field conditions is not possible [8], and the need to assess them leads to solving the so-called inverse problems of mathematical physics [9-12]. More specifically, this gives rise to two classes of objectives – identification of model parameters and assessment of the initial state of the system based on the results of indirect measurements [13-16].

The solution to many practical tasks in the construction of logging roads requires knowledge of the thermal and moisture properties of soils [17]. Among such tasks are, for example, the calculation of moisture transfer in the roadbed at different periods of the year; calculation of the depth of freezing and defrosting of the roadbed; determination of the optimal length of leveling and compression of roadbed soils; study of the processes of soils mixing with binders, etc.

To systematize the methods of measuring thermal and moisture properties, it is expedient to distinguish between two types of heat and mass transfer: operational and technological. Operational heat and mass transfer considers various heat and moisture processes of operated forestry roads and is aimed at substantiation of standards for the operation and design of the roadbed and road surface.

Technological heat and mass transfer covers a wider range of processes accompanied by temperature and moisture changes in many technological operations, such as moistening, drying, grinding, transportation, compaction, leveling, and mixing of soils and materials. The problem of constructing observable systems in moisture and heat transfer models has several features. The conditions of strong sparsity of the transition matrix of the differential equations determining the dynamics of transfer processes in the soil cause weak information links between individual components of the system state vector and possibly require more measurements for the system to be observable. Yet the great labor intensity or simple impossibility of observing individual components of the vector of state (water potential and soil temperature) [2,4,10] entails the need to minimize the volume of input measurement data that provides the observability of the discrete system.

The novelty of this study consists in the development of a general structural scheme for the study of heat and mass transfer properties of soils, which makes it possible to substantiate the most rational methods of measuring moisture, thermal fluxes, coefficients of heat and temperature conductivity, moisture conductivity, and the thermogradient coefficient.

The study aims to develop an intelligent information system to address the processes of heat and mass transfer processes in soils for different calculation schemes in computer-aided design systems for logging roads. The research questions were as follows:

1. What is the physical essence of heat and mass transfer in the layers of the roadway under construction or operation?
2. What calculation schemes for the heat and mass transfer processes of the studied samples should be developed?
3. What are the analytical solutions for various calculation schemes and boundary conditions?

2. METHODS

In this paper, we develop a general method for constructing observable discrete systems with minimal input data. It is shown that the observability conditions of the direct and inverse systems are identical if they exist. Based on the results, we investigate the observability conditions for discrete systems with a tridiagonal transition matrix.

In roadbed soils, moisture is transferred from higher potential to lower. Under capillary and osmotic forces in isothermal conditions, the moisture tends to spread evenly over the entire volume. Moisture and heat transfer potentials can be expressed as:

$$P_h = -\frac{1}{t}\nabla^2 t; P_m = -\nabla^2 F + \frac{F}{t}\nabla^2 t \tag{1}$$

where $\nabla^2 = \frac{\partial^2}{\partial z^2}$ – the Laplace operator;

$F = \frac{\partial F}{\partial v}$ – free energy potential F in the direction of the generalized coordinate ν of substance mass.

It follows from equation (1) that moisture transfer in soils occurs due to the presence of the potential gradient of vapor transfer ∇P, liquid moisture transfer with changes in the temperature field proceeds by the same laws – it migrates from warm to cold places.

Throughout the year, the temperature and moisture of roadbed soils are constantly fluctuating. Therefore, the transfer of moisture in soils can be examined as a process that occurs under the combined potential of ∇P and ∇W.

Proceeding from the examination of the physical nature of heat and mass transfer, as well as scientific research, diffusion processes in soils can be presented as density potentials. According to several sources [18-20], energy potential gradient q=-K∇E, where K – energy (E) potential conductivity coefficient. As applied to this formula, we present the flows q_m of moisture as q_n – vapor and q_f – fluid in soils as follows:

$$q_m = -\lambda \nabla t = -acs\nabla t \tag{2}$$

$$q_f = -\lambda_f \nabla W_f = -a_f s \nabla W_f \tag{3}$$

$$q_f = -a_f s \nabla W_f - a_f b_f s \nabla t \tag{4}$$

$$q_v = -a_v s(\nabla a_v + b_v \nabla t) \tag{5}$$

$$q_v = -\lambda_v \nabla P = -a_v s \nabla d_v \tag{6}$$

$$q_v = -a_v b_v s \nabla t \tag{7}$$

where λ – coefficient of thermal conductivity of soils, W/(m.K);
c – specific heat capacity, J/(kg.K);
s – soil density, kg/m^3;
λ_f – liquid phase migration proportionality coefficient, kg/(m·s);
a_f – moisture conductivity coefficient of liquid moisture phase, m^2/s;

$$a = \frac{\lambda_o}{j} \tag{8}$$

$$b_f = \left(\frac{\partial W_f}{\partial t}\right) W \tag{9}$$

λ_v – water vapor diffusion proportionality coefficient, kg/(m·Pa·s);
a_v – vapor conductivity coefficient, m^2/s;

$$a = \frac{\lambda_v}{lj} \tag{10}$$

b_v – thermogradient diffusion coefficient of water vapor, 1/K;

$$b_v = l\left(\frac{\partial P}{\partial t}\right) t \tag{11}$$

where l – specific moisture capacity, i.e. the amount of vapor required to increase the partial vapor pressure of 1 kg of soil by 1 Pa;
d – water vapor moisture capacity.

