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SOIL PHYSICS

Relationship between Water Tension and Electrical Resistivity in Soils

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Abstract—An increase in the soil water content results in a decrease in the electrical resistivity of soil. This relationship obeys an exponential equation. When the water content is below the range of capillary-film water, the clearest relationship between the electrical resistivity and water content is observed, which allows the soil and ground waters to be studied. At a high water content, the dependence of the electrical resistivity on the content of exchangeable anions, the pH, and some other properties is detectable.

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Water is retained in the soil by Van der Waals forces, electrostatic forces between molecules of different solutes and the solid phase, and interfacial tension in the capillaries. At low water contents, the forces of molecular attraction are predominant [11, 29]. Changes in the basic mechanisms of water retention in the soil under varying water content were described by numerous authors [3, 11, 12, 17, 20, 23, 30].

Electrical parameters (such as resistivity) are exponentionally related to the density of mobile electrical charges in soils by the Boltzmann distribution law

$$\sum_{i=1}^{i=m} N_i/N_{i0} = \exp\left(-\varphi\sum_{i=1}^{i=m}\nu_i e/kT\right), \qquad (1)$$

where $\sum_{i=1}^{i=m} N_i/N_{i0}$ is the relative density of the mobile electrical charges in a local volume under standard conditions, ν_i is the valence of the i-th ion, e is the electron charge, k is the universal gas constant, and T is the absolute temperature. Therefore, the density of the mobile electrical charges is exponentially related to the electrical potential. According to Ohm's law, the electrical potential is directly proportional to the electrical resistivity. If a change in some soil properties such as the water content, bulk density, or salt content results in a proportional change in the density of the mobile electrical charges, the relationship between the electrical parameters and the soil properties (SPs) can be expressed as follows:

$$SP = a_1\exp(-b_1\varphi) = a_2\exp(-b_2 ER), \qquad (2)$$

where a_1, a_2, b_1, and b_2 are empirical parameters; φ is the electrical potential; and ER is the electrical resistivity of the soil. Some relationships between the soil properties and the bulk density of the electrical charges can be nonlinear and complicated.

In soil studies, especially in the in situ measurements of electrical parameters, it is difficult to separately study the relationships between the soil properties and electrical parameters. Therefore, the relationship (2) can be less strict when many different soil properties are measured simultaneously. However, general exponential relationships were obtained for many soil properties both under laboratory and field conditions.

Different models are reported in the literature for describing the relationships of the electrical parameters with the soil water content, temperature, and salt content (table). The electrical conductivity and resistivity are the electrical parameters usually measured under laboratory and field conditions. The relationships between the soil water content and electrical parameters were measured under field and laboratory conditions, and linear models were mainly derived [4, 6]. Linear equations were also proposed to describe the relationships between the electrical resistivity and temperature. It was shown experimentally that an exponential relationship exists between the electrical resistivity, soil temperature, and soil water content.

Many authors obtained nonlinear relationships between the electrical parameters and soil salinity [26, 27]. However, other authors showed that nonlinear relationships are derived when the soil salinity varies in a wide range.

Thus, if strongly saline samples are included in the analysis, the correlations are usually nonlinear. The shape and closeness of the correlations between the salinity and electrical parameters are given in the table. Other authors proposed polynomial functions of different orders to describe the nonlinear relationships

Some relationships between soil properties and electrical parameters (from literature data)

