

Electrical fields and soil properties

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Abstract

The electrical fields in the surface of soils appear as many different kinds. Methods of self-potential (SP), electrical profiling (EP), vertical electrical sounding (VES), and non-contact electromagnetic profiling (NEP) was used to measure the electrical properties of basic soil types, such as Spodosols, Alfisols, Histosols, Mollisols, and Aridisols (USA Soil Classification) of Russia *in situ*. The density of mobile electrical charges, reflected in measured electrical properties, was related to many soil physical and chemical properties. Soil chemical properties (humus content, base saturation, cation exchange capacity (CEC), soil mineral composition, and amount of soluble salts) are related to the total amount of charges in soils. Soil physical properties, such as water content and temperature, influence the mobility of electrical charges in soils. The electrical parameters were related with soil properties influencing the density of mobile electrical charges in soils by exponential relationships based on Boltzmann's distribution law of statistical thermodynamics ($r=0.657-0.990$). Generally, the electrical methods can be used for *in situ* soil mapping and monitoring when the studied property lone highly influences the distribution of mobile electrical charges in the soil. The electrical properties were used to improve soil characterization for soil morphology and genesis studies; to develop accurate soil maps for precise agriculture practices; and to evaluate soil pollution, disturbance, and physical properties for engineering, forensic, and environmental applications.

Keywords: stationary and non-stationary electrical fields, soil morphology, soil genesis, electrical resistivity and potential, soil properties

Introduction

Soil surveys require quick and, when possible, non-disturbing estimations of numerous soil properties, such as salinity, texture, stone content, groundwater depth, and horizon sequence in soil profiles; however, conducting soil measurements with a high sampling density is costly and time-consuming. Conventional methods of soil analysis mostly require disturbing soil, removing soil samples, and analyzing them in a laboratory.

Electrical geophysical methods, on the contrary, allow rapid measurement of soil electrical properties, such as electrical conductivity, resistivity, and potential, directly from soil surface to any depth without soil disturbance. The *in situ* methods of electrical conductivity (e.g. four-electrode probe and electromagnetic induction) are routinely used to evaluate soil salinity (Halvorson and Rhoades, 1976; Chang *et al.*, 1983; Rhoades *et al.*, 1989b). Some electrical geophysical methods were used to map groundwater tables (Arcone *et al.*, 1998), preferential water flow paths (Freeland,

1997a), and perched water locations (Freeland, 1997b); to outline locations of landfills (Barker, 1990); and to evaluate water content, temperature, texture, and structure of soils. However, the relationships between electrical properties and other soil chemical and physical properties are very complex because many soil properties may simultaneously influence *in situ* measured electrical parameters (Rhoades *et al.*, 1976b.).

Despite the advantages of electrical geophysical methods, their applications to soil science problems are not straightforward and require thorough study. First, the theory about the nature of development and distribution of soil electrical fields, whose parameters are measured with the electrical geophysical methods, is still being developed (Pozdnyakov *et al.*, 1996a; Pozdnyakova, 1999). Second, the equipment for geophysical methods of vertical electrical sounding, four-electrode profiling, ground-penetrating radar, etc. manufactured and readily available is not suited for measuring electrical properties in shallow (0-5 m) soil profiles. Finally, the *in situ* measurements of electrical parameters need a specific calibration in every study to be reliable to monitor and map different soil properties. To address the discussed problems, the objectives of this study were: (i) to study the basic law of electrophysics governing the electromagnetic fields in soils; (ii) to modify conventional electrical geophysical methods for measuring various electrical properties in soil studies; (iii) to establish relationships between measured electrical properties and other soil physical and chemical properties; (iv) to evaluate the influence of soil-forming processes on distributions of electrical properties in soil profiles; (v) to apply the modified electrical geophysical methods and the developed relationships for estimating spatial distribution of soil properties essential in soil surveys, precision agriculture practices, and environmental engineering.

