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Estimation of soil resistivity by the assembly of a vertical electrical sounding equipment at a university campus at Turbaco, Bolívar

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Abstract. A low-cost geoelectric equipment was implemented for academic purposes to carry out the Vertical Electrical Sounding method in order to determine the resistivity and depth of a point on the surface of a university zone and obtain the contrasts of that resistivity parameter for each type of soil. A model was reproduced at the laboratory to calibrate the equipment, and then the technique was tested in the field. Among the results, layers of sandy loam, soft limestone and dark clay with thicknesses of 0.3 m, 0.75 m and 12 m respectively were obtained, finally a clear clay was obtained whose thickness is unknown. These were compared with reference samples by well drilling method. There was a concordance between the results through the method of statistical confidence intervals with a normal distribution. The data behaved according to a soil model of lower-higher-lower resistivity.

1. Introduction

Geophysics is understood as an application of physics at earth's studies for many purposes such as soil studies, engineering tasks, the search for hydrocarbons and metal ores, etc. From measurements taken on the surface, several data can be obtained about the internal configuration of the earth, such as its physical properties [1].

The methods of geophysical prospecting are used for the study of geological structures in the superficial part of soil. Among these is the resistive method, better known as vertical electrical sounding [2].

The vertical electrical sounding is based on the stimulation of soil by the injection of current through two electrodes (A, B) and in response, the measurement of potential in two other electrodes (M, N). These are aligned to a center [2].

From these data on the surface and the geometric constant k for each arrangement, parameters of the subsurface resistivity are estimated according to the electrical properties of each type of rock [1].

Subsequently, through the inversion of geophysical data, vertical profiles of spacing (AB/2 or AB/3) vs. resistivity (ρ) are created, thus estimating soil types and the depth in which they are found.

The township of Turbaco, Bolívar (Colombia) has zones with clay presence. One type of clay is the expansive one, named because of the variation of its volume due to the expansion that it suffers [3]. It usually causes damage to buildings and roads [4].

It also presents mud diapirism, generating mud volcanoes along with deformations in soil. [5] There might be expansive clay in volcano compounds [6] [7], in addition to the risk associated with sag, affecting nearby populations. [8]

The type of soil is very important when making the foundation of a building because it will receives the live, dead and seismic loads transmitted by the superstructure. [9]

A study about vertical electrical sounding will be done inside an area of a university campus, next to classroom buildings, to discriminate the different types of soil on which the structure was built.

2. Theory

2.1. Mathematical model

The potential (V) at a certain distance (r) has a relationship between resistivity (ρ) and current (I), as shown:

$$V(r) = \frac{\rho}{2\pi r} I. \tag{1}$$

The figure 1 gave and illustration about as shown where δV can be replaced for V:
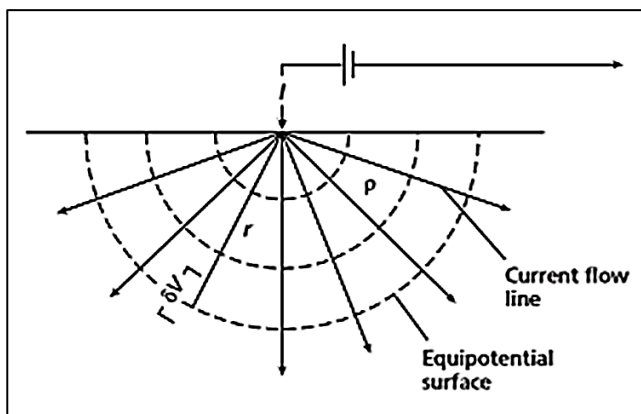

Figure 1. Current flow from a single surface electrode

The potential expressed in equation (1) can be evaluated for each distance from which the total current of an electrode will travel to another point in the electric field thus, being able to calculate the potential at any point of surface at a homogeneous space.

Then the potential at the electrodes M and N can be considered as:

$$V_M = \frac{\rho I}{2\pi} \left(\frac{1}{AM} - \frac{1}{MB} \right), \tag{2}$$

$$V_N = \frac{\rho I}{2\pi} \left(\frac{1}{AN} - \frac{1}{NB} \right). \tag{3}$$

Taking equations (2) and (3) for the potential difference as:

$$V_{MN} = V_N - V_M = \frac{\rho I}{2\pi} \left[\left(\frac{1}{AM} - \frac{1}{MB} \right) - \left(\frac{1}{AN} - \frac{1}{NB} \right) \right]. \tag{4}$$

In the configuration, the voltage can be read on the equipotential lines (generated by the equipotential points) with the equation (4), since in them the potential will be the same.

