DETERMINATION OF THE MOISTURE CONTENT OF SOME SOILS BY THE METHOD OF shf ABSORPTION

V. K. Benzar', V. A. Daineko,
B. L. Tsentsiper, and Yu. N. Yaroshevich

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We investigate analytically and experimentally the attenuation of shf energy in various types of moist soils and grounds. We develop an shf hygrometer for soils.

The study of the distribution of moisture in capillary-porous materials is necessary in the solution of many problems of heat and mass transfer. It is important that the influence of the measuring methods and instruments on the object investigated and on the transfer processes taking place in it be minimal. This requirement is satisfied by a method based on the measurement of the attenuation of shf energy in the moist material, which is distinguished from others by its high sensitivity, broad range of variation of the moisture content, and lesser susceptibility to the effect of other (perturbing) factors [1-4].

However, it should be noted that the metrological characteristics of the shf method in measuring the moisture content of various substances, including soils, has not been sufficiently studied, and the existing analytical investigations require further refinement and development.

The purpose of the present paper is to investigate how the attenuation of the shf energy N, in dB, varies with the volumetric moisture content Q of various types of soils and grounds (sand, clay, sandy—load soils, and loamy soil), as well as to analyze the degree to which the perturbing factors influence this parameter [6].

The variation of the attenuation of the shf energy N as a function of the volumetric moisture content Q, the temperature t in °C, and the salt concentration C in the soil solutions can be estimated analytically in the linear-model approximation [7]. Assuming that the layer of moist ground is a passive reversible quadrupole, we obtained in [7] the formula

$$N = 8.686\,(\alpha l + |\Gamma_{12}|^2), \tag{1}$$

which is valid if the following inequality is satisfied:

$$2\,|\Gamma_{12}|^2 \exp(-2\alpha l) \leqslant 0{,}1. \tag{2}$$

It can be shown that when $\lambda = 3.2$ cm and $l = 3$ cm, (2) is satisfied for moist soils if $Q \geqslant 0.02$ [6]. Let α_0 be the coefficient of attenuation for the moist soil. Then, according to [8]:

$$\alpha_0 = \frac{2\pi}{\lambda}\left[\frac{\varepsilon'}{2}\left(\sqrt{1 + (\varepsilon''/\varepsilon')^2} - 1\right)\right]^{1/2}. \tag{3}$$

Since even for water (when $\lambda = 3$ cm) we have $\varepsilon''/\varepsilon' < 0.5$, it follows that $\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2}$ can be represented in the form

$$\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} = 1 + \frac{1}{2}\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 + 0\left\{\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right\}. \tag{4}$$

Limiting ourselves to the first two terms of the expansion, we have

$$\alpha_0 = \frac{\pi\varepsilon''}{\lambda\sqrt{\varepsilon'}}. \tag{5}$$

If the specimen is placed in a waveguide, (3) is transformed [9] to

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$$\alpha = \frac{2\pi}{\lambda}\left[\frac{\varepsilon' - P}{2}\left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon' - P}\right)^2} - 1\right)\right]^{1/2}. \tag{6}$$

Expanding (6) in a series in the same manner as (4), we obtain

$$\alpha = \frac{\pi\varepsilon''}{\lambda\sqrt{\varepsilon' - P}}. \tag{7}$$

Since the condition $P/\varepsilon' \leqslant 0.3$ is satisfied, expression (7) is transformed to

$$\alpha = \frac{\pi\varepsilon''}{\lambda\sqrt{\varepsilon'}}\left\{1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}\right\} \tag{8}$$

or, taking account of (5), we have

$$\alpha = \alpha_0\left\{1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}\right\}. \tag{9}$$

Thus, the coefficient of attenuation α depends on the type of measuring cell used and increases as its transverse dimensions decrease.

