Application of electrical resistivity for the control of water content and density in loess

V. Rinaldi
National University of Córdoba, Argentina

ABSTRACT: Argentinean loess is a typical collapsible soil which strength and stiffness are mainly governed by water content and unit weight. Electrical resistivity of soils depends fundamentally from water content, porosity, and salt concentration in the pore fluid. The interest of this work is to discuss the applicability of electrical resistivity survey to predict variations in density and water content in loess. Samples of loess were prepared in laboratory at varied densities and water contents. The results show that loess resistivity depends mainly on water content and that soil density has little influence. Mapping water content distribution by means of resistivity measurements is possible if salt concentration in pore fluid is known in advance and assumed uniformly distributed in the whole soil mass. A real scale work is described here for which resistivity mapping was used successfully to evaluate distribution of water content in loess formation.

1 INTRODUCTION

The Argentinean loess is of eolian origin and can be classified in the unstable group of soils as collapsible (Aitchinson, 1973).The most relevant properties Argentinean deposit has been extensively described by Moll & Rocca (1991), and Rinaldi et al. (2007). Most loess deposits were naturally deposited by wind (primary loess) while others were removed and re-deposited by water (secondary loess). Additionally, is of common practice to improve the behavior of loess by means of static and dynamic compaction. In any case, natural water content and final density mainly governs shear strength, permeability and compressibility of the soil.

McCarter (1984), Kalinski & Kelly (1994), Knight, (1991), Abu-Hassanein et al. (1996) Zhou et al. (1997), and Rinaldi & Cuestas (2001) discussed the potential application of electrical conductivity (or its inverse value, the resistivity) to evaluate soil compaction. In general, electrical conduction in soils depends mainly on temperature and frequency of measurement, electrolyte type and concentration in the porous, water content and density. Minor influence can be attributed to soil structure and saturation history of the soil.

The possibility of monitoring soil density by means of an electrical methods is advantageous since the control in the field can be performed from the surface to any depth just working with different separation of electrodes when any of the four-electrode configuration is adopted (see for example ASTM G57). On the other hand, to the experience of the authors, measurement of conductivity is fast and little data processing is required in order to obtain accurate and repeatable results.

The purpose of this work is to present a fundamental study to discuss the applicability of electrical resistivity to predict water content and density of loess soil. Thus, various samples were prepared in the laboratory at different densities and water contents. Electrical conductivity was measured for each sample by using a two electrode device. The relationship between the electrical conductivity, soil density and water content is described in terms of the well known Archie´s law. An example of in-situ control by mean of conductivity measurement is presented.

2 BACKGROUND

The influence of the different parameters in the electrical conductivity of compacted specimens of loess was discussed elsewhere (Rinaldi & Cuestas, 2001). The most relevant are: frequency of measurement, electrolyte type and concentration (c), initial salt concentration in the soil, dry unit weight (γd), degree of saturation (S), and temperature (T). At a constant temperature and frequencies of measurement, these authors showed that the influence of the different variables in the electrical conductivity of the soil can

be take in consideration by using the well known Archie´s expression (Archie, 1942) which for saturated conditions can be expressed as:

$$F = a\,n^{-m} \qquad (1)$$

Where F is the formation factor defined from the slope of the σ_e vs. σ_s curves as:

$$F = \frac{\sigma_e}{\sigma_s} \qquad (2)$$

Being σ_e and σ_s the electrical conductivity of the pore fluid and the saturated soil respectively, n is the porosity, a is the tortuosity factor, and m is the cementation factor. The value $1/F$ is also known as the resistivity index (RI).

