



A temperature behavior of frozen soils: Field experiments and numerical solution

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ARTICLE INFO

Article history:

Received 23 November 2011

Accepted 13 March 2012

Keywords:

Frozen soil (permafrost)

Thawing processes

Experimental measurements

Temperature distributions and phase front propagation

Equilibrium unfrozen water content

Numerical solution

ABSTRACT

On the basis of the field (natural) measurements, which were carried out by the authors in cold regions such as Siberia in The Russian Federation, the temperature distributions and the phase front propagation are analyzed during thawing process in frozen soils (permafrost).

The treatment of the experimental data was carried out on the basis of the likeness and dimensionality theory. In this way the temperature distribution as a function of the dimensionless values (criteria), characterizing the geometry of the calculation domain, thermo-physical properties of the soils and also level of the phase transitions – a criterion of Stefan was to be obtained in general form. The treatment of the experimental measurements in obtained general dimensionless form shows that the natural measurements for a wide range of both the soil surface temperature variation and thawing depth group near certain universal curves for the loamy and sandy soils, respectively. These curves may be approximated by the dimensionless self-similar function with a parameter which depends on the thermal and physical properties of the soil mass. By the method of linear regression the dependence of the front penetration coordinate on time is obtained and discussed in detail. It is shown that this dependence is different from the self-similar solution. The phase front propagation described by generalized approximation function obtained in this study is in good agreement with experimental data.

On the basis of the nonlinear system of equations (general Boundary Value Problem) corresponding to the considered problem, the numerical solution for the temperature distribution in the soil is presented. For the temperature distribution the good agreement between experimental measurements and numerical solution is observed.

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1. Introduction

The effects of the harsh climate found in regions such as Canada, The United States and North-East Asia on civil engineering structures cannot be neglected by designers and contractors. Almost all these areas are affected by frost penetration to a lesser or greater degree. A great number of buildings, roads, dams, pipelines, power transmission towers, etc. in these regions have experienced movement or have failed. For instance, in the northern part of Western Siberia there are more than 4000 tilted power transmission towers (Lyazgin et al., 2003). Providing stable support for these structures is an important scientific and practical problem. As is noted in the study by Ferris (2009), the condition of seasonal frost penetration occurs in nearly all parts of Canada; therefore the potential for frost heave is typically related to the presence of a water supply and having frost susceptible soils. It should be also noted that in areas where frost susceptible soils are presented, the soils can supply water to the freezing front through the process of capillarity

even if the depth to the water table is considerable. It is clear that in cold regions it is very important that the temperature behavior of frozen soils (permafrost) and in particular thawing processes be affected on the phase front propagation (frost penetration).

For example, in the Province of Quebec, with freezing indices ranging from 800 to over 2000 degree-days, frost penetrates to depths greater than 1.5 m and frost action mainly develops in frost-susceptible soils, leading to ice lens formation, surface heave, and eventual distress of structures (Konrad, 2005). In regions with even colder climates such as Siberia in The Russian Federation, freezing indices of 4000 to 6000 degree-days are found with frost penetration to depths greater than 2.5 m. (Feldman, 1988b). In this connection the analysis of the heat transfer processes in freezing and thawing soils is inseparably connected with the study of the dynamics of the temperature fields in theoretical and experimental directions. This combination leads to a reliable description of all regularities of the thermal structure. There are a number of investigations on permafrost in which the heat transfer processes in moist soils are carried out by means of theoretical and experimental analysis (Bronfenbrener, 2008; Bronfenbrener and Bronikova, 1980; Bronfenbrener et al., 1979; Bronfenbrener et al., 1989; Danielian and Yanitsky, 1983; Danielian et al., 1983; Ershov, 1979a; Feldman, 1973, 1977, 1988b; Grechischev et al., 1980; Lunardini, 1981, 1991, 1996; Yanitsky, 1986). In a theoretical aspect

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these investigations are based on the development and utilization of the mathematical models of the considered phenomenon. In this case the problems are solved in quasi-steady statement (Bronfenbrener, 2008; Feldman, 1973, 1977, Yanitsky, 1986) as well as by numerical methods (Bronfenbrener and Bronikova, 1980; Bronfenbrener and Korin, 1997; Bronfenbrener et al., 1979; Danielian and Yanitsky, 1983; Hansson et al., 2004). The experimental investigations include mainly the analysis of the soil characteristics and effects of the freezing and thawing zone formations on the moisture transfer process (Ershov, 1979a; Feldman, 1988a, 1988b; Mizoguchi, 1990). At the same time there are a rather limited number of publications in which the natural (field) studies results are presented (Ershov, 1979a; Feldman, 1988b; Konrad, 2005; Konrad and Morgenstern, 1980, 1982; Lunardini, 1981, 1991, 1996; Vtiurina and Vtiurin, 1970).

Nevertheless, the natural measurements (under their suitable treatment) are essential for generalization of main regularities of the soils' thermal state. They are also a basis for the choice of the principle of soil used as a foundation of buildings in cold regions.

Thus, the purpose of the present study is to investigate by field experiments the temperature behavior of frozen soils (permafrost) during annual fluctuations of environment temperature in cold regions. On the basis of likeness and dimensionality theory and correlation analysis the form for treatment of the experimental measurements and general approximations of temperature distributions and the phase front propagation (very important characteristics for design and construction) during the thawing process in frozen soils is obtained. For the verification results of treatments we present the statement of the appropriate Boundary Value Problem and its solution by numerical method.

