Design and Implementation of Special Electrodes for Electrical Prospecting

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ABSTRACT

This article presents the design and implementation of special electrodes for electrical prospecting, known as geoelectrodes. Geoelectrodes are based on highly conductive materials such as clay and marl, containing a bar of reinforcement all molded in a PVC tube. The geoelectrodes were manufactured by varying three parameters: the material used clay or marl, the diameter of the PVC of 75, 100 and 110 mm, the height of the PVC of 2, 3 and 5 cm. The resistivity measurements carried out on site showed that the clay-based geoelectrodes show low standard deviations below 4.5%, much closer to the values obtained with conventional metal electrodes. The 110 mm diameter and 5 cm height geoelectrodes give mostly low resistivity measurement errors, with a small difference compared to metal electrodes. Electrical tomography using the three types of electrodes, metal electrodes, clay-based geoelectrodes and marl-based geoelectrodes, produced approximately identical profiles. This work allows to find a solution to the general problem of non-polarizable electrodes characterized by a difficult ground-electrode contact with a high contact resistance in the presence of high resistivity grounds. It also makes it possible to circumvent the difficulties associated with the sinking of electrodes in hard terrain, reducing the measurement time during electrical prospecting campaigns.

INTRODUCTION

The electrical methods in geophysics are very diverse and are nowadays increasingly used in engineering sciences for one-dimensional, two-dimensional or three-dimensional investigation of the subsoil. The principle of electrical methods is to detect effects when a continuous or low frequency electric current passes through the subsoil [1].

Among the methods of electrical investigation, the method by measuring resistivity remains one of the most widespread and diversified and was developed by the Schlumberger brothers in 1912 [2]. The principle consists in characterizing the subsoil by measuring, from the surface, the distribution of electrical resistivity at depth.

Electrical prospecting uses different measuring devices. The device consists of several electrodes placed in the ground, divided into current injection and potential measurement [3]; [4]; [5]. In order to avoid self-polarization of the electrodes when they are put into contact with other conductive media, non-polarizable electrodes are recommended (Wang et al.). Typical non-polarizing electrodes are currently in Pb-PbCl2, Ag-AgCl, Pb-PbCl2, Cu-CuSO4 [6]; [7]. However, a general problem during electrical prospecting campaigns is the poor

soil-electrode contact, marked by a strong contact resistance around the electrodes [8]. This high contact resistance tends to oppose the good penetration of electric current into the soil, thus reducing the amount of current that is propagated in the soil. The contact resistance increases with the soil resistivity. High resistive terrain causes a series degradation of data quality [9].

To improve soil-electrode contact and current flow through the ground, apart from using capacitive electrodes [10]; [11] it is possible to reduce soil resistivity by watering [12], by multiplying the number of implanted electrodes or increasing the contact surface of soil/electrode [13]. The reduction in resistivity by watering can be limited by the intrinsic properties of the soil [13]. The multiplication of the number of electrodes requires an increasing effort, since the decrease in contact resistance is proportional to the number of electrodes. Increasing the diameter of electrodes is not very effective beyond 20 mm because electrodes are increasingly difficult to implant [13].

This work aims to investigate a solution to the problem of electrode implantation in electrical prospecting by manufacturing special electrodes that we have designated as «geoelectrodes». Our approach is to reduce the resistivity contrast between the electrode and the soil by interposing a conductive material such as clays or marls. Our approach aims at reducing the contact resistance between the ground and electrode via the interlayer material.

MATERIALS & METHODS

The contact resistance can be evaluated by the following formulas [14]:

$$R = \frac{\rho}{2\pi}\left(\frac{1}{r} - \frac{1}{l}\right) \quad (1)$$

- Rudenberg's relation (1907)

$$R = \frac{\rho}{2\pi l}\left(\ln\frac{4l}{d}\right) \quad \text{(Error! No text of specified style in document.)}$$

- Dwight-Sunde 's relation (2009)

$$R = \frac{\rho}{2\pi l}\left[\ln\left(\frac{8l}{d}\right) - 1\right] \quad (3)$$

- Liew-Darveniza 's relation (2009)

$$R = \frac{\rho}{2\pi l}\left[\ln\left(\frac{r+l}{r}\right)\right] \quad (4)$$

In these relations ρ is the resistivity of the ground, l is the length of the electrode r is the radius of the electrode and d the diameter of the electrode.