The expressions demonstrate the basic laws of heat and mass transfer in the soil samples.

3. RESULTS

Based on the analysis of the system of heat and mass transfer processes in the roadbed soils, the mathematical model can be represented by the following system:

$$\frac{\partial t}{\partial \tau} = i\frac{\partial^2 t}{\partial z^2} + k\frac{\partial W}{\partial t} \tag{12}$$

$$\frac{\partial W}{\partial \tau} = i_1 \frac{\partial^2 W}{\partial z^2} + i_1 k_1 \frac{\partial^2 t}{\partial z^2} \tag{13}$$

where t – temperature, K;
W – moisture in fractions of a unit;
τ – time, s;
z – variable coordinate by depth, m;
a – temperature-conductivity coefficient, m^2/s;
b – coefficient of heat transfer due to phase transformation of moisture, K;
b_1 – thermogradient coefficient, 1/K.

Coefficient a_1 accounts for the moisture conductivity of two-phase moisture and can be expressed as:

$$a_1 = \frac{a_o}{1-\varepsilon} \quad (14)$$

where ε – phase transformation criterion for the condensation of water vapor into the liquid phase.

Thermogradient coefficient b_1, similarly to (9), can be presented as:

$$b_1 = \frac{\delta W}{\delta t} \quad (15)$$

Heat transfer coefficient due to phase transformations for thawed soils:

$$b = \frac{\varepsilon \rho_n}{c} \quad (16)$$

where ρ_n – latent heat of vaporization, J/kg;
c – specific heat capacity of thawed soils, J/(kg·K).

Equations (12) and (13) describe the laws of heat and moisture migration in the roadbed. These include coefficients a, a_1, b, and b_1 characterizing heat and mass transfer processes in the roadbed.

These properties of soils can be determined with undisturbed structures. It is difficult to determine the heat and mass transfer properties of soils in field conditions because it involves very complex and time-consuming studies. The known express methods still produce significant errors in measurements. Experimental determination of heat and mass transfer properties of soils on samples allows one to widely use the arsenal of physical converters of heat and moisture processes into multiparameter electric signals. Therefore, the greatest interest at present lies in the study of heat and mass transfer properties of roadbed soils on samples under laboratory conditions [21].

When examining heat and mass transfer properties on samples based on (12) and (13), it is necessary to justify the conditions of unambiguity that allow one to simulate heat and mass transfer in soils to the greatest extent. For this purpose, it is necessary to substantiate the form and properties of samples, as well as the initial and boundary conditions of heat and mass transfer.

In theory and research practice, heat and mass transfer properties are typically studied based on samples in the form of plates and shafts. For these forms of samples, there is the greatest variety of calculation schemes and analytical solutions. This is especially true in the theory of heat and mass transfer. The choice of the plate and shaft shape depends primarily on the guaranteed directionality of heat and moisture diffusion in the body under study, i.e. the created directionality of gradients.

If the law of distribution of heat and moisture along the sample is homogeneous and linear, then it is recommended to take a sample in the form of a plate, which reduces the test time and increases the reliability of the obtained results. If the sample has a nonlinear field, it is advisable to use a shaft-shaped sample.

In the study of samples by mathematical modeling using (12) and (13), it is required to specify heat and mass transfer properties with linear or nonlinear laws of their change throughout the sample. In the practice of studying capillary-porous bodies, the samples are generally taken from homogeneous materials [21,22].

The initial and boundary conditions in the studies are different depending on the calculation schemes and the conditions of temperature stabilization, thermal fluxes, and moisture at the edges of the samples.

The present study considers the following calculation schemes:

1. Complex heat and mass transfer in the sample (equations 12 and 13). This scheme is the most common. The moisture content of the samples is within $W_{mg} < W < W_{sat}$, and the temperature is $t_i < t < t_\delta$, where t_δ – maximum regular temperature of roadbed soil. Scheme 1 allows us to analyze simultaneously heat diffusion and moisture migration, as well as their general influence on each other, and to determine the real water-heat regime of the soil most completely. However, the study of heat and mass transfer properties based on this scheme is difficult.

This scheme is common in the construction of the roadbed and various conditions of its operation. It applies to the analysis of the water-heat regime of the roadbed in winter and summer periods, the analysis of properties during the mixing of soils with binders, during compaction of freezing soils, during the transportation of soils, and other cases.

2. Heat transfer without mass transfer. This scheme is typical for the study of heat diffusion with low moisture content in samples (W< W_{mg}), in the study of heat and mass transfer properties on plates, on samples from sandy and debris soils, as well as in the study of the properties of road surface layers made of crushed gravel, gravel, and other materials.

The mathematical model for the second calculation scheme:

$$\frac{\partial t}{\partial \tau} = a \frac{\partial^2 t}{\partial z^2} \quad (17)$$

In road construction, this scheme is used when calculating heat treatment of soils, freezing soils when entering water-saturated strata, and mixing soils of low moisture with binders [12].

3. Mass transfer without heat transfer. This scheme is typical for the study of heat and mass transfer properties in the presence of significant moisture gradients during isothermal moisture exchange when layers with different moisture content are in contact, as well as in the case of rapid and intensive moistening.

