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Methods for field measurement of electrical parameters of soil as functions of frequency

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ABSTRACT

In this article, the application of four-electrode and two-electrode arrays to measure electrical parameters of soil as functions of frequency is investigated and its feasibility is evaluated by simulations and measurements. First, the experimental arrays are simulated using finite element method to solve a rigorous electromagnetic problem. New geometric factors are presented, which yield correct estimates of resistivity and permittivity even for reduced spacing. Formulas are proposed for calculating the geometric factors. Then, a series of case studies is carried out considering different soil representations, geometric parameters and excitation frequencies. It was found that increasing excitation frequency and distance between electrodes decreases accuracy. However, resistivity and permittivity of soil can be determined for frequencies up to 2 MHz when using reduced spacing. For the four-electrode array, a discrepancy of less than 3% between estimate and reference is obtained when using distance between electrodes less than 0.5 m. Next, measurements using four and two electrode methods were performed, and it was found that the four-electrode method is the most suitable for measuring soil parameters, given that it was the one that provided consistent results. An analytical equation was also proposed to represent the electrical parameters measured for this case.

1. Introduction

Soil characterization is an essential step in the design of grounding systems, and several experimental arrangements have been proposed for the low-frequency representation of soil from field measurements. The most commonly used are the arrays proposed by Wenner [1,2], Schlumberger [2], dipole and the two-electrode arrangement [3,4]. Among them, the Wenner array is recommended by technical standards [2] for the characterization of soil with the purpose of application in grounding systems simulation [5,6]. Simulations commonly consider soil parameters frequency independent, which is not the case in practice [6-10]. In fact, dependence on frequency of soil parameters must be considered in order to increase the reliability of grounding during lightning strikes [6,9].

Laboratory measurements can be performed in order to determine variation in soil parameters with frequency [7,11-12]. However, they are not the most suitable for designing and simulation of grounding systems, since soil sampling necessarily leads to changes in the levels of compaction and humidity. To overcome these difficulties, field measurement methods were proposed in [13-18].

The experimental method proposed in [13-14] is based on obtaining a box-shaped soil sample, which is collected after excavating a few cubic meters of soil. In [15-17], a field method for measuring the electrical parameters of the soil is reported, which consisted of fixing a hemispheric copper electrode and an auxiliary grounding electrode to the soil to be investigated. Additionally, in [16-17], mathematical models were proposed for the representation of soil parameters. Although those models were based on theoretical considerations and measurements, obtaining a model that accurately represents a generic soil is a challenging task, given the immense variability that soils present due to their geological origin, mineral composition, compaction, porosity and humidity index. Therefore, when correctly performed, field measurements are still the most reliable method for characterizing soils with the aim of design and simulation of grounding systems.

The methods described in [13-15] present significant difficulties in their application because they require excavation, special electrodes or even the installation of auxiliary electrodes. Therefore, it is justified to investigate the application of simplified arrangements for characterizing the electrical parameters of the soil in frequency domain, such as the four-electrode array or the two-electrode array, with conventional

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rod-shaped electrodes. However, the current form of application of the methods associated to these arrays contains simplifications related to the associated geometric factors, which may reduce accuracy and, consequently, reliability, given that conventional methods are commonly applied with large spacing and relatively low frequencies. Thus, it becomes necessary to evaluate the applicability of those arrays at high frequencies and/or small spacing.

Recently, computer simulations have been used to analyze soil prospecting methods [19-22] or grounding system analysis [23-27]. In [19-20], the simulation of electromagnetic methods for prospecting soils using the finite-element method (FEM) was described. However, even being pioneer works, their main purpose was didactic and it was not their goal to use simulations for the improvement or proposition of new measurement methods.

In [21], FEM simulations were used to analyze and propose improvements in the experimental arrangement used in [15-17]. The authors of [22], in turn, used the method of moments to calculate soil's electrical potential resulting from the application of a four-electrode arrangement to resistivity measurement. They proposed a geometric factor to apply the method to reduced spacing, and compared it to the conventional factor proposed in [1] when applied to the apparent resistivity calculation in a typical soil representation. However, the effect of the electrode length is not considered and for field calculation, an approximation was used, which can result in inaccuracies if electrodes with reduced length are used. Additionally, frequency effects were not analyzed.

The paper [28] proposed an optimization-based inversion methodology to determine the soil parameters in frequency domain considering a multilayer soil model. However, [28] does not address a measurement method itself, only the treatment of pre-existing experimental results, so that synthetic data were used to test the proposed inversion method.

In [29], in turn, a method for characterizing soil in the frequency range of lightning currents was presented, which use dipole-type arrays applied to rod-shaped electrodes. The existence of measurement errors associated to electromagnetic coupling effects was pointed out, as well as the need of using small spacings for a correct characterization of the superficial layer of the soil. However, an assessment of the accuracy associated with the effects of the frequency, or of the effects caused by the use of nearby electrodes, has not been carried out. Thus, the feasibility and necessary conditions of applying the four-electrode array at higher frequencies have not been completely established and must therefore be rigorously evaluated and delimited.

In this context, this paper proposes and investigates the use of four-electrode and two-electrode arrays, applied with conventional rod-shaped electrodes, for the characterization of electrical soil parameters, resistivity and relative permittivity, as functions of frequency. The main contributions obtained were the proposed geometric factors that allow the correct interpretation of the results obtained from the application of the arrangements for both large and reduced spacing, and the analysis of the accuracy of the proposed methods according to arrangement parameters and frequency of the excitation signal. To achieve both ends, computer simulations based on electromagnetic models, solved by FEM-based software, were elaborated and applied to a series of case studies.

2. Computational simulations

In this work, four-electrode and two-electrode arrangements were studied in order to propose new methods that allow the application of the arrangements to measure soil parameters as functions of frequency. Initially, the effect of the arrays' geometry was analyzed separately, in order to determine geometrical factors for interpreting experimental results. Then, the proposed geometric factors were assessed in a new analysis with an excitation signal varying in frequency. The adopted steps were:

- Computer simulations for determining geometric factors applicable to a wide range of spacing between electrodes, which are necessary for the study of soil characterization as a function of frequency;
- Mathematical modeling of the geometric factors obtained;
- Proposition of equations for the estimation of soil parameters in the frequency domain;
- Analysis, through computer simulation, of the applicability and accuracy of the methodology proposed in the previous steps to the frequency range representative of lightning discharge currents (up to 2 MHz) [13-14].

In the next subsections, the procedures adopted for the construction of the simulations and the analysis steps for each of the analyzed arrangements are described.

2.1. Electromagnetic models and simulation procedure

To perform the simulations, the AC/DC module of the COMSOL Multiphysics® computational platform was used. Simulations with stationary signals involve solving the Laplace equation for the electrical potential (1) [30-32]:

$$\nabla\cdot(\sigma\nabla V) = 0. \tag{1}$$

COMSOL®'s *Electric Currents* physics was used. The simulations with variable frequency signals were performed using *Magnetic and Electric Fields* physics, which applies Eqs. (2) to (4) for the calculation of the electromagnetic field [30-32]:

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t}, \tag{2}$$

$$\vec{B} = \nabla \times \vec{A} \tag{3}$$

and

$$\frac{1}{\mu_r\mu_0}\nabla \times \vec{A} + \left(j\omega\sigma - \omega^2\epsilon_r\epsilon_0\right)\vec{A} = 0. \tag{4}$$

In Eqs. (1) to (4), V and A represent the electric and magnetic potentials, respectively, E is the electric field, B is the magnetic flux density, and σ is the electrical conductivity. In (4), ϵ_0 represents the permittivity of free-space, with an approximate value of 8.8542×10^{-12} F/m, and ϵ_r is the relative permittivity of the material. In (4), μ_0 represents the magnetic permeability of free-space, with a value of $4\pi \times 10^{-7}$H/m, and μ_r is the relative permeability of the material. ω represents the angular frequency of the considered excitation signal.

To perform the simulations, the electromagnetic models were associated with a geometry representative of each experimental arrangement considered. Due to the symmetry inherent to the four-electrode and two-electrode arrays, the potential across the domain can be obtained from a simulation performed with only one quarter of the domain associated to appropriate boundary conditions, as shown in Fig. 1 for the case of a four-electrode array with 1-m spacing. In Fig. 1, the outermost electrode (1) is the current electrode, the innermost electrode (2) is the potential electrode.

