Development of an electrical resistivity measure for geotechnical and geoenvironmental characterization

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ABSTRACT: The resistivity piezocone (RCPTU) has become a very useful tool in the geoenvironmental investigation of contamination plumes. Using this device, bulk resistivity of soil can be measured in series of tests, allowing for the detection of the probable presence of certain substances by comparing them to reference values. In areas where reference values are exceeded, complementary evaluations can be made using samples collected at discrete depths for subsequent chemistry analysis. These reference values are established from field work or from similar geological environments. However, the values reported in the literature refer to typical soils from temperate climates, and thus do not reflect the behavior of tropical soils. Therefore, this paper discusses the development of a laboratory device to determine soil resistivity in order to study the intervening factors such as moisture, compaction, porosity and degree of saturation. In addition, two resistivity modules with different diameters were built to study the scale effect.

1 INTRODUCTION

The detection of contamination plumes is extremely important, since they may represent serious risks for the population and the environment of a given region. The resistivity piezocone (RCPTU), as Campanella & Weemees (1990) and Campanella & Kokan (1993) suggestions, is a relatively recent technological development of the piezocone, in which a resistivity module is installed at the back of a standard piezocone. This resource enables continuous measurements to be taken of the resistance to an electric current applied to the ground. When measured in the ground in a series of tests, this current flow allows for the detection of the probable presence of certain substances by means of comparison against reference values. These reference values are established based on field work or on similar geological environments. However, the values reported in the literature refer to typical soils of temperate climates and do not reflect the behavior of tropical soils.

To allow for a study of reference values in tropical soils, a device was developed to read resistivity in the laboratory, using the same configuration as the resistivity sensor of the RCPTU (Figure 1).

In addition, resistivities were also measured directly by means of plates attached to the ends of test specimens with the same characteristics as those tested with the newly developed device. These analyses indicated the influence of the excitation frequency through the function generator.

Initially, as Archie (1942), the development of this device allowed for analyses of the variation of resistivity as a function of the variation in the moisture content, degree of saturation and void index.

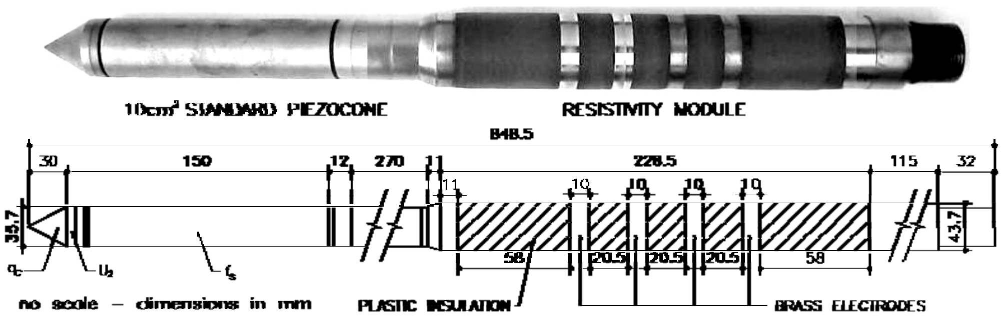


Figure 1 – RCPTU Squematic diagram *apud* Giacheti *et al* (2006)

2 THEORETICAL CONCEPTS

Numerous scientific works as Campanella (2008), Chan (2008), Hassona *et al* (2008) and Oh *et al* (2008) published in recent years have reported on the increasing use of the RCPTU in the practice of environmental engineering.

In general, the Wenner array (Fig. 2 and Eq. 1) has been used to determine resistivity by means of these pointwise devices.

In its ASTM G57-95a standard, the American Society for Testing and Materials Standards describes both field and laboratory procedures for measuring soil resistivity using four electrodes in the Wenner configuration, in which they are spaced equally in the arrangement shown in Figure 2. The measure of apparent resistivity in this arrangement is calculated from Equation 1:

$$\rho_{ap} = 2a \times \frac{\Delta V}{I} \qquad (1)$$

where: ρ_{ap} is the apparent resistivity (Ω.m)

a is the distance between the electrodes (m)

ΔV is the difference in potential (mV), and

I is the current intensity (mA).