Such a process is described by the following boundary conditions:

$$t(z,0)=t_{in};\ 0 \le z \le l \tag{18}$$

$$t(0,\tau) = t_{in} + m_1\tau;\ m_2 < m_1 \tag{19}$$

$$t(l,\tau) = t_{in} + m_2\tau;\ 0 \le \tau \le 3{,}6 \cdot 10^3 c \tag{20}$$

$$W(z,0) = W_{in};\ m_3 > m_4 \tag{21}$$

$$W(0,\tau) = W_{in} - m_3\tau \tag{22}$$

$$W(l,\tau) = W_{in} + m_4\tau \tag{23}$$

Systems (12) and (13) were solved under boundary conditions (21). Substituting the second equation of the system (21) in the first, we receive:

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial z^2} + a_1 b_1 b\frac{\partial^2 t}{\partial z^2} + ba_1\frac{\partial^2 W}{\partial z^2} \tag{24}$$

$$\frac{\partial W}{\partial \tau} = a_1 b_1\frac{\partial^2 t}{\partial z^2} + a_1\frac{\partial^2 W}{\partial z^2} \tag{25}$$

Applying the new functions:

$$T=t-t_n;\ W_1 = W - W_{in} \tag{26}$$

The vector of variables and the matrix of coefficients of the equation system (54) is as follows:

$$X=|T\ W_1\ |;\ A = |i + a_1b_1b\ a_1bai_1b_1\ a_1\ | \tag{27}$$

Let us write the system (24) in matrix form:

$$\frac{\partial X}{\partial \tau} = A\frac{\partial^2 X}{\partial z^2} \tag{28}$$

$$X(z,0)=0;\ X(0,\tau)=|m_1\tau\ -m_3\tau\ |;\ X(l,\tau) = |m_2\tau\ m_4\tau\ | \tag{29}$$

Reducing matrix A to a diagonal matrix S:

$$S=BAB^{-1} = |\lambda_1 0\ 0\lambda_2\ | = \left|0.5[\ a + a_1b_1b + a_1 + \sqrt{(a + a_1b_1b + a_1)^2 - 4a_1a}\ 0\ 0.5[\ a + a_1b_1b + a_1 - \sqrt{(a + a_1b_1b + a_1)^2 - 4a_1a}\ \right| \tag{30}$$

where λ_1 and λ_2 – the eigenvalues of matrix A.

$$\lambda_1 = 0.5[\ a + a_1b_1b + a_1 + \sqrt{(a + a_1b_1b + a_1)^2 - 4a_1a} > 0 \tag{31}$$

$$\lambda_2 = 0.5[\ a + a_1b_1b + a_1 - \sqrt{(a + a_1b_1b + a_1)^2 - 4a_1a} > 0 \tag{32}$$

$$B=\left|\frac{\lambda_1 - a}{\sqrt{(\lambda_1 - a_1)^2 + a_1^2b^2}}\ \frac{\lambda_2 - a}{\sqrt{(\lambda_2 - a_1)^2 + a_1^2b^2}}\ \frac{a_1b}{\sqrt{(\lambda_1 - a_1)^2 + a_1^2b^2}}\ \frac{a_1b}{\sqrt{(\lambda_2 - a_1)^2 + a_1^2b^2}}\right| = |b_{11}\ b_{12}\ b_{21}\ b_{22}\ | \tag{33}$$

$$B^{-1} = \left|\frac{\sqrt{(\lambda_1 - a_1)^2 + a_1^2b^2}}{\lambda_1 - \lambda_2}\ \frac{(a_1 - \lambda_2)\sqrt{(\lambda_1 - a_1)^2 + a_1^2b^2}}{(\lambda_1 - \lambda_2)a_1b}\ \frac{\sqrt{(\lambda_2 - a_1)^2 + a_1^2b^2}}{\lambda_1 - \lambda_2}\ \frac{(\lambda_1 - a_1)\sqrt{(\lambda_2 - a_1)^2 + a_1^2b^2}}{(\lambda_1 - \lambda_2)a_1b}\right| = |b'_{11}\ b'_{12}\ b'_{21}\ b'_{22}\ | \tag{34}$$

Let us introduce the notations:

$$d_1 = \sqrt{(\lambda_1 - a_1)^2\ + a_1^2b^2} \tag{35}$$

$$d_2 = \sqrt{(\lambda_2 - a_1)^2\ + a_1^2b^2} \tag{36}$$

Then matrices B and B^{-1} can be presented as:

$$B=\left|\frac{\lambda_1-a_1}{d_1}\ \frac{\lambda_2-a_1}{d_2}\ \frac{a_1b_1}{d_1}\ \frac{a_1b}{d_2}\right| \quad (37)$$

$$B^{-1}=\left|\frac{d_1}{\lambda_1-\lambda_2}\ \frac{(a_1-\lambda_2)d_1}{(\lambda_1-\lambda_2)a_1b}\ \frac{d_2}{\lambda_1-\lambda_2}\ \frac{(\lambda_1-a)d_2}{(\lambda_1-\lambda_2)a_1b}\right| \quad (38)$$

Now we introduce a new vector $\gamma = BX$.
Then equation (29) takes the form:

$$B\frac{\partial X}{\partial \tau}=\frac{\partial^2 X}{\partial z^2} \quad (39)$$

or

$$B\frac{\partial X}{\partial \tau}=BAB^{-1}B\frac{\partial^2 X}{\partial z^2} \quad (40)$$