If we consider the potential in the electrodes M and N for the equation (1) and we isolate the resistivity, we obtain:

$$\rho = \frac{V_{MN}}{I} (2\pi r) = \frac{V_{MN}}{I} k,$$

Wherein:

$$k = 2\pi \left[\left(\frac{1}{AM} - \frac{1}{MB} \right) - \left(\frac{1}{AN} - \frac{1}{NB} \right) \right]. \tag{5}$$

In equation (5) we obtain the geometric factor (k), which is in terms of the distance between the electrodes and varies according to the type of arrangement, that is, according to the spacing of the electrodes.

2.2. Inversion of geophysical data
In nature, the geological environment is not isotropic or homogeneous, so the equipotential surfaces and the current lines are not regular.

For this reason, when taking measurements from the surface, as in our case currents and voltages, we obtain the value of the apparent resistivity. The process of moving from the measured data to model parameters is known as an inverse problem. In geophysics, it is called geophysical data inversion. This occurs through formulations that relate data with parameters.

In the case of vertical electrical sounding, we estimate the apparent resistivities and thicknesses, as data obtained. Then, with the data inversion process we obtain the true resistivities and thicknesses of each layer of soil.

2.3. Wenner arrangement
It is the simplest electrode arrangement and from this one, the other configurations arises. All the electrodes are at a distance (a) from each other as seen in figure 2. For this reason, it is considered symmetrical and this distance increases proportionally for all the electrodes.
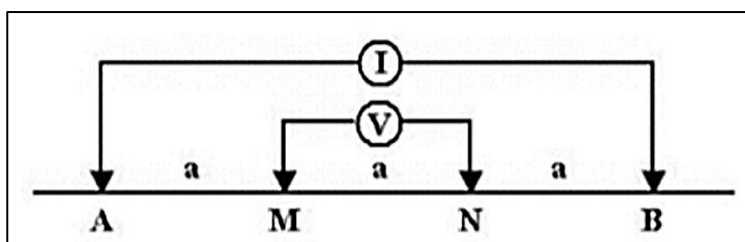

Figure 2. An arrangement according to the Wenner type, it has the electrodes A and B that inject current I, and M and N that measure potential difference V at *a* distances

In this arrangement, the geometric constant acquires the value of:

$$k = 2\pi a \qquad (12)$$

An advantage of this arrangement is that highly sensitive multimeters are not necessary for its realization. A negative aspect is that the toil involves deploying all the electrodes continuously along the entire line of the study [10]

3. Methodology

3.1. Assembly of the equipment
We used a source to supply power and another one to measure potential and current as Rhett did [10]. The first mentioned consists of a car battery. This source emits 12 V of direct current with 40 ampere-hour, which is passed through an inverter (pure sine wave inverter) that transforms it to 120 V alternating current at 60 Hz frequency, this alternating current output of the inverter is low frequency and was the one supplied to the electrode array to take the data on the surface. The other source was two multimeters used to measure potential and current, as well as cabling and alligator clips for the connection of the inverter equipment with the electrode array. At the inverter's output, an ammeter was connected in series to measure the current that was supplied to the ground, this arrived at the electrodes A and B, another multimeter was used to measure the voltage that reached the M and N electrodes, also there were used as electrodes stainless steel rods 33.5 cm long and 0.7 cm in diameter, as shown in figure 3.
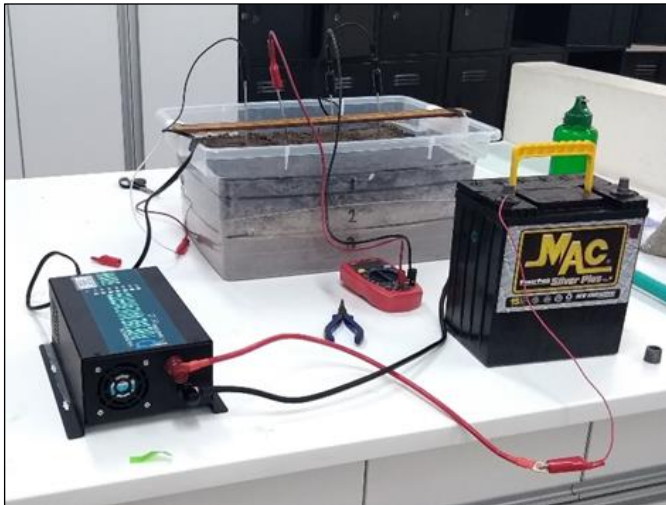
Figure 3. Image of the assembly equipment for vertical electrical sounding (VES)

Although the study can be done with both alternating and continuous current, the alternating one was chosen because it prevents erroneous potential measurements due to polarization or natural currents of earth, as it also helps to avoid abrupt decreases in the intensity of current according the depth.