The approach used to improve contact resistance is the implementation of special electrodes, which reduce the resistivity contrast by interposing a conductive material between the electrode and the ground. On the other hand, a larger diameter of the interlayer material allows a reduction in the contact resistance between the ground and the interlayer material.

Thus, geoelectrodes are made from clay and marl. The clay and marl samples used were taken in the department of Rufisque (Senegal). They belong to the Eocene-age Bargny formation, consisting of the marnocalcary series with phosphate beds [15]. The samples were characterized by identification and mechanical tests to determine certain parameters such as water content [16], grain size [17], [18] Atterberg limits [19], solid particle density [20], the methylene blue test [21] and the Proctor test [22]. These parameters are necessary for the manufacture of electrodes.

The electrodes are cylindrical in shape. For their manufacture we used, for the clays or marl, the passes to the sieve 400 μm after drying and manual crushing. The use of fines is intended to reduce gaps between soil grains in geoelectrodes.

PVC tubes were used to facilitate the casting of geoelectrodes. PVC also acts as an insulating envelope to direct the current towards the ground. The diameters and heights of PVC used are shown in the table below: **(Table 1)**

Table 1: Dimension of PVC tubes

External diameter (mm)	High (mm)
110	50
100	30
75	20

HA steel bars were used as the conductor to allow the junction with the measuring

cables. Since a contact resistance will be developed at the metal/ filling material of PVC tubes, it is wise to take large diameter armatures. Thus, high-adhesion reinforcement bars with a diameter of 12 mm (HA 12) were used. Depending on the height of the PVC tubes used, these bars have different heights **(Table 2 et Figure 1).**

Tableau 2: Dimensions of the reinforcement bars according to the height of the PVC

Tube height (mm)	Length of the frame (mm)
50	70
30	50
20	40

Figure 1 : Rebar and PVC tubes

The production of clay and marl geoelectrodes was done in two main steps. The first step, after drying and manual crushing, is molding. The clay and marl masses were moistened on the basis of optimal water contents determined by the Proctor test. To facilitate casting, the clay masses were moistened at twice their optimum volume and the marls at three times their optimum volume. The reinforcement bars being positioned vertically in the center of the PVC tubes, the casting is done manually with a slight compaction of the material in the PVC tube. The PVC tube is first placed on the base of the CBR mould with plastic to ensure the flatness of the bottom side of the cylindrical electrodes. The second step is the drying of the electrodes. These were dried under the same conditions inside a ventilated room for one week.

In summary, the geoelectrodes were made by varying the following parameters:
- The material used: clay or marl.
- The diameter of the PVC tube: 75 mm, 100 mm or 110 mm.
- The height of the PVC tube: 20 mm, 30 mm or 50 mm.

Table 3 summarizes the quantities used for making. Geoelectrodes

Tableau 3: Summary of quantities used for the construction of geoelectrodes

Outside diameter PVC tubes (mm)	Tube PVC height (mm)	Total mass of clay (g)	Volume water wetting clay (mL)	Volume of water wetting marl (mL)
110	50	1000	210	939
	30	600	121,2	564
	20	500	101	470
100	50	1000	210	939
	30	600	121,2	564
	20	500	101	470
75	50	1000	210	939
	30	600	121,2	564
	20	500	101	470

Figure 2 shows the geoelectrodes obtained

Figure 2: Clay-based geoelectrodes (bottom) and marl-based geoelectrodes (top)

To test the performance of geoelectrodes against the building parameters, spot measurements of resistivity and an electrical resistivity tomography profile were performed. A comparison is made with measurements performed with commonly used metal electrodes (Figure 3).

Figure 3 : Experimental device for testing geoelectrodes and metal electrodes

RESULT AND DISCUSION

The results of geotechnical tests on marl and clay samples are presented in table 4

Table 4 : Identification and mechanical test results

Test	Norm	Parameters	Clays	Marls
Natural moisture content	NF P 94-050	W_n (%)	7,53	13,53
particle size analysis	NF P 94-056	D_{max} (mm)	3,15	3,15
		% ⩽ 2 mm	99,00	99,72
		% ⩽ 80 μm	58,60	98,43
		% ⩽ 63 μm	46,00	82,00
Atterberg Limits	NF P 94-051	W_L (%)	40,75	40,75
		W_P (%)	13,53	108,78
		I_P (%)	27,22	131,52
Density solid particles	NF P94-054	γ_s (kN/m^2)	26,67	26,10
Blue test of methylene	NF P 94-068	VBS	3,82	8,05
Proctor test	NF P 94-093	γ_d (kN/m^2)	19,10	10,26
		W_{opt}(%)	10,10	31,30

Table 5 shows the electrical resistivity values obtained and the contact resistance around special electrodes and metal electrodes.