Let us estimate the quantity $1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}$. For a wave with λ = 3.2 cm and a standard rectangular waveguide with cross section 2.3 × 1 cm, we have λ_{cr} = 4.6 cm. When ε' = 2 (Q = 0), it is equal to 1.12; for a large waveguide with radius 1.15 cm, when ε' = 2, we obtain 1.17.

Thus, for identical characteristic dimensions the coefficient of attenuation in a rectangular waveguide differs little from the coefficient of attenuation in a circular waveguide. The volume in a circular waveguide is almost twice as large as in a rectangular one, and consequently it is better to use a circular waveguide as the measuring cell.

According to the linear model [7]:

$$\alpha_0 = \alpha_{H_2O}Q. \tag{10}$$

It is known that the dielectric permeability for pure water is described by the Debye equation

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(\frac{\lambda_s}{\lambda}\right)^2}, \tag{11}$$

$$\varepsilon'' = \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(\frac{\lambda_s}{\lambda}\right)^2}\left(\frac{\lambda_s}{\lambda}\right). \tag{12}$$

When t = 20°C, water has the following parameters [10]: ε_s = 80, ε_∞ = 5.1. Substituting (11) and (12) into (6), we have

$$\alpha_{H_2O} = \frac{\pi}{\lambda}\frac{(\varepsilon_s - \varepsilon_\infty)\frac{\lambda_s}{\lambda}}{\sqrt{\left\{1 + \left(\frac{\lambda_s}{\lambda}\right)^2\right\}\left\{\varepsilon_s + \varepsilon_\infty\left(\frac{\lambda_s}{\lambda}\right)^2\right\}}}. \tag{13}$$

Since $\varepsilon_s \gg \frac{\lambda_s}{\lambda}\varepsilon_\infty$, it follows that (13) can be simplified:

$$\alpha_{H_2O} \simeq \frac{\pi}{\lambda}\sqrt{\frac{\varepsilon_s}{\left\{\left(\frac{\lambda_s}{\lambda}\right)^2 + 1\right\}}}. \tag{14}$$

Expression (14) depends implicitly on the temperature. Indeed, according to [10]:

$$\varepsilon_s = 88.2 - 0.41t, \tag{15}$$

$$\lambda_s = 1.87 - 0{,}027t + 1.47^{-0.063t}. \tag{16}$$

We assume that at $t = t_0$ (t_0 = 20°C), $\alpha_{H_2O} = \alpha^{(0)}$ and $(\partial\alpha_{H_2O})/\partial t = \xi$; then we can write

$$\alpha_{H_2O} = \alpha^{(0)} + \xi(t - t_0) + 0[t - t_0]. \tag{17}$$

TABLE 1. Coefficient of Attenuation for Water as a Function of the Concentration of Salts at a Wavelength of 3 cm

C	α_{dip}	α_σ	α_{H_2O}
0	4,15	0	4,15
0,2	3,98	0,631	4,61
0,4	3,81	1,29	5,1
0,6	3,65	1,97	5,62
0,8	3,49	2,69	6,18
1,0	3,34	3,44	6,77

Substituting (15) and (16) into (14), taking account of the numerical values for ε_s and ε_∞, we arrive at the following estimates: $\alpha^{(0)} = 385\ \mathrm{m}^{-1}$; $\xi = -7.6\ \mathrm{deg}^{-1}\cdot\mathrm{m}^{-1}$.

Since $\xi < 0$, it follows that α_{H_2O} decreases as the temperature increases. Now let us consider expression (1). According to (17) and (9), we have

$$N = 8{,}686\left\{[\alpha^{(0)} + \xi(t - t_0)]\left[1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}\right] Ql + |\Gamma_{12}|^2\right\}. \qquad (18)$$

It can be shown [6] that even for Q = 0.02, the ratio

$$\frac{|\Gamma_{12}|^2}{\{\alpha^{(0)} + \xi(t - t_0)\}\left\{1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}\right\}} \leqslant 0{,}1,$$

and consequently

$$N \simeq 8{,}686\,[\alpha^{(0)} + \xi(t - t_0)]\left[1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}\right] Ql. \qquad (19)$$