Materials and Methods

Electrical geophysical methods used in this study can be broadly classified as methods measuring natural electrical potentials of the ground without introducing additional electrical field and methods utilizing artificial electrical or electromagnetic fields to measure soil electrical parameters. Method of self-potential (SP) measures the naturally existing stationary electrical potentials in the soil. Vertical electrical sounding (VES) and electrical profiling (EP) methods measure electrical resistivity or conductivity of soil to any depth when a constant electrical field is artificially created on the surface. VES and EP methods as well as laboratory method of measuring electrical resistivity in soil samples are based on four-electrode principle, but vary considerably in electrode array lengths and arrangements, which makes the methods suitable for different applications. The VES, EP, and SP methods evaluate parameters of the stationary electrical fields in soils. All the methods of stationary electrical fields require grounding electrodes on the soil surface; therefore, measurements with these methods can be made only in agricultural fields, rural areas, or in the laboratory in soil samples.

Electromagnetic induction methods (EM), non-contacted electromagnetic profiling (NEP), and ground penetrating radar (GPR) introduce electromagnetic waves of different frequencies into soils. The EM, NEP, and GPR evaluate properties of the non-stationary electromagnetic fields in soils. All the methods of non-stationary electromagnetic fields are mobile. The methods do not require a physical contact with the soil surface and can measure electrical resistivity or conductivity in soils covered

with firm pavement. The NEP method, which we used in this study, has been specifically designed in Russia for shallow-subsurface environmental studies (Pozdnyakova *et al.*, 1996).

Self-potential method is based on measuring the natural potential differences, which generally exist between any two points on the ground. These potentials are associated with electrical currents in the soil. In our study we are especially interested in the measurement of electrical potentials created in soils due to soil-forming process and water/ion movements. The electrical potentials in soils, clays, marls, and other water-saturated and unsaturated sediments can be explained by such phenomena as ionic layers, electro-filtration, pH differences, and electro-osmosis. The soil-forming processes can create electrically variable horizons in soil profiles. Another possible environmental and engineering application of self-potential method is to study subsurface water movement (Pozdnyakova *et al.*, 2001). The SP method utilizes two electrodes (trailing and leading), a potentiometer, and connecting wire. Two measuring techniques, fixed-base (or total field) and gradient (or leapfrog), are suggested in conventional geophysics. We used the fixed-base technique to obtain distributions of electrical potentials in soil profiles. Measurements were conducted on the walls of open soil pits. The base or trailing electrode was permanently installed in the place of high potential, usually in illuvial, wet, fine-textured, or salty soil horizon. To obtain maps of electrical potential the gradient technique was implied. The usage of non-polarizing electrodes is mandatory when the SP method is applied in soil and environmental studies. The non-polarizing electrode consists of a metal element immersed in a solution of salt of the same metal with a porous membrane between the solution and the soil (Corwin and Butler, 1989). Because of easy breakage of the membrane and leakage of the electrode solution we adopted firm non-polarizing electrodes (carbon cores from the exhausted electrical cells) (Pozdnyakov *et al.*, 1996).

Four-electrode probe. All the electrical resistivity methods applied in geophysics and soil science are based on the standard four-electrode principle suggested by Wenner in 1915 to minimize soil-electrode contact problems. The four-electrode principle is illustrated in the laboratory conductivity cell (Figure 1). The cell is a rectangular plastic box with the current electrodes A and B as brass plates on the smaller sides. The potential electrodes M and N are the brass rods in the middle of the long side of the cell. A constant current (I) is applied to the two outer electrodes (A and B) and the arising difference of potential (Δu) is measured between the two inner electrodes (M and N). The electrical resistivity (ER) is calculated from the Ohm's law as

$$ER = K \frac{\Delta U}{I} \quad [1]$$

where K is a geometrical factor (m) depending on the distance among electrodes, ΔU is difference of potentials (mV), and I is magnitude of current (mA). The geometrical factor for a cell is obtained from the calibration solutions of a known resistivity (conductivity). The sample of soil paste or suspension is placed in a cell to measure electrical resistivity from the readings of voltage and current. The cell construction shown in Figure 1 ensures the induction of static uniform electrical field in the cell. The field is imposed on the homogeneous soil sample to measure an accurate electrical resistivity of a sample. The time variation and the difference in electrical resistivity are less than 0.5%

when measured in the same soil sample by the cells with different distances between electrodes. The measurements in four-electrode laboratory cell were utilized to develop the relationships between various soil properties and electrical resistivity.