Table 5: Summary of measurement results with the different electrodes

Type	PVC (mm)	High (cm)	contact resistance (Ω)				Ecart (%)	R$_{sol}$ (Ω)	ρ_{app} (Ω.m)
			RC1	RC2	RP1	RP2			
Metal	-	-	679	680	679	689	0,04	55,2	346,8
Clays	110	5	679	680	679	689	0,07	54,7	343,6
	110	3	679	680	679	689	0,09	54,1	339,9
	110	2	679	680	679	689	1,3	55	345,5
	100	5	679	680	679	689	0,1	53,6	336,7
	100	3	679	680	679	689	0,05	54,0	339,2
	100	2	679	680	679	689	4,4	54,9	344,9
	75	5	679	680	679	689	0,04	53,5	336,1
	75	3	679	680	679	689	0,2	52,5	329,8
	75	2	679	680	679	689	0,04	54,1	339,9
Marls	110	5	679	680	679	689	0,2	52,9	332,3
	110	3	679	680	679	689	0,3	53,3	334,8
	110	2	679	680	679	689	0,2	53,2	334,2
	100	5	679	680	679	689	2	52,6	330,4
	100	3	679	680	679	689	4	51,8	325,4
	100	2	679	680	679	689	0,2	52,4	329,2
	75	5	679	680	679	689	0,1	51,5	323,5
	75	3	679	680	679	689	0,2	51,4	322,9
	75	2	679	680	679	689	0,05	52,0	326,7