For the unsaturated condition equation (1) can be extended as follows:

$$F_s = F\,S^{-p} \qquad (3)$$

Where S is the degree of saturation and p is the saturation exponent. Then, by replacing (1) in (3):

$$F_s = a\,n^{-m}\,S^{-p} \qquad (4)$$

The values of a, m and n are normally determined from experiments for a given soil. Notice that for saturated samples $S=1$, and $n = \theta_v$ and equations (4) reduce to equation (1), which was empirically obtained by Archie for some saturated rocks and then extensively validated in practice for a variety of porous formations. Equations (1) and (4) assume that in the porous media the particles and the air are non conductive phases and conduction takes place only through the fluid (Glover, 2010).

In terms of the volumetric water content (θ_v), equation (4) can be rewritten as:

$$F_s = a\,n^{(p-m)}\theta_v^{-p} \qquad (5)$$

Thus, for soils in the saturated condition, the measured conductivity of the soil mass becomes:

$$\sigma_s = \frac{\sigma_e}{a}n^{m} \qquad (6)$$

Equation (7) shows that electrical conductivity for saturated soils is mainly dependent on porosity or the volumetric water content (since $n = \theta_v$) and salt concentration of the pore fluid which governs the value of σ_e. The values of σ_e and a are difficult to be obtained in practice specially in fine grained soils.

Therefore, for a given soil in saturated conditions for which salt concentration in the pore fluid is approximately the same along the whole soil mass (σ_e=constant), there is always possible to find a correlation between the measured bulk conductivity and the porosity as follows:

$$\sigma_s = \alpha\,n^{m} \text{ (saturated soil)} \qquad (7)$$

or alternatively,

$$\sigma_s = \alpha\,\theta_v^{m} \text{ (saturated soil)} \qquad (8)$$

Where α is a curve fitting parameter.

For unsaturated soils, the bulk electrical conductivity of the soil can be obtained from equation (5) as:

$$\sigma_s = \frac{\sigma_e}{a}n^{(m-p)}\theta_v^{p} \qquad (9)$$

In a similar approach developed for the saturated conditions, it is always possible to find a more general expression for a given soils assuming that σ_e is constant everywhere in the soil mass of the type:

$$\sigma_s = \alpha\,n^{(m-p)}\,\theta_v^{p} \qquad (10)$$

Equation (10) is a more general expression for soils at any compaction density and water content condition. It can be seen that for saturated soils ($n = \theta_v$) and equation (10) reduces to equation (8).

Notice that in equations (6) to (10) soil dry density is included in n and also in θ_v since:

$$\theta_v = \frac{\gamma_d}{\gamma_w}w \qquad (11)$$

Where (γ_d) is the dry unit weight of the soil, (γ_w) is the unit weight of water and (w) is the gravimetric moisture content.

Equations (10) and (11) are the basic relationship to determine water content and density from the measured soil resistivity of the soil. From these equations it becomes clear that soil conductivity depends on soil density and water content (w). In saturated soils, conductivity is directly related to volumetric water content. The parameters a and m depend mainly on mineral composition, grain size distribution and fabric. The exponent p for a given soil is slightly dependent on soil density.

3 TESTING PROGRAM

The soil tested here is the typical loess obtained from the campus of the Universidad Nacional de Córdoba which can be classified in USCS as ML. In natural state the dry density is $\gamma_d= 13.5$ kN/m^3, liquid limit LL=31, and plasticity index PI = 26.

The electrical conductivity of the soil samples was measured in the two-electrode cell. Basically the cell consists on a cylindrical glass tube (33.4 mm internal diameter) and two circular electrodes of the same diameter located at both ends of the tube. Electrodes were made of cooper and coated with nickel. The measurements of conductivity were performed by means of a Stanford Research impedance analyzer SR715 at the frequency of 10 kHz. Specific details of the testing cell used here and its calibration procedure are described in Rinaldi & Cuestas (2001).

The natural samples of loess were air-dried, sieved through sieve No 40 and then oven dried at 105 ºC.

The dried soil was then mixed with the different volumes of NaCl electrolyte prepared at concentrations between 0,5 % and 2% by weight. The prepared soil specimens were then compacted to the desired density in the glass tube of the cell.

