ISSN 1068-3712, Russian Electrical Engineering, 2015, Vol. 86, No. 5, pp. 275–281. © Allerton Press, Inc., 2015.
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Determination of Soil Parameters to Calculate Soil Resistivity

N. M. Zaitseva[a], B. B. Isabekova[b], and M. Ya. Kletsel'[c]

[a] *Innovative University of Eurasia, Pavlodar, Kazakhstan*
[b] *Toraighyrov Pavlodar State University, Pavlodar, Kazakhstan*
[c] *National Research Tomsk Polytechnic University, Tomsk, Russia*
e-mail: journal-elektrotechnika@mail.ru

Received April 14, 2015

Abstract—This paper is dedicated to the development of techniques allowing for design solutions to be refined on grounding devices. The resistivity is used in the design of grounders in dependence on the soil humidity, temperature, and density. To determine soil humidity at the depth of soil occurrence, two models are used: depending on the season at a depth of up to 1 m and depending on the level of groundwaters at depths of more than 1 m. The models are developed based on the fuzzy logic theory and data from water stations and geological exploration. The technique and corresponding dependencies are used to find the temperature of soil layers during a year and calculate soil resistivity. Temperature was simulated based on the Fourier theory of thermal conductivity and data from weather stations. It is shown that these methods and dependencies allow one to calculate more precisely the resistances of grounders at the design stage. The obtained in vitro dependencies of soil resistivity on the soil humidity and density are considered. These dependencies allow one to refine the dynamics of change in the grounder resistance from the time of installation to complete soil subsidence.

Keywords: grounding device, soil, soil resistivity, temperature, humidity, density, fuzzy logic

DOI: 10.3103/S1068371215050119

Grounding devices (GDs) of electric stations and substations are designed to provide safety and reliability of their operation, which is regulated by the *Electrical Installation Code* (PIC, first and second standard) [1]. Solutions should be found to reduce GD resistance for any object. To calculate the resistance of GDs, it is necessary to know soil resistivity ρ, which changes over wide ranges depending on temperature t, humidity ν, density d, and kind of soil. For example, for dry soil, $\rho = 1500–4200\ \Omega$ m, while for very wet soil $\rho = 10–60\ \Omega$ m [2]. The known formulas [2] and seasonal coefficients recommended by the PIC allow one to obtain only approximate values of ρ. Paper [3] suggests a method based on the use of fuzzy-set theory. The method makes possible to determine a value of ρ depending on t, ν, and kind of soil more exactly that the previous ones, but requires a lot of time-consuming measurements of temperature and soil humidity. The problem of determining the soil temperature at depth (0–15 m in the middle and 0–10 m in southern latitudes, with the layer of constant temperature being lower, as deep as 50 m) in any season without such measurements is solved in [4] (the formula by which t is calculated is given in Appendix 1). The paper proposes techniques of determination of natural soil humidity at such depths. The techniques allow one to refine the resistivity formulas obtained in [3] and control the change in the resistance of soil layers over a year. The density dependencies of resistivity were also obtained in [4]. (Corresponding formulas are given in Appendix 2.)

The methods of determination of soil humidity are based on using fuzzy logic, data of weather stations (for depths less than 1 m), and geological exploration centers (for depths more than 1 m). The humidity depends on the depth, season, and climatic conditions in the first case and on the proximity to groundwaters in the second.

The first method. Here, "humidity at depth" is an unclear notion. Therefore, two notions are used: "close to surface" and "far from surface" with membership functions (MFs) $\mu_1(h)$ and $\mu_2(h)$. Hence, there are two intervals: the first interval is $0 \le h \le 20$ cm, while the second is $h \ge 100$ cm, where h is the soil depth at which soil humidity is determined. Such limits of the intervals are chosen because the weather stations give data on humidity ν_{20} and ν_{100} at depths of 20 and 100 cm, although the intervals are determined by the regions of wind forcing, temperature at soil surface, and rainfall. It is believed that such action ceases at a distance of 80–100 cm from the surface, while humidity is strongly affected by all the aforementioned parameters at a distance less than 20 cm. The transition area between the intervals is $20 \le h < 100$ cm. If there are two intervals, standard membership Z- and S-functions are recommended as $\mu_1(h)$ and $\mu_2(h)$ in