1.1. Influence of geoelectrode material on measured resistivity

To study the influence of the material used on the measured resistivity, we compared the resistivities measured at the geoelectrodes with those of the metal electrodes and the relative measurement errors corresponding to the standard deviation over 4 measurements. The results are shown in Figure 4 below:
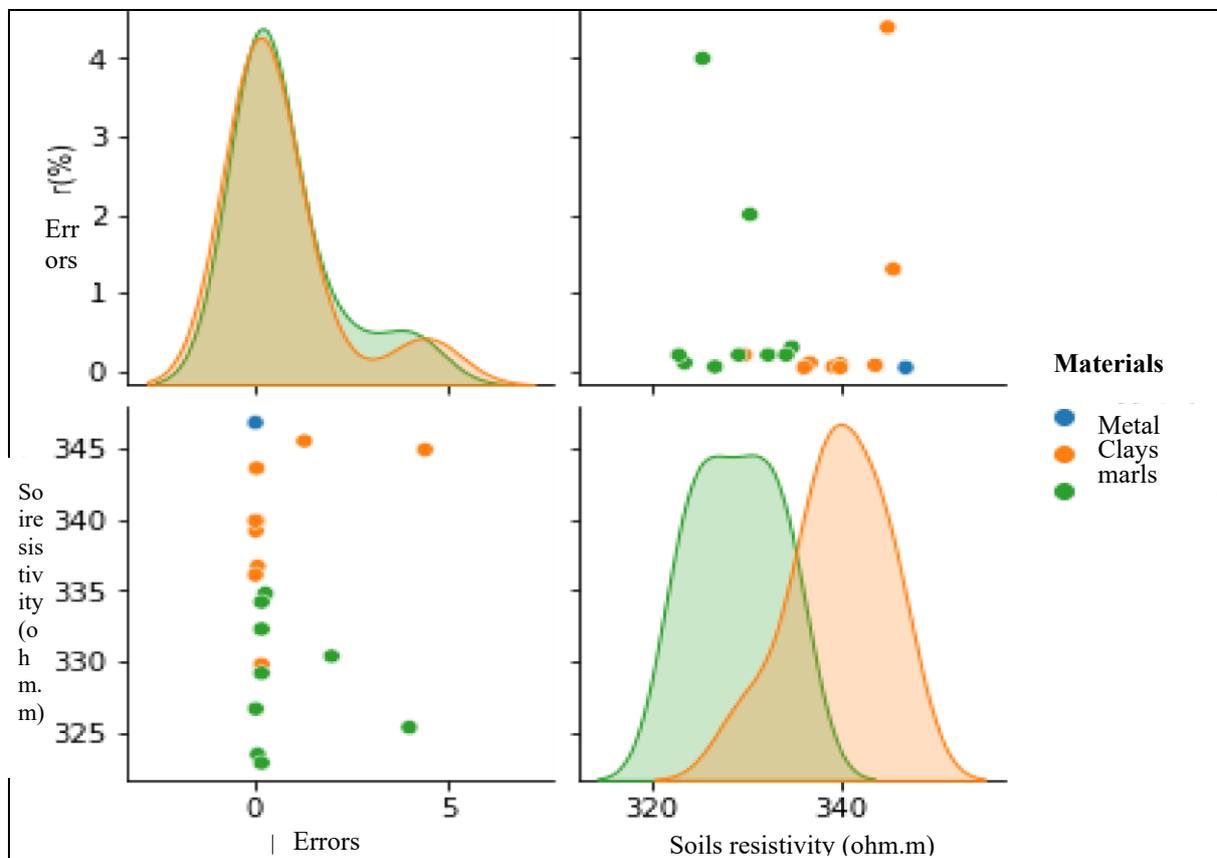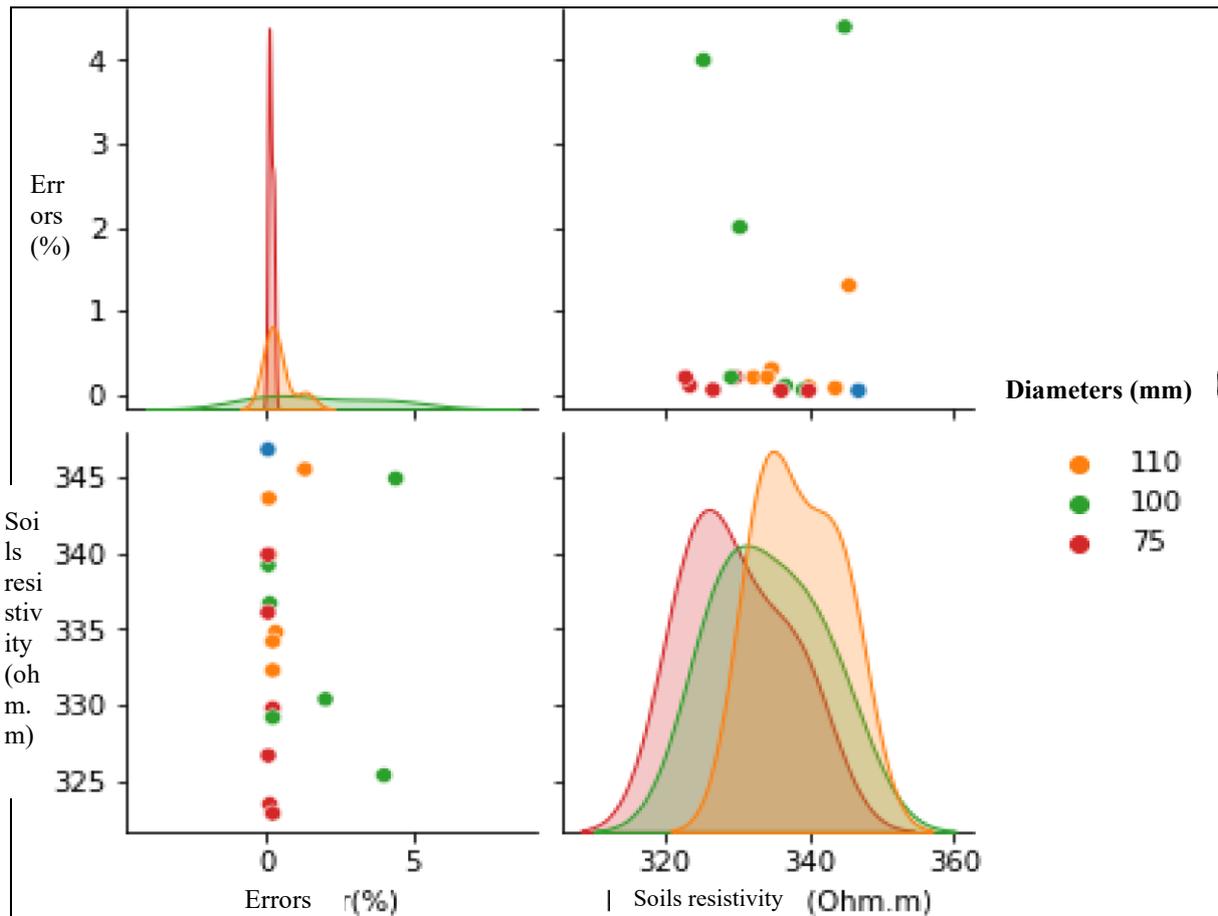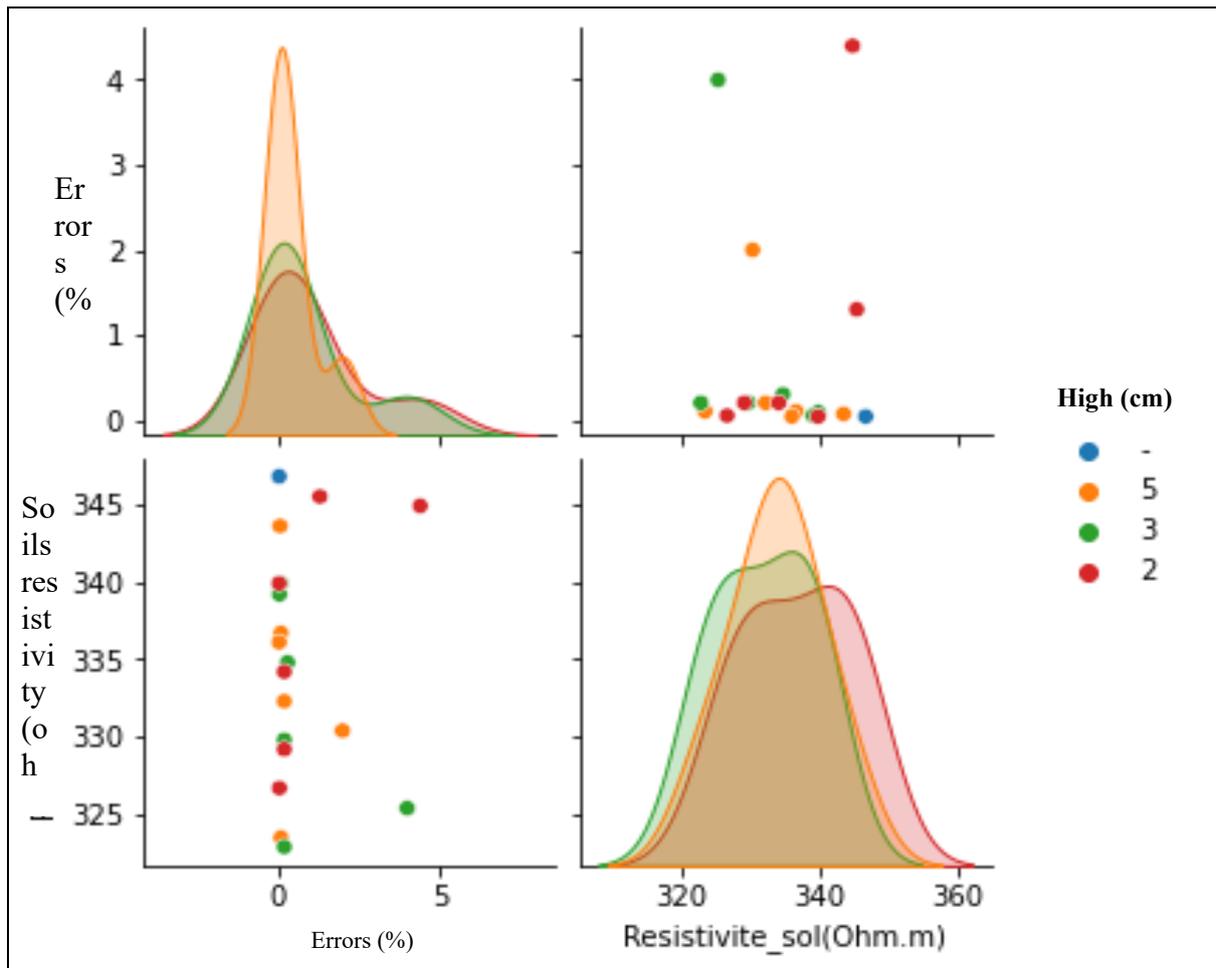