Under boundary conditions:

$$\gamma(z,0)=0 \quad (41)$$

$$\gamma(0,\tau)=B|m_1\tau\ -m_3\tau\ | \quad (42)$$

$$\gamma(l,\tau)=B|m_2\tau\ m_4\tau\ | \quad (43)$$

The solution of equation (40) under boundary conditions (42) is as follows:

$$\gamma(z,\tau)=\frac{2S\pi}{l^2}\sum_1^\infty n\exp\left[\frac{Sn^2\pi^2\tau}{l^2}\right]Sin\frac{\pi nz}{l}\text{x}\int_0^\tau exp\frac{Sn\pi^2\eta}{l^2}[\gamma(0,\tau)-(-1)^n\gamma(l,\tau)]d\eta \quad (44)$$

From this:

$$\gamma(z,\tau)=\frac{2}{\pi}\sum_1^\infty\frac{Sin\frac{\pi nz}{l}}{n}S\left[\frac{\tau}{S}-\frac{l^2}{S^2\pi^2n^2}-\frac{l^2\exp\left(-S\pi^2n^2(l^2\text{x}\tau\right)}{S^2\pi^2n^2}\right]\cdot B\cdot M \quad (45)$$

where

$$M=|m_1\ -(-1)^n m_2\ -m_3\ -(-1)^n m_4\ | \quad (46)$$

From this we find vector $X=B^{-1}\gamma$ and the components of X – temperature t in K and moisture W in %.

The final expression for the temperature field in the sample, considering the moisture transfer, is:

$$t(z,\tau)=t_{\text{H}}+\frac{2}{\pi}\sum_1^\infty\frac{Sin\frac{\pi nz}{l}}{n(\lambda_1-\lambda_2)}\{\left[\tau-\frac{l^2}{\pi^2n^2\lambda_1}\left(1+\exp\left(-\frac{\lambda_1\pi^2n^2}{l^2}\tau\right)\right)\right]\cdot[(\lambda_1-a_1)(m_1-(-1)^n m_4)]+\left[\tau-\frac{l^2}{\pi^2n^2\lambda_2}\cdot\left(1+\exp\left(-\frac{\lambda_2\pi^2n^2}{l^2}\tau\right)\right)\right]\text{x}[(a_1-\lambda_2)(m_1-(-1)^n m_2)-\frac{(a_1-\lambda_2)d_1}{d_2}(m_3+(-1)^n m_4)]\} \quad (47)$$

The final expression for the moisture field in the sample is:

$$W(z,\tau)=W_n+\frac{2}{\pi}\sum_1^\infty\frac{Sin\frac{\pi nz}{l}}{n(\lambda_1-\lambda_2)}\{\left[\tau-\frac{l^2}{\pi^2n^2\lambda_1}\left(1+\exp\left(-\frac{\lambda_1\pi^2n^2}{l^2}\tau\right)\right)\right]\cdot[\frac{d_2(\lambda_1-a_1)}{d_1(\lambda_1-\lambda_2)}(m_1-(-1)^n m_2)-(\lambda_2-a_1)\text{x}(m_3+(-1)^n m_4)]+\left[\tau-\frac{l^2}{\pi^2n^2\lambda_1}\left(1+\exp\left(-\frac{\lambda_2\pi^2n^2}{l^2}\tau\right)\right)\right]\text{x}[\frac{(\lambda_1-a)d_2}{d_1}\cdot(m_1-(-1)^n m_2)+(\lambda_1-a)(m_3+(-1)^n m_4)]\} \quad (48)$$

The obtained analytical expressions satisfy boundary conditions (21). The accuracy of their solution is also confirmed by the analysis of dimensionality.

Consider another solution to the problem for scheme 1. When investigating heat and mass transferring properties on shafts thermally insulated from the cold end, the scheme can be presented in the form of a semi-isolated shaft.

Let us consider the solution of (12) and (13) without considering thermal-moisture conductivity (i.e., without the second member of the right-hand side of (13). Such a scheme is applicable when determining the heat and mass transfer properties of samples with increased initial moisture ($W \geq 0.65\, Wi$).

In this case, the boundary conditions can be written as:

$$t(z,0) = t_{in};\ t(0,\tau) = t_{in} + m_1\tau;\ \frac{\partial t}{\partial z}|z = l = 0 \tag{49}$$

$$W(z,0) = W_{in};\ W(0,\tau) = W_{in} - m_2\tau;\ \frac{\partial W}{\partial z}|z = l = 0 \tag{50}$$

Now we introduce the variable:

$$V(z,\tau) = W(z,\tau) - (W_{in} - m_2\tau) \tag{51}$$

Substituting (51) and (50) into (13), we obtain an inhomogeneous equation with new boundary conditions:

$$\frac{\partial V}{\partial \tau} = a_1 \frac{\partial^2 V}{\partial z^2} + m_2 \tag{52}$$

$$V(z,0)=0;\ V(0,\tau)=0;\ \frac{\partial V}{\partial z}|z = l = 0 \tag{53}$$

where $a_1 = \frac{a_f}{1-\varepsilon}$ – moisture conductivity coefficient of two-phase moisture.

$$V(z,\tau) = \sum_{0}^{\infty} V_n(\tau)\cdot Sin\frac{(2n+1)\pi z}{2l} \tag{54}$$

