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Improved measurements of the apparent resistivity for small depths in Vertical Electrical Soundings

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ABSTRACT

In this work, a full simulation of a Vertical Electrical Sounding of a multilayer soil using a Wenner array is performed when both the active and the measurement electrodes consist of bare rod length L buried vertically at ground level. The apparent resistivity is calculated for a wide range of values of the separation between the electrodes using the values of the potential between the measuring electrode and a proposed function that characterizes the behavior of the electrodes used which substantially improves the measurements for small depths. The results allow comparing the values of apparent resistivity obtained by known calculation expressions with the results found by using a characteristic function of the electrodes, which is proposed in this paper. In order to obtain a complete vertical sounding of the soil, the convenience of using adapted methods to the type of electrode used in the sounding is discussed.

1. Introduction

The Electrical Resistivity Survey method is one of the most commonly used methods in geophysical explorations (Samouelian et al., 2005). A detailed knowledge of the electrical structure of the soil is useful in fields such as mining, environmental geophysics, engineering, hydrology and soil sciences among others (Loke et al., 2013; Herman, 2001). The knowledge of the electrical structure of the ground at shallow depths is especially very important for detection of archeological deposits and suitable designs of grounding systems in electrical engineering. The most common electrical methods used are the Vertical Electrical Soundings (VES) to explore the resistivity versus the depth and Resistivity Profiling (RP) to detect lateral resistivity variations. With reference to the VES method, the Wenner arrangement is considered here (Wenner, 1916). The Wenner 4-pin probe consists of four aligned and equally separated electrodes. The center point O of the array remained fixed, but the spacing a between the electrodes was increased to obtain information about the deeper sections of the subsurface. Fig. 1 shows the known diagram of electrodes in a Wenner array.

From measurements of the potential difference between points 2 and 3, $V(a)$, the apparent resistivity $\rho_{app}(a)$ can be defined. This magnitude is defined as the actual resistivity that would have a homogeneous soil if by a Wenner probe with electrode spacing a, a potential difference of $V(a)$is obtained between the measurement electrodes. For homogeneous soil, the apparent resistivity is constant and independent of the electrode separation a, being its value equal to the actual soil resistivity. However for a non-homogeneous soil the apparent resistivity depends on the separation between electrodes. In general, it can be stated that

$$\rho_{app}(a) = \frac{V(a)}{I} F(a) \qquad (1)$$

where $F(a)$ is a function of the separation between the electrodes whose functional form depends on the type of electrodes used for the Wenner VES. This function will be called here the characteristic function of the Wenner electrode array. For point electrodes at ground level the characteristic function is written as

$$F(a) = 2\pi a \qquad (2)$$

In real soundings, thin rods of radius r and length L buried at ground level are normally used as electrodes. For such electrodes, it is suggested (Wenner, 1916; IEEE, 2012) to employ the characteristic function $F(a)$,

$$F(a) = \frac{4\pi a}{1 + \frac{2a}{\sqrt{a^2 + 4L^2}} - \frac{a}{\sqrt{a^2 + L^2}}} \qquad (3)$$

which can be used for all values of the separation a in the case that both active and measurement electrodes are only in contact with the soil at its ends, so the array is equivalent to four point electrodes at a depth L.

When the spacing between electrodes a is large compared with L, the size and shape of the electrodes become unimportant and they all behave in practice as points at ground level again finding expression (2). In reference (IEEE, 2012), $a > 10L$ distances are recommended in the case of the electrodes being bare rods, so (2) can be used instead

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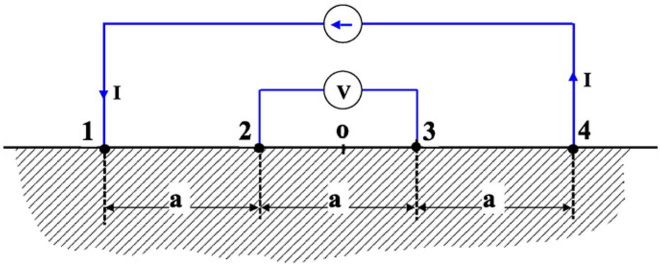

Fig. 1. Four-point Wenner probe.

of (3) with less than 3% error. When bare rods are considered as electrodes and one wants to measure for any value of the electrode, the form of F(a) is more complex. In this work, a rational expression of the form

$$F(a) = \frac{p_1 a^2 + p_2 a + p_3}{a + q_1} \tag{4}$$

will be numerically fitted to the characteristic function associated with a Wenner probe using bare rod electrodes buried at ground level. Expression (4) has a linear asymptotic behavior $F(a) \rightarrow p_1 a + p_2$ for sufficiently large a values. Once the appropriate characteristic function of the electrodes used in the Wenner probe has been found, the apparent resistivity can be found for all values of the separation a from the $V(a)$ measures. The functional form of $\rho_{app}(a)$ depends on the type of soil and it is important to provide measures for the widest possible range of a values.

