Exploration of Sub Surface and its Properties with Soil Resistivity Data

Bhukya Pavan Kumar
Student
Department of Civil Engineering
National Institute of Technology Raipur, Chhattisgarh, India

Abstract— Electrical resistivity of the soil can be considered as a proxy for the spatial and temporal variability of many other soil physical properties (i.e. structure, water content, or fluid composition). Because the method is non-destructive and very sensitive, it offers a very attractive tool for describing the subsurface properties without digging. It has been already applied in various contexts like: groundwater exploration, landfill and solute transfer delineation, agronomical management by identifying areas of excessive compaction or soil horizon thickness and bedrock depth, and at least assessing the soil hydrological properties. The surveys, depending on the areas heterogeneities can be performed in one-, two- or three-dimensions and also at different scales resolution from the cent metric scale to the regional scale. In this review, based on many electrical resistivity surveys, we expose the theory and the basic principles of the method, we overview the variation of electrical resistivity as a function of soil properties.

Key words: Ground Water, Water Content, Porosity, Soil Density, Ionic Concentration

I. INTRODUCTION

The changes caused on soil by intensive agricultural production are variable in space and time. As a consequence, a continuous and precise spatially and temporal follow-up of the soil physical and chemical properties is required. Geophysical methods have been applied to soil sciences for a considerable period. The general principle of geophysical exploration is to non-intrusively collect data on the medium under investigation. Among such methods, those based on the electric properties seem particularly promising because soil materials and properties are strongly correlated and can be quantified through the geo electrical properties. Indeed, the flux of electrical charges through materials permits conductor materials like metal or electrolytes, where the conductivity is great, to be distinguished from insulating materials like air, ice and plastics, where it is small. Among the latter, soil materials exhibit intermediate electrical properties depending on their physical and chemical properties (texture, salinity or water content). Schlumberger in 1912 cited by Meyer de Stadelhofen (1991) introduced the idea of using electrical resistivity measurements to study subsurface rock bodies. This method was first adopted in geology by oil companies searching for petroleum reservoirs and delineating geological formations. In soil science, Bevan (2000) reported that the first known equipotential map was compiled by Malamphy in 1938 for archaeological research at the site of Williamsburg in USA. Since that early study, the interest in subsurface soil prospecting by electrical prospecting has steadily increased. In this paper, we review the literature dealing with the use of electrical resistivity applied to soil. We present the basic concept of the method.

II. THEORY AND BASIC PRINCIPLES

The purpose of electrical resistivity surveys is to determine the resistivity distribution of the sounding soil volume. Artificially generated electric currents are supplied to the soil and the resulting potential differences are measured. Potential difference patterns provide information on the form of subsurface heterogeneities and of their electrical properties (Kearey et al., 2002). The greater the electrical contrast between the soil matrix and heterogeneity, the easier is the detection. Electrical resistivity of the soil can be considered as a proxy for the variability of soil physical properties (Banton et al., 1997). The current flow line distributions depend on the medium under investigation; they are concentrated in conductive volumes. For a simple body, the resistivity r (Ω m) is defined as follows:

$$\rho = R\frac{S}{L} \qquad (1)$$

With R being the electrical resistance (Ω), L the length of the cylinder (m) and S is its cross-sectional area (m2). The electrical resistance of the cylindrical body R (Ω) is defined by the Ohm's law as follows:

$$R=\frac{V}{I} \qquad (2)$$

With V being the potential (V) and I is the current (A). Electrical characteristic is also commonly described by the conductivity value σ (Sm-1), equal to the reciprocal of the soil resistivity. Thus:

$$\sigma=\frac{1}{\rho} \qquad (3)$$

In a homogeneous and isotropic half-space, electrical equipotential are hemispherical when the current electrodes are located at the soil surface as shown in Fig. 1 (Scollar et al., 1990; Kearey et al., 2002; Sharma, 1997; Reynolds, 1997). The current density *J* (A/m2) has then to be calculated for all the radial directions with:

$$J = \frac{I}{2\pi r^2} \qquad (4)$$

Where 2πr2 is the surface of a hemispherical sphere of radius *r*. The potential *V* can then be
Expressed as follows:

$$V = \frac{\rho I}{2\pi r} \qquad (5)$$

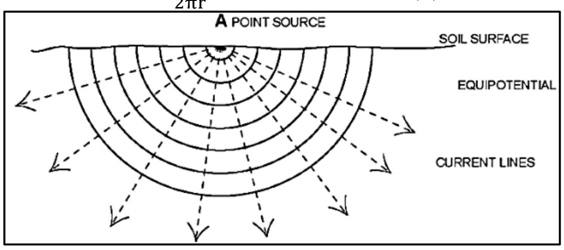

Fig. 1: Distribution of the current flow in a homogeneous soil.

Measurement of electrical resistivity usually requires four electrodes: two electrodes called A and B that are used to inject the current (''current electrodes''), and two other electrodes called M and N that are used to record the resulting potential difference (''potential electrodes''). The potential difference ΔV measured between the electrodes M and N is given by the equation:

$$V = \frac{\rho I}{2\pi}\left[\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right] \qquad (6)$$

Where K is a geometrical coefficient that depends on the arrangement of the four electrodes A, B, M and N. The current electrodes A, B and the potential electrodes M and N can be placed in the field at the soil surface, or in boreholes. As compared with the surface methods, the cross borehole methods present the advantage of a high resolution with depth (Slater et al., 2000). This technique requires nevertheless intrusion into the studied bodies for the insertion of the electrodes. At the laboratory scale this technique can also be applied by placing the electrodes around the soil sample at various depths (Olsen et al., 1999).

III. Variation of Electrical Resistivity as a Function of Soil Properties

The electrical resistivity is a function of a number of soil properties, including the nature of the solid constituents (particle size distribution, mineralogy), arrangement of voids (porosity, pore size distribution, connectivity), degree of water saturation (water content), electrical resistivity of the fluid (solute concentration) and temperature. The air medium is an insulator (i.e. infinitively resistive), the water solution resistivity is a function of the ionic concentration, and the resistivity of the solid grains is related to the electrical charges density at the surface of the constituents. These parameters affect the electrical resistivity, but in different ways and to different extents. Electrical resistivity experiments have been performed to establish relationships between the electrical resistivity and each of these soil characteristics.

A. *Nature and arrangement of solid constituents*

In the context of soil mapping, electrical resistivity exhibits a large range of values from 1 Ω m for saline soil to several 105 Ω m for dry soil overlaying crystalline rocks. The electrical conductivity is related to the particle size by the electrical charge density at the surface of the solid constituents. In clay soil, the electrical charges located at the surface of the clay particles lead to greater electrical conductivity than in coarse-textured soils because of the magnitude of the specific surface (Fukue et al., 1999). The electrical resistivity recorded by Giao et al. (2003) on 25 clay samples collected worldwide ranged from 1 to 12 Ω m. Lamotte et al. (1994) studied two cultivated sandy soils of very similar composition but significantly different electrical resistivity: in the sandy soil showing the greatest resistivity, few clay micro aggregates were juxtaposed to the sand grains, while in the other soil the sand grains were coated and bridged by clay leading to a great continuity of the clay phase. The geometry of the pores (void distribution and form) determines the proportion of air and water according to the water potential. Robain et al. (1996) linked resistivity variations with the structure of the pedological materials, identifying that high and low resistivity values were related to macro- and meso porosity, respectively. This enabled the detection of badger burrows and the study of their network as demonstrated by Butler et al. (1994). This also enabled the study of the crack opening at the cent metric scale by Sam ouelian et al. (2003).