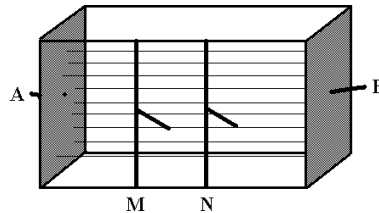


Figure 1 Scheme of the four-electrode laboratory conductivity cell. Electrical field lines are shown with thin straight lines (uniform electrical field).

Electrical profiling. The uniform static electrical field can be created in field conditions to measure soil electrical resistivity or conductivity *in situ* (Petrovsky, 1925). However, most modern geophysical methods, such as four-electrode profiling and vertical electrical sounding apply non-uniform electrical field to soils through the point electrodes (Figure 2). The electrical resistivity measured with these methods is termed apparent or bulk electrical resistivity, to distinguish it from the resistivity measured in laboratory in homogeneous samples with uniform electrical field. The electrical profiling method is based on the same four-electrode principle as the conductivity cell (Figure 2). The electrical field is distributed in a soil volume, which size can be estimated from the distance among AMNB electrodes. The geometric factor (*K*) can be precisely derived from the array geometry based on the law of electrical field distribution. Using the Laplace's equation in polar coordinates, Keller and Frischknecht (1966) derived the electrical potential functions around the source (A and B) and measuring (M and N) electrodes. The geometric factor *K* can be obtained for central-symmetric four-electrode array of AMNB configuration (Figure 2) as

$$K = \pi \frac{[AM][AN]}{[MN]} \tag{2}$$

where $[AM]$, $[AN]$, and $[MN]$ are the distances (m) between the respective electrodes.

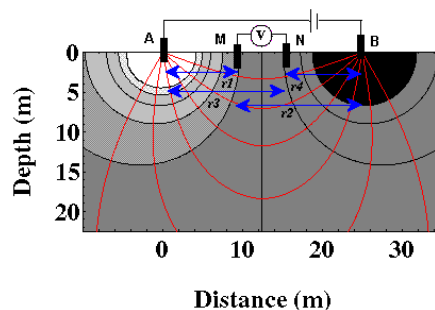


Figure 2 Scheme of the four-electrode method. Electrical field lines are shown with thin curvilinear lines (non-uniform electrical field).

The arrays of different geometries are suitable for various applications. Equally spaced arrays ($AM=MN=NB=a$) in the Wenner configuration with small a distances from 2 to 6 cm were used for measurement of electrical resistivity on the walls of open soil pits. Arrays with a from 15 to 80 cm were applied for mapping of lateral changes in electrical resistivity on the soil surface. The electrode array is moved along a surveyed line and the electrical measurements result in a horizontal profile of apparent resistivity. The final results include subsurface apparent resistivity values from the measured locations. Results may be plotted as profile lines or contour maps (isopleth resistivity map), or in other presentations according to the specific needs. The method is more accurate than electromagnetic profiling although slower and more labor-effective.