The imposed boundary conditions are: zero potential condition ($V = 0$) applied on the $x = 0$ plane and the following Neumann boundary conditions on the $y = 0$ plane (using the coordinate system defined in Fig. 1):

$$\hat{n} \times \vec{H} = 0 \tag{5}$$

and

$$\hat{n}\cdot\vec{J} = 0, \tag{6}$$

in which $\hat{n}$ represents the unit vector normal to the plane $y = 0$. The boundary condition defined in (6) was also applied to the plane $z; = 0$,

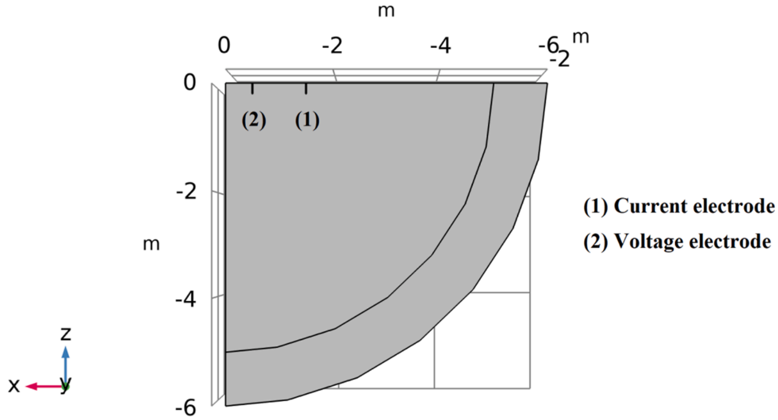

Fig. 1. Geometric model used to simulate the of four-electrode array with 1-m spacing.

which represents the soil surface.

Reducing the size of the domain facilitates convergence and reduces the computational effort of the simulation, which is convenient, above all, in simulations carried out at higher frequencies, which have a high computational cost.

The next simulation step is the definition of the physic constraints. For the case of the simulation of the four-electrode arrangement, they are:

- Definition of the potential $V = 0$ on the outer surface of the domain to represent the remote-earth condition;
- Imposition of $a+$ 1 A current on the external electrode, which are the current electrodes in the four-electrode method;
- Zero current for the internal electrode, which are the electrode used for potential measurement.

In the case of the simulation of the two-electrode method, the internal electrodes are omitted and the other conditions are maintained.

To simulate the soil, which, for practical purposes, should be considered a semi-space (unlimited domain), two approaches can be used. The first involves truncating the problem at a finite distance, but large when compared to the dimensions of the finite objects present in the simulation (in this case, the array electrodes). As highlighted by [33], this representation requires greater computational effort and, in some cases, can reduce the accuracy of the simulation. The second approach involves the use of alternative methods for the representation of unlimited domains, such as the infinite element technique. This technique allows to perform a special form of mapping in which certain elements of the domain have their dimensions associated with physical lengths greater than the other elements. There is not the same proportion between the length of the element and the physical length for all elements of the domain, which allows to represent regions with large dimensions.

In the simulations, whenever possible, infinite elements were used for the representation of the soil, to reduce the computational effort. However, in some cases, in order to ensure convergence, the truncation technique was applied. In these cases, it was considered that the radius of the hemispheric domain that represented the soil was equal to $9a$ (where a is the distance between adjacent electrodes), a condition that, according to preliminary tests carried out, results in a discrepancy less than 0.5% in the electrical potential calculated in the region of interest.

After defining the geometry and boundary conditions for each case, an automatically generated finite element mesh was produced. Tetrahedral elements were used in the inner domain, while hexahedral elements were used in the infinite-element region. To ensure a correct representation of the electrode region, the minimum size of the elements was specified as 0.008 m. An example of a domain simulated for the four-electrode arrangement, already discretized, is shown in Fig. 2.

To ensure the reliability of the results obtained through the simulations, the computational model used was validated by comparing the results obtained for a special case with analytical results. The validation process is described in the Appendix.

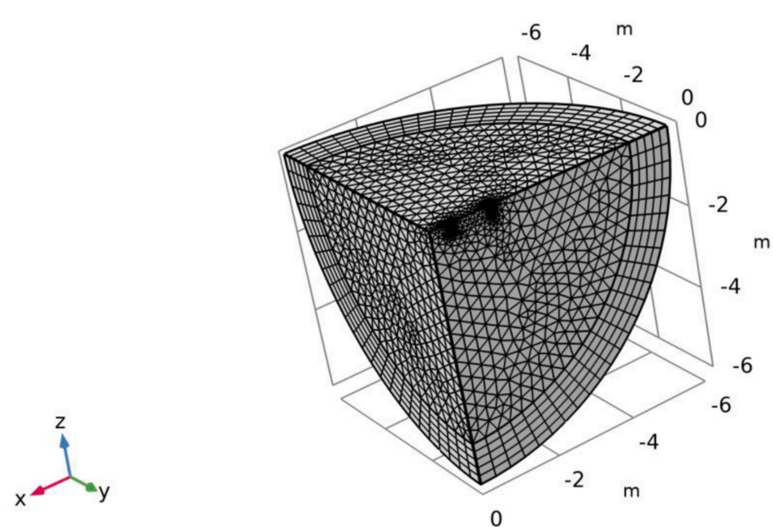

Fig. 2. FEM domain used to simulate a four-electrode arrangement.

2.2. Analysis of the four-electrode arrangement

2.2.1. Proposition of a new geometric factor

The first stage of the analysis consisted of evaluating and quantifying the errors resulting from the application of the Wenner four-electrode method in its conventional formulation. Additionally, an alternative mathematical formulation was proposed for the interpretation of the experimental data obtained from the four-electrode arrangement.

The apparent resistivity of a soil can be estimated through the arrangement of four electrodes using (7):

$$\rho(x) = 2\pi a K_1(x)\frac{\Delta V}{I}, \tag{7}$$

where K_1 is a geometric factor, $x = b/a$ represents the spacing between electrodes, I is the electric current in the external electrodes and ΔV is the potential difference between the internal electrodes of the array. In the conventional mathematical formulation of the Wenner method, the $K_1(x)$ factor is given by:

$$K_1(x) = \frac{2}{1 + \frac{2}{\sqrt{1+4x^2}} - \frac{1}{\sqrt{1+x^2}}}. \tag{8}$$

From simulations of the arrangement, it is possible to determine the value of the geometric factor K_1 that provides the correct apparent resistivity associated with a uniform soil, in which a four-electrode array with specified spacing characteristics is used. Thus, the geometric factor $K_1(x)$ can be determined as:

$$K_1(x) = \frac{\rho I}{2\pi a \Delta V}. \tag{9}$$

Thus, to characterize the results obtained from the four-electrode arrangement in the case of small spacing, computational models were created that represented measurement arrangements with different ratios between the buried electrode length (b) and the distance between electrodes (a). The situation considered in this study was stationary. In the simulations, the soil was considered to be a uniform medium with a resistivity equal to 100 Ωm. The resistivity value used in the simulation itself does not influence the calculated geometric factor, since the resistivity value chosen does not alter the electric current lines in the soil and does not change the ratio obtained from the arrays.

The electrodes were represented according to the following cases:

- Electrode radius equal to 8 mm, corresponding to a diameter typical of grounding rods used in resistivity measurements;
- Buried electrode length $b = 0.1$ m; 0.2 m; 0.3 m; 0.4 m;
- Ratio between the buried electrode length and the distance between electrodes (b/a) assuming values between 0 and 2.

The potential difference between the central electrodes of the array was obtained for each case analyzed and (9) was used to calculate the proposed geometric factor [$K_1(x)$]. In Fig. 3, the $K_1(x)$ factor, obtained through simulations performed with different values of electrode length b, is presented and compared with the conventional factor represented in (8). As the Wenner method in its conventional formulation has its application recommended for small b/a ratios (as evidenced in Fig. 3), the proposed and conventional geometric factors converge when $x = b/a$ tends to zero, i.e., when the length of the electrode is much less than the distance between electrodes. However, when the b/a ratio becomes greater than 0.1 (the electrode length becomes the same order of magnitude as the distance between the electrodes), the effect of the electrode length becomes relevant and the geometric factor proposed in the conventional formulation method of the Wenner method fails to adequately estimate soil resistivity from the measured voltage and current values.

When larger values of b/a are considered, the length of the electrode will have a greater influence on the value of the geometric factor. When

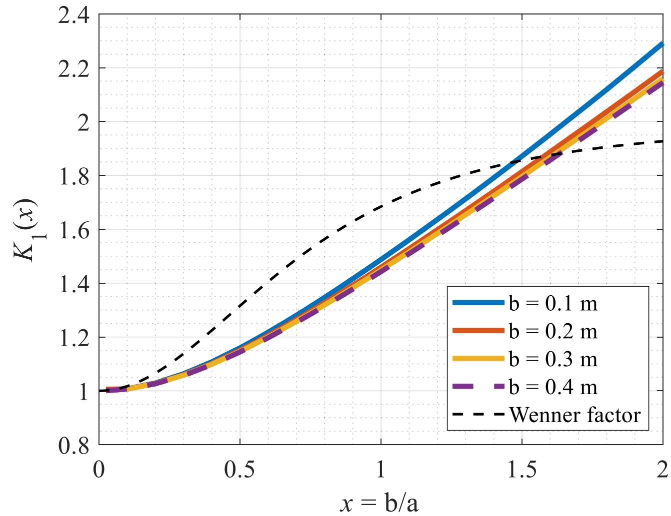

Fig. 3. Conventional and proposed geometric factors for applying the four-electrode array to the measurement of soil resistivity.

comparing the values of the geometric factor obtained through simulation with the analytical factor defined by Wenner, significant differences were found for small spacings ($b/a > 0.1$). However, if the b/a ratio is less than 0.2 (that is, $a > 5b$), the errors associated with the Wenner factor are less than 4%. For $a > 10b$, the errors associated with the Wenner factor are less than 1%.