From (19) we obtain the following expression for Q:

$$Q = \frac{N}{8{,}686\,[\alpha^{(0)} + \xi(t - t_0)]\left[1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{cr}}\right)^2 \frac{1}{\varepsilon'}\right]}. \qquad (20)$$

The error ΔQ_t resulting from the influence of the temperature is determined from the expression

$$\Delta Q_t = Q\frac{|\xi(t - t_0)|}{\alpha^{(0)}}, \qquad (21)$$

ΔQ_t is proportional to the absolute value of the volumetric moisture content, and for large values of Q it becomes quite substantial. For example, when Q = 0.2, the error when the temperature varies from 20°C by ±10°C is ±0.04.

Let us estimate the influence of the salt concentration C on the total attenuation N in soil specimens. The presence of salts in soil solutions leads to the appearance of the ionic conductivity σ. In this case the imaginary part ε'' of the dielectric permeability is determined by the expression

$$\varepsilon'' = \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(\frac{\lambda_s}{\lambda}\right)^2}\left(\frac{\lambda_s}{\lambda}\right) + \frac{\sigma}{\varepsilon_0\omega}. \qquad (22)$$

Obviously the first term in (22) is the dipole part of ε'', while the second term is determined by the ionic conductivity, i.e.,

$$\varepsilon'' = \varepsilon''_{dip} + \varepsilon''_\sigma. \qquad (23)$$

It is known that the presence of ions in water leads, on the one hand, to a decrease in ε_s (screening of the ions), and on the other hand, to a decrease in λ_s. According to [11], for univalent-salt concentrations C ≤ 1 g-eq/liter of the NaCl or KCl type, the following relations are satisfied:

$$\lambda_s = \lambda_{s0} + C\delta_\lambda, \qquad (24)$$

$$\varepsilon_s = \varepsilon_{s0} - KC, \qquad (25)$$

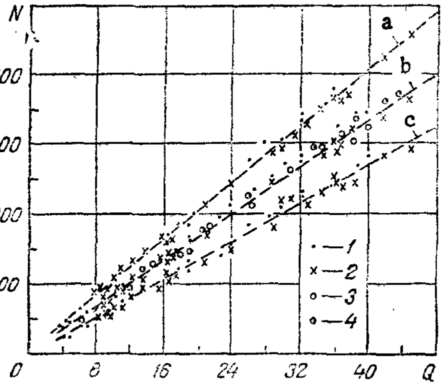

Fig. 1

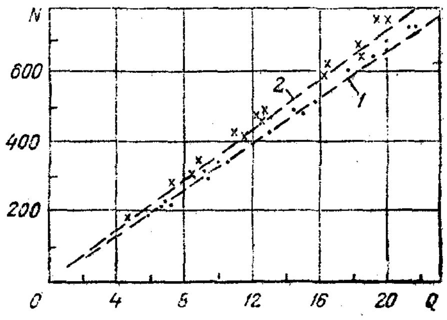

Fig. 2

Fig. 1. Attenuation of the shf energy in the 3-cm wavelength range as a function of the volumetric moisture content and the temperature (a: 10; b: 20; 3: 30°C) for some soils and grounds: 1) sand; 2) clay; 3) loamy soil; 4) sandy—loam soil. Q, %; N, dB/m.

Fig. 2. Attenuation of shf energy as a function of the moisture content of sand for two salt concentrations: 1) C = 0; 2) 0.01 g-eq/liter; the dashed lines represent the theoretical function.

where $\delta_\lambda = -0.15$ Ω/g-eq; $K = 16$ g-eq^{-1}.