A large part of these devices are built with four electrodes because they are less subject to the effect of polarization in the electrodes. Devices that use two electrodes working at low frequencies are subject to the effect of polarization in the electrodes, which strongly interferes in resistivity readings. However, as higher frequencies are used, this effect tends to decrease since the ions cannot polarize in the electrodes (Weemees, 1990).

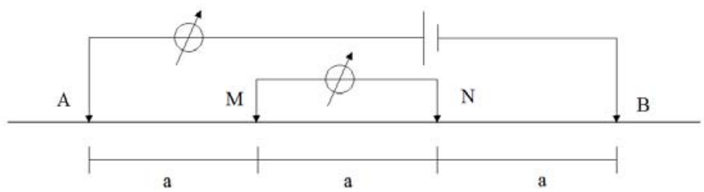


Figure 2 – Wenner Configuration

Figure 3 illustrates the effect of polarization in the electrodes, where the resistance was normalized according to Equation 2 and plotted on a graph of normalized resistance on the coordinate axis and of frequency on the abscissas.

$$\rho_n = \frac{\rho}{\rho_{1000}} \qquad (2)$$

where: ρ_n is the normalized resistivity

ρ is the measured resistivity, and

ρ_{1000} is the resistivity measured at a frequency of 1000Hz.

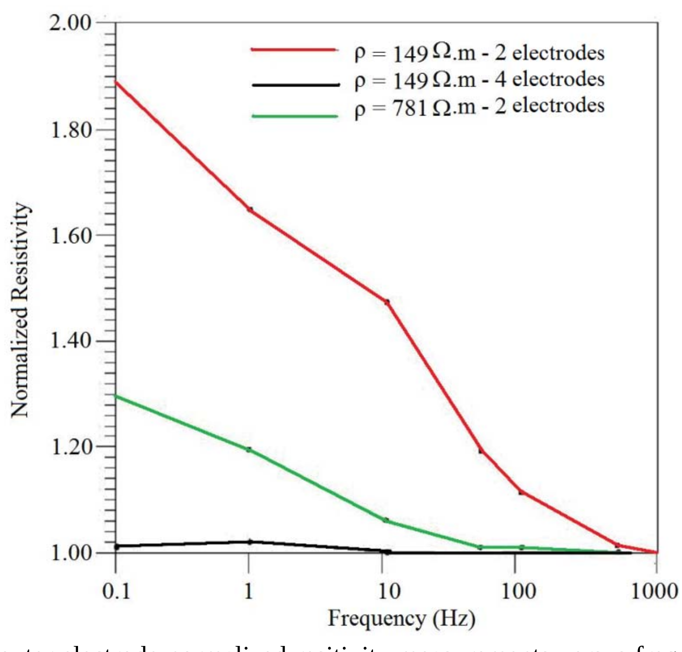


Figure 3 – Inner and outer electrode normalized resitivity measurements versus frequency *apud* Weemees (1990)

According to Davies & Campanella (1995), the resistivity piezocone can be used for the evaluation of environmental and geotechnical parameters. In areas where the reference values are exceeded, complementary evaluations can be made using samples collected at discrete depths for subsequent chemistry analysis. These reference values are established from field work or from similar geological environments. Table 1 summarizes several typical resistivity measurements of saturated bulk soil mixtures and pore fluid.

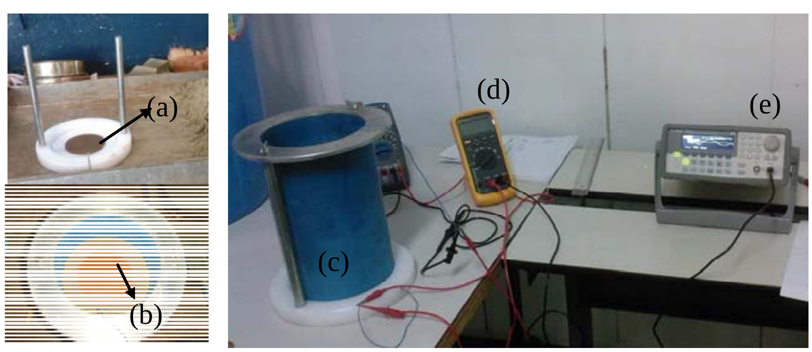
Table 1 – Summary of some typical resistivity measurements of saturated bulk soil mixtures and pore fluid (after Campanella, 2008)

