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DETERMINATION OF TWO LAYER EARTH STRUCTURE PARAMETERS

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Summary**:** In this paper, a methodology has been proposed, according to which one can compute the parameters of the two-layer earth structure after carrying out a set of soil's resistivity measurements. On that purpose, different optimization functions have been used. These optimization functions are the relative error, the absolute error, the square error, and the L-infinity norm. By comparing the results of each optimization function, the relative error is being proved to be the most suitable optimization function that gives the best fitting curve to the experimental data.

Keywords: Genetic Algorithms, grounding system, soil resistivity measurements, two-layer earth structure.

1. Introduction

The soil type significantly affects the behavior of a grounding system. The effect of earth structure can be studied out through measurements of soil resistivity. The analysis of the results coming from such measurements is an important procedure for the accurate analysis of grounding systems [1-3]. The measurements of the soil resistivity have shown that the soil has to be simulated as a two-layer structure (at least) [1-9].

The calculation of the parameters of the earth's two-layer structure is transformed into a problem of minimization. A methodology based on a Genetic Algorithm (GA) is proposed in this paper, which calculates the parameters of the earth's two-layer structure using the measurements of soil resistivity. The parameters (soil resistivity and thickness) of the earth structure are the necessary input data for the circuital or field simulations of grounding systems. Hence, by the use of the suggested methodology, it is possible to accurately calculate the two-layer earth parameters for a specific ground. These parameters will be thereafter used as essential input data for the simulation of the behaviour of the grounding system that will be installed in this ground. On that purpose, different optimization functions have been used. These optimization functions are the relative error, the absolute error, the square error and the L-infinity norm. By comparing the results of the GA for each optimization function, the most suitable function derives.

2. Soil resistivity measurements

It has been found that, usually, the ground incorporates a multilayer structure [3-9]. The determination of the soil's structure parameters (soil resistivity and thickness of each soil's layer) is essential to the design of grounding systems. These parameters can be calculated through the analysis of data coming from soil resistivity measurements. After that, the most suitable earth structure is chosen (according to the thickness of the layers) in order to proceed to the design of the grounding system [6].

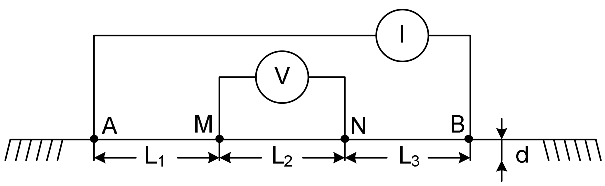

Fig. 1. The four point method

For an electrode pair (Fig. 1) with current I at electrode A, and $-I$ at electrode B, the potential at a point is given by the algebraic sum of the individual contributions [2]:

$$U = \frac{r \cdot I}{2 \cdot p} \cdot \left(\frac{1}{r_A} - \frac{1}{r_B} \right) \quad (1)$$

where r_A and r_B are the distances from a point to electrodes A and B, respectively.

Between current electrodes A and B, an additional pair of electrodes M and N is placed, where the potential difference *V* may be measured. According to eq. 1 the potential difference *V* is given by the formula [2]:

$$V = U_M - U_N =$$

$$= \frac{r \cdot I}{2 \cdot p} \cdot \left[\left(\frac{1}{AM} - \frac{1}{BM} \right) - \left(\frac{1}{AN} - \frac{1}{BN} \right) \right] \qquad (2)$$

where U_M and U_N are the potentials at points M and N. (*AM*), (*BM*), (*AN*), (*BN*) are distances between the electrodes AM, BM, AN and BN, respectively.

The impact of soil resistivity on ground resistance is substantial. Many techniques have been developed for the measurement of soil resistivity [1-3]. The most commonly used are Wenner, Schlumberger, and dipole-dipole. An electrode array with constant spacing is used to investigate lateral changes in apparent resistivity reflecting lateral geologic variability or localized anomalous features. To investigate changes in resistivity with depth, the size of the electrode array is varied. The apparent resistivity is affected by soil's composition at increasingly greater depths (hence larger volume) as the electrode spacing is increased. In any case, the geometric factor for any four-electrode system can be calculated from eq. 2 and can be developed for more complicated systems by using the rule illustrated by eq. 1 [2].