Substituting (22)-(25) into (6), we obtain

$$\alpha_{H_2O} = \alpha_{\text{dip}} + \alpha_\sigma, \tag{26}$$

where

$$\alpha_{\text{dip}} = \frac{\pi}{\lambda}\sqrt{\frac{\varepsilon_{s0} - KC}{1 + \left(\frac{\lambda}{\lambda_{s0}}\right)^2 (1 - 2c\delta_\lambda)}}, \tag{27}$$

$$\alpha_\sigma = \frac{\sigma}{2\varepsilon_0 C_0}\sqrt{\frac{\left(1 + \frac{\lambda_{s0}}{\lambda}\right)^2 (1 + 2C\delta_\lambda)}{\varepsilon_{s0} - KC}}. \tag{28}$$

From (27) it follows that α_{dip} decreases as C increases. The value of σ can be determined from the expression

$$\sigma = 0.1beCN_0(U^+ + U^-)\ [\Omega^{-1}\cdot m^{-1}]. \tag{29}$$

Assuming that $(1/\varepsilon_0 C_0) = Z_0$ and is equal to 377 Ω, we finally obtain for α_σ the expression

$$\alpha_\sigma = 0.1\frac{Z_0 eCN_0(U^+ + U^-)}{2}\sqrt{\frac{\left(1 + \frac{\lambda_{s0}}{\lambda}\right)^2 (1 + 2C\delta_\lambda)}{\varepsilon_{s0} - KC}}. \tag{30}$$

Table 1 shows the calculated values of α_{dip}, α_σ, and α_{H_2O} as functions of the NaCl concentrations; in the calculations it was assumed that b = 1 and $U^+ = 6.53\cdot10^{-9}$ m^3/V·sec; $U^- = 0.79\cdot10^{-9}$ m^3/V·sec [10]. Analogously to (17) we can set:

$$\alpha_{H_2O} = \alpha^{(0)} + \Theta C + 0(C), \tag{31}$$

where $\Theta = \partial\alpha_{H_2O}/\partial C$.

As the data of Table 1 show, Θ = 2.62. Thus, when the temperature is constant and salts are present, Q is determined by the formula

$$Q = \frac{N}{8.686l\,[\alpha^{(0)} + \Theta C]\left[1 + \frac{1}{2}\left(\frac{\lambda}{\lambda_{\text{cr}}}\right)^2 \frac{1}{\varepsilon'}\right]}, \tag{32}$$

$$\Delta Q_c = Q\frac{\Theta C}{\alpha^{(0)}}. \tag{33}$$

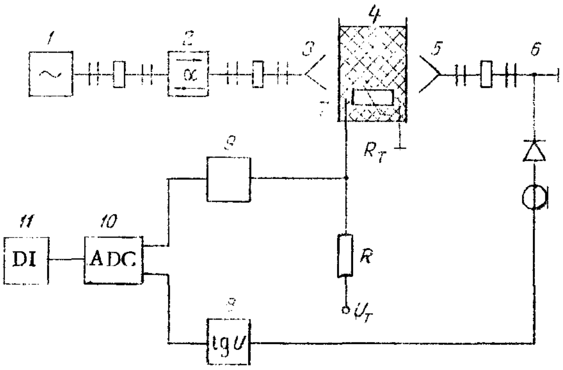

Fig. 3. Structural schematic for a transfer-type shf soil hygrometer: 1) shf generator; 2) ferrite valve; 3) radiating antenna; 4) cuvette with soil; 5) receiving antenna; 6) shf detector; 7) temperature sensor; 8) logarithmic amplifier; 9) temperature-correction scheme; 10) analog-digital converter; 11) digital moisture indicator.

From (33) it is obvious that ΔQ_c has a substantial influence on the results of the moisture measurements only at large salt concentrations. According to the data given in [12], the natural concentration of salts in soils does not exceed 0.01 g-eq/liter. Substituting this quantity into (33), we find that for $Q = 0.2$ the value of ΔQ_c is 0.002.

