LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2023, N 4

DOI: 10.2478/lpts-2023-0024

THE INFLUENCE OF THE THERMAL EFFECT ON THE STRESS-STRAIN STATE OF THE SOIL

N. Remez[1], A. Dychko[1], A. Kraychuk[2], S. Kraychuk[2], N. Ostapchuk[2]

[1] National Technical Universty of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
37 Peremohy Ave., Kyiv, 03056, UKRAINE
[2]Rivne State University of Humanities
12 Stepana Bandery Str., Rivne, 33028, UKRAINE
E-mail: aodi@ukr.net

The present paper provides the dependence of the temperature change on time and the depth of the soil massif based on numerical calculations. Mathematical modelling of the one-dimensional soil temperature field via an algorithm and a PC program is carried out without taking into account the influence of the phase transition of moisture in the soil pores during seasonal freezing and thawing using the finite difference method. The amplitude of fluctuations in the temperature regime is obtained as that decreases with depth from the soil surface. It is established that over time heat spreads from the pipeline to the surface of the soil, and over time more intense heating occurs both near the pipeline and in the body of the soil massif.

Keywords: *Heat transfer, mathematical modelling, soil, stress-strain state.*

1. INTRODUCTION

The temperature field of the soil and the influence of the thermal effect on its stressed and deformed state are quite important factors that must be taken into account when erecting structures and buildings on these soils. If one of these factors is completely or partially neglected in the designing of structures, unacceptable deformations occur, which complicate their operation and lead to partial or complete destruction [1], [2].

If the sediments that occur during the thawing of frozen soils around the foundations of buildings are not foreseen by the project, and their value is greater than the limit values for this building, then unacceptable deformations and destruction of the foundations and super-foundation structures occur inevitably.

The simultaneous influence of static load and thermal effect on the stress-strain state of the soil massif is one of the key issues in the design and operation of any buildings or structures. Therefore, the definition and justification of this factor is relevant.

In recent decades, interest in understanding the thermomechanical behaviour of soil has increased significantly, which is explained by many reasons, the main ones of which are: 1) deep burial of waste, which is a source of heat, in geological formations; 2) carrying out drilling operations; 3) laying of high-voltage cables in the soil; 4) seasonal and daily temperature fluctuations, which significantly affect road surfaces and building foundations [3]–[5].

Sources of heat release that heat groundwater can be conventionally divided into two types. The first includes natural underground sources of heat release. The second one – heat-releasing structures erected on the surface of the earth or near it.

In [6], [7] it is stated that the influence of temperature on the physical state of porous sedimentary rocks is manifested in the form of changes in the characteristics of rock-forming minerals, as well as structural changes of rocks due to thermal expansion of minerals: additional compaction of rocks under the action of mechanical stresses due to an increase in the plasticity of some minerals (for example, calcite) with increasing temperature; other minerals, on the contrary, lose plasticity and become brittle as the temperature increases. At the same time, the compressive strength of these minerals decreases, which leads to the formation of microcracks in the rock. Thermal stresses lead to the fact that micro-destructions occur in various parts of the rock, which are reflected in the rock structure.

Thus, the physical properties of rocks change as the temperature increases not only due to the change in the characteristics of individual rock phases, but also due to the deformation of the skeleton and the reduction of the pore volume [8].

The aim of the research is to predict changes in the stress-strain state of the soil as a result of the thermal effect of natural and man-made factors.

2. THERMAL EFFECT ON THE STRESS-STRAIN STATE OF THE SOIL SIMULATION

At the first stage, the problem of the non-stationary annual thermal regime of the soil is considered. The differential equation of thermal conductivity through the soil has the form

$$c\rho\frac{\partial t}{\partial z}=\frac{\partial}{\partial x}\left[\lambda\frac{\partial t}{\partial x}\right],\quad z>0. \qquad (1)$$

Equation (1) of each homogeneous layer of the soil can be rewritten as follows:

$$\frac{\partial t}{\partial z}=a\frac{\partial^2 t}{\partial^2 x},\quad z>0, \qquad (2)$$

where c – specific heat capacity of the soil, J/(kg °C); ρ – density of the soil, kg/m^3; λ – coefficient of thermal conductivity of the soil, W/(m °C); a – coefficient of thermal conductivity of the soil, $a=\frac{\lambda}{c\rho}$, m^2/c; x – distance along the coordinate deep into the soil, starting from its surface, m; $t(x,z)$ – temperature, °C, at any point x in the depth of the soil and at any moment of time z from the beginning of the countdown.