Solution (54) satisfies boundary conditions under any $V_n(\tau)$. Substituting (54) into equation (52), we obtain:

$$\sum_{0}^{\infty} V_n^{н}(\tau) + a_1[\frac{(2n+1)\pi}{2l}]^2 * Sin\frac{(2n+1)\pi}{2l} = m_2 \tag{55}$$

For condition (55) to be met, it is necessary that:

$$\begin{aligned} V_n'(\tau) + a_1[\frac{(2n+1)}{2l}]^2 V_n(\tau) &= \frac{2m_2}{l}\int_0^l Sin\frac{(2n+1)\pi}{2l}zdz \\ &= -\frac{2m_2}{l}Cos\frac{(2n+1)\pi}{2l}\cdot\frac{2l}{(2n+1)\pi}|_0^l = \frac{4m_2}{(2n+1)\pi} \end{aligned} \tag{56}$$

$$V_n'(\tau)|_{\tau=0} = 0 \tag{57}$$

The solution of the system of equations (56)-(57) is as follows:

$$\begin{aligned} V_n(\tau) &= \frac{4m_2}{(2n-1)\pi}\int_0^\tau \exp\{[-a_1\frac{(2n+1)^2\pi^2}{4l^2}](\tau-\tau')\}d\tau \\ &= \frac{16m_2 l^2}{(2n+1)^3\pi^3 a}\{1-\exp[-a_1\frac{(2n+1)^2\pi^2\tau}{4l^2}]\} \end{aligned} \tag{58}$$

From expression (50) we have:

$$V(\tau,z)=\frac{16m_2l^2}{a_1\pi^3}\sum_0^\infty\frac{1-\exp\left[-\frac{a_1\tau(2n+1)^2\pi^2}{4l^2}\right]}{(2n+1)^3}\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (59)$$

Substituting (59), we obtain an expression to calculate the moisture field:

$$W(z,\tau)=W_{\text{н}}-m_2\tau+\frac{16m_2l^2}{a_1\pi^3}\sum_0^\infty\frac{1-\exp\left[-a_1\frac{(2n+1)^2\pi^2\tau}{4l^2}\right]}{(2n+1)^3}\cdot\ Sin\frac{(2n+1)\pi z}{2l} \quad (60)$$

Rate of change in moisture

$$\frac{\partial W}{\partial t}=-m_2+\frac{4m_2}{\pi}\sum_0^\infty\frac{\exp\left[-a_1\frac{(2n+1)^2\pi^2}{4l^2}\tau\right]}{(2n+1)}\cdot\ Sin\frac{(2n+1)\pi z}{2l} \quad (61)$$

Substituting (61) in (12) and using the boundary conditions (26), we obtain:

$$\frac{\partial t}{\partial\tau}=a\frac{\partial^2t}{\partial z^2}+b[f(z,\tau)-m_2] \quad (62)$$

$$t(z,0)=t_{in};\ t(0,\tau)=t_{in}+m_1\tau;\ \frac{\partial t}{\partial z}|_{z=l}=0 \quad (63)$$

where

$$f(z,\tau)=\frac{4m_2}{\pi}\sum_0^\infty\frac{\exp\left[-\frac{a_1\tau(2n+1)^2\pi^2}{2l}\right]}{2n+1}\cdot\ Sin\frac{(2n+1)\pi z}{2l} \quad (64)$$

To solve equation (62), we introduce the variable:

$$V(z_1,\tau)=t(z,\tau)-(\tau_{in}+m_1\tau) \quad (65)$$

Then we receive:

$$\frac{\partial V}{\partial\tau}-a\frac{\partial^2V}{\partial z^2}=[f(z,\tau)-m_2]b-m_1 \quad (66)$$

$$V(z,0)=0;\ V(0,\tau)=0;\ \frac{\partial V}{\partial z}|_{z=l}=0 \quad (67)$$

The solution to the problem (66) and (67) is found in the following form:

$$V=V_1+V_2 \quad (68)$$

where V_1 – solution for (66) and (67) with $m_1=m_2=0$;
V_2 – under $f(z,\tau)$=0.

By analogy with the solution of the system (28) and (29), we have:

$$V_2\,(z,\tau)=-\frac{16(m_2b+m_1)l^3}{a\pi^3}\cdot\sum_0^\infty\frac{1-\exp\left[-a_1\frac{(2n+1)^2\pi^2}{4l^2}\tau\right]}{(2n+1)^3}\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (69)$$

$$V_1(z,\tau)=\sum_0^\infty V_{n1}(\tau)\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (70)$$

Substituting it into equation (66) with $m_1=m_2=0$, we obtain:

$$\sum_0^\infty V_{n1}(\tau) + \mathrm{a}\frac{(2n+1)^2\pi^2}{4l^2}V_{n1}(\tau)Sin\frac{(2n+1)\pi z}{2l} = \sum_0^\infty \frac{4m_2 b}{(2n+1)\pi}\exp\left[-\frac{a(2n+1)^2\pi^2}{4l^2}\tau\right]Sin\frac{(2n+1)\pi z}{2l} \quad (71)$$

This equality is only possible if:

$$V_{n1}(\tau) + a\frac{(2n+1)^2\pi^2}{4l^2}V_{n1}(\tau) = \frac{4m_2 b}{(2n+1)\pi}\cdot exp\left[-a_1\frac{(2n+1)^2\pi^2}{4l^2}\tau\right] \quad (72)$$