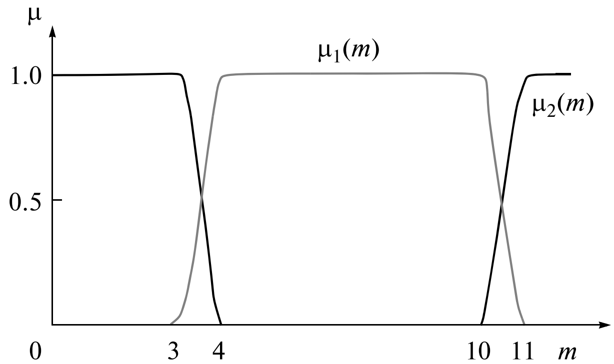

Fig. 1. Rectangular membership functions: (*1*) $\mu_1(m)$; (*2*) $\mu_2(m)$.

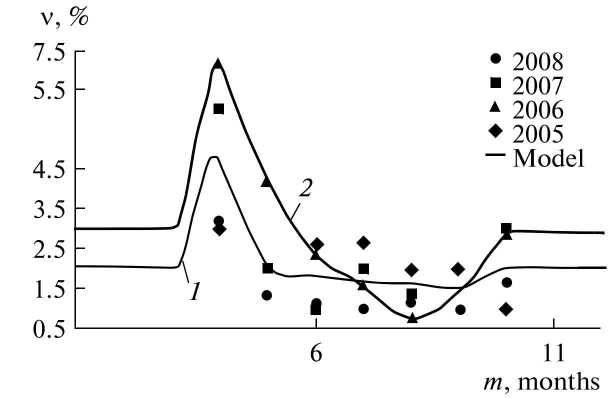

Fig. 2. Time dependencies of humidity at a depth of 1 m: (*1*) from data of weather stations in 2005–2008; (*2*) in 2006.

fuzzy logic theory. Moreover, for the notion "close to surface" $\mu_1(h) = 1$ and $\mu_1(h) = 0$ on the first and second intervals, respectively, while, for the notion "far from surface," $\mu_2(h) = 1 - \mu_1(h)$. Upon the transition, interval $\mu_1(h) = 1 - \frac{h-20}{100-20}$. As a result, the soil humidity at depth h is

$$\nu_h = \nu_{20}\mu_1(h) + \nu_{100}\mu_2(h). \qquad (1)$$

Functions ν_{20} and ν_{100} can be find using multifactor regressive modeling from the data of weather stations for each month (excluding the soil freezing period). The dependencies of functions on the rainfall r_{av}, mm; soil surface temperature $t_{s.s.}$, °C; and mean wind velocity v_w, m/s. For example, for an arid region and zone of weak spring moistening in 2005–2008, the following formulas were obtained: $\nu_{20} = 8 + 0.03r_{av} - 0.2t_{s.s.} - 0.8v_w$ and $\nu_{100} = -4 + 0.03r_{av} - 0.007t_{s.s.} + 1.3v_w$. The soil humidity at depths up to 1 m in the soil freezing period (from November to February) is unchanged, since rainfall is accumulated in the form of snow and ice on the ground surface and does not penetrate deeply. Therefore, the humidity is not measured by weather stations in this period.

To determine humidity in any season at a depth up to 1 m, the linguistic variable "month" was introduced. The months in which the air temperature is stably kept below zero (for the considered climatic zone from November to February) are in the first interval; April to October are in the second interval. Therefore, it can be assumed that the membership functions $\mu_1(m) = 1$ and $\mu_2(m) = 0$ from November to February, while $\mu_1(m) = 0$ and $\mu_2(m) = 1$ from April to September, where m is the month number. The transition intervals are March (month of intensive snow melting) and October (month, in which soil temperature approaches negative values); for northern latitudes in the month of intense snow melting. the rainfall that has accumulated in the form of snow cover in the winter months is calculated by summing (for southern latitudes soil surface temperature is above zero during a year). The membership functions are represented in the form of a rectangular pulse (Fig. 1)