Figure 4 : Variation of the measured resistivity in relation to the reference metal electrode and variation of measurement errors for the different electrode base materials

Taking as a reference the resistivity measured with metal electrodes, we find that in absolute value, Soil resistances measured with clay geoelectrodes are closer to the reference resistances than those measured with marl geoelectrodes. However, it is noted that the error on measurements, apart from a few outliers, remains very lower than 5% and is very close or even identical for metal electrodes and geoelectrodes.

To study the influence of the diameter of geoelectrodes on the measured resistivity, we compared the measured resistivities at the geoelectrodes with those of metal electrodes as well as the relative measurement errors corresponding to the standard deviation over 4 measurements. The results are shown in Figure 5.

Figure 5: Variation of the measured resistivity in relation to the reference metal electrode and variation of measurement errors for the different diameters of the geoelectrodes

Taking as reference the resistivity measured with metal electrodes, we find that when the diameter increases, the values of measured resistivities are generally close to those measured with metal reference electrodes. However, this trend is not always respected because the results show several cases or the smaller diameters are closer to the value measured by the reference electrode. We find that the error on the measurements, apart from some aberrant measurements, remains much less than 5% and is very close to or even identical to that of metal electrodes regardless of the diameter of the geoelectrodes.

To study the influence of geoelectrode height on measured resistivity, we compared the measured resistivities at the geoelectrodes with those of metal electrodes and the relative measurement errors corresponding to the standard deviation on 4 measurements. The results are shown in Figure 6.

Figure 6 : Variation of the measured resistivity as a function of measurement errors for different heights of geoelectrodes

Taking as a reference the resistivity measured on site with metal electrodes, we find that some resistivities measured at geoelectrodes of heights 5 cm are closer to the reference values. However, there are many cases where geoelectrodes with lower heights give measurements closer to the reference value. However, small measurement errors, well below 5% are noted in some heights, except for a few outliers.

From the results of table 4.1, we find that the contact resistance around each metal electrode (C_1, C_2, P_1, P_2) compared to the contact resistances around special geoelectrodes (C_1, C_2, P_1, P_2) has not changed. These values appear to be outliers and are probably due to the unupdated contact resistance measurement by the resistor meter after each measurement. Normally, the contact resistance should vary due to the contrast between the resistance of the soil and those of the materials used (clay, marl or metal).

The exploitation of these in situ measurement results allowed to evaluate the influence of geoelectrode characteristics (base materials, diameter and height) on measured resistances. We can then deduce that: The clay used in this work allows to measure resistances approximately equal to the reference resistances measured with metal electrodes. It should also be added that clay-based electrodes mostly have low resistivity measurement errors.

The measured resistivity is not clearly related to the diameter or height of the geoelectrodes. We note variations in absolute values; however, the small errors of resistivity measurements remain very low and within acceptable limits in electrical prospecting.

To test the real-world performance of geoelectrodes, we created tomograhie profiles of electrical resistivity (ERT) in order to compare the different materials used

3.2 ERT profiles

The three ERT profiles made using metal electrodes, clay geoelectrodes and marl geoelectrodes respectively are shown in the figures below (figure 7, 8 et 9):
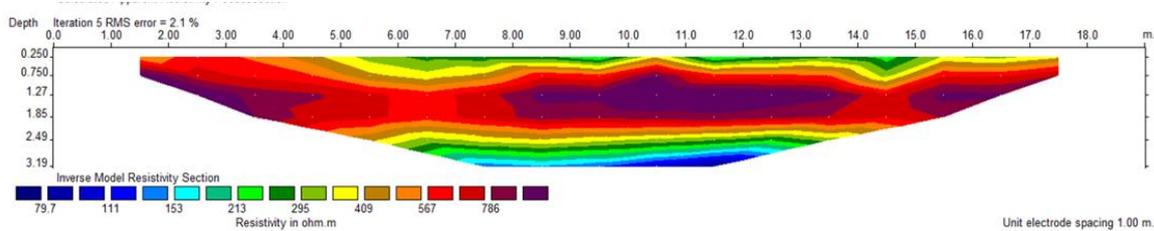