The initial temperature distribution in the soil layer is known (for example, it can be assumed to be constant in depth and equal to the average multi-year, average annual temperature of the surrounding air):

$$t(x,0) = t^0(x) = idem, \; 0 \le x \le H, \; z = 0; \tag{3}$$

$$t(x,z) = g(x,z), \quad 0 \le x \le H, \quad z = 0, \tag{4}$$

where H – depth of the considered soil massif, m.

As limit conditions on the surface of the earth, the heat exchange of the outer surface with the outer air, absorption of heat from solar radiation falling on the horizontal surface, and long-wave radiation into the Earth's atmosphere are taken into account:

$$\lambda \frac{\partial t}{\partial x}\Big|_{x=0} = a_h (t_c - t_s|_{x=0}) + Pq_{tr} - \varepsilon \cdot q_{lr}; \;\; \mathrm{x} = 0; \;\; z > 0. \tag{5}$$

The condition can be written more simply by entering the conditional temperature of the environment:

$$t_c = t_o + q_{tr} \cdot \frac{P}{a_h} - \frac{\varepsilon \cdot q_{lr}}{a_h}, \tag{6}$$

i.e., on the Earth's surface, heat exchange takes place with the environment, which has a temperature equal to the conventional one:

$$-\lambda \frac{\partial t}{\partial x}\Big|_{x=0} = a_h (t_c - t_s|_{x=0}), \quad \mathrm{x} = 0; \;\; z > 0. \tag{7}$$

Since the heat flow from the centre of the Earth [9] is 0.06–0.10 W/m^2, which is on average equal to 0.03 % of the flow of solar radiation absorbed by the Earth's surface, then the condition of heat flow at the lower boundary of the soil massif is assumed as

$$-\lambda \frac{\partial t}{\partial x}\Big|_{x=\mathrm{H}} = 0, \quad \mathrm{x} = \mathrm{H}, \;\; z > 0, \tag{8}$$

where t_o, t_c – known variable throughout the year temperatures of outdoor air and conditional of environment, ^{o}C; t_s – unknown variable throughout the year temperature of the soil surface, ^{o}C; a_h – known coefficient of heat exchange on the soil surface, W/(m^2 ^{o}C), can be variable over time depending on the wind speed; $q_{t.}$ – intensity of total solar radiation falling on the soil surface, W/m^2; P – coefficient of absorption of solar radiation by the soil surface; q_{lr} – heat flow of long-wave radiation from the soil surface to the Earth's atmosphere; ε – degree of blackness of the radiating body. For soil, according to recommendations [9], the value is taken as equal to 0.96.

According to ASHRAE recommendations, the value of heat flux for horizontal surfaces should be taken as 63 W/m^2. Research on the transfer of long-wave radiation in the atmosphere [10] indicates the possibility of calculating the heat flow using the sky temperature, which is equal to the temperature of the surface of the clouds, component – 12 °C. Calculating the heat flow according to the Stefan-Boltzmann law, we will get 80.4 W/m^2 for the conditions of Kyiv. The heat transfer coefficient of the Earth's surface (a_h, W/m^2 ^{o}C), is calculated as follows:

$$a_h = 1{,}16\,(5 + \sqrt{v}), \tag{9}$$

where v – wind speed at the moment of time under consideration, m/s.

The solution of the problem is carried out by the method of finite differences using an implicit difference scheme with a lead, which has an approximation error of the order of $O(\Delta z + \Delta x^2)$ [11], an algorithm and a program for a PC in the Pascal are developed.

Figures 1–4 present the results of numerical calculations for a soil massif with a depth of 20 m with thermophysical parameters c=840 J/(kg ·K); ρ=1800 kg/m^3; λ=1.2 W/(m·K) in the form of graphical dependences of temperature on time (month) at different depths of the soil. Different colours indicate different distances from the free surface of the soil.

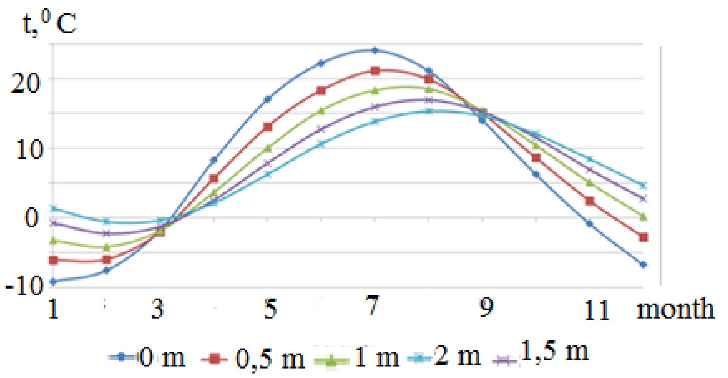

Fig. 1. Distribution of temperature over time at a soil depth of up to 2 m.

