A computer model for the interpretation of soil resistivity measurement data collected in the vicinity of grounding systems

B. Handziski², V. Handziski¹ V. Dimcev² & P. Vrangalov²
¹Technical University, Berlin, Germany
²Department of Electrical Measurements and Materials
Faculty of Electrical Engineering Skopje
St. Cyril & Methodius University, Macedonia

Abstract

The accuracy of the soil parameters obtained by the interpretation of soil resistivity measurement data is essential for an accurate parametric grounding analysis. Ideally, soil resistivity measurements should be made in the absence of buried metallic structures and interpreted by computer models tailored for that purpose. However, there are cases when the soil resistivity measurements have to be made in the presence of grounding systems and to be interpreted by the computer models tailored to take into account the influence of the metallic structures. This paper presents a methodology and a computer model tailored to interpret this kind of measurement data so to obtain as accurate soil models as possible. The computer model has been verified against experiments. It is shown that the accuracy of the soil structure parameters obtained by this model, is within ±4%.

1 Introduction

The computer-based analyses of grounding systems buried in non-uniform soils carried out over the past two decades undoubtedly have shown that their performance is heavily dependent on soil parameters. Thus, these sophisticated computer programs generated the need to improve the methodology for generating as accurate multilayer soil models as possible. Consequently, a number of computer-based techniques for the interpretation of soil resistivity measurement data collected in native soils have been developed [1,2,3].
The accuracy of the obtained soil models has been tested using scale-down soil structures constructed in electrolytic tank [4,5,6]. Our computer model WINTEQ0 developed for the interpretation of soil resistivity measurements, beside the interpretation technique comprises the model of the measurement system and estimation procedure. In the case of the Wenner method four ground probes are driven into the soil along a straight line at identical spacing $a_i$ (Fig.1).

For every equal electrode spacing $a_i$ the Wenner configuration will yield the set data $(R_{mi}, a_i)$ i.e. $(\rho_{mi}, a_i)$, necessary to obtain the measured curve $\rho_{mi}=f(a_i)$, where:

$$\rho_{mi} = 2 \cdot \pi \cdot a_i \cdot R_{mi}$$  \hspace{1cm} (1)

The basic idea is to adjust the resistivities $\rho_x$ and the thicknesses $h_i$ of the layers in such a way that the computed $\rho_{ci}=f(a_j)$ and measured $\rho_{mi}=f(a_j)$ values are as close as possible. It should be noted that the calculations of $\rho_{ci}=f(a_j)$ by the algorithms based on the classical electrostatic image method require large computation time. To reduce the computation time of $\rho_{ci}=f(a_j)$ our algorithm is based on a method where the depths of the layers are expressed as a multiple of one common base value $h_0$, following the technique described in [7], were:

$$\rho_{ci} = \rho_x a_i \sum_{0}^{k} \left( \frac{q_{uk}}{\sqrt{a_i^2 + (kh_0)^2}} - \frac{q_{lk}}{\sqrt{4a_i^2 + (kh_0)^2}} \right) + \left( \frac{q_{uk}}{\sqrt{a_i^2 + (H_1 + kh_0)^2}} - \frac{q_{lk}}{\sqrt{4a_i^2 + (H_1 + kh_0)^2}} \right)$$  \hspace{1cm} (2)

$H_1$ is depth of the first layer, $h_0$ is base value (largest common divider) of the depths of the layers, $k$ is the total number of the optic images and $q_{uk}, q_{lk}$ are the
intensities of the images at the upper and lower interface of the layer at distance 
$r=kh_0$ from the source located at the surface of the soil. 
An additional reduction of the computation time has been achieved by combining 
the images in groups subsequently used for considering reflections in multilayer 
soils. Hence, the computation time achieved is quite reasonable and is less than 
10 times greater than the one required for uniform soils. This gain in computation 
time enables efficient evaluation of the sensitivity factors such as the first and 
second gradient of the distance with respect to the model parameters used in 
the first order iterative scheme as the Marquardt method. Since it is not possible to 
make the computed values exactly equal to the measurements, it is necessary 
mathematically to minimise the sum of the differences between these two values. 
In that regard, least squared minimisation techniques prove to be unavoidable for 
evaluating layer resistivities and thicknesses so to agree with measurements. The 
results obtained are expressed in terms of the error of the parameters versus 
confidence level and pictorial view of how well the estimated soil model fits the 
measurements. Hence, the methodology for interpreting soil measurement data 
collected in native soils provides the best estimated parameters $\rho_n$, $h_l$ of the soil 
layers.