Author	Method	Relationship	Property series
Nizenkov, 1932	4-electrode	$W = a/ER^3 + b/ER^2 + c$	$NW - S_w$
Davydov, 1936	4-electrode	$W = a/ER^2 + b$	N/S
Archine, 1942	4-electrode	$EC = EC_w S_w^a \phi^b$	N/S
Anyang, 1961	4-electrode	$ER = e^{a+bt} W^c$	$WP - FC$
Gupta and Hanks, 1972	4-electrode	$EC = aEC_s W^b$	$HW - FC$
Rogozov, 1977	4-electrode	$W = 0.01ER + 2.1$	0.021–0.1 g g^{-1}
Trotskii, 1979	4-electrode	$ER = b - aW$	$HW - FC$
Semenov, 1980	4-electrode	$\varphi = b - aW$	N/S
Borovinskaya et al., 1981	4-electrode	$ER = a/W^b$	$WP - FC$
Seyfried, 1993	2-electrode	$\theta = a + b\log(ER)$	0.1–0.4 m^3 m^{-3}
Ferre et al., 1998	2-electrode	$EC = EC_w \theta^a \phi^{b-a}$	0.13–0.35 m^3 m^{-3}
Temperature (t) relationship			
Anyang, 1961	4-electrode	$ER = e^{a+bt} W^c$	N/S
Raisov, 1973	4-electrode	$ER_{t2} = ER_{t1}[1 + a(t_2 - t_1)]$	0–50°C
Wells, 1978	4-electrode	$\ln EC_{t1} = \ln EC_{t2} + b_1(t_2 - t_1) - b_2(t_2^2 - t_1^2)$	N/S
Salinization relationship			
Campbell et al., 1948	2-electrode	$TC = aEC_w^b$	N/S
Halvorson and Rhoades, 1976	4-electrode	$EC = aEC_w - b$	N/S
Chang et al., 1982	4-electrode	$TC = aEC_w^b$	N/S

between the electrical resistivity or conductivity and the salinity of the soils, solutions, and groundwater. Many authors [15–17] compared different relationships for calculating the ionic composition of soil solutions and found that the exponential model was the best fit. In the study of the simultaneous effect of salts and water on the electrical resistivity of soil pastes, it was found that the electrical conductivity of soil pastes is the sum of the exponential functions of the water content and soil solution conductivity [13–18].

Most relationships (table) are nonlinear or linear in a specific range of soil properties. This fact can be considered as indirect evidence of the applicability of the Boltzmann distribution law for describing the relationships between the electrical parameters and the soil properties affecting the bulk charge density. According to the Boltzmann distribution law, these relationships should be exponential in shape. The statistical differences between the exponential, power, and polynomial functions are usually insignificant, especially in a limited range of arguments.

Let us dwell on the characterization of the relationship between the electrical resistivity and the soil water content. These are the key relationships for choosing the conditions of using field electrophysical methods for soil, reclamation, or agricultural purposes. These relationships should be primarily assessed by field electrophysical techniques, because it is important to know the effect of water on, e.g., the resistance, in different ranges of water content. By selecting a specific range of water content where it affects the resistivity, we can estimate its changes; study its distribution in the soil; and, hence, assess the zone of desiccation, the depth of the groundwater table, etc. On the other hand, using electrophysical methods in the range of water content where its effect is insignificant, other soil characteristics (e.g., genetic features or chemical properties) can be studied.

The soil water content affects the mobility of electrical charges in a complicated way. Electrical charges are mobile when they occur in the free soil solution or form a double electric layer on the surface of soil particles. When the soil water content increases from air-dry to water-saturated soil, ions adsorbed on the surface of solid soil particles are released, which affects the formation of a double electric layer, and large soil pores are filled with free soil solution. Therefore, the mobility of electrical charges usually increases with increasing soil water content. However, the mobility of electrical charges is also affected by the mobility of soil water itself, because water also forms ions, including hydroxonium ions. Water is retained in the soil by molecular attraction forces; Van der Waals forces; electrostatic forces between water molecules, solute molecules, and solid surfaces. At low water contents, most soil water is strongly retained in the form of films typical for the predominant forces of molecular attraction. At high water contents, most water is retained by relatively weak capillary forces between soil particles and capillaries [11, 29]. The contributions of different forces to the reten-