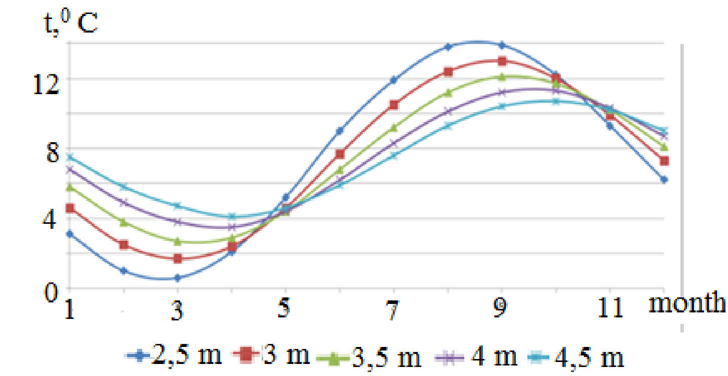

Fig. 2. Distribution of temperature over time at a soil depth of 2.5 up to 4.5 m.

The obtained dependences indicate the delay of the temperature maximum and temperature minimum relative to the fluctuation of the annual conditional temperature of the atmospheric air; the more the temperature, the deeper the calculated soil mark. The resulting effect occurs due to the thermal inertia of the soil and depends on its type and properties.

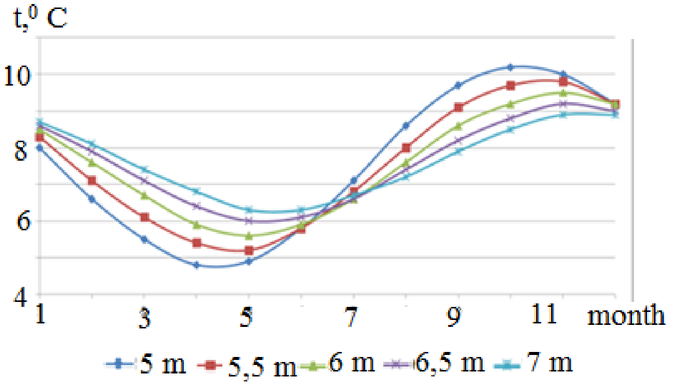

Fig. 3. Distribution of temperature over time at a soil depth of 5 up to 7 m.

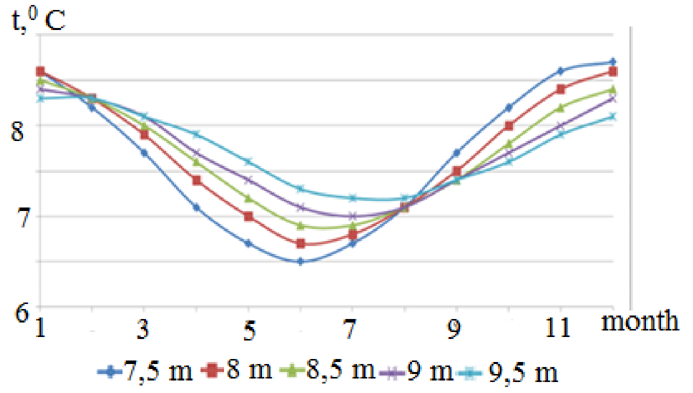

Fig. 4. Distribution of temperature over time at a soil depth of 7.5 up to 9.5 m.

Based on the obtained data, a graph of the range of values of the annual temperature amplitude in the depth of the soil massif is constructed (Fig. 5).

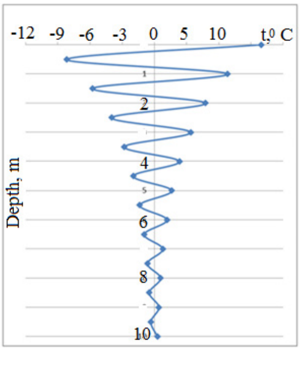

Fig. 5. Range of the annual temperature amplitude deep into the soil massif.

From the analysis of this dependence, it is worth noting that the nature of the attenuation of the temperature amplitude deep into the soil massif has a smaller scope due to the fact that the processes of seasonal freezing and thawing of the soil and the influence of snow cover are not taken into account. However, it should be noted that the influence of these factors decreases with depth, and minor temperature fluctuations remain at significant depths throughout the year. This gives grounds for using the soil massif as a working fluid in heat pumps.