4 ARCHIE´S LAW FOR LOESS

Figure 1 display the variation of the formation factor obtained for a sample of loess saturated with NaCl solutions and compacted at various densities. The exponent of the correlation was $m = 2.6$ and the factor $a = 0.5$. The range of porosities included in Figure 1 range between 0.37 and 0.50 which are the maximum and minimum densities that may be observed in the field. The agreement of equation (1) is acceptable in the rage of densities tested. The values of the constants a and the exponent m may be different even for the same soil at other compaction densities.
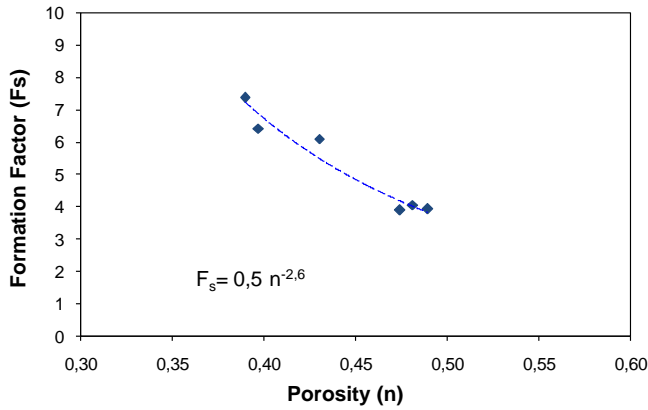

Figure 1. Formation factor of loess saturated with NaCl solutions at concentrations between 0.5% and 2% as a function of porosity (n).
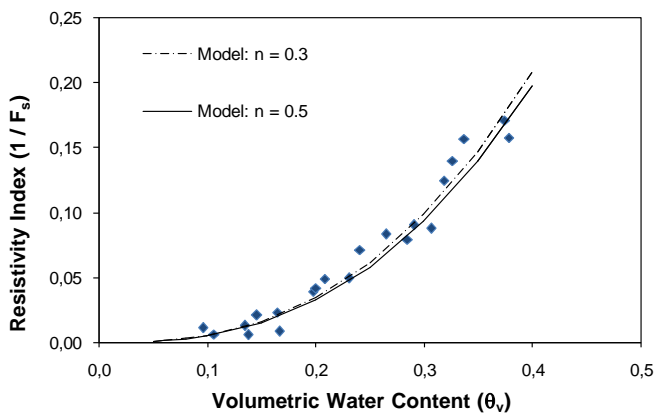

Figure 2. Formation factor of loess samples prepared with NaCl solutions at concentrations between 0.5% and 2% as a function of volumetric water content (θ_v).

Figure 2 shows the variation of the formation factor for samples prepared at various water content and concentrations of NaCl. Equation (5) was evaluated for porosities $n = 0.3$ and $n = 0.5$ and plotted in the same figure. The constant parameters were fixed as a

$= 0.5$, $m = 2.6$ and $p = 2.4$. The variation of the exponent p is presented on Figure 3 for samples prepared at different densities and mixed with different concentrations of NaCl. Therefore, equation (5) can be written for the present results as:

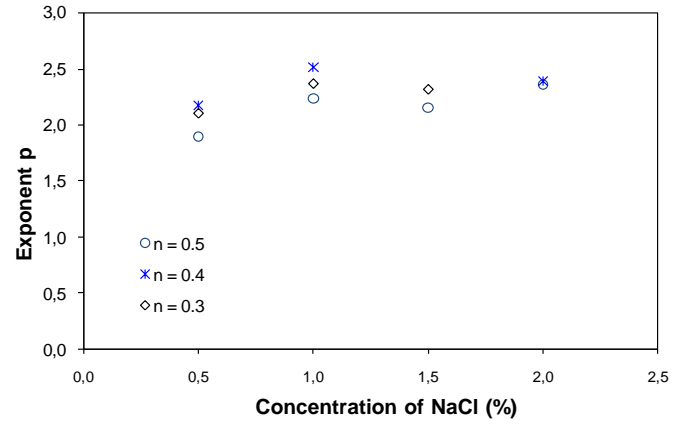$$\frac{\sigma_s}{\sigma_e} = \frac{1}{a} n^{(2.6-2.4)} \theta_v^{2.4} \qquad (12)$$

Figure 3. Variation of the exponent p for samples of loess of loess prepared at various porosities and mixed with NaCl solutions at concentrations between 0.5% and 2%.