The Wenner method [1-3] is the most accurate for the measurement of the average soil resistivity. Four electrodes (rods) are driven in a depth ***d*** in four points of the soil, which are in the same line and they have the same distance $\alpha = L_1 = L_2 = L_3$ from each other (Fig. 1). The quotient ***V/I*** gives the apparent resistance ***R*** (in Ohms). According to eq. 2 the apparent soil resistivity of the soil ρ is given by the following equation [1-3]:

$$r \cong 2 \cdot p \cdot R \cdot a \qquad (3)$$

A more accurate formula [3] is:

$$r = \frac{4 \cdot p \cdot R \cdot a}{1 + \frac{2 \cdot a}{\sqrt{a^2 + 4 \cdot d^2}} - \frac{a}{\sqrt{a^2 + d^2}}} \qquad (4)$$

The Schlumberger method [1-3] uses four electrodes in the same line, with the distance $L_1 = L_3 = b$ (Fig. 1) and $L_2 = a$. In usual field operations, the inner (potential) electrodes remain fixed, while the outer (current) electrodes are adjusted to vary the distance ***b***. The spacing ***b*** must be larger than 3***a***. Also, the ***a*** spacing may sometimes be adjusted with ***b*** held constant in order to detect the presence of local inhomogeneities or lateral changes in the neighborhood of the potential electrodes. According to eq. 2 the apparent soil resistivity of the soil ρ is given by the following equation [2]:

$$r = p \cdot R \cdot \frac{(a + b)}{a} \cdot b \qquad (5)$$

The dipole-dipole method [2] is one member of a family of arrays using dipoles (closely spaced electrode pairs) to measure the curvature of the potential field. If the separation between both pairs of electrodes (Fig. 1) is the same $\alpha = L_1 = L_3$, and the separation between the centers of the dipoles is restricted to $L_2 = a(n+1)$, the apparent resistivity is given by:

$$r = p \cdot R \cdot a \cdot n \cdot (n+1) \cdot (n+2) \qquad (6)$$

The dipole-dipole method is especially useful for measuring lateral resistivity changes and has been increasingly used in geotechnical applications.

3. Estimation of two-layer earth structure parameters

The parameter calculation of the two-layer earth structure is an optimization problem which involves the calculation of three parameters (the soil resistivity ρ_1 of the upper layer, the soil resistivity ρ_2 of the lower layer and the depth h_1 of the upper layer) and the minimization of the objective function [6, 7]. In this paper four different optimization functions (F_1, F_2, F_3, and F_4) have been used.

F_1 represents the relative error between the measured and the optimized data. The computation of the parameters requires the minimization of the function F_1. F_1 is given by the following equation:

$$F_1 = \sum_{i=1}^{N} \left| \frac{r_{ai}^{m} - r_{ai}^{c}}{r_{ai}^{m}} \right| \qquad (7)$$

where r_{ai}^{m} is the i^{th} measurement of the soil resistivity of the soil, using the Wenner method [3] for a distance between two sequentially auxiliary electrodes equal to α, and r_{ai}^{c} is the calculated value of the soil resistivity at distance α between the auxiliary electrodes corresponding to the i^{th} pair of measurements. N is the total number of soil resistivity measurements. The calculation of the soil resistivity is made using equations (8-11) [3, 6]:

$$r_a^c = r_1 \cdot \left(1 + 4 \cdot \sum_n K^n \cdot \left(\frac{1}{\sqrt{A}} - \frac{1}{\sqrt{B}} \right) \right) \qquad (8)$$

where $n = 1 ... \infty$.