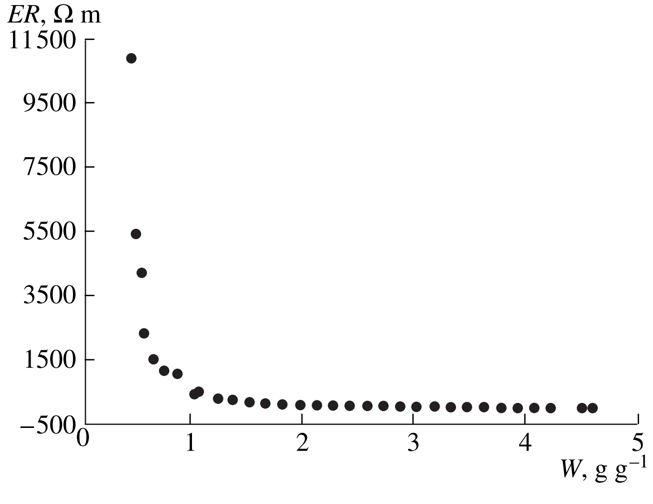

Fig. 1. An example of experimental relationship between the electrical resistivity and water content of peat soils.

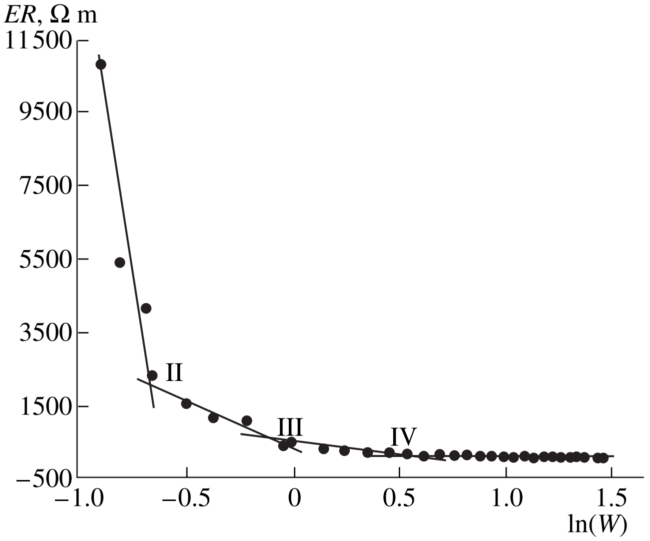

Fig. 2. An example of linearization of the relationship between electrical resistivity and water content.

tion of water vary with changing soil water content [3, 19, 23, 30]. To understand the effect of different forces on the retention of water in the soil and on the stability of electrical charges, we studied the interactions between the electrical resistivity and the soil water content under laboratory conditions.

Nonlinear relationships between the electrical resistivity and soil water content were observed for all 31 soil samples. The relationship was not linear, but it consisted of four linear fragments (Fig. 1). All together, the linear segments represented an exponential relationship between the water content and electrical resistivity in the characteristic ranges of water content and indicated similarity in the relationships of the soil water properties in these ranges (Fig. 2).

The break points between the segments correspond to the specific water contents separated into the ranges of film, film-capillary, capillary, and gravitational water according to the Voronin concept [2]. The water content in break point II is very close to the characteristic water content between the ranges of film and film-capillary water. Break point III corresponds to the water content between the ranges of film-capillary and capillary water, and break point IV corresponds to the field capacity.

Break point I was difficult to identify, because the measurements of electrical resistivity by the direct-current technique could not provide a sufficient number of experimental points in the range of the adsorbed water. The break point between the ranges of the adsorbed and film water can be determined at a high measuring frequency by electrometric methods.

The Boltzmann distribution law was used as the theoretical basis of the model, because it determines the relationship between the number of molecules and the system's energy:

$$N_i/N_j = \exp[-(E_i - E_j)/kT], \tag{3}$$

where N_i and N_j are the numbers of molecules in the states i and j, respectively, and E_i and E_j denote the system's energy in these states. Equation (3) considers all kinds of energy existing in the system, while Eq. (4) describes a system with predominant electric energy. The energy of the soil solution is affected by electrical Maxwell forces resulting from the changes in the density of the mobile electrical charges in the solution and the matrix potential [3]. Therefore, for two states i and j of the soil solution with different water contents (different energy states within the same infinite soil volume), the difference between their energies can be determined as follows [23]:

$$E_i - E_j = ze(\varphi_i - \varphi_j) + V(p_i - p_j), \tag{4}$$

where the indices i and j denote the different states of the soil solution, E is the energy of the soil solution, p is the matrix potential, and z is the total valence of the mobile ions in the solution.