Experimental investigations were conducted at a frequency of 9400 MHz in a waveguide sensor consisting of two waveguide transitions passing from a rectangular cross section to a circular one with an inner diamter of 23 mm, between which there was a segment of circular waveguide with flanges. Because of the throttle-type flanged joining of the sensor, we were able quickly and easily to extract and reinsert the waveguide segment with the soil from and into the body of the sensor. The thickness of the specimens tested was 3 cm. The waveguide segment was covered on both sides with teflon half-wave shields. For the temperature measurements, a temperature sensor and a heater were placed on the outer surface of the waveguide with the specimen. The soil specimens (dehydrated in advance) were passed through a sieve and humidified with distilled water or an NaCl solution and were placed in the circular waveguide segment.

The standard method used for determining the moisture content was a thermostatic method with a drying temperature of 105°C for 6-8 h (to constant weight), followed by weighing on an analytical balance.

An analysis of the functions represented in Figs. 1 and 2 indicates good agreement between the experimental data and their calculated values.

Our investigations served as a basis for developing a transfer-type shf soil hygrometer, the structural schematic for which is shown in Fig. 3. The hygrometer was used under laboratory and field conditions on various types of soils with artificial and natural humidification. The main technical characteristics of the instrument are the following: range of moisture-content values monitored, 2-40% by volume; error of measurement of the moisture content, 2.5% by volume; power supply: independent 12-V source and power-grid source with 220 V, 50 Hz; mass of the instrument, 4.5 kg.

NOTATION

N, attenuation of shf energy, dB; Q, volumetric moisture content; α, coefficient of attenuation in moist soil, m^{-1}; t, temperature, °C; C, concentration of salts in the soil solution, g-eq/liter; l, length of specimen, m; $|\Gamma_{12}|$, modulus of the coefficient of reflection at the interface between the air and the moist material; α_0, coefficient of attenuation for moist soil in free space, m^{-1}; ε', real part of the complex dielectric permeability of the soil; ε'', imaginary part of the complex dielectric permeability of the soil; λ, wavelength in free space, m; P, parameter numerically equal to the square of the ratio of the wavelength in free space to the critical wavelength in the waveguide; λ_{cr}, critical wavelength in the waveguide, m; α_{H_2O}, constant of attenuation for free water, m^{-1}; ε_s, static dielectric permeability of water; ε_∞, high-frequency dielectric permeability of water; λ_s, resonance wavelength at which the maximum ε'' is observed for water, m; $\alpha^{(0)}$, constant of attenuation in water at 20°C, m^{-1}; t_0, temperature, equal to 20°C; ξ, first derivative $\partial\alpha_{H_2O}/\partial t$, $deg^{-1}\cdot m^{-1}$; ΔQ_t, error in the determination of Q caused by temperature; σ, conductivity of the soil solution, $\Omega^{-1}\cdot m^{-1}$; ε_0, absolute dielectric permeability of vacuum, F/m; ω, angular frequency of the electromagnetic field, sec^{-1}; ε''_{dip}, dipole part of ε''; ε''_σ, the part of ε'' determined by the ionic conductance; ε_{s_0}, static dielectric permeability of water at $C = 0$; λ_{s_0}, resonance wavelength for water at $C = 0$; δ_λ, first derivative $\partial\lambda_s/\partial C$, $g\text{-}eq^{-1}\cdot m^{-1}$; α_{dip}, constant of attenuation of water, determined by the dipole losses, m^{-1}; α_σ, constant of attenuation of water determined by the conductance, m^{-1}; U^+, U^-, anion and cation mobility, respectively, $m^3/V\cdot sec$; e, charge of the electron, C; N_0, Avogadro's number; b, concentration of dissociated molecules of electrolyte, m^{-3}; Z_0, wave resistance of vacuum, Ω; C_0, velocity of light, m/sec; θ, first derivative $\partial\alpha_{H_2O}/\partial C$, $g\text{-}eq^{-1}\cdot cm^{-1}$; ΔQ_C, error in the determination of Q caused by the presence of conductance.

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