From Figure 2 it can be observed that for the model porosity has negligible effect on the formation factor and that water content is the main parameter that governs conduction trough the soil. This result can be explained from the close values obtained for the exponent p and m. The physical meaning of this result can be further clarified from the phase diagram for the soil displayed on Figure 4. Three conduction paths can be identified through the soil in the unsaturated condition: solid particles (σ_p), fluid (σ_e) and air (σ_a). Thus, the total conduction can be expressed in a simplified approach as:

$$\sigma_s = (1-n)\, \sigma_p + (n - \theta_v)\, \sigma_a + \theta_v \sigma_e \qquad (13)$$
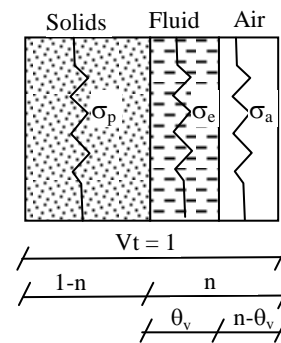

Figure 4. Phase diagram of soil and simplified conduction paths assumed.

The second term of equation (12) vanishes since conductivity of the air is close to zero. Additionally, the first term also has a negligible influence for soils

which particles can be considered as nonconductive. Then, the total conduction depends mainly from the volumetric water content of the soil. Notice from Figure 4 that for any variation in the fraction volume of solids and air (which changes soil density), conductivity through the fluid will remain practically unchanged.

The volumetric water content depends also from the soil unit weight (γ_d) according to equation (11) however, this parameter has not significant variation from the loosest to densest condition for most soils. For example in loess density usually ranges from 13,5 kN/m^3 to 16,5 kN/m^3 when heavily compacted which represent an increment of 20 % . Conversely, water content (*w*) may vary from 2% in the air dry condition to almost 40 % in the saturated condition which represent an increment of 2000 %. Then for practical purposes and for loess, equation (12) can be simplified to: (5) as:

$$\frac{\sigma_s}{\sigma_e} = \chi\, \theta_v^{p} \tag{13}$$

That for the soil tested here yield:

$$\frac{\sigma_s}{\sigma_e} = 2.14\, \theta_v^{2.6} \tag{14}$$

In order to obtain the soil conductivity from equation (14) it is required to know in advance the conductivity of the pore fluid (σ_e). This parameter is normally unknown, however it is clear that for a given soil formation, the concentration of salt in the pore fluid can be assumed homogeneously distributed in the whole mass (due to ion diffusion) and thus the value of σ_e can be considered the same everywhere.

5 FIELD EVALUATION

Figure 5 displays the variation of electrical resistivity obtained in an area of 60 m x 150 m located at the south of the city of Córdoba. The thickness of loess formation at the site is larger than 60 m. Measurements were performed by using the four electrode configuration equally spaced 5m apart. Separations of electrodes were kept constant and measurements of resistivity were performed at different points in the surface of the soil following a square grid of 20m. The measured resistivity was estimated to correspond to an average thickness of 2.5 m.