K is the reflection coefficient:

$$K = \frac{r_2 - r_1}{r_2 + r_1} \qquad (9)$$

A and B are two parameters, which are given by the following equations:

$$A = 1 + \left(\frac{2 \cdot n \cdot h_1}{a} \right)^2 \quad (10)$$

$$B = A + 3 \quad (11)$$

Another objective function, which will be used by the GA, is the absolute error, which is given by the formula:

$$F_2 = \sum_{i=1}^{N} \left| r_{ai}^{m} - r_{ai}^{c} \right| \quad (12)$$

An extra objective function, which will be used, is the square error, which is given by the formula:

$$F_3 = \sum_{i=1}^{N} \left(\frac{r_{ai}^{m} - r_{ai}^{c}}{r_{ai}^{m}} \right)^2 \quad (13)$$

Also, the L-infinity norm has been used as an objective function for the optimization of the values of the parameters of two-layer earth structure parameters.

$$F_4 = \max_i \left| r_{ai}^{m} - r_{ai}^{c} \right| \quad (14)$$

for i=1,…,N.

4. Application of genetic algorithm

Genetic algorithms are adaptive algorithms widely applied in science and engineering for solving practical search and optimization problems. Many problems can be efficiently tackled by using a GA approach because correlation between the variables is not a problem. The basic GA does not require extensive knowledge of the search space, such as solution bounds or functional derivatives [10, 11].

This paper proposes a methodology, which uses the developed GA for the optimization of the parameters of the soil structure parameters. This GA has been developed using Matlab. The same GA produces excellent results in several optimization problems [6, 12-15]. It has been applied for the computation of earth structure parameters [6, 7], factorization of multidimensional polynomials [12], filter design [13], calculation of arc parameters at polluted insulators [14] and estimation of electrostatic discharge current parameters [15].

The applied GA starts with a randomly generated population of P_s=30 chromosomes. It generates 30 random values for the first layer resistivity ($0<\rho_1<1500$), 30 random values for the second layer resistivity ($0<\rho_2<1500$) and 30 random values for the thickness of first layer ($0<h_1<6$). Each parameter is converted to a 20-bit binary number. Each chromosome has variables m=3 so 60-bits are required for the chromosome. Each pair of parents with crossover generates N_c=4 children. The crossover begins as each chromosome of any parent is divided into N_p=6 parts, the pair of parents interchange their genetic material. After crossover there is a P_m=10% probability of mutation. Through reproduction the population of the "parents" is enhanced with the "children". By applying the process of natural selection only 30 members survive. These are the members with the lower values of the objective function, since a minimization problem is solved. In this paper four different optimization functions have been used. By repeating the iterations of reproduction under crossover, mutation and natural selection, GAs can find the minimum error. The best values of the population converge at this point. The termination criterion is fulfilled when the mean value of the optimization function in the P_s-members population is no longer improved or the number of iterations is greater than the maximum defined number of iterations N_{max}=50.

5. Results

Experimental results, which have been published by Del Alamo [4], are presented in Tab. 1.

Table 1. Experimental results [4]

α_i [m]	ρ_i [Ωm]	α_i [m]	ρ_i [Ωm]
2.5	451.6	1	136
5.0	366.7	2	140
7.5	250.2	4	214
10.0	180.0	10	446
12.5	144.2	20	685
15.0	120.2	40	800
20.0	115.5		
25.0	96.5		

Experimental results, which have been published by Seedher and Arora [5], are presented in Tab. 2.

Table 2. Experimental results [5]

α_i [m]	ρ_i [Ωm]	α_i [m]	ρ_i [Ωm]
1	693.74	2.5	320
2	251.62	5.0	245
3	84.56	7.5	182
4	37.64	10.0	162
5	25.32	12.5	168
		15.0	152

Table 3. Our experimental results (4/11/2006 & 8/2/2007)

α_i [m]	ρ_i [Ωm]	α_i [m]	ρ_i [Ωm]
1	87.9	1	40.8
2	62.8	2	40.3
3	56.5	3	38.2
4	37.7	4	32.7
5	29.5	5	26.7
6	26.4	6	24.5
8	17.6	8	20.1
10	15.7	10	17.6

The measurements, which are presented in Tab. 3, have been carried out at the Technological Education Institute of Athens Campus [7] applying the Wenner method. Four electrodes of 50cm in length have been used, which were placed on a straight line. The conductors that connected the auxiliary electrodes with the ground meter had a cross section of $2.5mm^2$. The distance between two successive electrodes was α and it was varying with discrete steps.