To apply the proposed geometric factor to field measurements, the curves shown in Fig. 3 can be used to determine the value of the factor corresponding to a given ratio of length-spacing between electrodes. However, mathematical representations are generally more practical and provide more accurate results. Thus, an equation to represent the geometric factor $K_1(x)$ was proposed after a series of tests using curve fitting with a nonlinear, least-squares method. Eq. (10) was defined, which resulted in a good fit with the data obtained from the field calculations, and an NRMSE (normalized root-mean-square error) value equal to 0.5%:

$$K_1(x) = c_1 x + c_2 + \frac{c_3}{x + c_4}, \tag{10}$$

where parameter c_1 is a function of electrode length b and is approximated by (11), which provides a good fit for b values between 0.2 m and 0.4 m:

$$c_1 = d_1 + d_2 b + d_3 b^2. \tag{11}$$

The obtained values for the parameters are presented in Table 1, together with the respective 95% confidence intervals.

When applied to (10) and (11), the mean values of the parameters described in Table 1 allow to represent mathematically the geometric factor with good accuracy (relative errors smaller than 0.4%) for any spacing value $a > 0.5b$.

Table 1
Equation parameters for determining the geometric factor K_1 associated with the four-electrode arrangement.

Parameter	Value
d_1	0.9193 ± 0.0200
d_2	−0.6122 ± 0.0595
d_3	0.8464 ± 0.1171
c_2	0.3816 ± 0.0695
c_3	0.4117 ± 0.1081
c_4	0.6604 ± 0.1055

2.2.2. Evaluation of the four-electrode arrangement for measuring soil parameters as functions of frequency

After defining a new geometric factor for the analysis of the four-electrode arrangement, a mathematical model was proposed to estimate the resistivity and permittivity of the soil as functions of frequency. The model is based on the analysis of the total electrical current density (J) in the soil, which can be expressed in the frequency domain by:

$$\vec{J} = (\sigma + j\omega\epsilon)\vec{E} = \sigma_* \vec{E}. \tag{12}$$

Thus, when applying the four-electrode arrangement using a harmonic excitation signal, a new version of (7) can be defined to determine the complex conductivity σ_*:

$$\sigma_*(\omega) = \sigma(\omega) + j\omega\epsilon_0\epsilon_r(\omega) = \frac{\mathbf{I}(\omega)}{2\pi a K_1(x)\Delta\mathbf{V}(\omega)}. \tag{13}$$

In (13), $\mathbf{I}$ and $\Delta\mathbf{V}$ are phasors that represent the sinusoidal current and voltage measured with the four-electrode array. In addition, here the geometric factor $K_1(x)$ proposed in Section 2.2.1, in (10) is considered, which allows accurate results for the application of the four-electrode arrangement with small spacing between electrodes.

From (13), it is possible to calculate the apparent resistivity of the soil as:

$$\rho(\omega) = 1/\text{Re}\{\sigma_*(\omega)\}. \tag{14}$$

In turn, the relative permittivity is determined by:

$$\epsilon_r(\omega) = \frac{1}{\omega\epsilon_0}\text{Im}\{\sigma_*(\omega)\}. \tag{15}$$

To evaluate the combined effect of the frequency of the used excitation signal, electrode length and distance between the electrodes on the results obtained with the four-electrode arrangement, a new series of simulations of the application of the arrangement was carried out. The objective was to compare the parameters of a reference soil representation, based on the Visacro-Alípio model [17], with the parameters estimated using the proposed method. The following low-frequency resistivity values were considered for the analysis: $\rho_0 = 300$ Ωm, 1000 Ωm and 3000 Ωm, which resulted in the values of electrical parameters shown in Fig. 4.

The frequency range was defined in the format $f = 2 \times 10^n$ [Hz], with $2 \leq n \leq 6$, to reach frequency values up to 2 MHz. For frequencies less than or equal to 200 Hz, the resistivity change is negligible, as is the permittivity influence on grounding systems response. The variables analyzed in the series of studies are described in Table 2.

For each analyzed case, the reference values shown in Fig. 4 were used as simulation parameters and compared to the values calculated from the synthetic data obtained from the simulation, in order to calculate the error associated to the resistivity and permittivity estimates as a function of the frequency and distance between electrodes. The comparison was made using the parameters $\rho(f)/\rho_{\text{ref}}(f)$ and $\epsilon(f)/\epsilon_{\text{ref}}(f)$, where ρ_{ref} and e ϵ_{ref} are respectively the reference values of resistivity and permittivity shown in Fig. 4. The closer to 1, the better the estimate.

Table 2
Analysis variables for the simulation of the four-electrode method with variable frequency.

Variable	Assumed values
Low-frequency resistivity (ρ_0) [Ωm]	300, 1000, 3000
Buried electrode length (b) [m]	0.1; 0.2; 0.3
Distance between adjacent electrodes (a) [m]	0.25 to 8.00
Excitation signal frequency (f)	200 Hz to 2 MHz

2.3. Analysis of the two-electrode arrangement

2.3.1. Proposition of a new geometric factor

In the case of the two-electrode method, the first step of the study was also the proposal of a geometric factor associated with the arrangement. For this arrangement, the conductance (G) between two electrodes fixed on a uniform soil with conductivity σ can be represented by:

$$G = \sigma K_2(x, b), \tag{16}$$

where K_2 is a geometric factor to be defined and which, as shown below, can be represented as a function of the geometric ratio $x = b/a$ and of the electrode length b itself.

In order to propose a new geometric factor that would allow the application of the two-electrode arrangement to measure the electrical parameters of the soil, a series of simulations was carried out. As in the analysis of the geometric factor associated with the four-electrode arrangement, a series of simulations was performed for different ratios between the buried length of the electrodes (b) and the distance between the electrodes (a). The situation considered in this study was stationary. The soil was modeled as a uniform medium with resistivity equal to 100 Ωm and the electrodes were represented according to the cases described in Section 2.2.1.

The potential difference between the electrodes of the array was obtained for each case analyzed and (17) was used to calculate the K_2 factor associated with each case:

$$K_2(x, b) = \frac{G}{\sigma} = \frac{I}{\sigma\Delta V}. \tag{17}$$

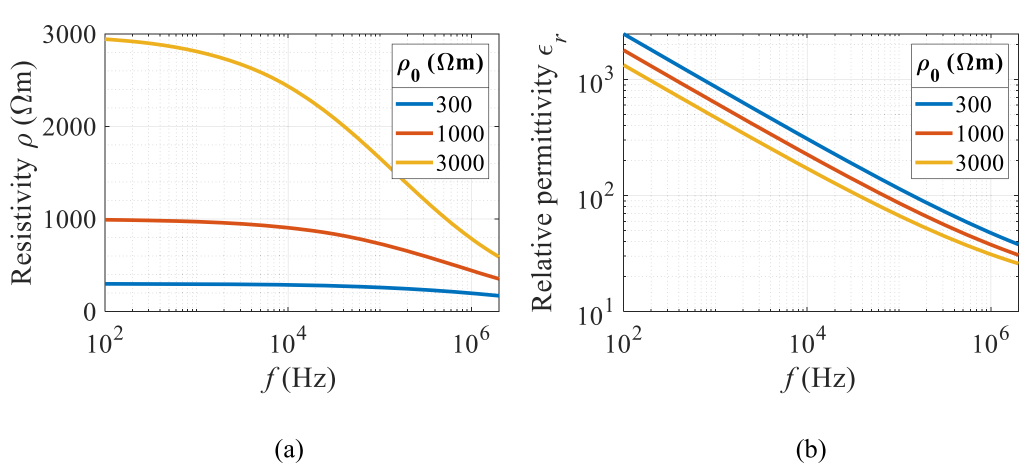

Fig. 4. Electrical parameters resistivity (a) and relative permittivity (b) calculated with the Visacro-Alípio model [17] for three soils of different levels of resistivity at low frequency.

In Fig. 5, the K_2 factor obtained through the simulations performed with different values of electrode length b is shown. As Fig. 5 shows, unlike the K_1 factor associated with the four-electrode array (Fig. 3), the K_2 factor associated with the two-electrode array has a significant dependence on the electrode length (b). In addition, the values of K_2 calculated when the ratio x tends to zero, converge to the expected value calculated with the Dwight equation [34] for the grounding resistance of rod-shaped electrodes.

For a practical application of the two-electrode arrangement to estimate soil resistivity, the curves of Fig. 5 can be consulted directly in order to obtain the value of the geometric factor corresponding to a specific combination of geometric parameters of the arrangement. However, it should be noted that mathematical representations are commonly more practical to apply. Thus, the non-linear least squares method was again applied in a study that aimed to adjust the curves shown in Fig. 5. After testing some of the functions, (18) was proposed to represent the geometric factor K_2:

$$K_2(x,b) = \frac{p_1 b}{ln(p_2 b) - p_3 ln(x + p_4)}. \tag{18}$$

This was chosen because it is based on the Dwight equation [23] for calculating the resistance and capacitance of grounding rods and, therefore, has a physical correspondence. In addition, it resulted in a relatively low error value with a relatively small number of fitting parameters. The application of (18) to the fitting of the curves obtained in Fig. 5 resulted in an excellent adjustment, with an NRMSE value equal to 1.4%. The validity range of the equation is the geometric ratio $x = b/a$ between 0 and 2 and electrode length (b) between 0.1 m and 0.4 m. The values obtained for the parameters of (18) by fitting the curves are shown in Table 3, together with the respective 95% confidence intervals.