At the second stage, the process of interaction between the thermal fields of the soil and the underground pipeline is considered.

The process of heat transfer in the soil layer is analysed, on one boundary of which there is heat exchange with the environment, and on the other – with the hot water supply pipeline. Heat transfer is considered based on the Stefan-Boltzmann law.

The mathematical formulation of the problem is based on the Fourier-Kirghoff equation, which establishes the relationship between temporal and spatial changes in temperature at any point of the area under consideration, and has the form

$$\rho c\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \quad \begin{vmatrix} 0 < x < L \\ 0 < y < H \end{vmatrix}, \tag{10}$$

where ρ – soil density, kg/m^3; c – specific heat capacity of the soil, W/m °C; λ – coefficient of thermal conductivity, W/m °C; L – length of the soil open-cast, m; H – depth of the soil open-cast, m.

The initial and limit conditions are written as follows:

$$\begin{aligned} &t = 0: && T = T_0, \quad 0 \le x \le L, \quad 0 \le y \le H; \\ &x = 0: && -\lambda\frac{\partial T}{\partial x} = \chi_1(T^{e1} - T) + \varepsilon\sigma((T^{e1})^4 - T^4), \quad t > 0, \ \chi_1 > 0; \\ &x = L: && \lambda\frac{\partial T}{\partial x} = \chi_2(T^{e2} - T) + \varepsilon\sigma((T^{e2})^4 - T^4), \quad t > 0, \ \chi_2 > 0; \\ &y = 0: && -\lambda\frac{\partial T}{\partial y} = \chi_2(T^{e2} - T) + \varepsilon\sigma((T^{e2})^4 - T^4), \quad t > 0, \ \chi_2 > 0; \\ &y = H: && \lambda\frac{\partial T}{\partial y} = \chi_3(T^{e3} - T) + \varepsilon\sigma((T^{e3})^4 - T^4), \quad t > 0, \ \chi_3 > 0; \end{aligned} \tag{11}$$

where ε – given degree of blackness; σ = 5,669W/(m^2 K^4) – Stefan-Boltzmann constant.

To approximate the differential level (10), a locally one-dimensional scheme [11] is used, which is absolutely stable and has the property of total approximation. To calculate the temperature field, an algorithm and a PC program in Pascal are developed.

The heat transfer process in the soil massif is analysed, on one boundary of which there is heat exchange with the environment, and on the other – with the hot water supply pipeline.

To solve the problem, an open-cast of the soil with a length L = 30 m and a depth H = 5 m is considered, on which the hot water pipeline is located. Thermophysical parameters of the solution area of the problem and soil properties are given in Tables 1 and 2.

Table 1. Parameters of the Problem Solution Area

Parameter	Designation	Value	Dimensionality
Coefficient of heat exchange at the soil-soil border	χ_1	25	W/m^2°C
Coefficient of heat exchange at the soil-environment border	χ_2	50	W/m^2°C
Coefficient of heat exchange at the soil-pipe border	χ_3	100	W/m^2°C
Initial temperature of the junction area	T_0	3	°C
Temperature at the soil-soil boundary	T^{e1}	3	°C
Temperature at the soil-environment boundary	T^{e2}	5	°C
Temperature at the pipe boundary	T^{e3}	80	°C
Given degree of blackness	ε	0.76	-

Table 2. Thermophysical Properties of the Soil

Properties	Designation	Value	Dimensionality
Coefficient of thermal conductivity	λ	1.6735	W/m °C
Density	ρ	1950	kg/m³
Heat capacity	c	833.76	J/kg °C

As a result of numerical calculations, the distribution of temperatures and isotherms of the soil under the thermal influence of the pipe for different periods of time is obtained. The dependence of the distribution of the soil temperature field on the spatial coordinates is shown in Figs. 6 and 7.

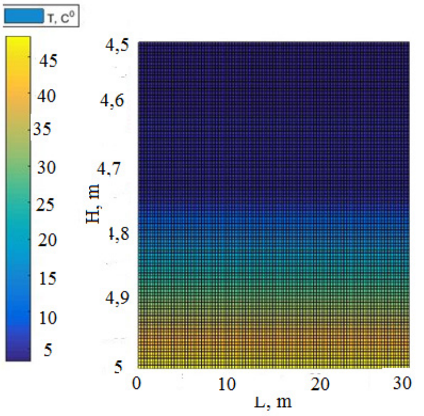

Fig. 6. Dependence of temperature distribution on spatial coordinates during the thermal influence of the pipe per hour.