$$\mu_1(m) = \begin{cases} 0, m \le 3, m \ge 11, \\ \exp(-3(m-4)^2), \ 3 \le m \le 4, \\ 1, 4 \le m \le 10, \\ \exp(-3(m-10^2)), \ 10 \le m \le 11; \end{cases}$$

$$\mu_2(m) = 1 - \mu_1(m).$$

As a result, for a depth of 1 m, the humidity is calculated as a function of r_{av}, $t_{s.s.}$, v_w, and season (by months) by the formula

$$\nu = \sum_{i=1}^{2} \eta_i(m)\mu_i(m) = \eta_1(m)\mu_1(m) + \eta_2(m)\mu_2(m), \qquad (2)$$

where $\eta_1(m) = \nu_h^{(m=10)}$ and $\eta_2(m) = \nu_h$ are the humidity calculated by Eq. (1) for October and warm months ($m = 4$–10). In winter months ($m = 1, 2, 11, 12$), the humidity is unchanged. Thus, two different notions of humidity depending on depth h and month m are grouped according to fuzzy logic. The appropriateness of the model has been proven from Fischer's criterion [4]. A typical dependence of soil humidity on the climatic conditions and seasons is shown in Fig. 2. The dependence is plotted from weather station data averaged over 4 years. Analysis showed that the error in humidity determination by such dependencies is no higher than 30% and the dependencies can be used in designing grounding devices in subsequent years.

Determination of soil humidity at depths of more than 1 m. Humidity at such depths is unaffected by the climatic conditions [5] but changes depending on the level of groundwaters ($h_{g.w}$, m). In addition to the rules of fuzzy logic, height of capillary water rise $h_{c.r}$ (0.5 m for sand, 1 m for loamy sand, 2.5 m for clay [6]), as well as data from geological exploration centers, are used in the developed method. The linguistic variable "proximity to groundwaters" $h_{g.w}$ and two notions, "near" with membership function $\mu_1(h_{g.w})$ and "far" with membership function $\mu_2(h_{g.w})$, are introduced in the model. Hence, there are two intervals: the first interval is $0 \le h_{g.w} < 0.8h_{c.r}$, m ($0.8h_{c.r}$ is used because, starting at this distance, soil begins drying); the second one is $h_{g.w} \ge h_{c.r}$, m; the transition interval is $0.8h_{c.r} \le h_{g.w} < h_{c.r}$, m. The kind of MF for two intervals is chosen similarly to the previous functions as Z- and S-functions. For the notion "near" $\mu_1(h_{g.w}) = 1$ and $\mu_1(h_{g.w}) = 0$ on the first and second intervals, respectively, on the transition interval $\mu_1(h_{g.w}) = 1 - \frac{h_{g.w} - 0.8h_{c.r}}{0.2h_{c.r}}$. The latter is determined as usual: if $\mu_1(h_{g.w})$ is decreasing, $\mu_1(h_{g.w}) = 1 - \mu_2(h_{g.w})$, while $\mu_2(h_{g.w}) = \frac{x-a}{b-a} = \frac{h_{g.w} - 0.8h_{c.r}}{h_{c.r} - 0.8h_{c.r}}$, which is calculated from the ratio of sides $ae/ax = ce/bx$ of triangles *acd* and *xea* (Fig. 3a), since they are similar. The membership functions are shown in Fig. 3a, and the dependence $\mu_1(h_{g.w})$ can be expressed by

$$\mu_1(h_{g.w}) = \begin{cases} 1, \ 0 \le h_{g.w} < 0.8h_{c.r}, \\ 1 - \dfrac{h_{g.w} - 0.8h_{c.r.}}{0.2h_{c.r}}, \ 0.9h_{c.r} \le h_{g.w} \le h_{c.r}, \\ 0, \ h_{g.w} \ge h_{c.r}. \end{cases} \quad (3)$$

The formula to determine ν will be derived by analogy with Eq. (2), where $\eta_1(h_{g.w})$ is plotted by the data of a geological exploration center, for example, for sand $\eta_1(h_{g.w}) = 18–27h_{g.w}$, while $\eta_2(h_{g.w})$ is taken as a mean value for undisturbed soil (for example, 4.5% is humidity of natural sand occurrence).