Figure 2 shows the measured curve $\rho_m=f(a)$ constructed from the measurement 
data collected in our grounding systems experimental area “Mralino” on 6th of 
June 2002. The experimental area is carefully selected so as to have horizontal 
stratification and homogenous and isotropic resistivity of the layers.

![Graph showing calculated and measured values of resistivity against probe spacing]

Figure 2: Interpretation of Wenner soil resistivity measurement data

Our computer program WINTEQ0 shows that the best agreement between the 
calculated $\rho_c$ and the measured $\rho_m$ values is achieved with the following 
parameters of the seven layer soil model: $\rho_1=36.0\Omega m$; $\rho_2=15.0\Omega m$; $\rho_3=47.0\Omega m$;  
$\rho_4=16.0\Omega m$; $\rho_5=39.0\Omega m$; $\rho_6=27.0\Omega m$; $\rho_7=105.0\Omega m$ and $h_1=0.02m$; $h_2=0.04m$;  
$h_3=0.04m$; $h_4=0.28m$; $h_5=0.36m$; $h_6=4.20m$; $h_7\to\infty$. 

2 Brief description of the problem

The above illustrated efficiency and accuracy of the methodology for generation of soil models from the measurement data collected in the absence of buried metallic structures do not relate generally for the cases where the soil resistivity measurements are to be made in the presence of grounding systems. There are two such cases: when it is necessary analytically to review or evaluate the grid performance, or when it is necessary to measure ground resistance and ground potential rise by Fall-of-Potential method. In that regard, the best information about the soil structure could be obtained when the measurements are made in the vicinity of the grounding system. The problem is that when making soil resistivity measurements in the vicinity of the grounding system its metallic structure lowers measured resistivity values. The results from one detailed study of the influence of buried metallic structures on soil resistivity measurements carried by Ma and Dawalibi were published in [8]. One of the cases analysed has been conducted using one 100mx50m 16-mesh grounding grid buried at a depth of 0.5m in a multilayer soil with the following parameters: \( \rho_1 = 300 \Omega \cdot m; \rho_2 = 500 \Omega \cdot m; \rho_3 = 100 \Omega \cdot m \) and \( h_1 = 0.4m; h_2 = 2.0m; h_3 = 4.7m; h_4 \rightarrow \infty \). The soil resistivity measurements were stimulated by the low frequency grounding analysis computer algorithm described in [8].

![Soil Resistivity Measurement Profile](image)

Figure 3: Plan views of the grid and the measurement profile

Figure 3 shows a plan view of the grid and the Wenner soil resistivity measurement electrode arrangement and profile. The results for the same case, obtained by our computer program WINTEQGRID developed for the computation of the soil resistivity measurement data \( \rho_\alpha = f(a) \) collected in the
presence of buried metallic structures, are shown on Figure 4. As it could be seen they agree extremely well with those published in [8].

![Figure 4: Simulated soil resistivity measurements with and without the grid](image)

The interpretation of soil resistivity data $\rho_{e}=f(a_j)$ with the computer models tailored for the interpretation of the soil measurement data collected in the absence of buried metallic structures will yield rather false values for the soil model parameters. Thus, our computer program WINTEQ0 yields the following parameters of the soil model: $\rho_1=300 \Omega m$; $\rho_2=50 \Omega m$; $\rho_3=8500 \Omega m$; $\rho_4=47 \Omega m$; $\rho_5=170 \Omega m$ and $h_1=0.40m$; $h_2=2.00m$; $h_3=0.40m$; $h_4=60.0m$; $h_5 \rightarrow \infty$ (Fig5).