It is common to make measurements from a value of a for which (3) or (4) behaves very approximately to expression (2). However, the apparent resistivity for small a values may contain valuable information on the electrical structure of the ground near the surface. Note that many of the grounding electrodes are buried between 0.5 and 3 m deep, so it is useful to know whether this layer of the soil is part of a constant resistivity layer that extends to greater depths or on the contrary it has a more complex structure. A careful simulation that takes into account the behavior of the Wenner probe for all the a distances is of great practical importance. In this work, a Wenner VES from values $a \geq 4$ m is presented. That sounding provides apparent resistivity values consistent with a two-layer soil model and also with a three-layer soil model in the case that the top layers are very thin. The choice of either model crucially depends on the sounding for small values of the separation a, while the behavior of grounding electrodes

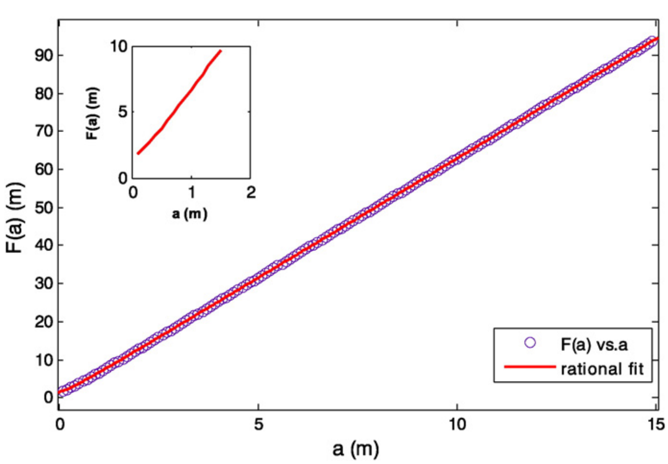

Fig. 2. Four-pin Wenner function F(a) vs. a for real rod-like electrodes. The fit to a rational function according to (4) is also shown.

is very sensitive to the type of model adopted for the soil (Colominas et al., 2007; Ma et al., 1996).

This paper presents a comparative study of data from a Wenner VES according to the models (2), (3) and (4) when these data come from measurements within a range of a values that also include small values. The sounding is applied to a two-layer soil and also to a three-layer soil model but can easily be extended to multilayer soils. For this purpose, the paper is organized as follows: After the introduction to the problem in the present Section 1, the theoretical foundation and calculation scheme that has been used, are developed in Section 2. In Section 3, the results of the simulation are presented and the analysis is performed. Finally, the conclusions of this work are summarized in Section 4.

2. Theoretical background

The problem of finding the potential profile, created by a system of conductors in mutual interaction immersed in an electrically inhomogeneous medium, can essentially be solved by finding a solution of,

$$\vec{\nabla} \bullet \left(\sigma(\vec{r}) \vec{\nabla} \varphi(\vec{r}) \right) = 0 \tag{5}$$

in a 3D domain, where $\sigma(\vec{r})$ is the conductivity function and $\varphi(\vec{r})$ the potential that satisfies a set of boundary conditions which define univocally the configuration of the conductors, their electrical state and the properties of the inhomogeneous medium (Colominas et al., 2002). The conductors may be independent or be electrically interconnected. The initial domain can be decomposed into several regions or volumes. For each region R of the domain where conductivity is a constant, the equations that need to be solved are

$$\begin{aligned}
&\vec{\nabla}^2 \varphi_R = 0 \\
&\varphi_R(\vec{r})\Big|_{\vec{r} \in S_{C_i}} = V_i \\
&\vec{n} \bullet \vec{\nabla} \varphi_R \big|_G = 0 \\
&\varphi_R(\vec{r})\Big|_{\vec{r} \in S_I} = \varphi_{R'}(\vec{r})\Big|_{\vec{r} \in S_I} \\
&\sigma_R \vec{\nabla} \varphi_R(\vec{r}) \bullet \vec{n}\Big|_{\vec{r} \in S_I} = \sigma_{R'} \vec{\nabla} \varphi_{R'}(\vec{r}) \bullet \vec{n}\Big|_{\vec{r} \in S_I}
\end{aligned} \tag{6}$$

where S_{C_i} stands for the surface of the C_i conductor, the subscript G refers to the ground surface and S_I stands for the interface between two media of different properties. The last two equations in (6) express the continuity of both the electric potential and the current density flow through the interface S_I, separating the R and R′ regions of constant conductivities σ_R and $\sigma_{R'}$. The vector $\vec{n}(\vec{r})$ is a unitary vector normal to S_I along R–R′.

If the soil is composed of horizontal layers separated by flat interfaces, (6) can be solved using cylindrical coordinates and a separation of variables (Sunde, 1949)–Zou et al., 2004). Consider a two layer soil where ρ_1 is the resistivity of the upper layer which has a thickness h, and ρ_2 is the resistivity of the lower layer. For a current point in the upper layer at (x',y',z') (source point), it can be shown that the potential generated at any point (x,y,z) (field point) of this upper layer is

Table 1
Resistance between electrodes 2 and 3 of Fig.1 vs. their separation a for the Madrid two-layer model and the apparent resistivity calculated by using the (2), (3) and (11) characteristic functions $F(a)$.

a (m)	R(a) (Ω)	ρ_{app} (2)	ρ_{app} (3)	ρ_{app} (11)
2	1.75	22.01	22.84	22.34
5	0.57	18.00	18.11	18.04
10	0.22	13.51	13.53	13.52
15	0.14	13.10	13.11	13.11