Vertical electrical sounding. The vertical electrical sounding similarly to the method of electrical profiling is based on the four-electrode principle. The VES array consists of a series of the electrode combinations AMNB with gradually increasing distances among the electrodes for consequent combinations. The depth of sounding increases with the distance between A and B electrodes. The result of VES measurements with central-symmetric arrays is apparent (bulk) electrical resistivity as a function of half of the distance between the current electrodes, i.e. $ER = f(AB/2)$ (Beck, 1981). The relationship between ER and $AB/2$ can be converted into a relationship between electrical resistivity and actual soil depth through a computer interpretation. Pozdnyakov *et al.* (1996a) developed programs for soil VES interpretations based on an updated R-function (Vanjuan and Morozova, 1962). We modified the conventional VES method for adequate evaluation of soil horizons by developing special arrays with smaller distances between electrodes. Other modifications of the traditional method included the reduced size and weight of electrodes, arrays with the fixed distances among electrodes, and automatic commutator for the electrode combinations. The equipment with such features allows measuring a detailed VES profile within about 15 min at one location.

Non-contact electromagnetic profiling. Traditional EM methods have difficulty focusing on targets buried at the depths less than 5 m and can provide only local measurements of electrical conductivity or resistivity. At the other extreme, most ground-penetrating radar systems, although generate continuous electrical profiles, can only investigate the top meter or so when salts or clay minerals are present in the soil. Hence, in many applications there is a depth range where neither traditional EM nor GPR systems are adequate. The advantages of NEP method are that it automatically records continuous profiles of electrical resistivity and allows easy changing inter-coil spacing to survey different soil depths. A generator constantly excites electromagnetic field through the two radiating antennas. The antennas form the transmitting coil through the soil. Parameters of a secondary electrical field created in the soil are received by the receiving coil and automatically recorded in a graphical form of continuous electrical resistivity profile in the receiver-register block. The NEP equipment operates on user-defined frequencies of the primarily electromagnetic field within the range from 12.5 to 14.5 kHz. Due to the low frequency, the properties of the created electromagnetic field are similar to those of the stationary electrical field created by the methods of constant current (VES and EP). Thus, we can easily vary the depth of electromagnetic profiling by changing the distance between radiating and receiving antennas. The minimal depth of 0.4 m can be investigated with the method at a 5-m

spacing between radiating and receiving antennas. Layers as deep as maximum 20 m can be investigated.

All the methods used in this study have different advantages and limitations. Therefore, no single method could be a priori recommended as universal for all soil applications. Three methods of the stationary (SP, EP, and VES) and one methods of the non-stationary electrical fields (NEP) were tested in different applications in soil genesis studies, civil and environmental engineering, agriculture, and soil monitoring. Detail description of the applied methods can be found in Pozdnyakov *et al.*, 1996; Pozdnyakova, 1999; and Pozdnyakova *et al.* 2001.

Results and Discussion

The geophysical methods do not measure individual charges in soils, but rather outline places with different densities of electrical charges. Thus, the measured with the geophysical methods electrical parameters provide information about volume density of mobile electrical charges in soils. Volume density of electrical charges is proportional to the number of electrically charged particles in an elementary volume of media. Volume density of mobile electrical charges designates the content of ions, which neutralize charges on a free surface (Schuffelen, 1972). As surface charge in soils is formed by sorbed (exchange) cations and anions (Sparks, 1997), the ion exchange capacity is equivalent to the density of exchange surface charges. The ion exchange capacity of the soil is the product of the soil specific surface and surface charge density (Uehara and Gillman, 1981).

Soil charge is determined by an ion exchange, which in turn depends on three factors: isomorphic substitutions in clay minerals, breakage of ionic bonds in organo-mineral complexes, and alteration of charge distribution in macromolecules of soil organic matter. Therefore, soil chemical properties, such as humus content, base saturation, cation exchange capacity (CEC), soil mineral composition, and the amount of soluble salts influence the ion exchange in soils. These soil properties are related with the volume density of mobile electrical charges in soils and, in turn, with the soil electrical parameters. Soil chemical properties, responsible for the formation of soil ion exchange capacity, are related with the total amount of available charges in soils.