The GA was applied on the experimental data (Tabs. 1-3), which were obtained by the experimental setup described in second section. The α_i and ρ_i values were used as input data in each GA application.

In Tabs 4 - 9 the optimized values of the two-layer earth structure parameters and the errors for each objective function are presented. Useful conclusions about the accuracy of the equation can be drawn from the values of the errors F_1, F_2, F_3 and F_4.

Both first columns of Tab. 1 are the input data of the GA for the calculation of the earth parameters presented at Tab. 4, while both last columns of Tab. 1 are the input data of the GA for the calculation of the earth parameter of Tab. 5.

Table 4. Genetic algorithm results (Tab. 1)

	F_1	F_2	F_3	F_4
ρ_1 [Ωm]	499.827	480.293	492.161	490.842
ρ_2 [Ωm]	89.847	87.387	93.785	93.687
h_1 [m]	4.409	4.594	4.379	4.507
Error	0.203	37.166	0.011	9.095

Table 5. Genetic algorithm results (Tab. 1)

	F_1	F_2	F_3	F_4
ρ_1 [Ωm]	132.186	123.736	124.957	109.353
ρ_2 [Ωm]	1060.623	1002.308	1146.874	1049.927
h_1 [m]	2.998	2.376	2.750	2.038
Error	0.275	89.548	0.0151	26.955

Both first columns of Tab. 2 are the input data of the GA for the calculation of the earth parameters presented at Tab. 6, while both last columns of Tab. 2 are the input data of the GA for the calculation of the earth parameter of Tab. 7.

Table 6. Genetic algorithm results (Tab. 2)

	F_1	F_2	F_3	F_4
ρ_1 [Ωm]	950.159	971.111	900.098	950.012
ρ_2 [Ωm]	5.000	5.015	5.000	5.938
h_1 [m]	1.061	1.052	1.094	1.062
Error	0.418	18.646	0.079	9.637

Table 7. Genetic algorithm results (Tab. 2)

	F_1	F_2	F_3	F_4
ρ_1 [Ωm]	367.739	377.912	360.916	350.171
ρ_2 [Ωm]	143.569	145.336	142.601	143.626
h_1 [m]	2.708	2.500	2.875	2.930
Error	0.165	32.955	0.008	9.166

Both first columns of Tab. 3 are the input data of the GA for the calculation of the earth parameters presented at Tab. 8, while both last columns of Tab. 3 are the input data of the GA for the calculation of the earth parameter of Tab. 9.

Table 8. Genetic algorithm results (Tab. 3)

	F_1	F_2	F_3	F_4
ρ_1 [Ωm]	91.355	91.295	84.341	89.234
ρ_2 [Ωm]	14.066	15.632	14.063	11.300
h_1 [m]	2.107	2.052	2.229	2.129
Error	0.399	19.609	0.031	6.305

Table 9. Genetic algorithm results (Tab. 3)

	F_1	F_2	F_3	F_4
ρ_1 [Ωm]	42.623	42.502	42.186	42.185
ρ_2 [Ωm]	12.486	11.302	13.495	15.624
h_1 [m]	3.491	3.751	3.289	3.125
Error	0.198	7.298	0.007	2.190

An example of the convergence of two-layer earth parameters is presented in Fig. 2.