The porosity can be obtained for the electrical property via the Archie's law, which for a saturated soil without clay is written as:

$$F = \frac{\rho}{\rho w} = a\phi^{-m} \qquad (7)$$

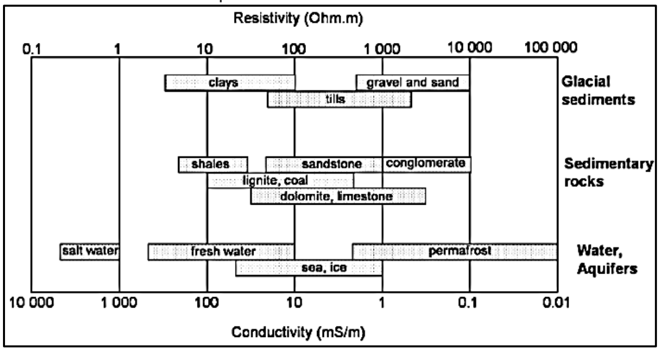

Table 1: Typical ranges of electrical resistivity's of earth materials (after modified Palacky, 1987)

Where the proportionality factor *F* is called the formation factor, a and m are constants related, Respectively, to the coefficient of saturation and the cementation factor, p and pw are, respectively, the resistivity of the formation and the resistivity of the pore-water, f is the porosity. The factor F depends then on the pore geometry. Knowing the pore-water resistivity and a, m constants the porosity can be calculated from the resistivity value. The calculated porosity should be considered as an ''apparent'' porosity values because Archie's law assumes that all the void space is filled with water excluding the possibility of the gas presence.

B. *Water Content*

Electrical current in soils is mainly electrolytic, i.e. based on the displacement of ions in pore water, and is therefore greater with the presence of dissolved salts. Thus, electrical current in soils depends on the amount of water in the pores and on its quality. In most studies concerning the water content, the electrical conductivity of the solution is assumed to remain relatively constant to be neglected against its variation related to water content variation. Prior to field surveys, preliminary calibration of the volumetric water content related to the electrical resistivity is usually performed in the laboratory. The electrical resistivity decreases when the water content increases. It can also be seen that for water content <15%, the electrical resistivity rapidly decreases with increasing water content. The relationship between the electrical resistivity (or its reciprocal, the conductivity, expressed in Siemens/m noted mho/m) and the water content has firstly been studied by authors mainly in the field of petroleum research. Archie (1942) proposed an empirical relationship based on laboratory measurements of clean sandstone samples. This relationship was a modified form of the previous equation (8), taking into account that the porosity can be filled by another medium as water, for example air or petroleum. The water saturation was expressed in function of the formation factor F, of the formation resistivity p and of the water resistivity pw:

$$s^n = \frac{F\rho w}{\rho} \qquad (8)$$

From Equation 7 we obtain:

$$s^n = \frac{a\rho w}{\rho\phi^m} \qquad (9)$$

Where S is the saturation degree and n is a parameter related to the saturation degree. It was established to be valid for medium to coarse-grained soils. It assumes that the characteristic of the solid phase does not influence the electrical current conduction. Froehlich and Parke (1989) reported that the great practical success of Archie's law was related to the assumed validity of the determined constants on a large range of soils except for clayey soil. Indeed, this relationship was successfully used for water content estimation in numerous studies (Binley et al., 2002; Zhou et al., 2001). An empirical linear relationship between the resistivity and the water content was proposed by Goyal et al. (1996) and Gupta and Hanks (1972) as follows:

$$\rho_{(z,t)} = a + b_{(z,t)} \quad (10)$$

Where a and b are empirical constants implicitly containing the soil and water characteristics (i.e. porosity, temperature, salinity) and assumed to be invariant with time. Temporal variations in the soil moisture profile are estimated by using electrical resistivity sounding data acquired at different times (Aaltonen, 2001; Michot et al., 2003).

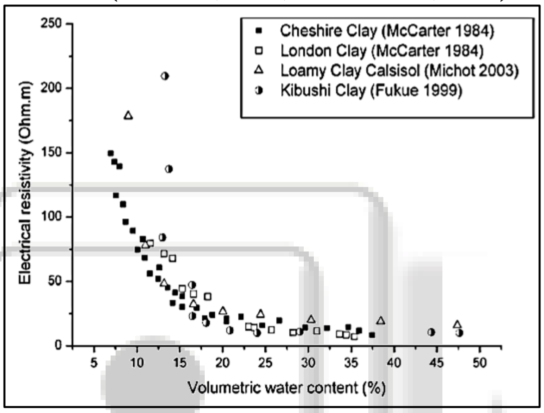

Fig. 2: Relationship between the volumetric water content and the electrical resistivity for Different soil types (values issues from Fukue et al., 1999; Michot et al., 2003; McCarter, 1984).