Soil physical properties, such as water content and temperature, influence the mobility of electrical charges in soils. From our studies of the relationships between electrical resistivity and soil bulk density or soil water content (Figure 3) in laboratory conditions the mobility of electrical charges exponentially increases with the increase in those properties (Pozdnyakova, 1999). Other soil physical properties, such as soil structure, texture, and bulk density, alter the distribution of mobile electrical charges in soils. Thus, the volume density of mobile electrical changes is related to many soil physical and chemical properties.

Electrical parameters, such as resistivity and potential are exponentially related with the volume density of mobile electrical charges based on Boltzmann's distribution law (Bolt and Pech, 1953):

$$\sum_{i=1}^{i=m} N_i / N_{io} = \exp\left(-\varphi \sum_{i=1}^{i=m} v_i e / kT\right) \quad [3]$$

here $\sum_{i=1}^{i=m} N_i/N_{i0}$ is the ratio of the density of mobile electrical charges in the local

volume vs. standard conditions, ν_i is the valence of the i -th ion, e is the electronic charge, k is the universal gas constant, and T is the absolute temperature. Therefore, from Eq. [3] the volume density of the mobile electrical charges is exponentially related to the electrical potential. According to Ohm's law the electrical potential is in direct proportion to the electrical resistivity. If the change of a soil property, such as water content, bulk density, or salt content causes a proportional change in the volume density of the mobile electrical charges, a relationship between electrical parameters and soil property (SP) can be expressed as

$$SP = a_1 \exp(-b_1\varphi) = a_2 \exp(-b_2ER) \quad [4]$$

where a_1 , a_2 , b_1 , and b_2 are empirical parameters; φ is the electrical potential, and ER is the bulk electrical resistivity of the soil. Some relationships between soil properties and volume density of mobile electrical charges may not obey a single exponential equation on the whole range of property variation. For example, the relationship between soil water content and electrical resistivity was approximated with different exponents at different ranges of soil water content due to the influence of soil-water retention (Pozdnyakova, 1999).

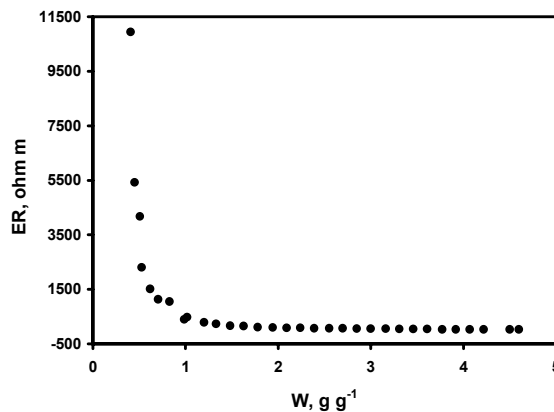


Figure 3 An example of experimental relationship between electrical resistivity and water content of a peat soil.

While measuring electrical parameters *in situ*, it is difficult to study separately the relationship between a soil property and electrical parameters. Therefore, the relationship of Eq. [4] may be less strong when measured under the simultaneous variations of many soil properties. Nevertheless, the general exponential relationships were obtained for many soil properties, such as total soluble salts, CEC, base saturation, humus content, etc. both in laboratory and field conditions (Pozdnyakov *et al.*, 1996; Pozdnyakova, 1999; Pozdnyakova *et al.*, 2001).

Considering the qualitative structure of mobile electrical charges soils can be broadly subdivided into two groups. The first group is soils with low soluble salts and CEC filled by Ca^{+2} , Mg^{+2} , Al^{+3} , and H^{+} . These soils are formed by the processes of podzolization, lessivage, eluviation-illuviation, humification, mineralization, and

gleization in humid areas (Wilding *et al.*, 1983). Spodosols, Alfisols, Gelisols, Histosols, Ultisols, and Mollisols can be considered as soils of the first group. The processes of calcification, salinization, alkanization, pedoturbation, humification, and mineralization in arid and semiarid areas form the second group of soils with CEC filled by Ca^{+2} , Mg^{+2} , and Na^{+} and, in some soils, high salinity. Soils of the second group represented by Aridosols, Vertisols, and some Mollisols. Inseptosols and Entisols can be assigned to either the first or second group depending on the primarily soil processes dominating in the soils.