2.3.2. Evaluation of the two-electrode arrangement for measuring soil parameters as functions of frequency

Once the geometric factor associated with the two-electrode arrangement was defined and an equation was proposed to represent it, it was possible to analyze the application of the arrangement to the estimation of the resistivity and relative permittivity parameters of the soil. For this, it is assumed that, when extending (16) to the frequency domain, the admittance Y between the electrodes is given by:

$$Y(\omega) = \frac{\mathbf{I}(\omega)}{\Delta\mathbf{V}(\omega)} = \sigma_* K_2(x,b) \tag{19}$$

Table 3
Parameters from Eq. (18) for determining the geometric factor K_2 associated with the two-electrode arrangement.

Parameter	Value
p_1	3.174 ± 0.0062
p_2	$(165.2 \pm 5.9)\ m^{-1}$
p_3	1.149 ± 0.0218
p_4	0.9413 ± 0.0033

and, therefore,

$$Y(\omega) = [\sigma(\omega) + j\omega\epsilon_0\epsilon_r(\omega)]K_2(x,b). \tag{20}$$

From (20), resistivity and relative permittivity can be estimated as:

$$\rho(\omega) = \frac{K_2(x,b)}{\mathrm{Re}\{Y(\omega)\}} \tag{21}$$

and

$$\epsilon_r(\omega) = \frac{\mathrm{Im}\{Y(\omega)\}}{\omega\epsilon_0 K_2(x,b)}. \tag{22}$$

After mathematically defining the method for estimating electric soil parameters by means of the two-electrode arrangement, a series of case studies was carried out, in which synthetic data were obtained through computer simulations and used to assess the accuracy of the two-electrode measurement method. For this, the soil represented in Fig. 4 was used again. The variables analyzed in the study are described in Table 4.

For each configuration of the geometry and frequency analyzed, the parameters were estimated using (21) and (22) and compared to the reference parameters. The comparison was made in the same way as in the previous section. Eq. (18) was used to obtain the values of the K_2(x,

Table 4
Analysis variables for the simulation of the two-electrode method with variable frequency excitation.

Variable	Assumed values
Low-frequency resistivity (ρ_0) [Ωm]	300, 1000, 3000
Buried electrode length (b) [m]	0.1; 0.2; 0.3
Distance between adjacent electrodes (a) [m]	b/2 to 10b
Excitation signal frequency (f)	200 Hz to 2 MHz

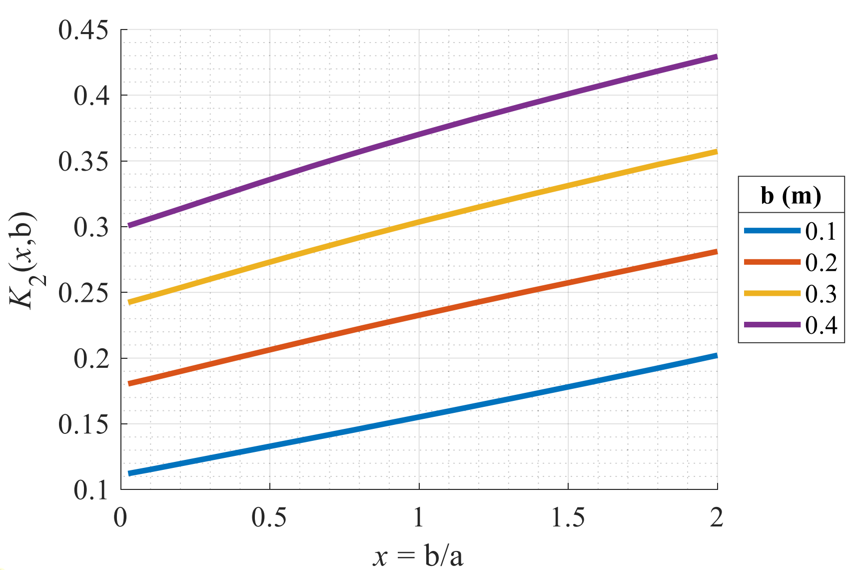

Fig. 5. Geometric factor K_2 calculated by simulating the application of the two-electrode arrangement for measuring soil resistivity.

b). factor.

The way in which the variables were defined makes the values assumed by the geometric factor $x = b/a$ equal for all of the electrode lengths (b) analyzed, whereas the maximum value of the distance between the electrodes (a) varied according to the electrodes length (b). This made it possible to evaluate the effect of distance on the accuracy of the estimated parameters.

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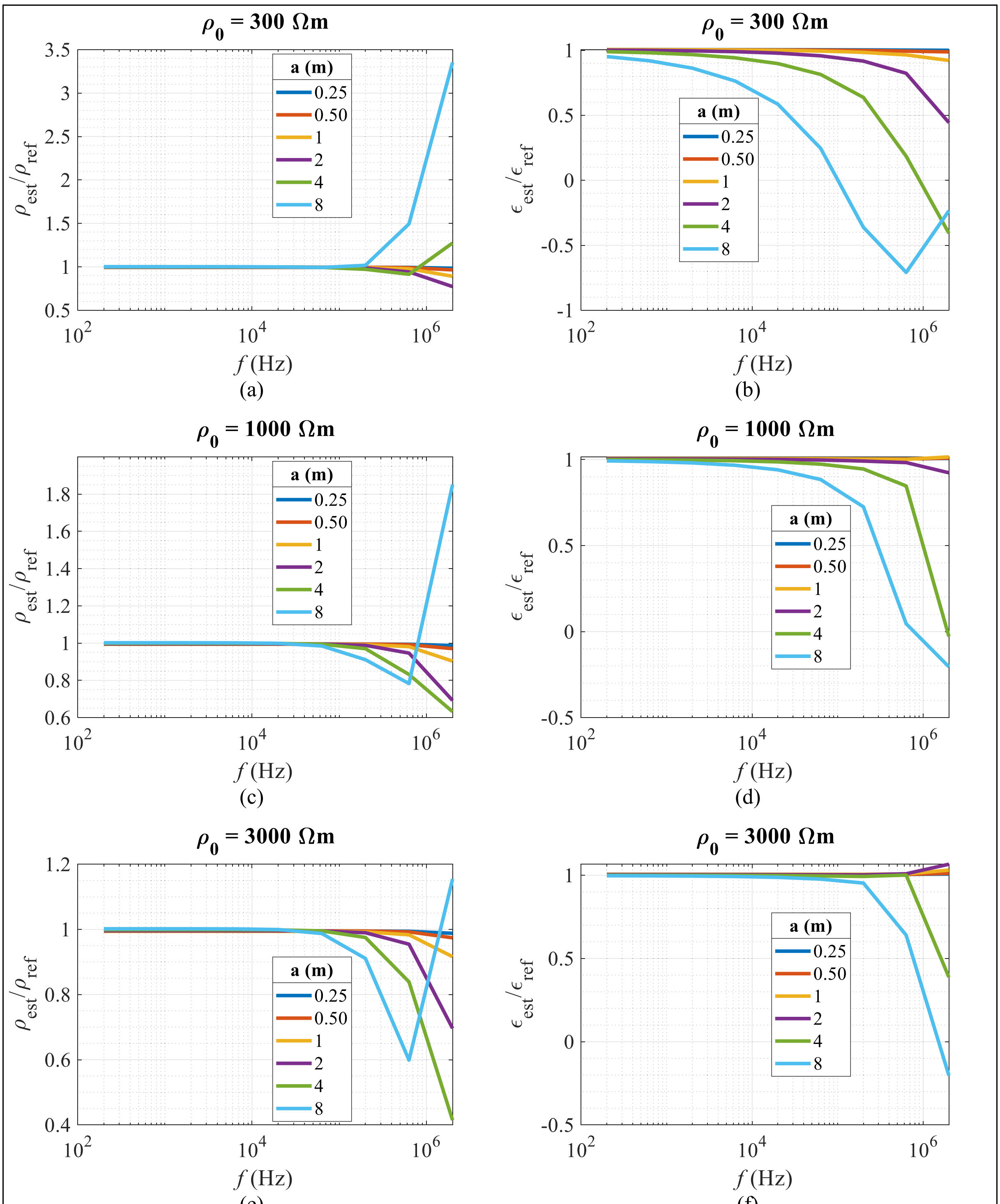


Fig. 6. Resistivity and permittivity estimated by simulating the application of the four-electrode arrangement with variable frequency.

3. Simulation results

This section presents the results of the simulations performed to evaluate and define the range of application of the proposed methods for measuring the electrical parameters of soil as functions of frequency.