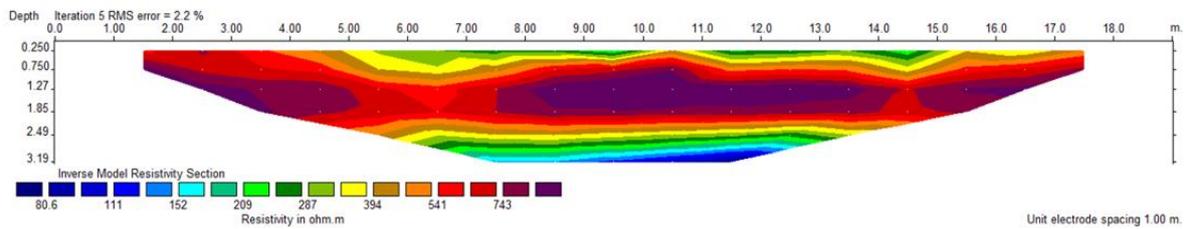**Figure 7 : ERT profiles obtained with metal electrodes**

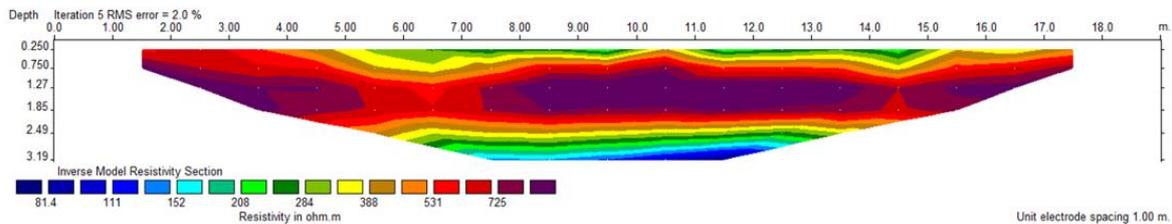**Figure 8 : ERT profiles obtained with clay-based geoelectrodes**

Figure 9 : ERT profiles obtained with marl geoelectrodes

It should be noted that the three profiles required five (5) iterations to achieve model convergence. The mean square error (RMS) is 2.1%, 2.2% and 2.0% for metal electrodes, clay-based geoelectrodes and marl-based geoelectrodes respectively.

The three ERT profiles show broadly the same geological structures. We have:

- a surface layer with resistances below 388 Ω.m. these are sand-clay formations with lateritic gravel.
- At 0.5 m depth, a layer of resistivity greater than 388 Ω.m corresponding to a lateritic formation of about 2 m thickness.
- At 3 m depth, a layer of resistivity below 208 Ω.m corresponding to marly formations.

- Some rare, negligible differences are noted on the geometry of the formations. To these differences, small variations in the resistance ranges of ERT profiles can be added, as already found on test measurements. The resistances measured on site with metal electrodes vary between 79.7 Ω.m and 786 Ω.m, in contrast to clay-based and marl geoelectrodes or the ranges of resistances vary respectively between 80.6 Ω.m and 743 Ω.m and between 80.6 Ω.m and 725 Ω.m.

We always note that the resistances measured with clay-based geoelectrodes are closer to the resistances obtained with metal electrodes than those measured with marl-based geoelectrodes.

Nevertheless, the ERT profiles are almost identical and show the same sequences of geological layers. Differences between profiles are statistically and geologically negligible and not significant.

CONCLUSION

We always note that the resistances measured with clay-based geoelectrodes are closer to the resistances obtained with metal electrodes than those measured with marl-based geoelectrodes.

Nevertheless, the ERT profiles are almost identical and show the same sequences of geological layers. Differences between profiles are statistically and geologically negligible and not significant.

The differences observed between measurements are in absolute values. Measurements obtained with metal electrodes tend to be higher (346.8 Ω.m) than those measured in clays (345.5 Ω.m) and marls (334.8 Ω.m). However, in terms of accuracy, compared to the standard deviation over 4 measurements, the materials present identical performances with very low errors. Indeed, the errors are all below 0.3% except for the few measurements which gave 1.3 and 4.4% for clays and 2 and 4% for marls. Nevertheless, the errors are still small compared to the 5% value commonly accepted in geophysical prospecting.

Since electrical prospecting measurements can be relative, geoelectrodes seem suitable for use in prospecting.

To further investigate, we suggest investigating the influence of seasonality on the in-situ measurements performed with these geoelectrodes, since our measurements were carried out at the beginning of the wet season.

- Investigate the influence of other parameters such as water content in the manufacture of these electrodes.
- Improve the integrity of geoelectrodes, as outliers obtained on some measurements could be related to defects on geoelectrodes.
- Investigate the influence of mineralogy and petrography on geoelectrode performance by further diversifying the materials used.

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