It follows from the initial condition that:

$$V_{n1}(\tau)|_{\tau=0} = 0 \quad (73)$$

The solution of the system (72) and (73) is the function:

$$V_{n1}(\tau) = \frac{4m_2 b}{(2n+1)\pi}\cdot\int_0^\tau \exp\left[-a_1\frac{(2n+1)^2\pi^2}{4l^2}\tau'\right]\cdot\exp\left[-\mathrm{a}\frac{(2n+1)^2\pi^2}{4l^2}(\tau-\tau')\right]d\tau' = -\frac{16m_2 bl^2}{(a_1-a)(2n+1)^3\pi^3}\cdot\left\{\exp\left[-a_1\frac{(2n+1)^2\pi^2}{4l^2}\tau\right] - \exp\left[-\mathrm{a}\frac{(2n+1)^2\pi^2}{4l^2}\tau\right]\right\} \quad (74)$$

Substituting (74) and (70), we have:

$$V_1(z,\tau) = -\frac{16m_2 bl^2}{(a_1-a)\pi^3}\sum_0^\infty \frac{1}{(2n+1)^3}\cdot\left\{\exp\left[-\frac{a_1(2n+1)^2\pi^2}{4l^2}\tau\right] - \exp\left[-\frac{a(2n+1)^2\pi^2}{4l^2}\tau\right]\right\}\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (75)$$

Using (66) and (68), we finally obtain from the calculation of heat and mass transfer in the sample:

$$t(z,\tau) = t_{\text{н}} + m_1\tau - \frac{16l^2}{a\pi^3}\sum_1^\infty \frac{1}{(2n+1)^3}\left\{\frac{m_2 b}{a_1-a}\cdot\exp\left[-\frac{a_1(2n+1)\pi^2}{4l^2}\tau\right] + \left(-\frac{m_2 b}{a_1-a} - \frac{m_2 b + m_1}{a}\right)\cdot\left[-\frac{a(2n+1)\pi^2}{4l^2}\tau\right] + \frac{m_2 b + m_1}{a}\right\}\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (76)$$

where $b = \frac{\varepsilon\rho_n}{c}$.

Now we will consider the solution of (12) and (13) without considering the second member of the right-hand side of (12) under boundary conditions (26).

Omitting the intermediate solutions, we have expressions for calculating the temperature field:

$$t(z,\tau) = t_{\text{н}} + m_1\tau - -\frac{16l^2}{a\pi^3}\sum_1^\infty \frac{1}{(2n+1)^3}\cdot\left\{1 - \exp\left[-\frac{a(2n+1)^2\pi^2}{4l^2}\tau\right]\right\}\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (77)$$

$$W(z,\tau) = W_{\text{н}} - m_2\tau + \frac{16l^2}{a\pi^3}\sum_1^\infty \frac{1}{(2n+1)^3}\cdot\{\exp[-\frac{a(2n+1)\pi^2}{4l^2}\tau]\cdot\frac{a_1 m_1 b}{a-a_1} - (m_2 + \frac{m_1 b_1 a_1}{a-a_1}) \cdot -\exp[-\frac{a(2n+1)^2\pi^2}{4l^2}\tau] + m_1 b_1 + m_2\}\cdot Sin\frac{(2n+1)\pi z}{2l} \quad (78)$$

Let us consider solutions to the problem of the scheme without mass transfer.

We solve the equation:

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial z^2} \quad (79)$$

under the following boundary conditions:

$$\{t(z,0) = t_{in}\ 0 \le z \le l\ t(0,\tau) = t_{in} +\ t(l,\tau) = t_{in} + m_2\tau\ 0 \le \tau \le 3.6\cdot 10^3 c\ m_1\tau\ m_2 < m_1 \quad (80)$$

We introduce a new function $T(z,\tau) = t(z,\tau) - t_{in}$.

$$\frac{\partial T}{\partial \tau} = a\frac{\partial^2 T}{\partial z^2} \quad (81)$$

Then we have the following equation with new boundary conditions:

$$\{T(z,0) = 0\ T(0,\tau) = T(l,\tau) = m_2\tau\ m_1\tau \quad (82)$$

The solution to equation (81) is found as:

$$T=\frac{2a\pi}{l^2}\sum_1^\infty n\exp\left[-\frac{an^2\pi^2}{l^2}\tau\right]\cdot sin\frac{\pi nz}{l}\cdot\int_0^\tau exp\frac{an^2\pi^2}{l^2}\lambda\cdot[m_1\lambda-(-1)^n m_2\lambda]d\lambda = \frac{2a}{l^2}\sum_1^\infty\exp\left[-\frac{an^2\pi^2}{l^2}\tau\right]\cdot\int_0^\tau exp\frac{an^2\pi^2}{l^2}\lambda d\lambda = \frac{2l^2}{a\pi^3}\sum_1^\infty\frac{m_1-(-1)^n m_2}{n^3}sin\frac{\pi nz}{l}\cdot[\frac{an^2\pi^2}{l^2}\tau - 1 + \exp(-\frac{an^2\pi^2}{l^2}\tau)] \quad (83)$$