3.1. Four-electrode arrangement

After simulating the four-electrode array for the cases defined in Section 2.2.2, the estimated values of resistivity and relative permittivity were compared to the reference values. The simulations showed that the influence of the electrode length (b) on the estimated parameters is insignificant. Thus, the results corresponding to a representative case with the electrode length equal to 0.2 m are shown in Fig. 6. In each graph, the vertical axis represents the ratio between the estimated parameter and the reference parameter. It should be noted that, in Fig. 6 graphs, a flat profile close to 1 indicates that, for that case, the electrical parameter was properly estimated, that is, the resistivity or permittivity estimated with the method as a function of frequency agreed with the corresponding reference curve (see Fig. 4).

When comparing Figs. 6a, 6c and 6e, it appears that, for the lowest resistivity analyzed (300 Ωm, Fig. 6a), there is a significant deviation in the estimated resistivity for the limit frequency of 2 MHz with the spacing $a = 8$ m, with the calculated resistivity greater than 3 times the reference value for the borderline frequency. When increasing the resistivity considered in the simulation (Figs. 6b and 6c), the discrepancy value decreases, and underestimations of resistivity are likely to occur for frequencies greater than 80 kHz and spacings greater than 1 m.

Regarding the determination of relative permittivity (Figs. 6b, 6d and 6f), it can be seen, when comparing these figures, that there is a tendency to underestimate the permittivity value, especially in soils with less resistivity and in case of a values relatively large are used. In Fig. 6b, corresponding to the 300-Ωm resistivity, significant discrepancies were found for spacing values greater than 1 m. In the case of soils with higher resistivity values (Figs. 6d and 6f), the discrepancies become significant when $a > 2$ m.

In most cases, increasing the distance between electrodes and the excitation frequency resulted in an increase in the divergence between the estimated electrical parameters and the reference parameters. Resistivity could be determined with a discrepancy of less than 3% for all spacing values by increasing the frequency to about 80 kHz.

When analyzing the maximum values of the spacing between electrodes (a) that allow an acceptable accuracy in the estimation of the electrical parameters for the frequency range considered, it was observed that distances less than or equal to 0.5 m resulted in errors less than 3.5%. Thus, as in the previous simulation series, it was found that the limiting factor for the maximum distance between the electrodes is the maximum excitation frequency applied to the measurement (2 MHz).

It was also found that, in the case of the concomitant use of greater spacing between electrodes and higher excitation frequencies, it is impossible to define a simple relationship that allows direct estimation of resistivity or relative permittivity. The reason for this is that, for these cases, the ratio between the estimated parameter and the potential difference between the central electrodes varies erratically depending on the frequency, distance between electrodes and the soil's electrical parameters, due to electromagnetic induction effects. The conductive current and the displacement current are affected by additional electric field induced by the time-variation of magnetic field, according to Faraday-Lenz law. This effect is intensified to the point of becoming significant with increasing frequency and also with increasing distance between the electrodes, the latter corresponding to a scale change that results in a change in the shape of the electromagnetic fields in the soil. In addition, there is also an attenuation of the amplitude of higher-frequencies components of a signal due to the medium conductivity. All of these factors contribute to altering the results obtained for higher frequencies and spacing between electrodes.

However, the simulations carried out demonstrated that the proposed method makes it possible, using a four-electrode arrangement, to estimate both the resistivity and the permittivity of the soil with good accuracy (discrepancies less than or equal to 3%). For this, it is necessary to use relatively small values of spacing between electrodes ($a = 0.5$ m or less).

3.2. Two-electrode arrangement

For the case of the two-electrode arrangement, the accuracy of the estimated parameters was also analyzed. Figs. 7 and 8 show the results obtained for the extreme cases of electrode length considered: $b = 0.1$ m and $b = 0.3$ m, respectively. For the analysis of the two-electrode arrangement, values greater than 1.0 m were not considered for the spacing between the electrodes (in the case of the 0.1 m long electrode) or greater than 3.0 m (in the case of the 0.3 m long electrode).

In the case of the parameters that were estimated by considering the shortest electrode length (b = 0.1 m), the results of which are shown in Fig. 7, when comparing the resistivity estimate considering different soil types (Figs. 7a, 7c and 7e), it was found that in all cases the resistivity could be determined with a discrepancy less than 0.5%. In the case of the permittivity estimate, errors of less than 0.5% were also obtained considering all modeled soil types (Figs. 7b, 7d and 7f). The agreement of the results obtained for this case is due to the relatively small maximum spacing value ($a \leq 1{,}0$ m). It was also possible to verify that, for this case, the dispersion of the estimated parameters is directly related to the proposed equation for modeling the geometric factor used. The frequency effects start to change the parameter value estimated from 600 kHz. However, the change is not significant due to the relatively small distance between the electrodes.

In the case of simulations that considered 0.3 m electrodes (Fig. 8), the frequency effects are more pronounced due to the greater maximum distance associated with this case (3 m). Even for this value of maximum distance, the error in the estimated parameter remained below 2% for all simulated conditions. When comparing Figs. 8a, 8c and 8e, it appears that the errors were slightly higher for the case of resistivity at low frequency equal to 300 Ωm. However, the error values did not have a great influence on the reference resistivity value. A similar behavior was verified for the case of the permittivity estimate (Figs. 8b, 8d and 8f).

Thus, using relatively short distances for the application of the arrangement to two electrodes can be assumed to be an appropriate practice, especially when the excitation signal used has a frequency greater than 200 kHz. Even so, as was verified through the case studies carried out, distances of up to 3 m still produce results with considerable accuracy, at least in relation to the distortion caused by the effects of electromagnetic induction in the soil. Additionally, it is recommended that longer electrodes are used (b) if it is the objective of the experiment to characterize the largest possible portion of soil.

In the case of the two-electrode method, it is necessary to emphasize that the estimated parameters may present discrepancies associated with the contact impedance and the polarization effect of the electrodes, since the same electrodes are used for the measurement of current and potential [12, 21, 29]. However, as pointed out in [12], the effect of contact impedance can be mitigated by ensuring good contact between the electrodes and the ground.

The methods developed and evaluated in this study make it possible to characterize the soil response in the frequency domain for engineering applications. Thus, from common rod-shaped electrodes already used to low-frequency resistivity measurements, it is possible to obtain a soil model that allows determining the rise in ground potential (in the design stage) in the case of impulsive currents associated with lightning.

The application of the method proposed in this work with small spacing between electrodes results in apparent values of soil parameters that are more related to the superficial layers of the soil. However, the portion of soil with the greatest influence on grounding response is the

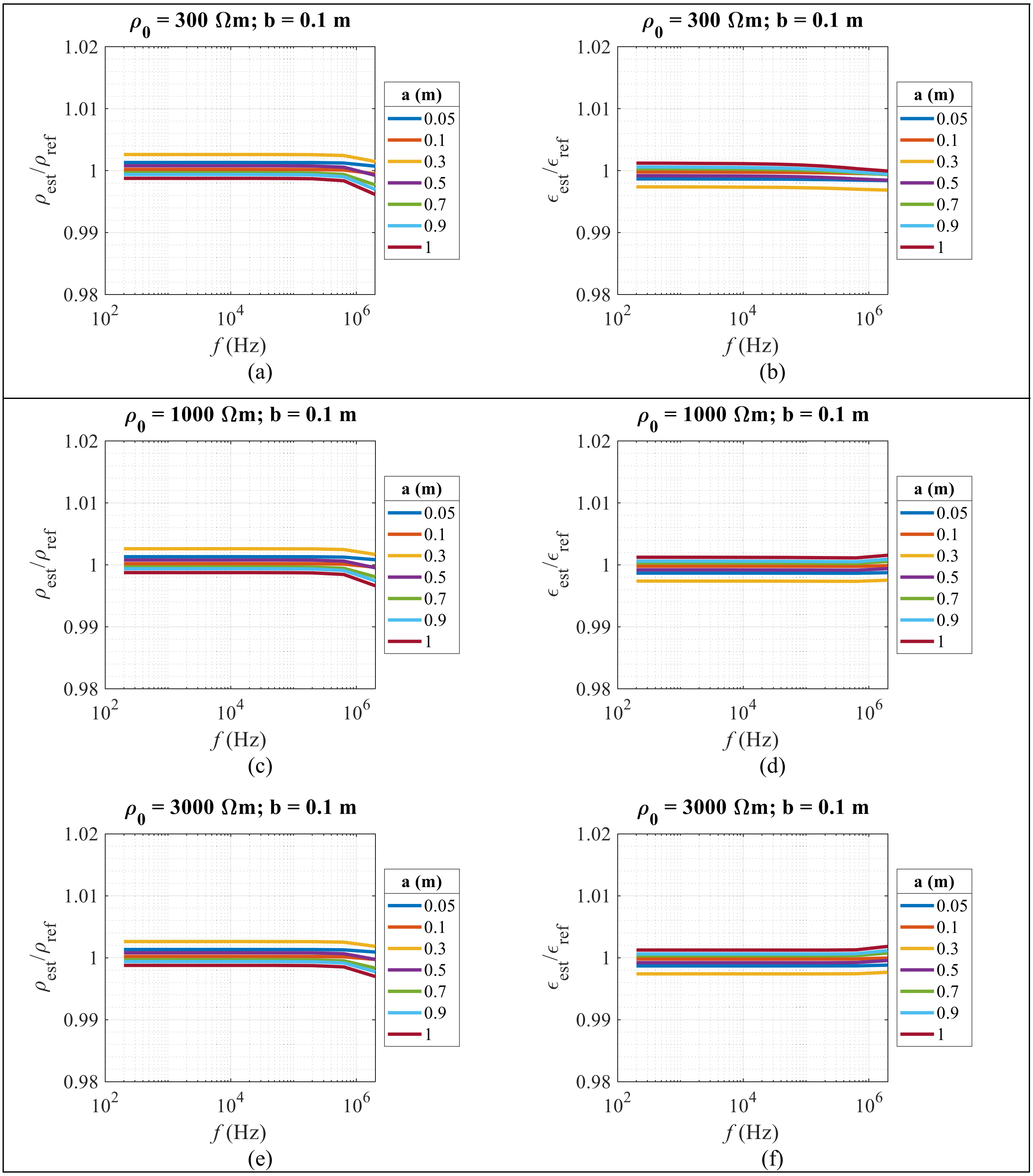


Fig. 7. Resistivity and permittivity estimated by simulating the application of the two-electrode arrangement with variable frequency (buried electrode length of 0.1 m).