As a result, the following formulas are obtained

$$\left.\begin{aligned} \nu_{sand} &= (18–27h_{g.w})\mu_1(h_{g.w}) + 4.5\mu_2(h_{g.w}), \\ \nu_{loamy\ sand} &= (23–19.3h_{g.w})\mu_1(h_{g.w}) + 3.5\mu_2(h_{g.w}), \\ \nu_{clay} &= (50–12.8h_{g.w})\mu_1(h_{g.w}) + 18\mu_2(h_{g.w}), \end{aligned}\right\} \quad (4)$$

where 18, 23, and 50 are the maximum water capacity (ability to keep water) of sand, loamy sand, and clay, respectively; 27, 19.3, and 12.8 are the coefficients obtained by the least-squares method and taking into account capillary water rise.

For example, for sand at depth $h = 5.2$ m (point x_1, Fig. 3b) soil humidity should be determined at groundwater level $h_{g.w.l} = 5$ m. It is calculated that $h_{g.w} = |h - h_{g.w.l}| = 0.2$ m, which corresponds to notion "near" since $0 \le h_{g.w} < 0.8h_{c.r}$ with MF $\mu_1(h_{g.w}) = 1$ and μ_2 (Fig. 3a), humidity $\nu = 18–27h_{g.w.} = 12.6\%$. If $h = 5.8$ m (point x_2), $h_{g.w} = 0.8$ m, $\mu_1(h_{g.w.}) = 0$, $\mu_2(h_{g.w}) = 1$, $\nu = 4.5\%$. If $h = 5.47$ m (point x), $h_{g.w.} = 0.47$ m. Since this point is at transition interval $0.8h_{c.r} \le h_{g.w} < h_{c.r}$, MF $\mu_2(h_{g.w}) = \frac{h_{g.w.} - 0.8h_{c.r.}}{0.2h_{c.r.}} = 0.7$, $\mu_1(h_{g.w}) = 0.3$, and we can determine by Eq. (4) $\nu = 4.7\%$.

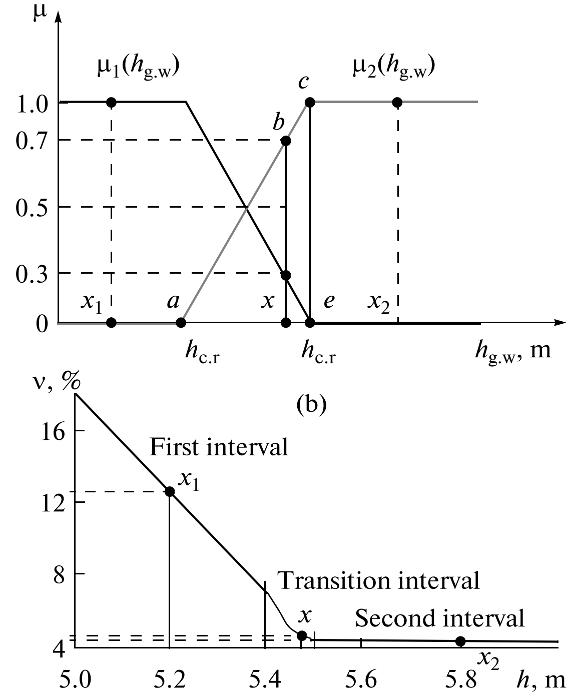

Fig. 3. Humidity as a function of groundwaters: (a) membership functions $\mu_1(h_{g.w})$ and $\mu_2(h_{g.w})$; (b) determination of sand humidity.

With the use of this model, the soil resistivity for some wells in the regions of Pavlodar and Novosibirsk oblasts was calculated. Comparison between the experimental data and simulation results showed that the calculation error is no higher than 20% for dry and 10% for damp soils.

The adequacy of the model is confirmed from Fischer's criterion. Thus, if the number of layers, layer type, and groundwater level are known, the humidity in any season at depths of more than 1 m can be determined by formulas (4) with a calculation error no higher than 20% for dry and 10% for damp soils, which gives calculation error ρ of no more than 15%.