3.2. Model and calibration

An experimental stage was carried out at the laboratory to calibrate the equipment and to discover the changes in resistivity, according to the analyzed soil types. The electrodes used in this stage were aluminum, 15 cm long and 0.3 cm in diameter, using a plastic box of dimensions 50 x 42 x 20.7 cm. We seek to obtain results that correspond to the established resistivity ranges for each type of soil.

The model that was sought was three layered, where the third one was considered as the table material on which we worked. Greater - lower - greater resistivity model was looked for, expecting a type H graphic. We worked on three different models with a Wenner arrangement until we obtained the expected result. From the bottom to the top of the box, the wetter layer had a thickness of 7.5 cm, the semi-wet layer a thickness of 2.3 cm and the dry layer a thickness of 5.7 cm respectively, for a total depth of 15.5 cm.

3.3. Field survey

Once the equipment was calibrated, the vertical electrical sounding was carried out in a garden next to the building of university rooms, this one has coordinates 10º22'09,4 " N and 75º27'51,8 " W. The Wenner arrangement was used, doing two soundings, one diagonal VES-1 and one horizontal VES-2, later these were averaged. VES-1 was done next to the point where soil extraction had previously been done by the well-drilling method according to figure 4.
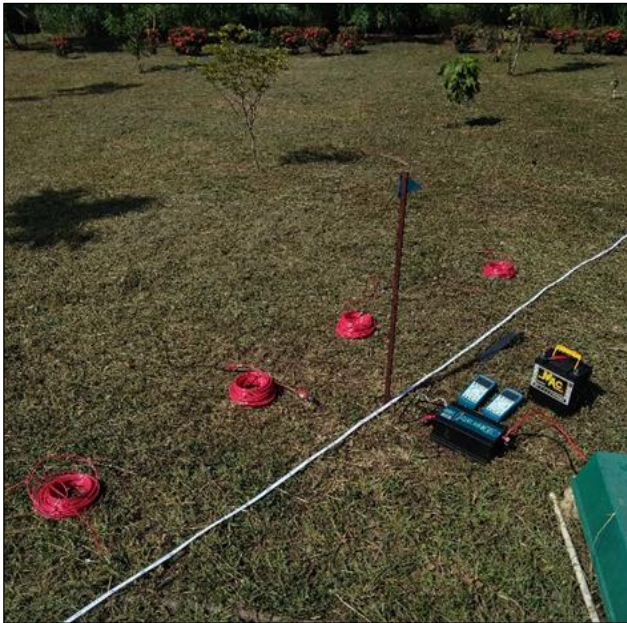
Figure 4. Second Vertical electrical sounding direction (VES-2) done in the university ground

We took an AB electrode distance from 30 cm to 30 m.

As Abd El-Gawad, Helaly and Abd El-Latif [11] we used a software which help us to interpret the vertical electrical sounding curves because it is an inverse modelling program for interpreting resistivity sounding data, but for this study we used IPI2WIN.

The methodology mentioned here can be reproduced again and is available for use by the entire scientific community.

3.4. Statistical analysis
As same as Ordoñez, Auvinet and Juarez [3] a statistical analysis was made to the results of the study. We worked with the VES-1 and VES-2 surveys. Initially, we made a lines graphic diagram to analyze the behavior of the data, then a Kolmogorov Smirnov test was done to estimate if the behavior of the data is near to a normal distribution.

For all the analyzes, we worked with a statistical confidence of $1 - \alpha = 95\%$.

Then, through confidence intervals for the ratio of two variances of normally distributed populations, it was determined if these were equal and finally by confidence intervals for the means difference of normally distributed populations it was determined if these were equal too.