superficial, since this is the region where the electrodes are installed and thus when the greatest potential drop occurs. In addition, the high frequency components, for which the variation of the soil parameters becomes relevant, suffer greater attenuation as a function of the propagation distance [14]. In [16-17], for example, results close to the experimental ones were obtained from simulations with a soil characterized by a measurement method that involved relatively short distances.

Thereby, a possible solution that can be applied to improve soil representation is to use a mixed soil model, in which the first layer is modeled with frequency-dependent parameters, while the deeper layers are considered to be frequency-independent. In this way, one can consider in the grounding analysis both effects associated with frequency and deeper layers of soil.

4. Experimental evaluation of the proposed methods

The purpose of this section is to describe measurements carried out to exemplify and evaluate the feasibility of applying the proposed measurement methods from a practical point of view. The tests were performed in a land with low frequency resistivity values ranging from about 230 Ωm to 324 Ωm, depending on the distance between electrodes used. The measurement procedures, results and analyzes performed are described in the following subsections.

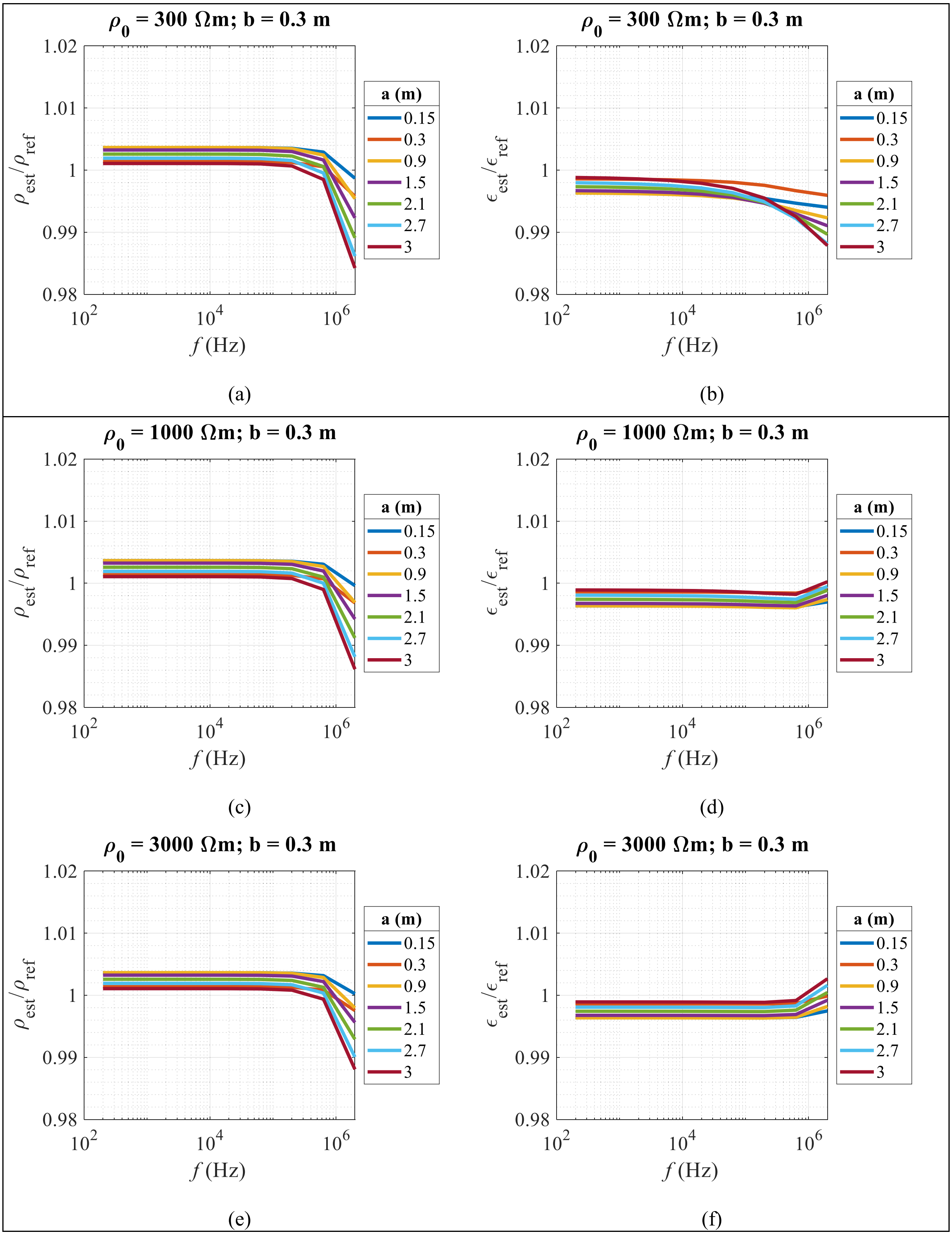


Fig. 8. Resistivity and permittivity estimated by simulating the application of the two-electrode arrangement with variable frequency (buried electrode length of 0.3 m).

4.1. Material and methods

To apply and analyze the proposed measurement methodologies, a Haefely recurrent surge generator (type 481) was used as source. This generator produces impulsive waveforms with configurable duration and amplitude. The maximum voltage is about 500 V. In order to obtain soil electrical parameters in the frequency range under study (200 Hz to 2 MHz), it is necessary to apply impulses with different durations and small rise times During measurements, capacitance values ranging between 0.75 nF and 1 μF were used, which resulted in five sets of impulse signals with duration of about 20 μs to 10 ms.

The circuit used in the measurements is presented in Fig. 9 diagram. In the figure, the impulse generator is represented by capacitor C. A series resistor (R_S = 9.974 Ω) was inserted into one of the generator outputs and used for current measurement. During tests preparation, care was taken to choose a resistor with a low parasitic inductance value, in order to reduce the associated measurement errors.

The rod shown on the left in Fig. 9 was adopted as a reference for the measuring instrument. The potentials in the three remaining rods were acquired. For the acquisition of voltage and current signals, a Keysight DSOX3014T oscilloscope was used. Cables of the shortest possible length were used, in order to reduce possible interference in the results caused by the associated inductances.

With the voltage and current signals represented in Fig. 9, the mathematical procedures proposed in Section 2 were used for the electrical characterization of soil. The proposed four-electrode method is applied through the use of Eqs. (10) to 11 for the calculation of the associated geometric factor, and Eqs. (13) to 15 for the estimation of the resistivity and relative permittivity values as functions of frequency. The same test can be used to apply the two-electrode method, simply by disregarding the internal electrodes. Eq. (18) should be used to determine the geometric factor, while Eqs. (20) to 22 should be used to estimate the electrical parameters of the soil.

The input variables $\mathbf{I}(\omega)$ and $\Delta\mathbf{V}(\omega)$ are obtained by applying the Fourier transform to the acquired signals. In the case of the four-electrode method, the potential difference in the time domain corresponds to:

$$\Delta v(t) = v_3(t) - v_2(t), \tag{23}$$

whereas, for the two-electrode method, there is simply:

$$\Delta v(t) = v_4(t). \tag{24}$$

The tests were carried out in a terrain located at the coordinates (7.072611; -36.724333). Two values of spacing between electrodes were analyzed: $a = 1$ m and $a = 0.5$ m, which corresponded to the values of low frequency resistivity 230 Ωm to 324 Ωm, measured with an AEMC earthmeter.

For both spacing values, 5 measurements were made with different capacitance values for the generator. The measurement parameters are described in Table 5.

To calculate the frequency response of the acquired signals, an FFT (fast Fourier transform) algorithm was used.