Taking into account Eq. (4), Eq. (3) can be divided into the electric-potential and matrix-potential fragments as follows:

$$\begin{aligned} N_i/N_j &= \exp[(-V(p_i - p_j))/kT] \\ &\times \exp[-ze(\varphi_i - \varphi_j)/kT]. \end{aligned} \tag{5}$$

The N_i/N_j ratio represents the relative content of mobile electrical charges in the soil solution.

The content of mobile electrical charges in the soil is proportional to the water content, because electrical charges in soils are mobile only in the hydrated form, in capillaries filled with water, or in water films around the solid soil phase (soil matrix). The difference between the electrical potentials $\varphi_i - \varphi_j$ is proportional to the electrical resistivity according to Ohm's law. Thus, from Eq. (5), the relationship between the soil water content W and the electrical resistivity ER can be expressed as follows:

$$W = a\exp(-bER). \qquad (6)$$

The parameter a accounts for the effect of the soil water retention on the electrical properties of the soil solution and can depend on the physical properties of the soil that affect the water retention in the soil, such as the porosity and others. The parameter b can be related to the chemical properties of the soil and the soil solution as can the content of dissolved inorganic and organic components affecting the valence of the mobile electrical charges in the soil solution. Since the nature and magnitude of the forces influencing the soil water retention vary considerably for different water content conditions, the parameters a and b change with the soil water content. It is assumed that a and b in Eq. (6) are constants within a certain water content range but may vary for different ranges of soil water content. This assumption yields a piecewise-linear relationship between the electrical resistivity and the logarithm of the soil water content.

Different parts of the piecewise-linear relationship between the electrical resistivity or conductivity of the soil and its water content were reported in the literature [8, 10]. The break points of the relationship are related to some soil water constants such as the hygroscopic water, wilting point, and field capacity separating different soil water categories [1, 7].

Voronin [2] developed a concept of soil water categories based on the theory of molecular attraction and capillary forces. The contribution of molecular attraction to the soil matrix potential increases with increasing water content from air-dry to water-saturated soil, because the contribution of capillary forces increases. Voronin showed that the nature and magnitude of the forces contributing to the soil matrix potential change abruptly at some specific conditions separating the different ranges of soil water such as adsorbed, film, film-capillary, capillary, and gravitational water. The Voronin concept was applied to characterize the effect of soil water retention forces on the relationship between the soil water content and electrical resistivity. The soil water retention restricts the mobility of electrical charges in the soil and, hence, affects the a and b parameters in Eq. (6). Since Voronin proposed an abrupt change in the nature and magnitude of the water retention forces between the soil water ranges, the parameters a and b in Eq. (6) vary among the ranges of adsorbed, film, film-capillary, capillary, and gravitational water.

The electrical resistivity decreases rapidly with increasing soil water content in the adsorption water range (Fig. 2). Although the solute and water molecules on the surfaces of the soil matrix are immobile in the adsorbed water range, the dipolar molecules of adsorbed water create a conductive path in the soil matrix, which rapidly decreases the resistance when the water content increases. The adsorbed water is strongly bound to the soil matrix by the force of molecular attraction, which restricts its effect. The molecular attraction forces include Van der Walls' attractions between solid surfaces and water molecules; attractions between water and solute molecules; and electrostatic interactions between solid surfaces, water dipoles, and solute molecules. Electrostatic forces are weaker than Van der Waals forces, which retain adsorbed water in the soil; therefore, the electrical resistivity decreases in the film water range slower than in the range of adsorbed water (Fig. 3).