From this:

$$t(z,\tau) = t_{\text{н}} + \frac{2l^2}{a\pi^3}\sum_1^\infty\frac{m_1-(-1)^n m_2}{n^3}sin\frac{\pi nz}{l}\cdot[\frac{an^2\pi^2}{l^2}\tau - 1 + \exp\left(-\frac{an^2\pi^2}{l^2}\tau\right)] \quad (84)$$

Since the series in the right part of equality (81) satisfies the conditions of Leibniz's theorem about alternating series, the remainder of the series does not exceed the absolute value of the first of the discarded members, i.e:

$$\left|R_n\left(\frac{l}{2},\tau\right)\right| = \frac{2l^2}{a\pi^3}\int_{k=n+1}^{+\infty}\frac{m_1-(-1)^n m_2}{n^3}\left[\frac{an^2\pi^2}{l^2}\tau - 1 + \exp\left(-\frac{an^2\pi^2}{l^2}\tau\right)\right] \le \frac{2l^2}{a\pi^3}\frac{m_1-(-1)^n m_2}{n^3}\cdot\left[\frac{a(n+1)^2\pi^2}{l^2}\tau - 1 + \exp\left(-\frac{a(n+1)^2\pi^2}{l^2}\tau\right)\right] \quad (85)$$

Let us estimate the ratio of the sum of all members of the series, starting from the second to the first member of this series. Given (85), we have:

$$\frac{R(\frac{l}{2},\tau)}{\frac{2l^2}{a\pi^3}(m_1+m_2)[\frac{a\pi^2}{l^2}\tau - 1 + exp\ exp\left(-\frac{a\pi^2\tau}{l^2}\right)]} \le \frac{1}{27}\frac{[\frac{9\pi^2 a}{l^2}\tau - 1 + exp\ exp\left(-\frac{9\pi^2 a}{l^2}\tau\right)}{[\frac{\pi^2 a}{l^2}\tau - 1 + exp\ exp\left(-\frac{\pi^2 a}{l^2}\tau\right)} \le \varepsilon \quad (86)$$

Since:

$$\frac{\pi^2 a}{l^2}\tau - \frac{1}{9} + exp\ exp\left(-\frac{9\pi^2 a}{l^2}\tau\right) < \frac{\pi^2 a\tau}{l} - 1 + exp\ exp\left(-\frac{a\pi^2\tau}{l^2}\right) \quad (87)$$

$$\frac{9[\frac{\pi^2 a}{l^2}\tau-\frac{1}{9}+exp-\frac{9\pi^2 a}{l^2}\tau]}{\frac{\pi^2 a}{l^2}\tau-1+exp\ (-\frac{a\pi^2}{l^2}\tau)} < 9 \qquad (88)$$

Thus, $\varepsilon = \frac{1}{3}$ and, accordingly:

$$\frac{R_1(\frac{l}{2},\tau)}{\frac{2l^2}{A\pi^3}(m_1+m_2)[\frac{a\pi^2}{l^2}\tau-1-expexp\left(-\frac{a\pi^2}{l^2}\tau\right)]} \qquad (89)$$

To estimate the error allowed when replacing the sum of series (83) by its partial sum in other points $x \neq \frac{l}{2}$, we use Abel's test. When approaching the ends of the interval $0 \leq x \leq l$ estimation of the remainder of the series using Abel's test becomes unsuitable.

To evenly estimate the remainder of the series over the entire interval $0 \leq x \leq l$, we use a different method:

$$R_n(z,\tau) = \left|\frac{2l^2}{a\pi^3}\sum_{k=n+1}^{\infty}\frac{m_1-(-1)^k m_2}{k^3}\left[\frac{ak^2\pi^2}{l^2}\tau - 1 + \exp\left(-\frac{ak^2\pi^2}{l^2}\tau\right)\right]\right| \cdot Sin\frac{\pi kz}{l} \leq \frac{2l^2}{a\pi^3}\sum_{k=n+1}^{\infty}\frac{m_1-(-1)^k m_2}{k^3}\left[\frac{ak^2\pi^2}{l^2}\tau - 1 + \exp\left(-\frac{ak^2\pi^2}{l^2}\tau\right)\right] < \frac{2l^2}{a\pi^3}\int_{A_n}^{+\infty}\frac{m_1+m_2}{x^3}\cdot\left[\frac{a\pi^2}{l^2}\tau\cdot x^2 - 1 + \exp\left(-\frac{a\pi^2}{l^2}\tau x^2\right)\right]dx = \frac{2l^2}{a\pi}(m_1+m_2)\int_{A_n}^{+\infty}\frac{1}{\xi}\cdot[\xi^2 - 1 + \exp(-\xi^2)]d\xi = \frac{2l^2}{a\pi}(m_1+m_2)\int_{A_n}^{+\infty}[\xi - \frac{1}{\xi} + \frac{\exp(-\xi^2)}{\xi}]d\xi \qquad (90)$$

where

$$\xi = \frac{x\pi}{l}\sqrt{a\tau}; \qquad (91)$$

$$A_n = \frac{\pi n}{l}\sqrt{a\tau}. \qquad (92)$$

After integration we receive:

$$\int_{A_n}^{+\infty}[\xi - \frac{1}{\xi} + \frac{\exp(-\xi^2)}{\xi}]d\xi = (\xi^2 - ln\xi|_{A_n}^{+\infty} + \int_{A_n}^{+\infty}\frac{\exp(-\xi^2)}{\xi}d\xi \qquad (93)$$

$$\int_{A_n}^{+\infty}\frac{\exp(-\xi^2)}{\xi}d\xi = \frac{1}{2A_n^2}\exp(-A_n^2) + \int_{A_n}^{+\infty}\frac{\exp(-\xi^2)}{\xi^3}d\xi \qquad (94)$$

$$\text{but } \int_{A_n}^{+\infty}\frac{\exp(-\xi^2)}{\xi^3}d\xi < \exp(-A_n^2)\int_{A_n}^{+\infty}\frac{d\xi}{\xi^3} = \frac{\exp(-A_n^2)}{2A_n^2} \qquad (95)$$