For the soils of first group the strongest exponential relationships were obtained for the exchange capacity and base saturation. The correlation coefficients for the relationships with base saturation were as high as 0.90 and 0.88 for soil and colloid suspensions, respectively. The correlation coefficients of the relationships between cation exchange capacity and electrical resistivity were 0.89 for soil suspension and 0.87 for colloid suspension. These two properties characterize the amount of exchange cations in soils. Since soils in humid areas have a low amount of soluble salts, the exchange cations play an important role in soil electrical conductivity. The soil base exchange cations are relatively mobile and primarily conduct electricity in soils of humid areas. Humus content also increases the cation exchange ability of the soils. Therefore, the relatively strong relationship ($r = -0.78$) was found for the total humus content and electrical resistivity of the colloid suspension. A high correlation coefficient ($r = -0.78$) was also obtained for the field water content and electrical resistivity of the colloid suspension. The water content in the soils of humid areas is not limited by precipitation and usually determined by the water retention ability of soils. Therefore, soils with high clay and humus contents tend to have high base saturation and high field water content. Thus, for soils in humid areas the basic source of mobile electrical charges is from soil exchange and retention capacity. Electrical resistivity has strong exponential relationships with soil properties characterizing soil exchange capacity, such as base saturation, water and humus contents, and cation exchange capacity. Similar relationships were obtained for the electrical resistivity measured *in situ* along open soil pits and on the soil surface with the EP and VES methods. The relationships were not as strong as those, measured in soil and colloid suspensions, but nevertheless appeared exponential. Since CEC and organic matter are the predominant sources of mobile electrical charges in soils of the first group, there is general exponential relationship between those properties and electrical parameters, measured *in situ* (Figure 4).

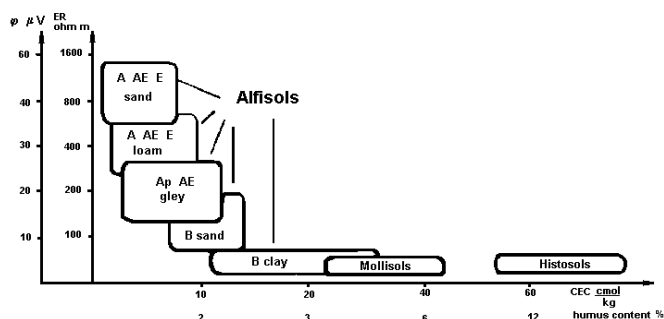


Figure 4 Schematic relationship between electrical parameters and soil properties showing approximate distribution of data for soils in humid areas.

The exchange capacity of soils in arid areas (second group) is filled with calcium, magnesium, and sodium cations and the same cations dominate in the soil solution. Therefore, the electrical parameters show strong relationships with these cations. A strong exponential relationship was obtained between electrical potential, measured on soil surface with the self-potential method and the sum of Ca, Mg, and Na ($r = 0.810$). For the sodium content alone and electrical potential, the relationship is also exponential with $r = 0.599$. The $\text{Na}/(\text{Ca}+\text{Mg}+\text{Na})$ ratio is related with the electrical potential by the linear relationship with $r = 0.543$. Electrical potential decreases with the increase of relative amount of sodium in Aridisols. The same type of linear relationship with $r = 0.356$ was obtained for $\text{Al}/(\text{Ca}+\text{Mg}+\text{Al})$ ratio and the electrical potential in Alfisols of humid areas. Such ratios are important for soil genesis studies, since they indicate the degree of sodicity in Aridisols, and the degree of eluviation (podzolization) in Alfisols and Spodosols. The obtained relationships can be used to study the soil-forming processes in these soils. Since soil salinity in soils of the second group is the summary characteristics of the available electrical charges, the electrical parameters are strongly related with the total soil salinity. Figure 5 shows the schematic curvilinear relationship between electrical resistivity or potential and soil salinity for the soils of second group.