Density dependence of soil resistivity. Degree of soil compactness d_s alongside humidity and temperature, has a direct influence on the soil resistivity.

To determine the dependence of ρ on d, a setup was manufactured [6]. The setup contained a tube fixed vertically, two internal electrodes placed in radial holes in the middle tube part, and two external electrodes

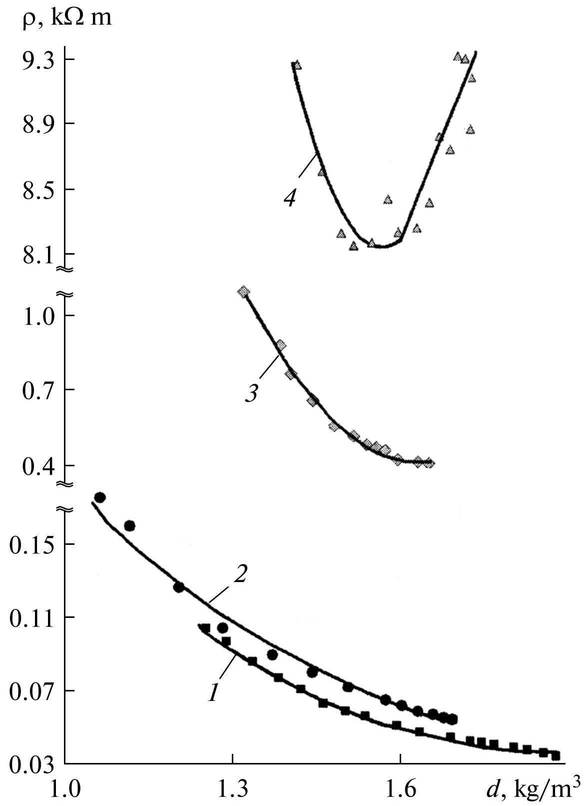

Fig. 4. Density dependence of resistivity for sand with humidity of (*1*) 9, (*2*) 5, (*3*) 1, and (*4*) 0%.

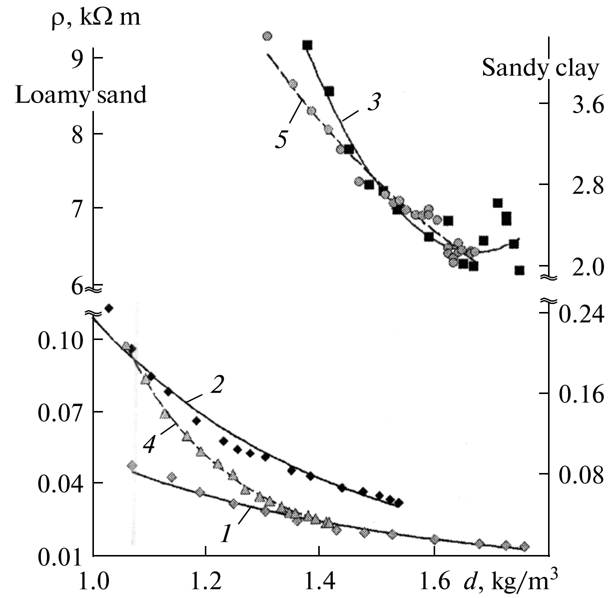

Fig. 5. Density dependencies of resistivity for loamy sand with humidity of (*1*) 9, (*2*) 5, and (*3*) 1% and sandy clay with humidity of (*4*) 7 and (*5*) 2%.

placed in the upper and lower parts. A sample of the soil with known mass, humidity, and temperature was loaded into the tube, the voltage with a frequency of 50 Hz was applied across the external electrodes, the current flowing through soil was measured by an ammeter, and the internal electrode voltage was measured by a voltmeter. Then, the setup was switched off and the soil was subjected by vibropilon for compacting. After a successive stage of compacting, the voltage was again applied and measurements were carried out. This was continued until final sample compacting.