$$\frac{1}{\rho} = \frac{1}{\rho_w}[a\theta^2 + b\theta] + \frac{1}{\rho_s} \quad (11)$$

Where ps and pw represent the solid matrix and the pore-water resistivity, respectively, a and b are coefficients depending on the solid phase characteristics, related to the texture and Mineralogy, and u is the volumetric water content (cm3). By using it, Kalinski and Kelly (1993) predicted the volumetric water content with a standard error of 0.009 for water contents ranging from 0.20 to 0.50 in soil containing 20% clay.

C. Pore Fluid Composition

As outlined above, the electrical conductivity is related to the mobility of the ions present in the fluid filling the pores. Conductivity depends on the concentration and the viscosity of the water (Scollar et al., 1990). The estimation of the water content by resistivity measurements requires knowledge of the concentration of dissolved ions. Early studies dealing with the determination of the soil water content were confronted with the problem of estimating the soil salinity variation (Rhoades et al., 1977). Since salts have to be in an ionized form to conduct the current, the amount of water in soil governs the available paths of conduction. Shea and Luthin (1961) found a close linear relationship between electrical resistivity and salinity for a soil water content ranging from saturation to -3kPa water potential. Thus, estimation of the soil salinity by electrical resistivity requires measurements made at the same water content. The soil salinity is usually measured at saturation, as this is considered as a standardized condition. Kalinski and Kelly (1993) estimated the volumetric water content using Eq. (12) and with pore solution resistivity (*p*w) of 1, 2 and 3 mho/cm. They found that at given water content, the electrical resistivity decreases when the water conductivity increases. Moreover, the different ions present in the solution (H+, OH-, SO42-, Na+, Cl-) do not affect the conductivity in the same way because of differences in ion mobility. This explains why soil solutions at the same concentration but having different ionic compositions, may have different electrical conductivities. This results in a large range of possible electrical conductivities because of concentration and ionic composition variations in different areas of the soil. This property was also used by Bernstone et al. (1998) to delineate landfill structure. The large resistivity contrast between salt water- and fresh water-saturated zones was used by several investigators to study salt water intrusion into coastal areas (Nowroozi et al., 1999; Acworth, 1999; Yaramanci, 2000). Van Dam and Meulenkamp (1967) considered the soil resistivity values of 40, 12 and 3 Ω m as representative of fresh, brackish and saline water, respectively.

D. Temperature

Ion agitation increases with temperature when the viscosity of a fluid decreases. Thus, the electrical resistivity decreases when the temperature increases. Comparisons of electrical resistivity measurements require the expression of the electrical resistivity at a standardized temperature. By conducting laboratory experiments on 30 samples of saline and alkaline soils, Campbell et al. (1948) showed that conductivity increased by 2.02% per °C between 15 and 35°C. Corrections can be then calculated to express the electrical conductivity at the standardized temperature of 25 °C as follows:

$$\sigma_t = \sigma_{25°C}[1 + \alpha(T - 25°C)] \quad (12)$$

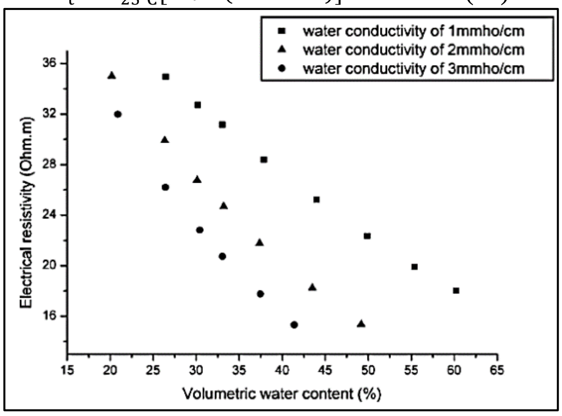

Fig. 3: Relationship between the volumetric water content and resistivity for different values of pore-water conductivity. (Values issues from Kalinski and Kelly, 1993).