Material Type	Bulk resistivity ρ_b, Ω.m	Fluid resistivity ρ_f, Ω.m
Deltaic sands with saltwater intrusion	2	0.5
Drinking water form sand	>50	>15
Typical landfill leachate	1-30	0.5-10
Mine tailings (base metal) & oxidized sulphide leachate	0,01-20	0.005-15
Mine tailings (base metal) no oxidizied sulphide leachate	20-100	15-50
Arsenic contaminated sand and gravel	1-10	0.5-4
Industry site: inorganic contaminants in sand	0.5-1.5	0.3-0.5
Industrial site: wood waste in clayey silts	200-1000	75-450
Industrial site: wood waste in clayey silts	300-600	80-200

Note: Conductivity (μS/cm) = 10,000 ÷ [Resistivity (Ω.m)]

3 ELECTRICAL RESISTIVITY EQUIPMENT

Electrical resistivity tests were carried out with two copper plates, with 10cm diameter each one, pressed against a sand specimen (Fig. 4). The compaction mold was built with an electrical insulator. A power supply was used to apply alternating current (AC) with an electrical potential of 5V. The tests were conducted with different moisture contents, varying the frequency from 60Hz to 245.760Hz in each test. As can be seen in Figure 5, the frequency of 1000Hz allowed for steady measurements.



(a) lower copper plate
(b) upper copper plate
(c) compaction mold
(d) multimeter
(e) power supply

Figure 4 – Apparatus for measuring electrical resistivity

Two sensors (Fig. 6) were also developed with diameters of 20mm and 30mm, respectively, according to the RCPTU configuration shown in Figure 1, i.e., using four electrodes arranged in the Wenner configuration. In that way, it is possible to study the scale effect and extend the reference values to field results.

The calibration system was set up in a tank with a known volume, in order to control the concentration of NaCl. Thus, current, voltage, electrical conductivity and water temperature measurements were taken for each measure of salt diluted in the tank. (Fig. 7).

The calibration tests were done several times until measures become repeated.

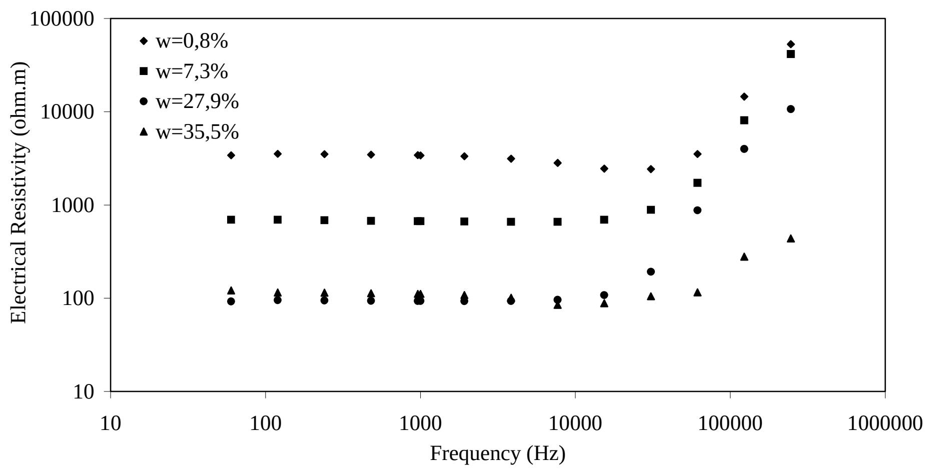


Figure 5 – Relationship between electrical resistivity and frequency of power supply