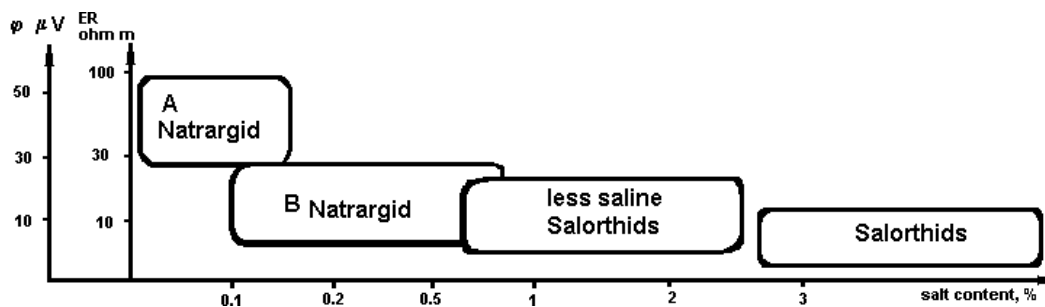


Figure 5 Schematic relationship between electrical parameters and soil properties showing approximate distribution of data for soils in arid areas.

Electrical parameters measured with geophysical methods *in situ* are related with different soil properties, easily measured, and can be used to study many soil problems. Different principles of applications should be considered for three types of problems.

The first-type problems are the monitoring of a soil property, which is only one to vary during the measurements. In such problems the measured electrical resistivity or potential can directly indicate the change in the soil property *in situ*. Such principle was utilized for measuring differences in peat soil compaction under seasonal road and monitoring soil melting in spring (Pozdnyakova, 1999).

The second-type problems include investigations of soil properties, which predominantly influence the measured electrical parameters. Therefore, the measured electrical parameters usually show strong relationships with such properties even in field conditions. For example, since the variation in stone content influences the soil electrical resistivity much stronger than variation of any other properties in soils of Crimea Peninsula, the VES method was able to accurately outline the layers with different stone contents in these soils and estimate the volumetric content of stones (Pozdnyakov *et al.*, 1996; Pozdnyakova, 1999). Pollution by petroleum products highly increases the electrical resistivity of Gelisols in northwest Siberia, while salty mining

solutions decrease resistivity of the soils. Therefore, methods of EP, VES, and NEP could be used to map pollution in these soils (Pozdnyakov *et al.*, 1996; Pozdnyakova, 1999). Extreme dryness of Histosol in some seasons highly increases the electrical resistivity at the top of the profile, whereas variation of soil water content around field capacity usually does not alter the typical profile distributions of electrical resistivity in the soils (Pozdnyakova *et al.*, 1996; Pozdnyakova, 1999). Disturbance of soils changes of the measured electrical resistivity in soils of humid area significantly enough to detect hidden burial places for forensic and archeological applications

The third-type problems require careful considerations of the relationships between many soil properties and electrical parameters measured *in situ*. Although soil electrical parameters depend simultaneously on many soil properties, such as salt, water, humus or stone content, CEC, texture, and temperature, in many situations the influence of some soil properties can be considered negligible if they vary around their maximum, based on Boltzmann's distribution law. For example, soil water content close to the field capacity does not practically influence the change in electrical resistivity (Figure 3). Therefore, *in situ* measurements of the electrical parameters of soils in humid areas is not influenced by water content variation and can be used to evaluate elluvial-illuvial horizons in soil profile and more stable soil properties, such as CEC, soil texture, and humus content (Figure 4). On the other hand, the high variation of soil water content within the whole possible range in the profiles of alluvial soils in Astrakhan' area allows locating the groundwater table (Pozdnyakova *et al.*, 2001). The simultaneous influence of various soil properties on the measured electrical conductivity were successfully studied with the methods of geostatistics, which consider not only intervariable but also spatial relationships (Pozdnyakova and Zhang, 1999).

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