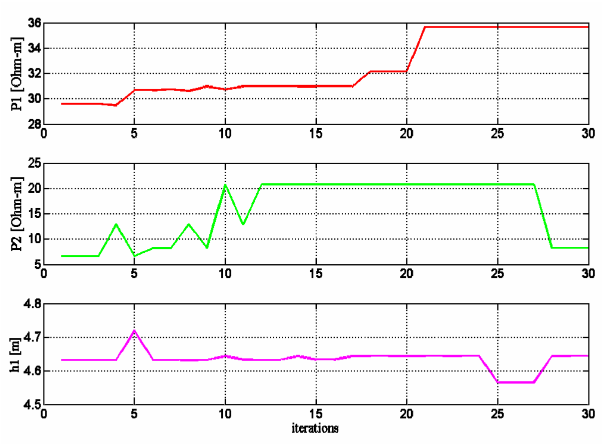

Fig. 2. Convergence of two-layer earth structure parameters.

In Figs. 3 - 8 common graphs of the experimental data of the apparent soil resistivity and the apparent soil resistivity for the optimized parameters values are illustrated.

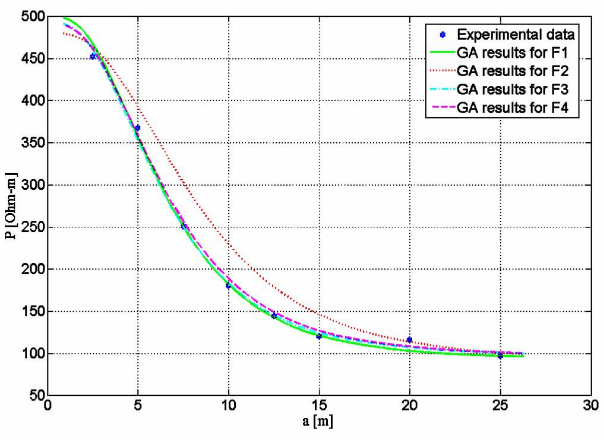

Fig. 3. Comparison between the experimental data of soil resistivity and the soil resistivity for the optimized parameter values of Tab. 4.

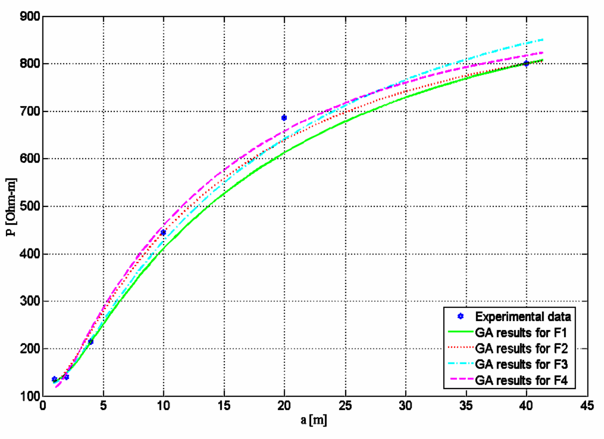

Fig. 4. Comparison between the experimental data of soil resistivity and the soil resistivity for the optimized parameter values of Tab. 5.

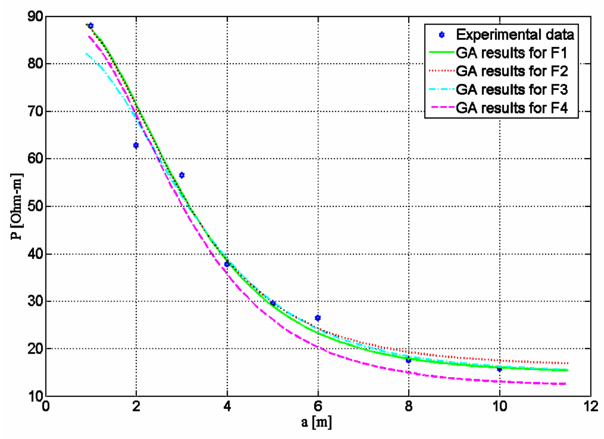

Fig. 7. Comparison between the experimental data of soil resistivity and the soil resistivity for the optimized parameter values of Tab. 8.