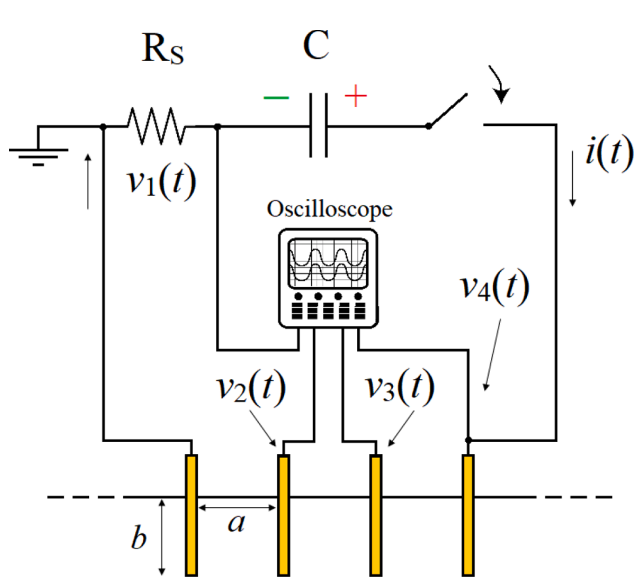


Fig. 9. Simplified diagram of the arrangement used to measure electrical parameters of soil.

Table 5
Characterization of impulse signal measurements.

Measurement	C (nF)	Acquired time (ms)
I	1000	10
II	100	1
III	10	0.1
IV	1.5	0.02
V	0.75	0.02

4.2. Results and discussion

Initially, the waveforms corresponding to the test performed with the 0.5-m spacing are presented in Fig. 10, in order to exemplify the procedure adopted and allow an analysis of the voltage waveforms and potential difference obtained.

As shown in Fig. 10, from measurement II (Fig. 10b), all current waveforms showed a spike, which is related to an initial oscillation present in the signal, and which can be observed in greater detail in Figs. 10d and 10e. This oscillation, resulting from the interaction of the capacitive and inductive elements of the circuit, had a frequency of about 5.3 MHz, and is therefore located outside the frequency range under analysis.

After the acquisition of the signals in time domain, the FFT was applied to obtain the corresponding signals in frequency domain, and the equations proposed in Section 2 were applied to determine the electrical parameters of soil. The first method evaluated was the four-electrode method.

Eqs. (13) to 15 were then used to estimate the electrical parameters of the soil for the two spacing values analyzed. Fig. 11 presents the results obtained for the analyzed frequency range: 100 Hz to 2 MHz. Fig. 11a refers to the spacing $a = 1$ m, while in Fig. 11b the parameters corresponding to the spacing $a = 0.5$ m are shown.

In Fig. 11, the points corresponding to each of the measurements made for each case were highlighted by using different colors. It should be noted that, in the case of the test with the 1.0 m electrode spacing, a distortion problem was found during the data analysis for the current signal acquired in measurement I and, therefore, the corresponding data were discarded.

It can be seen that, for both spacing values considered, the resistivity value estimated for the lowest analyzed frequency corresponded to the resistivity value measured with the conventional earthmeter, which indicates the consistency of the adopted procedure.

In addition to the points determined from the measurements, Fig. 11 shows curves representative of the soil parameters as a function of frequency, which were obtained through a curve fitting process. Eq. (25) was used for the fitting:

$$\rho(f) = \frac{m_1}{1 + \xi[\log_{10}(f)]^{\zeta}} + m_2. \tag{25}$$

It was chosen after a series of tests in which other analytical functions were also analyzed. In addition to represent well to the experimental data and representing the logarithmic characteristic of the frequency response of the variables analyzed, it has a reduced number of parameters and can be adjusted to represent a strictly decreasing function, which is the physical characteristic. expected for the electrical parameters of soil due to dielectric polarization mechanisms. Eq. (25) was used both to adjust resistivity and relative permittivity.

In Tables 6 and 7, the values determined for the fitting parameters are presented, as well as error metrics determined for each case. The maximum NRMSE was 8.8%, for the case of resistivity measured with a spacing of 1.0 m.

From the use of the presented equation and the parameters registered in the tables, the electrical parameters of the tested soil can be estimated analytically for the studied frequency range. Here, differently from what has been done in works such as [13-18], the main purpose of obtaining

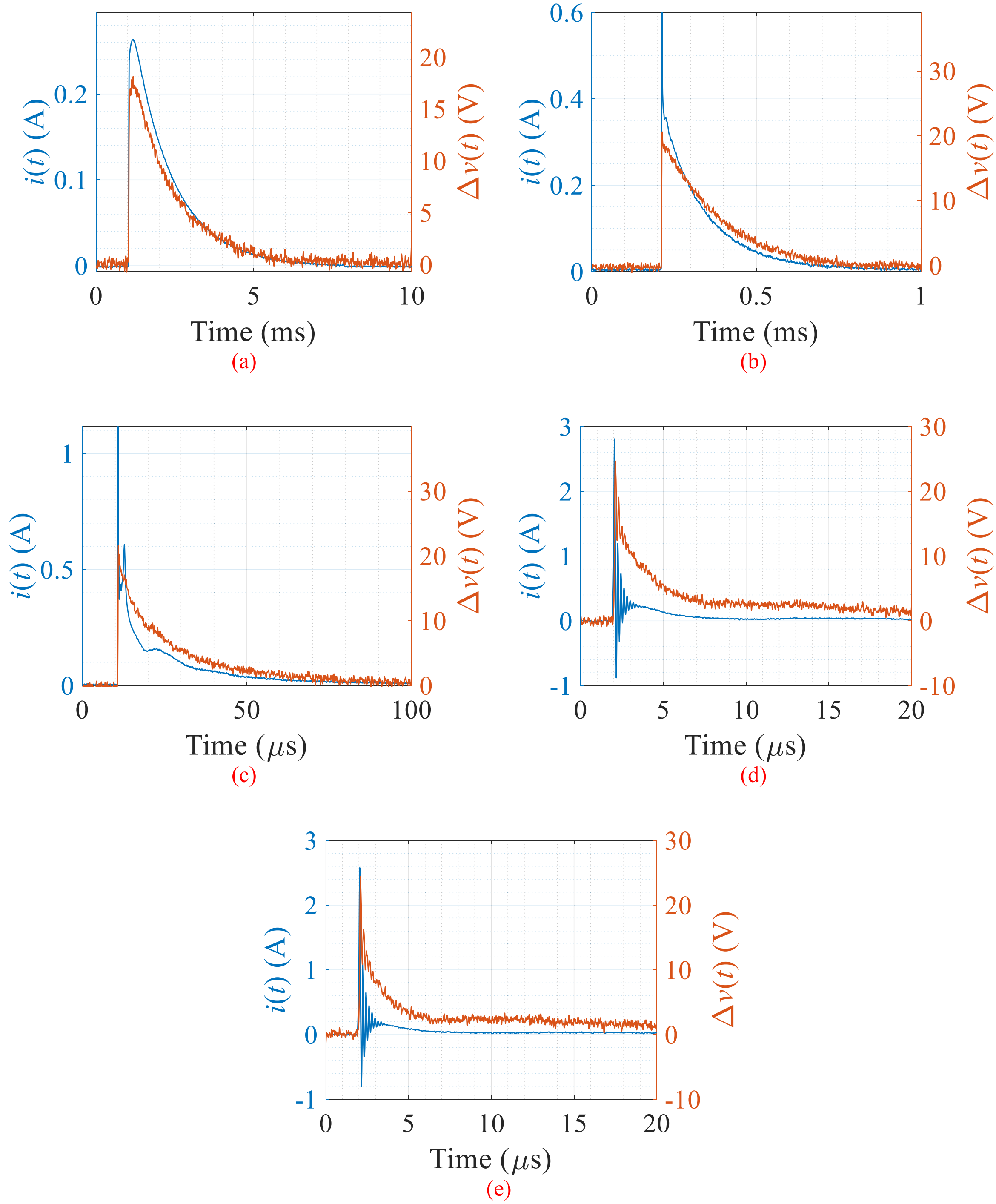
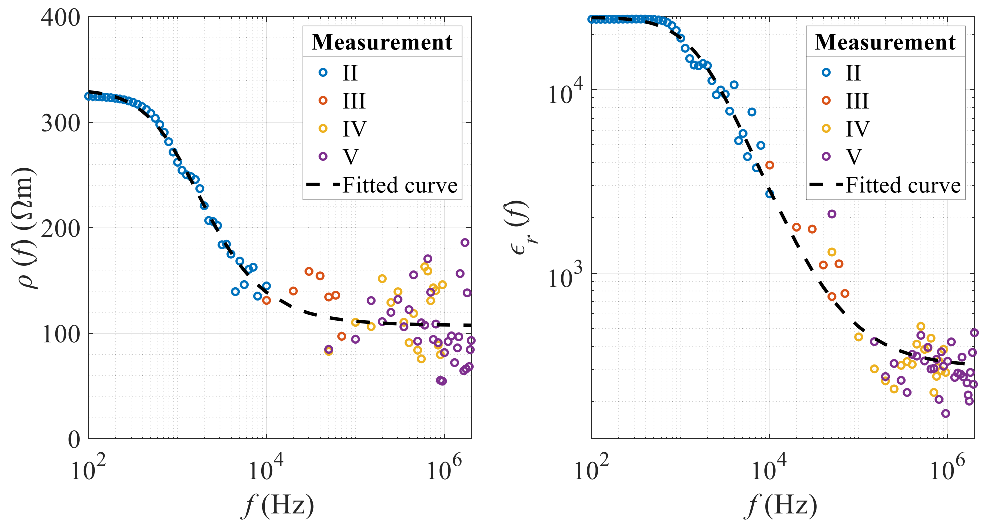