Thus, the expression for the uniform estimate of the series residual is as follows:

$$|R_n(x,\tau)| < \frac{2l^2}{a\pi}(m_1+m_2)\ \frac{expexp\ (-A_n^2)}{2A_n^2}, \qquad (96)$$

where

$$A_n = \frac{\pi n}{l}\sqrt{a\tau}. \qquad (97)$$

Expression (97) makes it possible to determine with a given accuracy the values of temperature t by (84).

The final expression for the moisture field in the sample is as follows:

$$W(z,\tau) = W_н + \frac{2l^2}{a_1\pi^3}\sum_1^{\infty}\frac{m_3-(-1)^n m_4}{n^3} * Sin\frac{\pi nz}{l}\,x\left[\frac{an^2\pi^2}{l^2}\tau - 1 + \exp\left(-\frac{an^2\pi^2}{l^2}\tau\right)\right] \qquad (98)$$

4. DISCUSSION

The temperature and moisture of roadbed soil change ceaselessly throughout the year. Therefore, the transfer of moisture in soils can be considered a process under the influence of the combined potential of ∇P and ∇W [23]. Two characteristic physical patterns of heat transfer can be distinguished in soils.

Scheme 1. Soil moisture is insignificant $0 < W < W_{mg}$ (in the range from 0 to 0.3 W_i), temperature $t \leq t_i$, where t_i – ice formation temperature; W_i – soil yield stress. Relative humidity of pore air $\varphi < 1$. The water vapor pressure is less than the vapor pressure at full saturation and is a

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complex function of P=$f(\varphi_1 W_1\, t)$, where W – soil moisture; t – temperature.

This scheme is characterized by the following: vapor formation; vapor condensation into adsorption moisture; the liquid phase of moisture does not migrate; thermodiffusion and condensation diffusion of unsaturated water vapor take place; heat transfer occurs due to conduction, convection, intravapor radiation, and phase transformations; ice formation is absent; the ground does not freeze and has a condensation structure.

This physical scheme is typical of several technological processes: mixing and strengthening soils with binders. In road construction, it is relatively rare.

Scheme 2. There are two phases of water in the soil: vapor + liquid phase. The moisture content is in the range $W_{mg} \leq W < W_{sat}$, where W_{sat} – total moisture capacity, approximately (0.8-0.9) W_{sat}. Temperature t< t_i, $\varphi = 1$, P=P_{in}, P=$f(t), W = f(W_f t)$, where W_f – fluid phase content.

This scheme is characterized by: vapor formation, condensation of vapor into film and capillary moisture; thermodiffusion of vapor; liquid phase migration due to its concentration potential and partially due to thermodiffusion; heat transfer, as in the first scheme; ice formation is absent; the ground is in the thawed state and has a coagulated structure.

This scheme is the primary one in the construction of public roads and logging roads as well. It is characteristic of all technological processes in which the soil as well as the roadbed bed layers are involved. The exception is the roadbed layers in the zone of excessive moistening, which is a limitation of this study.

5. CONCLUSION

The following conclusions can be made from the theoretical research performed.

1. The physical essence of heat and mass transfer in the layers of the roadway under construction or operation is considered. Soils are complex dynamic disperse systems in which irreversible thermodynamic processes take place, accompanied by phase transformations and heat and moisture transfer. Mass exchange in soils results from the presence of a gradient of vapor transfer potential, fluid moisture, and a gradient of heat potential. Heat transfer occurs due to the heat transfer potential. The temperature gradient causes additional moisture transfer.

2. Three calculation schemes for the heat and mass transfer processes of the studied samples are developed. Calculation scheme 1 reflects complex heat and mass transfer; the scheme allows for simultaneous analysis of heat diffusion and moisture migration, as well as their mutual influence on each other. It applies to the analysis of the water-heat regime of the roadbed in winter and summer periods; when analyzing the properties in the process of mixing soils with binders; during the compaction of freezing soils; during the transportation of soils, and in other cases. Calculation scheme 2 reflects heat transfer without mass transfer. The scheme is typical in the study of heat diffusion with low moisture content in samples. In road construction, the scheme is used when calculating the heat treatment of soils, when freezing soils, and when mixing low-moisture soils with binders. Calculation scheme 3 is characteristic of significant moisture gradients in isometric moisture transfer and rapid and intensive moisture transfer.

3. Analytical solutions have been obtained for various calculation schemes and boundary conditions. For calculation scheme 1, the solutions for the plate and the semi-organic shaft are derived. For calculation schemes 1, 2, and 3, expressions for the field of moisture and temperature are obtained. The error allowed for the replacement of the series sum by its partial sum is evaluated.

Further research should be aimed at developing a scheme that would be characteristic of technological processes in which the roadbed layers in the zone of excessive moistening are involved.

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