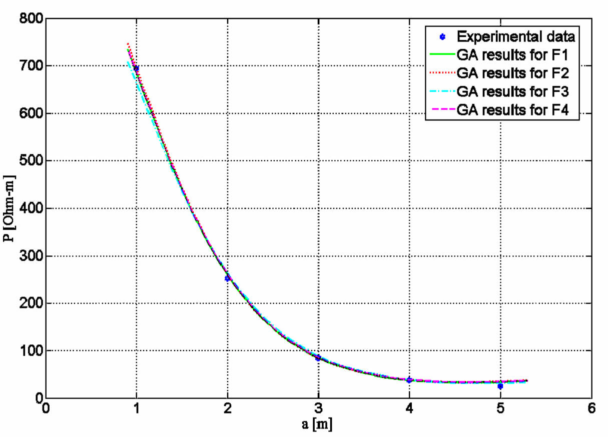

Fig. 5. Comparison between the experimental data of soil resistivity and the soil resistivity for the optimized parameter values of Tab. 6.

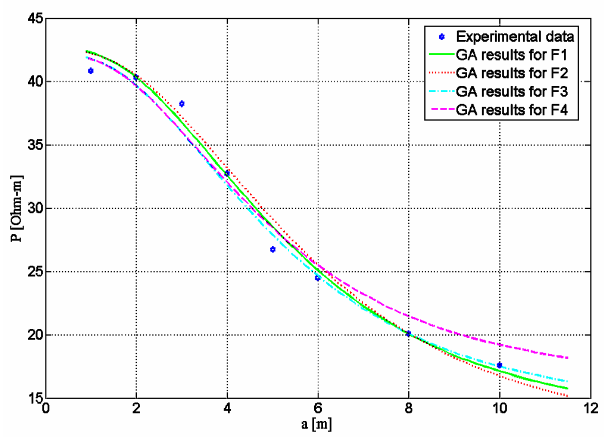

Fig. 8. Comparison between the experimental data of soil resistivity and the soil resistivity for the optimized parameter values of Tab. 9.

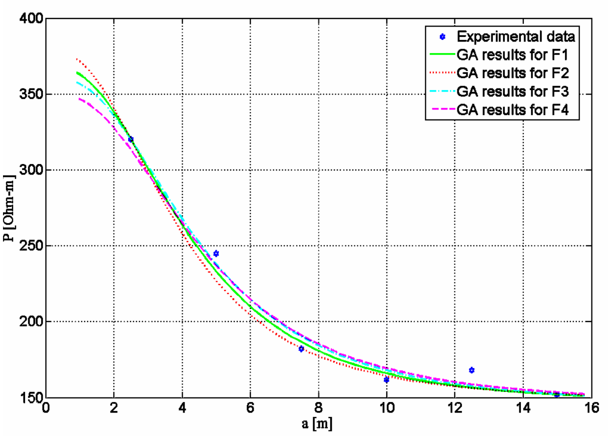

Fig. 6. Comparison between the experimental data of soil resistivity and the soil resistivity for the optimized parameter values of Tab. 7.

Comparison of the graphs provides clear evidence that soil resistivity measurements are best approached when the relative error is being used as an objective function. Besides that, the L-infinity norm function gives the worst fitting at most experimental data. In the case of Fig. 5 all objective functions give similar results. Comparing the curves of Figs. 3-8 for each equation it can be concluded that the equations can be sorted as follows: F_1, F_3, F_2 and F_4, with F_1 giving the best result. Comparing the runtime for each different objective functions (eq. 7 and eqs. 12-14) it can be concluded that the equations can be sorted as follows: F_4, F_2, F_1, and F_3, with F_4 giving the fastest result.

6. Conclusions

In this paper the GA has been successfully applied for the estimation of the parameters of the two-layer earth structure. By using different objective functions (eq. 7 and eqs. 12-14) for the application of the GA algorithm at experimental data coming from soil parameter measurements, it has been shown that, in most cases, the relative error function (eq.7) provides the best fit to the experimental data. The square error, given by eq. 13, is the second preferable function.

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