The range of resistivities values obtained in this test collapse in a narrow band between 22 Ohm-m and 43 Ohm-m, however, data are consistent. According to equation (14) the mapped resistivity is directly related to soil water content. In order to determine the relationship between the resistivity values and water content, the following procedure was used here:
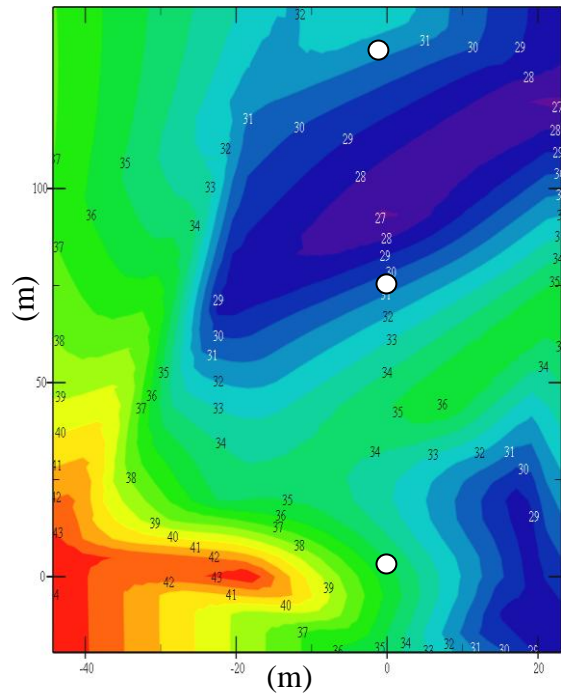

Figure 5. Resistivity variation obtained in an area of 60 m x 150 m of loess formation. Numbers on the figure display resistivity values in Ohm-m. White dots indicate the position of control points.

a) Three field points of control were selected and from each point were determined moisture content (*w%*) and soil density (γ_d). Figure 5 shows the location of each point.

b) Volumetric water content (θ_v) was determined for the three control points from equation (11).

c) For convenience, equation (14) was rewritten in terms of resistivity as:

$$\rho_s = \frac{\rho_e}{2.14}\, \theta_v^{-2.6} \tag{15}$$

d) From equation (15) the value of ρ_e was determined for the three control points since the values of θ_v and ρ_e are known.

e) Assuming constant density (γ_d) and fluid resistivity (ρ_e) everywhere, equation (15) is then the field curve that can be used to determine water content for any other point where resistivity is known.

Equation (15) is plotted on Figure 6 as a function of water content. The three control points are also shown on the same figure.

The study presented here assumes the validity of equation (14) obtained for loess formation. For any other formation, it is recommended to obtain in the laboratory a calibration of the model, or to increase the number of control points and to determine a field curve from these points.
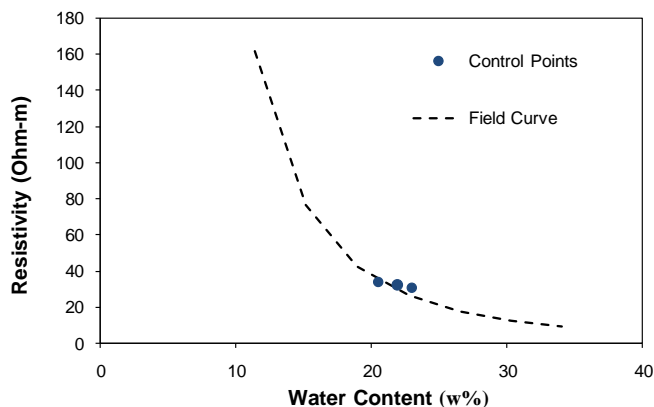
Figure 6. Variation of resistivity as a function of water content for the field test performed.

6 CONCLUSIONS

The main conclusion of this work can be summarized as follows:

a) Resistivity or electrical conductivity of loess has a significant dependence on water content and is little influenced by density.

b) Archie´s equation can be used to model the dependence of electrical resistivty from water content for loess in saturated and unsaturated condition.

c) The main dependence of soil resistivity from water content was explained here by means of a simple physical model.

d) A field procedure was described here which allows mapping the distribution of water content from electrical resistivity measurements. The procedure assumes little variation in the conductivity of the soil mass under test.

e) Further studies are required to evaluate the influence of fine contents and to what extends can be applied Archie´s model.

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