4. Results

4.1. Model and calibration
Because of the measurement of each type of soil resistivity values that were obtained, which were compared together with values already given in tables, there was found a soil type for each sample as shown in table 1. The resistivity values were also obtained according to the different spacings as shown in table 2.

Table 1. Types of soil used in the models.

Soil number	Resistivity ($\Omega \cdot m$)	Type	True resistivity ($\Omega \cdot m$)
1	413.14	Sandy loam	100 - 500
2	1836.23	Sand	100 - 3000

Table 2. Resistivity values due to laboratory tests.

Soil number	AB/2 (m)	MN/2 (m)	a (m)	Apparent resistivity ($\Omega \cdot$m)
1	0.03	0.01	0.02	363.97
2	0.06	0.02	0.04	320.30
3	0.09	0.03	0.06	315.09
4	0.12	0.04	0.08	328.94
5	0.15	0.05	0.1	354.94
6	0.18	0.06	0.12	426.65
7	0.21	0.07	0.14	498.45
8	0.24	0.08	0.16	537.97

Likewise, a graph represented in figure 5, which shows the behavior of the resistivity according to the number of layers and the depth in which they are.
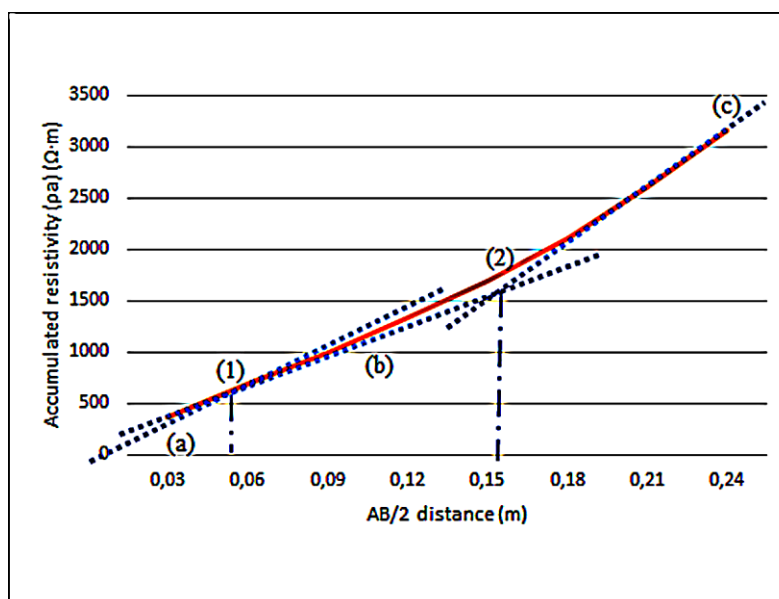

Figure 5. Graphic of AB/2 vs accumulated resistivity for three soil layers (a), (b) and (c), at depths of 10.5 cm (1) and 21 cm (2)

4.2. Field survey
Resistivity values were obtained according to the different spacings as shown in tables 3 and 4.

Table 3. Resistivity values of university ground studied.

Data number	AB/2 (m)	MN/2 (m)	a (m)	Apparent resistivity ($\Omega \cdot$m)
1	0.15	0.05	0.1	24.55
2	0.3	0.1	0.2	25.96
3	0.45	0.15	0.3	35.99
4	0.75	0.25	0.5	33.87
5	1.5	0.5	1	8.09
6	2.25	0.75	1.5	5.35
7	3	1	2	2.96
8	4.5	1.5	3	1.89
9	6	2	4	1.22
10	9	3	6	4.38
11	12	4	8	6.83
12	15	5	10	1.75

Table 4. Current and voltage values.

Data number	Current (±0.3) mA	Voltage (± 0.4) V
1	332.8	13.3
2	302.5	6.295
3	369.25	7.01
4	301.5	2.945
5	370.5	0.486
6	441	0.251
7	315.5	0.0745
8	376	0.036
9	409.5	0.02
10	406	0.046
11	321	0.0385
12	277.5	0.007