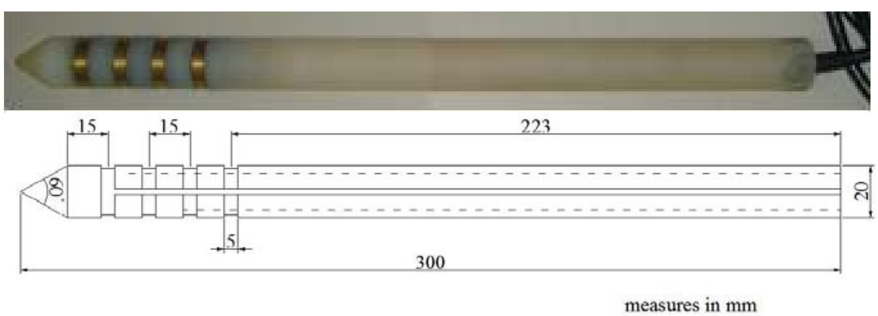


Figure 6 – Resistivity module

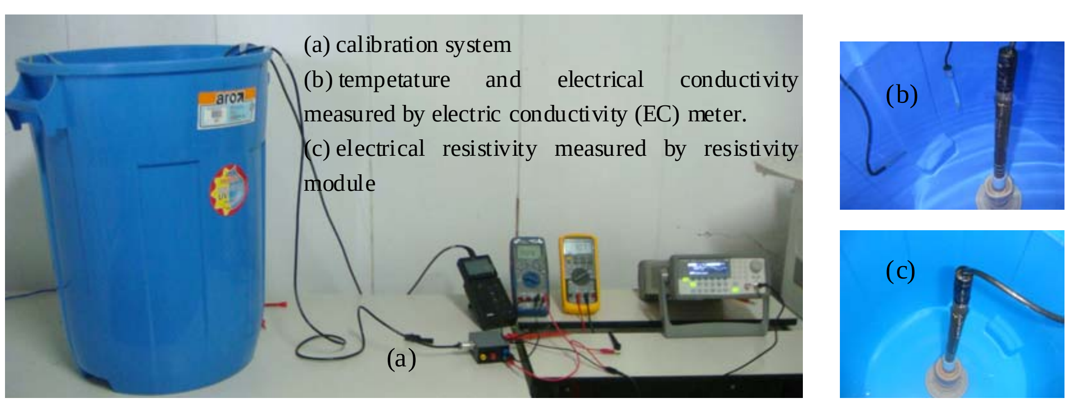


Figure 7 – Calibration System

4 RESULTS AND ANALYSES

4.1 *Frequency Study*

The equipment tests were first analyzed considering the normalized resistivity, Eq. (02), and the excitation frequency, Table 2. It was found that at values of frequency higher than 1960 Hz there is higher variability of normalized resistivity; hence the frequency of 1000 Hz is the recommended value.

In addition, it is possible to ensure that the frequency effect is minor with the increasing of the moisture content. In this specimen, the quartz does not have conductivity and the liquid in the porous influences the result.

4.2 *Calibration of Resistivity Module*

The system was calibrated seven times until the readings of the NaCl concentration remained constant. The calibration curve was then divided into three intervals to improve the relationship between V/I and electrical resistivity (Fig. 8).

The three equations in Figure 8 show the satisfactory response of the 20mm diameter sensor to the normal values of electrical resistivity in geoenvironmental characterization, according to Campanella (2008), Table 1. The same procedure was done to the 30mm diameter sensor and the resulting shape curves were alike.

4.3 *Scale Effect*

Electrical resistivity values determined at the same NaCl concentration for all sensors are presented in Figure 9 and the results are quite close. It can be assumed that the laboratory test data for the developed sensors are similar to the response of RCPTU tests and can be extended to the field testing data.

Table 2 – Normalized Resistivity versus Frequency

Frequency (Hz)	w = 0,8% ρ_n	w=7,3% ρ_n	w=18,0% ρ_n	w=27,9% ρ_n	w=35,5% ρ_n
60	1,00	1,04	1,05	0,99	1,09
120	1,04	1,03	1,03	1,02	1,03
240	1,03	1,02	1,02	1,01	1,03
480	1,02	1,01	1,01	1,00	1,02
960	1,01	1,00	1,00	1,00	1,00
1920	0,98	0,99	0,99	1,00	0,97
3840	0,92	0,98	0,99	1,00	0,91
7680	0,83	0,98	1,00	1,03	0,78
15360	0,72	1,04	1,08	1,16	0,79
30720	0,71	1,32	1,43	2,06	0,94
61440	1,04	2,58	2,98	9,38	1,04
122880	4,27	12,06	10,10	42,72	2,51
245760	15,60	62,01	30,84	114,22	3,93