Where σt is the conductivity at the experiment temperature, σ25° the conductivity at 25 °C, and α is the correction factor equal to 2.02%. Colman and Hendrix (1949) discussed the validity of the Campbell's equation using 13 soils showing a wide range of texture. These results are in agreement with Campbell and corresponded also to the references formula used to correct the temperature effect in the log interpretation chart of Schlumberger (1989). In soils, temperature variation during a year occurs at two temporal scales, day and season. In studies where the temperature effect is not corrected, an assumption is made that temperature remains stable mostly because measurements are done every day at the same time over a short period (Bottraud et al., 1984b). At the annual scale, it is not possible to avoid the effect of temperature on electrical field resistivity measurements. Usually, the greatest resistivity values are recorded from September to November (in the Northern hemisphere), while the smallest resistivity values are recorded from June to July. Aaltonen (2001) also reported that coarse-grained materials presented a wider range in seasonal resistivity variation than clayey soil. Thus, knowledge of the seasonal variation of the temperature and its consequences on the electrical resistivity is essential to avoid misinterpretation of field measurements when comparing resistivity acquisition at the same place but on different dates.

IV. Conclusion

Electrical resistivity prospecting is a very attractive method for soil characterization. Contrary to classical soil science measurements and observations which perturb the soil by random or by regular drilling and sampling, electrical resistivity is non-destructive and can provide continuous measurements over a large range of scales. In this way, temporal variables such as water and Plant nutriment, depending on the internal soil structure, are monitored and quantified without altering the soil structure. The applications are numerous: (i) determination of soil horizonation and specific heterogeneities, (ii) follow-up of the transport phenomena, (iii) monitoring of solute Plume contamination in a saline or waste context. It enables the improvement of our understanding of the soil structure and it's functioning in varying fields such as agronomy, pedology, geology, archaeology and civil engineering. Concerning agronomy, applications are present in precision farming surveys. Nevertheless, electrical measurements do not give a direct access to soil characteristics that interest the agronomist. Preliminary laboratory calibration and qualitative or quantitative data (i.e. after inversion) interpretations have to be done to link the electrical measurements with the soil characteristics and function.

References

[1] Abdelatif, M.A., Sulaiman, W.N., 2001. Evaluation of groundwater and soil pollution in a landfill area using electrical resistivity imaging survey. Environmental Management 28, 655–663.
[2] Benderitter, Y., Schott, J.J., 1999. Short time variation of the resistivity in an unsaturated soil: the relationship with rainfall. Eur. J. Environ. Eng. Geophysics 4, 37–49.
[3] Busby, J.P., 2000. The effectiveness of azimuthal apparent-resistivity measurements as a method for determining fracture strike orientations. Geophysics. Prospective 48, 677–695.
[4] Campbell, R.B., Bower, C.A., Richards, L.A., 1948. Change of electrical conductivity with temperature and the relation of osmotic pressure to electrical conductivity and ion concentration for soil extracts. Soil Sci. Soc. Proc. 66–69.
[5] Fukue, M., Minatoa, T., Horibe, H., Taya, N., 1999. The microstructure of clay given by resistivity measurements. Eng. Geol. 54, 43–53.
[6] Goyal, V.C., Gupta, P.K., Seth, P.K., Singh, V.N., 1996. Estimation of temporal changes in soil moisture using resistivity method. Hydrological Process. 10, 1147–1154.
[7] Panissod, C., Lajarthe, M., Tabbagh, A., 1997b. Potential focusing: a new multi electrode array concept, simulation study and field tests in archaeological prospecting. J. Appl. Geophysics. 38, 1–23.
[8] Tabbagh, A., Dabas, M., Hesse, A., Panissod, C., 2000. Soil resistivity: a non-invasive tool to map soil structure horizonation. Geoderma 97, 393–404.
[9] Yoon, G.L., Park, J.B., 2001. Sensitivity of leachate and fine contents on electrical resistivity variations of sandy soils. J. Hazard. Mater. 84, 147–161.
[10] Binley, A., Cassiani, G., Middelton, R., Winship, P., 2002. Vadose zone flow model parameterization using cross-borehole radar and resistivity imaging. J. Hydrology 267, 147–159.