Similarly, a graph represented in figure 6, which shows the behavior of the resistivity according to the number of layers and the depth in which they are.
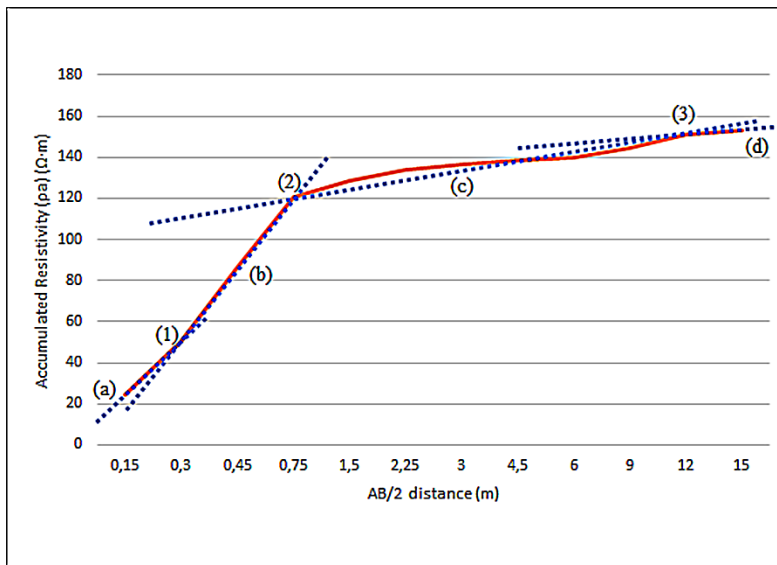
Figure 6. Graphic of AB/2 vs accumulated resistivity for four soil layers (a), (b), (c) and (d) at depths of 30 cm (1) and 75 cm (2), and 12 m (3)

The inversion process of the data obtained through the IPI2WIN software was also carried out to estimate the resistivities and layer thicknesses, obtaining estimated values of resistivity and thickness, like El-Gawad A, Helaly and El-Latif A [11] as shown on figure 7 and table 5.
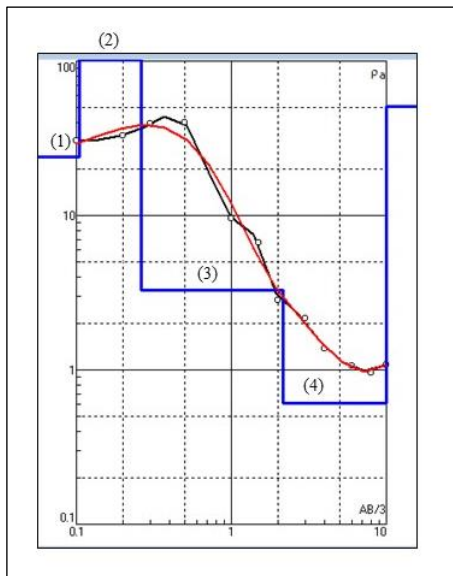

Figure 7. Adjustment curve for (1) one, (2) two, (3) three and (4) four layers of soil

Table 5. IPI2WIN software results

Layer number	Resistivity ($\Omega \cdot m$)	Thickness (m)
1	24	0.105
2	101	0.159
3	3.27	1.88
4	0.605	7.85
5	50.9	Undefined

The soil samples obtained in the well-drilling method are also included as shown in figure 8.

Figure 8. Soil samples identified as (a) Sandy loam, (b) Soft limestone and (c) Brown and dark clays

Identifying then the types of soil and the depth which they are, according to table 6.

Table 6. Soil types and thicknesses.

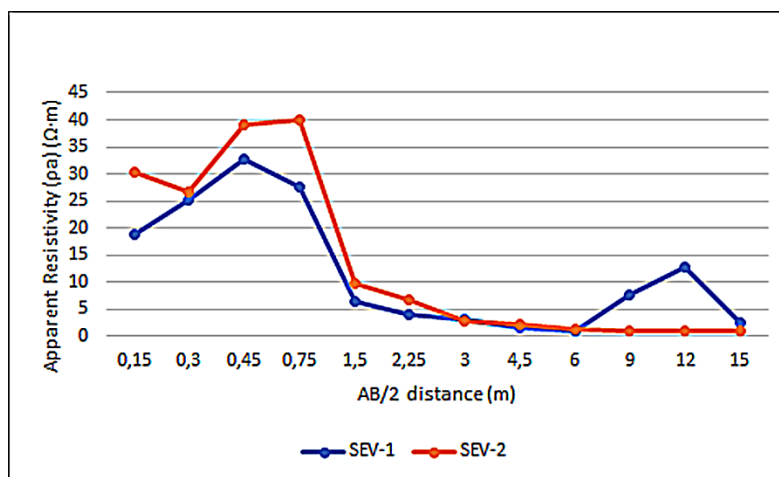| Soil type	Thickness (m)
Sandy loam	0.3
Soft limestone	0.75
Brown clay	12
Dark clay	Undefined