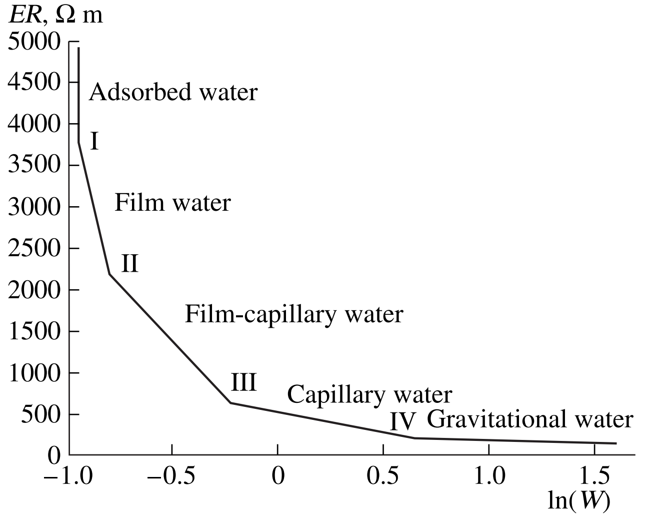

Fig. 3. A piecewise-linear relationship between the natural logarithm of water content and electrical resistivity.

After the maximal possible thickness of the water film is reached, water moves from the films to fissures. In the range of film-capillary water, the relative portion of film water decreases and the content of water held in the wedges and capillaries increases [2]. Since the forces of molecular attraction are much stronger than capillary forces, the film-capillary water is still held in the soil, mainly by the molecular attraction. However, the magnitude of the capillary forces becomes increasingly pronounced within the film-capillary water range.

Since the film-capillary water is partly influenced by capillary forces, which are weaker than molecular attraction forces, electrical charges are more mobile in the film-capillary water range than in the adsorbed and film water ranges. Therefore, the electrical resistivity decreases less dramatically in the range of film-capillary water (Fig. 3). Electrical charges are even more mobile in the range of capillary water, which is more affected by capillary forces.

In the gravitational water range, the mobility of water molecules does not affect the mobility of electrical charges (solute ions); therefore, the electrical resistivity is almost independent of the water content in this range [26, 27]. Nevertheless, a small decrease in the electrical resistivity can still occur in the gravitational water range due to the continuous dissolution of the adsorbed and precipitated ions from the soil solid phase (Fig. 3).

In sum, the exponential model is appropriate to describe the relationship between the electrical resistivity and the soil water content at all possible water contents. However, different model parameters should be used in the different ranges of water content (such as the adsorption, film, film-capillary, capillary, and gravitational water ranges) with different mechanisms of water retention. Theoretically, the relationship between the electrical resistivity and the logarithm of the water content should represent a series of linear segments with consequently decreasing slopes corresponding to different ranges of the water content (Fig. 3).

Thus, the interpretation based on the fundamental Boltzmann distribution law showed that the exponential model adequately describes the relationship between the water content and electrical resistivity. The model is applicable for all water conditions from air-dry to water-saturated soil. Different parameters can be used to characterize the exponential relationship under specific water content ranges, where the water retention in the soil is controlled by different mechanisms. The model parameters vary among the water content ranges such as the adsorption, film, film-capillary, capillary, and gravitational water. The proposed laboratory method is suitable for the rapid measurement of changes in water retention and electrical resistivity under varying soil water conditions.

The exponential relationship between the water content and resistivity leads to important conclusions related to the application of field electrophysical methods.

CONCLUSIONS

(1) In the low water content region, especially in the ranges of adsorbed, film, and film-capillary water, the effect of water on the resistivity is significant and can be used for its evaluation, as well as for the assessment of related parameters such as the water distribution, the zones and depths of desiccation, and the groundwater table depths in arid regions or in the humid zone during dry seasons and dry years.

(2) In the high water content region (the capillary and gravitational water ranges), where the effect of water on the resistivity is insignificant, it is advisable to use resistivity methods for studying the genetic and chemical properties of soil, e.g., for soil mapping and surveying for different soil, reclamation, and other purposes.

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