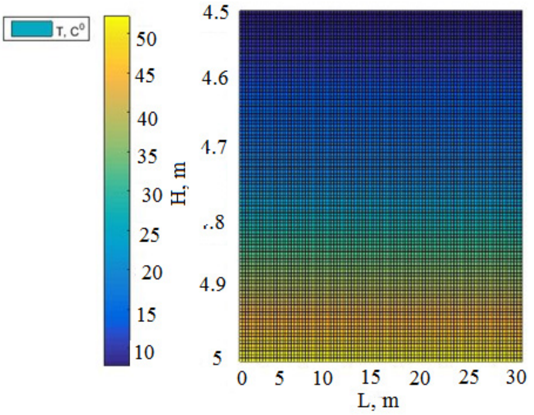

Fig. 7. Dependence of temperature distribution on spatial coordinates during the thermal influence of the pipe per 10 hours.

The analysis of the drawings demonstrates that heat spreads from the pipeline to the soil surface over time, and more intense heating is observed both near the pipeline and in the body of the soil massif.

3. CONCLUSIONS

1. An algorithm and a PC program for calculating the one-dimensional soil temperature field without taking into account the influence of the phase transition of moisture in the soil pores during seasonal freezing and thawing using the finite difference method have been developed.
2. On the basis of numerical calculations, the dependence of the temperature change on time and on the depth of the soil massif has been obtained. It has been established that the amplitude of fluctuations in the temperature regime decreases with depth from the soil surface.
3. It has been established that the delay of the temperature maximum and temperature minimum relative to the fluctuation of the annual conditional temperature of the atmospheric air is greater, the deeper the calculated soil mark is. The resulting effect occurs due to the thermal inertia of the soil and depends on its type and properties.
4. Mathematical modelling of the heat transfer process in the soil layer, on one boundary of which heat exchange occurs with the environment, and on the other with the hot water pipeline, has been carried out. An algorithm and a PC program have been developed to calculate the temperature field of the soil.
5. As a result of numerical calculations, the dependence of the distribution of the temperature field of the soil on spatial coordinates has been established, the analysis of which demonstrates that over time heat spreads from the pipeline to the surface of the soil, and over time more intense heating occurs both near the pipeline and in the body of the soil massif.

REFERENCES

1. Plum, R.L., & Esrig, M. J. (1969). Some Temperature Effects on Soil Compressibility and Porewater Pressure. *Highway Research Board*. *SpRpt, 103*, 213–242.
2. Campanella, R.G., & Mitchell, J.K. (1968). Influence of Temperature Variations on Soil Behavior. *J. Soil Mechanics and Foundations Division*, *94*, 709–734.
3. Laloui, L. (2001).Thermo-Mechanical Behavior of Soils. *Revue Francaisedegenie Civil, 5*, 809–843.
4. Ivanik, O.M., & Lavrenyuk, M.V. (2008). Factors Provoking Strained and Deformed State in the System of Geological Medium-Pipeline in Cryolithozone and their Quantitative Assessment (Numerical Data Based on Computer Modeling). *Geoinformatika, Ukraine, 1*, 53 –59.
5. Kovalchuk, V., Hnativ, Y., Luchko, J., & Sysyn, M. (2020). Study of the Temperature Field and the Thermo-elastic State of the Multilayer Soil-Steel Structure. *Roads and Bridges – Drogi i Mosty, 19* (1), 65–78.
6. Chornyi, S.G. (2018). *Assessment of Soil Quality: Study Guide*. Mykolaiv, Ukraine: MNAU.
7. Shutenko, L.M., Rud, O.G., Kichaeva, O.V. (2017). *Soil mechanics and Foundations: A Textbook.* Kharkiv, Ukraine: O.M. Beketov KhNUMG.
8. Remez, N., Dychko, A., Kraychuk, S., Ostapchuk, N., Yevtieieva, L., & Bronitskiy, V. (2018). Simulation of Seismic Explosion Waves with Underground Pipe Interaction. *Latvian Journal of Physics and Technical Sciences*, *55* (3), 27–33. DOI: 10.2478/lpts-2018-0018.

9. Tolstoy, M.I., Gozyk, A.P., Reva M.V. (2006). *Fundamentals of Geophysics*. Kyiv, Ukraine: KNU.
10. Shkolny, E.P. (1997). *Physics of the Atmosphere.* Odesa, Ukraine: Vipol.
11. Remez, N.S., Kiselyov, V.B., Dychko, A.O., & Minaieva, Y.Y. (2022). *Numerical Methods of Solving Technical Problems.* Odesa, Ukraine: "Helvetika" Publishing House.