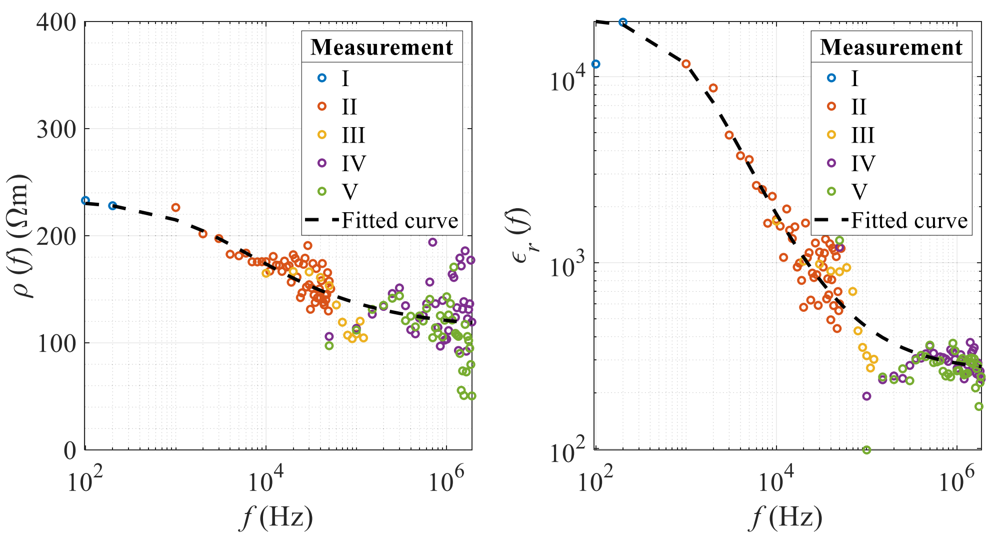
Fig. 10. Signals associated with the four-electrode method corresponding to measurements (a) I, (b) II, (c) III, (d) IV and (e) V, performed with $a = 0.5$ m.

an equation representative of the dependence of soil parameters with the frequency was not to define a general mathematical relationship that necessarily applies to a wide range of soil types, but rather to model the analyzed cases with a smooth curve.

Then, the applicability of the two-electrode method was evaluated using procedures similar to those adopted for the four-electrode method, however adopting specific variables and equations, as in Section 2. Divergent results were obtained, both when comparing the results obtained to those resulting from the four-electrode method, and from the point of view of internal consistency. Contrary to the pattern observed in the graphs in Fig. 11, there was no definite tendency to reduce soil parameters with frequency, and adjacent frequencies associated with



(a)



(b)

Fig. 11. Resistivity and relative permittivity estimated with the four-electrode array and the proposed method, for spacing between electrodes: (a) $a = 1.0$ m and (b) $a = 0.5$ m.

Table 6
Fitting parameters determined for modeling resistivity as a function of frequency.

Parameter	$a = 1.0$ m Value	$a = 0.5$ m Value
m_1 (Ωm)	223.4 ± 20.9	121.4 ± 18.2
m_2 (Ωm)	107.3 ± 7.2	110.5 ± 7.4
ξ	$(1.068 \pm 3.546) \times 10^{-5}$	$(2.176 \pm 5.008) \times 10^{-4}$
ζ	9.557 ± 2.672	6.025 ± 1.571
RMSE (Ωm)	23.8	8.4
NRMSE (%)	8.8	4.3

Table 7
Fitting parameters determined for modeling relative permittivity as a function of frequency.

Parameter	$a = 1.0$ m Value	$a = 0.5$ m Value
m_1	$(2.441 \pm 0.023) \times 10^4$	$(1.985 \pm 0.016) \times 10^4$
m_2	305.6 ± 87.5	253.6 ± 21.3
ξ	$(8.042 \pm 3.786) \times 10^{-7}$	$(1.880 \pm 0.413) \times 10^{-5}$
ζ	11.68 ± 0.38	9.619 ± 0.173
RMSE	316.6	90.4
NRMSE (%)	1.3	0.5

different measurements with close frequency spectrum showed significant deviations in the values of the estimated parameters. In addition, the noise level of the frequency responses obtained was significant, and in some cases the relative permittivity could not be estimated.

As pointed out in [35], the effect of contact impedance makes it difficult to measure using the two-electrode method, especially on dry soils, as was the case with the soil analyzed in this study. Still, mitigation measures can be proposed. According to [12], the effect of contact impedance can be mitigated by ensuring good contact between electrodes and the ground. However, in addition to contact impedance, inductance of measurement cables and polarization of the electrodes make it difficult to apply the method to two electrodes for the measurement of soil parameters.

5. Conclusion

In this work, the use of four-electrode and two-electrode arrangements for the field measurement of electrical soil parameters as functions of frequency was proposed and investigated through computer simulations and experiments. New methods that allow the estimation of soil parameters have been presented. It was found that it is possible to measure the electrical parameters of the soil using arrangements with rod-shaped electrodes for the frequency range associated with lightning strikes (0 to 2 MHz). For this, however, reduced spacing must be used. In this sense, the following contributions were presented:

- Geometric factors were defined as functions of the geometric parameters associated with the arrangements, which enabled the correct interpretation of the experimental results both in the case of the use of large spacing values between electrodes and in the case of the use of small spacing values;
- Equations have been proposed to represent the geometric factors associated with both experimental arrangements;
- Mathematical models were developed for the measurement of soil resistivity and permittivity based on the proposed arrangements and the feasibility, limitations and accuracy of the parameter estimation was determined by means of a series of simulated case studies.

From the simulations, it was found that:

- In order to measure the electrical parameters of the soil in the frequency range associated with lightning strikes, the use of reduced spacing between electrodes is necessary;
- The four-electrode arrangement can be applied, using the proposed geometric factor, to the measurement of soil resistivity and relative permittivity at frequencies up to 2 MHz. For this, distances between electrodes less than 1 m must be used to limit the error associated with electromagnetic induction. Errors less than 3% were obtained for distances between electrodes of less than 0.5 m.
- Regarding the two-electrode method, it was found that, at first, by using the proposed method and geometric factor it is also possible to determine the electrical parameters of the soil as a function of frequency.

The experiments carried out demonstrated that four-electrode arrays with simple rod-shaped electrodes can be applied in order to measure the electrical parameters of the soil in the representative frequency range of lightning strike currents. Additionally, an equation was proposed for the analytical representation of the obtained soil electrical parameters. However, in the case of the two-electrode method, the results indicate a difficulty in its application for practical measurements, mainly due to problems related to contact impedance and electrode polarization.

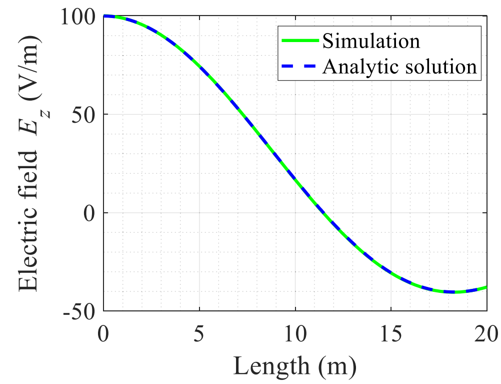


Fig. A1. Electric field inside a pair of disk-shaped electrodes for the frequency of 10 MHz.

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CRediT authorship contribution statement

A.F. Andrade: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **E.G. da Costa:** Supervision, Conceptualization, Writing – original draft, Writing – review & editing. **G.R.S. Lira:** Supervision, Resources, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix

In order to validate the electromagnetic model represented by Eqs. (2) to (4) associated with FEM for analyzing the frequency range under study, a relatively simpler case, which can be solved analytically, was simulated and compared to expected theoretical results. The case consists of a pair of disk-shaped electrodes, with a radius of 20 m and a separation distance of 1 m. The dimensions adopted aimed to replicate the order of magnitude of the dimensions of the distances analyzed in the work. The material between the plates was considered to be air ($\sigma = 0$, $\epsilon_r = 1$, $\mu_r = 1$). A potential difference with magnitude of 100 V and a frequency of 10 MHz was applied to the plates, in such a way that the electric field phasor points upwards in the center of the arrangement. According to [30], the electric field between the electrodes ($\hat{E}$) varies radially and has a value given by:

$$\widehat{E} = E_0 J_0\left(\frac{\omega r}{c}\right). \tag{26}$$

In (26), $\hat{E}$ represents the electric-field phasor, ω is the angular frequency, r represents the radial length, c is the speed of light in vacuum and J_0 is the primary first-order Bessel function.

The electric field along the central region between the electrodes was calculated by simulation, and the results were compared with the values evaluated using (26). The simulated and analytical results are compared in Fig. A1.

The maximum absolute difference between the analytically calculated and simulated electric fields was less than 0.2 V/m. The agreement between the simulated and analytical results attests to the validity of the computational model solved with MEF for field calculation at higher frequencies.

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