As was mentioned in [7], the higher d, i.e., the more soil is puddled, the less soil ρ. This has also been confirmed by our experiments (Fig. 4), and for sand with humidity more than 1% the dependence of ρ on the density shows an exponential behavior (curves *1–3*). In the wet state, $\rho_{sand} = 40\ \Omega$ m; in the dry state it can reach 10 kΩ m; i.e., the damper the soil, the lower ρ.

For sands in a dry state (from 0 to 1%), first a decrease in ρ by exponent as low as 1.6 kg/m^3 was observed with compacting, and a linear growth of ρ was then registered, unlike in [7] (Fig. 4, curve *4*). Such a picture was not observed for loamy sand and sandy clay, because, under real conditions, they cannot have humidity less than 1.5 and 1%, respectively, since they have a high hygroscopic property [5]. This fact once more corroborates the recommendations of [7]: the soil should be thoroughly puddled.

Based on the experimental investigations, the following dependence of ρ on the density was obtained for sand, loamy sand, and sandy clay:

$$\rho = \rho_{d0} e^{k_v(d - d_0)}, \quad (5)$$

where ρ_{d0} and d_0 are the resistivity and density of soil from geological exploration data that are taken before designing of grounding devices or ρ_{d0} can be calculated by Eq. (A2.3) with corresponding density d_0 (for example, sand $d_0 \approx 1.4$ kg/m^3); k_v is the coefficient: for sandy clay $k_v = e^{(-0.46v + 2.05)} - 5$; for sand $k_v = e^{(-0.08v + 1.08)}$; and loamy sand $k_v = e^{(-0.05v + 1.1)}$.

For loamy sand and sandy clay at humidity from 1% to the water-saturation state, ρ decreases exponentially with increasing density. The left and right scales of ρ values correspond to dependence $\rho(d)$ (Fig. 5) for loamy sand (Fig. 5, curves *1–3*) and sandy clay, respectively. For sandy clays and clays in the wet state, particle agglutination leading to the formation of numerous voids and cracks is typical, which decreases soil conductivity; this fact should be taken into account in designing grounding devices. A structure almost homogeneous over density was obtained for sandy clay with humidity of 10% using the laboratory setup.

It is known that, when a grounding device is installed, the parameters of the device are frequently worse than the calculated ones despite careful compliance with the technological requirements of construction works. In such a case, dependence (5) can be used since it allows one to determine the dynamics of decreasing ρ during soil packaging from the loosening state to complete soil subsidence. To do this, ρ is calculated by Eq. (A2.3) depending on the temperature and humidity. There are data on soil subsidence [8] that determine the time intervals of soil transition to the state of undisturbed soil. For example, for construction of the grounding with a use of thorough tamping, from 2 to 5 years are needed for clays and 1–2 years for sands, but without tamping from 10 to 15 and 2–5 years, respectively.

Using the obtained techniques, an algorithm and program to calculate ρ of soil were developed, they were applied to calculate and design of resistance of the grounding electrode. As initial data, the depth of soil occurrence, temperature t_S and temperature amplitude A_S, the time period for which the calculations are carried out, kind of soil, and distance from groundwaters $h_{g.w}$ are used.

The algorithm of calculations is as follows:

—humidity of soils is determined using Eqs. (1)–(3) for a depth of less than 1 m or (4) and (5) for higher depths;

—temperature of the given soil layers is calculated by formula (A1.1);

—ρ is calculated by dependencies (A2.3) and (A2.4);

—temperature and humidity dependencies of ρ during a year are plotted;

—the value depending on the density is determined from Eq. (5); and

—resistance of the grounding electrodes is determined.

The proposed program allows one to determine and plot dependencies of ρ on the soil temperature and humidity and to choose or determine the worst variant of value of ρ with an accuracy up to 12–30% relative to data from weather stations and geological exploration centers, as well as to deduce the result of ν and t calculations for each soil layer and plot their dependencies in any season to calculate resistances and design grounding electrodes. The program can be used as an assistance program for ones without ρ but giving exact calculation of resistances of more complicated structures of GDs. The Delphi programming language was used.