![Figure 5: The WINTEQ0 interpretation of the simulated values $\rho_e=f(a_j)$](image)
3 Brief description of the approach

To avoid the errors in the values of the soil models generated from the measurement data collected in the vicinity of the grounding systems, for given soil layer resistivities $\rho_i$ and thicknesses $h_i$, the algorithm should compute $\rho_{cl}=f(a_i)$ values taking into account the influence of the not energized metallic structure. For that purpose there is a need to compute the equivalent circuit model of the earth embedded electrodes of the Wenner soil resistivity arrangement, the grounding system and the conductive soil. Since the grid conductors are embedded at a certain depth of the multilayer soil, it is necessary, firstly, to rearrange the starting point for the generation of the images of the point current sources in such way to obtain the common value $h_0$ to be independent of the depth of the source. This will enable the derivation of the expression for the potential due to a point source buried at any depth. The potential in any point $(x, y, z)$ is a function of the position $(x, y, z)$, the position of the point source and the soil parameters. In the case of grounding grid with $i$ conductors, to obtain the potential $V_i(x,y,z)=R_i(x,y,z)I_i$, where $I_i$ is the total current emanating from the conductor, it is necessary to integrate this function over its entire length. If the conductor is portioned into $n$ segments the potential at point $(x,y,z)$ is computed from the superposition from all segments: $V_i(x,y,z)=\sum R_i(x,y,z)I_i$. This equation can be also used to compute the potential of a segment $k$ as a function of the currents $I_k$: $V_i=\sum V_i(x_k,y_k,z_k)=\sum R_i I_i$, where $(x_k,y_k,z_k)$ is a point on the surface of the segment $k$. Writing such an expression for every segment results in the set of equations:

\[
[V] = [R] \cdot [I]
\]

where:
- $[V]$ is the vector of segments voltages
- $[I]$ is the vector of segment total current
- $[R]$ is an $n \times n$ matrix

In the above equations, the resistance $R_{ki}$ may be self resistance of a cylindrical conductor segment or a planar electrode oriented in any of the $x$, $y$, $z$ direction, mutual resistances between two cylindrical conductor segments, or two planar electrodes, or between a cylindrical conductor segment and a planar electrode, and mutual resistances between a point and a cylindrical conductor segment or a planar electrode oriented in any of the $x$, $y$, $z$ direction. The model, among all, enables the computation of the potentials $V_2$ and $V_3$ of the potential probes 2 and 3 of the Wenner soil resistivity arrangement for any probe spacing $a$, due to the current $I=IA$ injected in the current probe I and emanating from the current probe 4 and affected by the buried not energized grid (Fig1). Once, the potential difference $\Delta V_i = V_{2i} - V_{4i}$ is computed, the resistance $R_{mi}$ is obtained through the relation $R_{mi} = \Delta V_i/I = \Delta V_i$ and the apparent resistivity $\rho_{cl} = f(a_i)$ through the relation (I). Hence, the computed values of the apparent resistivity $\rho_{cl} = f(a_i)$ reflect the influence of the not energized nearby grid, too.
The computer program WINTEQGRID based on the methodology described, is computing \( \rho_{ci} = f(a_i) \) values with and without the grounding grid and adjusting the soil layers’ resistivities \( \rho_i \) and thicknesses \( h_i \) in such a way that the computed values \( \rho_{ci} = f(a_i) \) fit the measured values \( \rho_{me} = f(a_i) \) as well as possible. The methodology has been evaluated and validated against measurements.

4 Results

Within the framework of the project “Improvement of the procedures for the assessment of the risk from electric shocks”, financed by the government of the Republic of Macedonia, last two years we have followed the seasonal variations of the soil structure parameters, grounding resistance, grounding potential rise, touch voltages and body currents of the grids constructed for that purpose in the experimental area “Mralino”, near Skopje. Hundreds of soil resistivity data sets were collected in the vicinity of the grids and interpreted to generate the actual soil models. It was proved that the best information about the actual soil structure could be obtained through the measurements conducted along parallel profiles to the grids, located away from them 10% of the length of their top perimeter.

Figure 6 shows a plan view of one experimental 10x10m four mesh square grid buried at a depth of 0.5m and the Wenner soil resistivity measurement profile away 1m from its perimeter.