4.3. Statistical analysis

Figure 9. Line chart of spacing (AB/2) vs resistivity of the vertical electrical soundings VES-1 and VES-2

4.3.1. Kolmogorov Smirnov test. For the Kolmogorov Smirnov test we found:

For VES-1 with a mean $\overline{x_1}$ = 13.49 and standard deviation δ_1 = 15.77, table 7 was obtained, the VES-2 with a mean $\overline{x_2}$ = 11.98 and standard deviation δ_2 = 11.33 was made with the same procedure than the VES-1, as shown below:

Table 7. Kolmogorov Smirnov test for VES-1.

Y	Arranged-y	J	F	Z	F_0	D+	D-
30.25	0.96	1	0.08	-0.7945	0.213	-0.130	-0.834
26.61	1.08	2	0.17	-0.7871	0.216	-0.049	-1.751
39.17	1.08	3	0.25	-0.7869	0.216	0.034	-2.668
40.12	1.38	4	0.33	-0.7681	0.221	0.112	-3.585
9.63	2.17	5	0.42	-0.7177	0.236	0.180	-4.502
6.64	2.84	6	0.50	-0.6756	0.250	0.250	-5.419
2.84	6.64	7	0.58	-0.4345	0.332	0.251	-6.336
2.7	9.63	8	0.66	-0.2453	0.403	0.264	-7.253
1.38	26.61	9	0.75	0.8314	0.797	-0.047	-8.170
1.08	30.25	10	0.83	1.0621	0.856	-0.023	-9.087
0.96	39.17	11	0.91	1.6281	0.948	-0.032	-10.004
1.08	40.12	12	1.00	1.6880	0.954	0.046	-10.921
					Dmax	0.264	-0.834
					D_1	0.264	

For the Kolmogorov Smirnov test we used a significance of α = 0.05
For an $n_1 = n_2 = 12$, with a critical value $D_\alpha = 0.375$, the following hypotheses were proposed:

$H_0: f(x) = f_0(x)$, that is, the random variable x follows the normal distribution.

$H_1: f(x) \neq f_0(x)$, that is, the random variable x does not follow the normal distribution.

As the test statistic $D_1 < D_\alpha$, with 95% confidence, the hypothesis that the data follows a Normal distribution for the diagonal orientation VES-1 is not rejected.
As the test statistic $D_2 < D_\alpha$, with 95% confidence, the hypothesis that the data follows a Normal distribution for the horizontal orientation VES-2 is not rejected.

After that, the results of the confidence intervals for the ratio of two variances of a normally distributed population are shown.

4.3.2. Confidence intervals for the ratio of two variances of normally distributed populations.
Through the Fisher distribution for α/2 = 0.025 and degrees of freedom $v_1 = v_2 = 11$ we have $F_{0.025,(11,11)} = 3.47$. Finally getting the intervals as shown:

$$0.558 < \frac{6_1^2}{6_2^2} < 6.72$$

4.3.3. Confidence intervals for the means difference of normally distributed populations. For $v_2 = 12 + 12 - 2 = 22$ degrees of freedom and a $t_{0.025,22} = 2.074$ the intervals are obtained:

$$-10.11 < \mu_1 - \mu_2 < 13.13$$

5. Conclusions

The comprehension of the operation of the vertical electrical sounding (VES) method allowed the design and assembly of a low-cost equipment to estimate soil resistivity which cost $1.600 USD in contrast of an electrical tomography equipment valued in $50.000 USD. The investigation was carried out in an academic environment, where tests of stratified models were made to smaller scales to calibrate the equipment. This was subsequently executed in the field where both results were satisfactory.

The field study allowed to determine the contrasts of the resistivities at different depths in the study site, where a comparison was also made with the rock samples with the well-drilling method. The statistical analysis through which the data passed provided us with statistical certainty in the interpretation of it, that help us to corroborate that the study showed consistent results according to the expected. With this technique we can understand how it has applications such as in civil engineering fields, especially in geotechnics for the search of optimal subsoil conditions for the correct location of the foundations, in hydraulics and the exploration of groundwater [12] [13], archeology and many others, in any case, must be carried out together with other studies that allow discriminating with greater accuracy the types of soil.

6. Acknowledgments

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