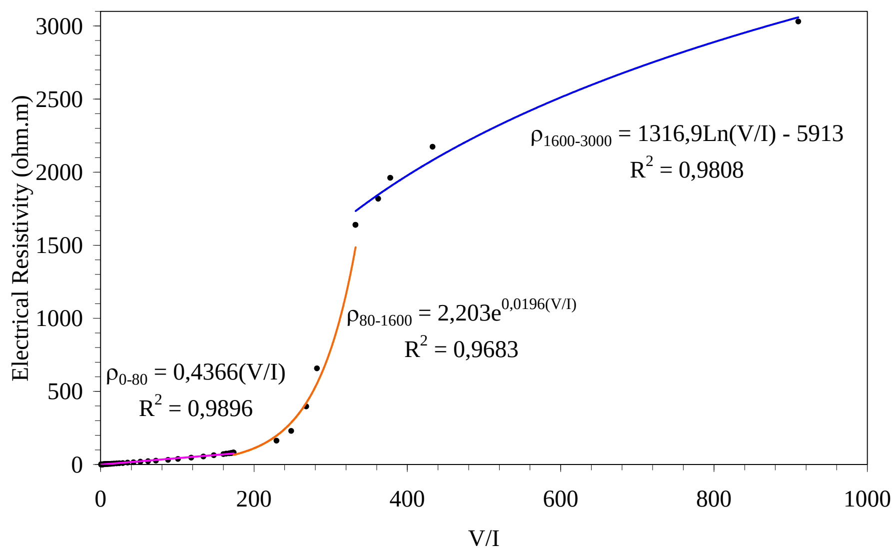


Figure 8 – Calibration Curves

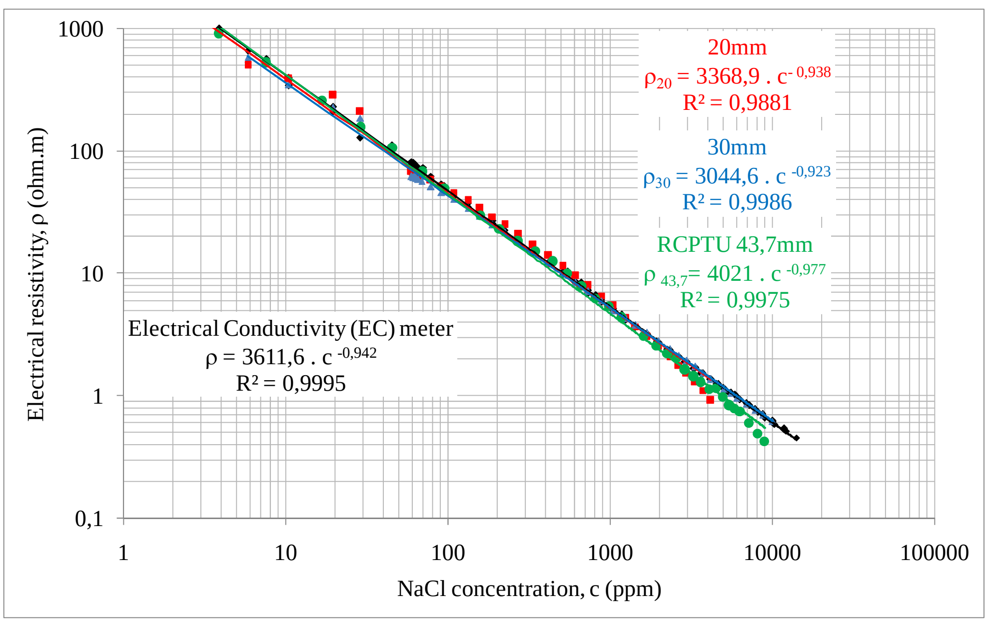


Figure 9 – Assessing scale effect by electrical resistivity versus NaCl concentration

5 FINAL COMMENTS

The response of the laboratory sensor will make it possible to extend this device to the study of factors that influence the bulk resistivity of soils, involving the Archie (1942) formulation adapted to tropical soils.

The tests with the copper plates showed that the frequency effect is more significant to unsaturated soil and small moisture content values. In this way, it is interesting to consider the 1000 Hz as a standard value.

The development of two different diameter module turned possible the beginning of study of the scale effect. The authors are currently engaged in a more detailed research, aiming to ensure the extrapolation of the values obtained in the laboratory to those obtained in the field by RCPTU.

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