APPENDIX 1

Determination of Soil Temperature at Depth of Soil Occurrence

On the basis of the Fourier theory of thermal conductivity and data from weather stations, the following formula was deduced [9] to determine soil temperature in any season for depths of less than 15 m in middle latitudes and less than 10 m in southern latitudes with an accuracy of less than 10%:

$$t = t_S - A_S\left(\frac{A_{c.t}}{A_S}\right)^{h/h_s}\cos\left[\frac{2\pi}{365}(g - 20h)\right]. \quad \text{(A1.1)}$$

Here, t_S is the temperature of the layer of constant t, °C, which is close to the mean year temperature of soil surface, for example for middle latitudes $t_S \approx 8$°C [10]; A_S is the soil surface temperature amplitude (relative to layer of constant year temperature) at required depth, °C; $A_S = (t_{Smax} - t_{Smin})/2$, where t_{Smax} and t_{Smin} are the maximum and minimum monthly mean temperature of the soil surface over a year for a given region (from weather station data); h is the depth, m; g is the number of days; the coefficient 20 takes into account a delay (in days) of maximum (minimum) year temperature oscillation at a depth of 1 m relative to soil surface temperature; and $A_{S.t}$ is the temperature oscillation amplitude at depths with constant year temperature, $A_{S.t} \approx 0.1$°C; and h_C is the depth of the constant temperature layer (15 and 10 m in middle and southern latitudes, respectively). Formula (A1.1) is not valid for the permafrost region.

The worth of the model was proven for regions in middle latitudes (the regions of Kaliningrad, Pavlodar, and Pskov) and southern latitudes (the regions of Stavropol and Vladivostok) [9]. Formula (A1.1) allows one, at the stage of grounder design, to determine soil temperature from weather station data with an accuracy of up to 10% in any season at depths of changing temperatures: less than 15 and 10 m in middle and southern latitudes, respectively, which that provides a calculation error of resistivity no higher than 5%.

APPENDIX 2

Determination of Dependencies of ρ on t, ν, and Kinds of Soil

This [3] is based on a use of the fuzzy-set theory [11], since humidity is a fuzzy notion.

The idea of the model is that a system of fuzzy rules is developed for each kind of soil. The system can be expressed as follows [11]:

$$\begin{cases} IF(x_1 \in A_{1i})AND(x_2 \in A_{2i})HOR(x_k \in A_{ki}), \\ THEN\ y = \eta_i(x),\ i = 1, K, M, \end{cases} \quad \text{(A2.1)}$$

where A_{ij} is the fuzzy subset, i.e., a fuzzy interval for variable x_j with MF $\mu_{Aij}(x)$; M is the number of rules (number of intervals); and $y = \eta_i(x)$ is the function determining a local model solution for set $x = (x_1, ..., x_k)$.

For a one-dimensional dependence, in our case, a parameter of soil humidity is considered; the system of fuzzy rules (A2.1) can be expressed by

$$IF\, x \in Ai\ THEN\, y = \eta_i(x),\ i = 1, K, M,$$

where A_i have membership function $\mu_{Ai}(x)$.

The membership functions have the property that the following condition is satisfied at any point

$$\sum_{i=1}^{M} \mu_{Ai}(x) = 1.$$

To describe a fuzzy set, two notions are introduced: fuzzy variable "humidity" with a basic term-set (for example, "dry," "slightly wet," "wet") and MF $\mu_i(\nu) \in [0,1]$, which is a some subjective measurement of fuzzy membership of element ν to the given set; the MF is constructed for each linguistic term. There are more than ten typical forms of curves to define MF, for example, the Z-function, etc. If MF $\mu_1(\nu) = 1$, the element is strictly belonged to the given set, if $\mu_1(\nu) = 0$, it is not belonged.