This paper is organized as follows. In the next section we describe the field experimental data. We give here the brief description of the thermal and physical properties of soils including temperatures of permafrost and thawing depths. We also discuss the apparatus and time-interval of measurements. In Section 3 on the basis likeness and dimensionless theory we obtain the general (functional) form for the treatment measured distributions of the temperature. We also present in this section the self-similar approximation of the temperature distributions as well as the treatment of the experimental points of thawing depth propagation. For this purpose we apply the regression method. The theoretical description of the problem is given in Section 4. In this section we describe the geometry, physical background of the process and mathematical statement of the Boundary Value Problem in dimensionless form. The brief description of the numerical method is also discussed in this section. Section 5 involves the results of numerical calculations and comparison with numerical solution and experimental measurements. It is shown in this section the good agreement between both distributions. Here we also discuss the physical aspects concerning the application of the calculation distribution of the equilibrium water content. In the end of the paper the conclusions resulting from this study are summarized.

2. The field data description

The studied region was divided on the sequence of loamy and sandy soils areas, respectively. It is known, that for the soil, as a heterogeneous porous media, the texture represents the relative proportion of its particles with different sizes, which is a fundamental physical property, correlated to just any other soil properties and, in particular, to thermal and physical characteristics. Therefore for the treatment of the experimental results and modeling, it is very important to know the distribution of the particle sizes of the soils, and based on this distribution to calculate the percentage of major components of soil in order to obtain its texture classification and then its corresponding properties. For this purpose the particle sizes were measured by sieving and light scattering methods, and textural class of the soils was defined according to USDA classification.

The distributions of particle sizes for studied soil areas are listed in Table 1 and illustrated by differential function of distributions in Fig. 1. These distributions allow the calculation of the percentage of each major component — sand, silt and clay, and on the basis of USDA classification to define the class of the soil.

The thermal and physical properties of each soil are listed in Table 2. In this table the values k_{pfr} , k_{unfr} and C_{pfr} , C_{unfr} are thermal conductivity and volumetric specific heat of the permafrost (frozen) and unfrozen soils, respectively. The temperature of permafrost was limited in the range of $-0.5^{\circ}\text{C} \leq T_{pfr} \leq -0.8^{\circ}\text{C}$ for the loamy soil and $-1.0^{\circ}\text{C} \leq T_{pfr} \leq -2.1^{\circ}\text{C}$ for the sandy soil, respectively.

The areas were equipped for the systematic control of the temperature behavior. For this purpose the resistance thermometers were used. In addition, on certain areas the slow-thermometers were also used. The rate of frequency for measurements was estimated by environment temperature fluctuations but did not exceed the value of $\Delta\tau = 0.5\delta^2/\alpha$ where δ is active layer thickness and α is thermal diffusivity of the soil.

In Fig. 2 we give the experimental profiles of the temperature for the loamy and sandy soils. The measurements correspond to the maximal depth of thawing (phase front propagation) — ξ_{max} .

It can be seen that the field measurements of the maximum phase front propagation in these examples are 1.42 and 1.7 m for the loamy and sandy soils, respectively. We note that in general in the studied region these characteristics varied from 0.75 to 1.8 m for a wide range of the soil surface temperature variations in time ($4.2^{\circ}\text{C} < T_b < 15^{\circ}\text{C}$).

3. Theoretical substantiation and treatment of the experimental data

In general case at every moment the temperature distribution T through depth of the soil can be represented as functional dependence

$$T = f(T_b, T_{pfr}, x, \xi, k_{unfr}, k_{pfr}, C_{unfr}, C_{pfr}, E), \quad (3.1)$$

where x, ξ are coordinate and phase front position; T_b, T_{pfr} are the temperatures at the soil surface and permafrost, respectively; $E = \rho_s L(W_0 - W_*)$ is a volumetric enthalpy of phase transition; L is latent heat of the water crystallization.

Now we introduce the differences $\Delta T = T - T_{pfr}$, $\Delta T_b = T_b - T_{pfr}$. According to the likeness and dimensionality theory (Barenblatt, 1996; Kutateladze, 1982), the dimensionless variables conforming to function (3.1) will have the following form:

$$\Delta T^{\nu_1} \Delta T_b^{\nu_2} x^{\nu_3} \xi^{\nu_4} k_{unfr}^{\nu_5} k_{pfr}^{\nu_6} C_{unfr}^{\nu_7} C_{pfr}^{\nu_8} E^{\nu_9}, \quad (3.2)$$

where $\nu_i (i = 1, 2, \dots, 9)$ are unknown powers.

Table 1

Distributions of the particle sizes for the loamy and sandy soils.

Size of particles (mm)	Percent of particles	Percentage of major components
<i>Loamy soil</i>		
1–0.5	2.1	Sand (32.1%)
0.5–0.25	5.6	
0.25–0.1	14.8	
0.1–0.05	9.6	
0.05–0.01	34.2	Silt (48.5%)
0.01–0.005	7.8	
0.005–0.002	6.5	
<0.002	19.4	Clay (19.4%)
<i>Sandy soil</i>		
1–0.5	10.2	Sand (99.8%)
0.5–0.25	14.6	
0.25–0.1	50.7	
0.1–0.05	24.3	
0.05–0.01	0.2	Silt (0.2%)

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