![Figure 6: Plan views of the grid and the measurement profile](image)

Table 1 shows the results from the soil resistivity measurement data collected 7\textsuperscript{th} of June 2002 along the measurement profile shown on Figure 6.
154  Computational Methods and Experimental Measurements XI

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{i[m]}$</td>
</tr>
<tr>
<td>$p_{m1}[\Omega m]$</td>
</tr>
<tr>
<td>$a_{i[m]}$</td>
</tr>
<tr>
<td>$p_{m2}[\Omega m]$</td>
</tr>
</tbody>
</table>

Soil model 1 with the following parameters:

$$
\rho_1 = 300 \Omega m; \quad \rho_2 = 24 \Omega m; \quad \rho_3 = 97 \Omega m; \quad \rho_4 = 20 \Omega m; \quad \rho_5 = 49 \Omega m; \quad \rho_6 = 16 \Omega m; \\
\rho_7 = 120 \Omega m; \quad \rho_8 = 80 \Omega m; \quad \rho_9 = 150 \Omega m \text{ and } h_1 = 0.01 m; \quad h_2 = 0.05 m; \quad h_3 = 0.06 m; \\
h_4 = 0.30 m; \quad h_5 = 0.40 m; \quad h_6 = 3.60 m; \quad h_7 = 0.50 m; \quad h_8 = 2.50 m; \quad h_9 \to \infty
$$

is obtained by the interpretation of the soil measurement data with the computer program WINTEQ0, tailored for the interpretation of the soil measurement data collected in the absence of buried metallic structures. Figure 7 shows the pictorial view of how well the calculated values $\rho_{ci} = f(a_i)$ fit the measured values $\rho_{mi} = f(a_i)$.

![Figure 7: The WINTEQ0 interpretation of the measured values $\rho_{ci} = f(a_i)$](image)

Soil model 2 with the following parameters:

$$
\rho_1 = 300 \Omega m; \quad \rho_2 = 24 \Omega m; \quad \rho_3 = 97 \Omega m; \quad \rho_4 = 20 \Omega m; \quad \rho_5 = 60 \Omega m; \quad \rho_6 = 27 \Omega m; \quad \rho_7 = 95 \Omega m; \\
\text{and } h_1 = 0.01 m; \quad h_2 = 0.05 m; \quad h_3 = 0.06 m; \quad h_4 = 0.30 m; \quad h_5 = 0.16 m; \quad h_6 = 3.60 m; \quad h_7 \to \infty.
$$

is obtained by the interpretation of the soil measurement data with the computer program WINTEQGRID, tailored for the interpretation of the soil measurement data collected in the vicinity of the buried metallic structure of the grid.
In order to evaluate and validate the efficiency and the accuracy of the proposed methodology i.e. of the computer model WINTEQGRID for generation soil models from the measurement data obtained in the vicinity of grounding grids, the grounding resistance $R$ and the ground potential rise $V$ (GPR) of the grid shown on Figure 8 were determined analytically and experimentally by Fall-off-Potential Method (FOP), using both of the generated soil models 1 and 2. The return electrode $R$ represented by a 2x2m square four mesh grid was located at a distance $D=38m$ from the main grid $E$. 

![Figure 8: 2D geometry of the FOP Method](image)

Figure 9 shows the computed values of the earth surface potential along the FOP profile, as well as their measured values, for $I=1A$. As it could be seen, the measured values agree extremely well with those computed with the soil model 2 generated by the computer model WINTEQGRID. 

![Figure 9: Computed and measured surface potentials along the FOP profile](image)
The required potential probe position \( x_0 = \frac{y}{D} = 0.618 \), for the determination of the grounding resistance \( R \) and the \( GPR-V \), has been determined by our computer program ETF-OSIP3, developed for low frequency analysis of the grounding systems. At that potential probe position the grounding grid resistances computed with the soil model 1 and 2 are \( R = 1.59\Omega \) and \( R = 1.91\Omega \), respectively. The measured grid resistance is \( R = 1.96\Omega \). As it could be seen, the measured and the computed value for soil model 2 differ less than \( \pm 4\% \), while for soil model 1 the difference is \( -23\% \). The same conclusion holds for the \( GPR-V \), too. It should be noted that values obtained for \( R \) and \( V \) with the model 1, are not conservative.

5 Conclusion

The paper presented an advanced methodology and computer model for the interpretation of soil resistivity measurement data obtained in the vicinity of the buried grounding systems. To underline the importance of interaction between computational methods and experimental measurements, the computer model has been validated and verified against experiments. It was shown that the computed and the measured values of the grounding resistance and grounding potential rise of the grounding systems buried in the soil structures generated by this model, differ less than \( \pm 4\% \), proving that this computer model is reasonable accurate.

References