For such soils as sand, loamy sand, and clay, the model is composed as follows: the number of fuzzy intervals is two: first interval is $0 \le \nu < 2\%$, the second one is $\nu > 6\%$, and the transition region is $2 \le \nu \le 6\%$. The membership functions are as follows [3]:

$$\mu_1 = \begin{cases} 1, & 0 \le \nu < 2, \\ e^{-0.8(\nu-2)^2}, & 2 \le \nu \le 6, \\ 0, & \nu > 6, \end{cases}$$

$$\mu_2 = \begin{cases} 0, & 0 \le \nu < 2, \\ 1 - e^{-0.8(\nu-2)^2}, & 2 \le \nu \le 6, \\ 1, & \nu > 6. \end{cases} \qquad \text{(A2.2)}$$

The composed model is $y = \sum_{i=1}^{M} \mu_i(\nu)\eta_i(\nu)$, where $\eta_i(\nu]$ is the regressive dependence obtained experimentally and N is the number of intervals. Thus, the dependencies for sand, loamy sand, and clay can be expressed by [2]

$$\rho_s = (6 \times 0.3^{\nu}\mu_1(\nu) + 1.5 \times 0.7^{\nu}\mu_2(\nu))e^{-0.022(t-20)},$$

$$\rho_{ls} = (90 \times 0.1^{\nu}\mu_1(\nu) + 0.3 \times 0.8^{\nu}\mu_2(\nu))e^{-0.022(t-20)}, \qquad \text{(A2.3)}$$

$$\rho_{cl} = (100 \times 0.25^{\nu}\mu_1(\nu) + 3 \times 0.8^{\nu}\mu_2(\nu))e^{-0.022(t-20)}.$$

At $t < 0$°C,

$$\rho_s = \rho_s^{t=0} k_s 0.87^{(t+1)},$$

$$\rho_{ls} = \rho_{ls}^{t=0} k_{ls} 0.88^{(t+1)}, \qquad \text{(A2.4)}$$

$$\rho_{cl} = \rho_{cl}^{t=0} 0.88^{(t+1)},$$

where $\rho^{t=0}$ is the soil resistivity calculated by Eq. (A1.2) at $t = 0$°C and k_s and k_{ls} are the coefficients [2] taking into account a stepwise increase in ρ in the range from 0 to –1°C. These coefficients are calculated by the formulas $k_s = -0.03\nu^2 + 0.86\nu - 1.9$ and $k_{ls} = 0.024\nu^2 - 0.022\nu + 0.2$. There is no such jump for clay, and ρ_{cl} changes smoothly with decreasing t, since wet clay is amorphous structure unlike sand.

Formulas (A2.3) and (A2.4) allow one to determine the dependencies of sand, loamy sand, and clay resistivity on the temperature and humidity with accuracy that is sufficient for practice.

APPENDIX 3

Calculations of Errors

1. There are data from geological exploration: sand, month is October, depth $h = 4$ m, $\rho = 2.5\ \Omega$ m, $\nu = 19\%$, and groundwater level $h_{g.w.} = 4$ m.

Soil temperature is calculated by Eq. (A1.1): $t = 13$°C. Humidity, from Eq. (4), is $\nu = 18\%$ (depth lower than 1 m, and $h_{g.w.} = 4$ m), ρ of sand is calculated by Eq. (A2.3): $\rho_s = (6 \times 0.3^{\nu}\mu_1(\nu) + 1.5 \times 0.7^{\nu}\mu^2(\nu))e^{-0.022(t-20)} = (6 \times 0.3^{18} \times 0 + 1.5 \times 0.7^{18} \times 1)e^{-0.022(13-20)} = 2.8\ \Omega$ m.

The computational errors of humidity and resistivity are 5 and 12%, respectively.

There are data from geological exploration: loamy sand, month is May, depth $h = 1.1$ m, $\rho = 141$ kΩ m, $\nu = 5\%$, and groundwater level $h_{g.w.} = 3$ m.

Soil temperature from Eq. (A1.1) is $t = 9.5$°C. Humidity, from Eq. (5), is $\nu = 3.5\%$ (depth more than 1 m, and $h_{g.w.} = 2$ m), ρ of loamy sand is calculated from Eq. (A2.3): $\rho_{gs} = (90 \times 0.1^{\nu}\mu_1(\nu) + 0.3 \times 0.8^{\nu}\mu_2(\nu))e^{-0.022(t-20)} = 150$ kΩ m. The computational errors of humidity and resistivity are 30 and 6%, respectively.

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Translated by M. Astrov