A Technique for Predicting Soil Resistivity and Earthing Resistance of Deep Earthing Electrodes

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ABSTRACT

The paper develops a technique for predicting from limited preliminary test earth rods the effective resistivity to use to calculate the resistance of deep earth electrodes. Such prediction produces considerable saving in electrode and installation costs necessary to achieve a required earth resistance value. The technique extrapolates preliminary test earth rods results of three meters or less in depth as a basis to a factor of up to eight times the known test rod depth within reasonable accuracy. The relatively constant ratio of change of the soil resistivity is important for an accurate prediction. The predicted values can then be used to assess the probable effectiveness of the deep earth electrodes in the evaluation of alternate earth systems. A favorable comparison has been obtained between the average predicted values and the average actual field test results.

Key words: Soil, Resistivity, Earthing Electrodes

INTRODUCTION

The earthing of electrical installations is primarily concerned with safety; in particular. The objective of designing safe grounding system is to provide easy and shortest path to the flow of fault current without exceeding the operation and equipment limits and adversely affecting the continuity of service [1]. The safety of personnel working in electrical system has always been of primary concern. It is also to make the site safe for sensitive electronic equipment under electrical fault conditions. The grounding electrode system protects equipment and people from electricity that has gone out of its indended path. There are two types of grounding electrode systems, simple and complex. Simple grounding system consists of a single ground electrode driven into the ground. Complex grounding system consists of multiple ground electrodes [2]. Complex networks dramatically increase the amount of contact with the surrounding earth and lower ground resistances. In this design, more than one electrode is driven into the ground and connected in parallel to lower the resistance. For additional electrodes to be effective, the spacing of additional rods needs to be at least equal to the depth of the driven rod. Without proper spacing of the ground electrodes, their spheres of influence will intersect and the resistance will not be lowered.

A good ground electrode system is important for the protection of an overall system facility. There are many factors that determine how well a ground electrode system performs. Two major parameters are its resistance to remote earth and the resistivity of the local soil. Each of these values can be measured to help determine and design the best solution for the ground electrode system [3]. The resistance to remote earth of the grounding system needs to be at a minimum in order to sustain its effectiveness [4]. The second major factor in determining how well a grounding system performs is the resistivity of the local soil. Soil resistivity has a direct effect on the resistance of the grounding system [5]. Poor grounding not only contributes to unnecessary downtime, but a lack of good grounding is also dangerous and increases the risk of equipment failure.

Low earth resistance is essential to meet electrical safety standards. There is a good deal of confusions as to what constitutes a good ground and what the ground resistance value needs to be [6]. Ideally a ground should be of zero ohms resistance. There is not one standard ground resistance threshold that is recognized by all agencies. The goal in ground resistance is to achieve the lowest ground resistance value possible that makes sense economically and physically. The resistance figure
can vary from 10 ohms for lightning protection to below 0.1 ohm for many sites where protective devices must operate in a very short time due to the large fault currents involved [7-8]. Rods must be spaced far enough apart so as to avoid the effects of the higher resistance shells, so that the voltage rise around each does not affect the other [9]. Soil resistivity data is required prior to a site-specific grounding system design. Soil resistivity data is the key factor in designing a grounding electrode system for a specific performance objective [10]. Earth resistivity measurements are shallowly inserted measurements electrodes, typically less or equal 0.5 m, to determine the resistance of deeper layer [11]. The surface soil is essentially being used as an interface to measuring the electrical resistivity of deeper structures.

The objective of this paper is to provide a technique for the extrapolation of the preliminary test earth rod data as a basis for predicting the soil resistivity and resistance for deep earth electrodes. The preliminary tests are limited to three meters or less in depth. Using the preliminary test, the soil resistivity and earth resistance values up to 20 meters or more are projected.

**Technique Analysis**

The reason for measuring soil resistivity when selecting a site is to find a location that has the lowest possible resistance. Correct data on resistivity of soil at greater depths is of special importance for designing of deep anode ground-bed in impressed cathodic protection system. The more data available, the more confidence you can have in the calculation. Once a site has been selected, soil resistivity test should be carried out to give the information necessary to design and build a ground field that will meet the safety requirements.

Soil resistivity will vary throughout the year in those areas where seasonal changes bring about a change in the moisture and temperature content of the soil. Since, soil and water are generally more stable at deeper strata it is recommend that the ground rods be placed as deep as possible into the ground. Soil resistivity of the grounding medium is of prime importance in siting ground electrodes on land. It does not have a constant value throughout the zone of investigation, but varies widely in vertically distinct strata. It is, therefore, essential in the investigation of sites for earth electrodes that as accurate resistivity data as possible are obtained for the sites. Measurements of resistivity at various depths are required for adequate evaluations of sites.

Based on field measurements obtained from actual field test earth rod [12], it was observed that, a logarithmic type relationship was eventually established between the known values of soil resistivity and depth of burial of electrodes. A general equation was given which closely duplicated the actual soil resistivity values for individual known earth rod test results. Then the value of the soil resistivity depending on the depth of burial x is statistically expressed by:

$$\rho_x = \rho_1 - C_\rho (k + \ln x)$$  \hspace{1cm} (1)

Where: x = distance between the selected points used for projection in meters  
L_x = depth of \( \rho_x \)  
L_1 = depth of \( \rho_1 \)  
\( \rho_1 \) = known value of soil resistivity at a depth L_1  
\( C_\rho \) = Soil resistivity constant determined from the known test data  
\( \rho_x \) = predicted soil resistivity value to be determined at a depth L_x

From the results of the limited preliminary field test earth rods an empirical equation can be developed between the known values of soil resistivity and rod resistance within the first few meters of depth which closely approximated the k and \( C_\rho \) constant values.
Where: \( \rho_1 \) and \( \rho_2 \) = selected known resistivity values used for projection
\( R_1 \) and \( R_2 \) = selected known resistance values used for projection

\[ n = -1 \quad \text{if} \quad \rho_1 < \rho_2, \quad n = +1 \quad \text{if} \quad \rho_1 > \rho_2. \]

\[
C_p = \frac{\rho_1 - \rho_2}{k + \ln (L_2 - L_1)}
\]

Where: \( L_1 \) = depth of \( \rho_1 \),
\( L_2 \) = depth of \( \rho_2 \)

Illustrating Example

Sometimes, the top soil layer had a high soil resistivity value and the preliminary earth system design indicated a very extensive electrode arrangements would be required unless deep earth rods could be used to lower the resistance of the earth system. A tabulation of the soil resistivity measurements and earth resistance measurements at various depths is shown in Table 1. This table gives the results of actual limited preliminary field test. The preliminary test earth rods were limited to nearly three meters in depth.

Table 1: preliminary earth field test data

<table>
<thead>
<tr>
<th>Depth Meters</th>
<th>Resistance ohms</th>
<th>Resistivity ohm meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6 *</td>
<td>1200*</td>
<td>975*</td>
</tr>
<tr>
<td>1.2</td>
<td>1200</td>
<td>1698</td>
</tr>
<tr>
<td>1.8</td>
<td>1150</td>
<td>2271</td>
</tr>
<tr>
<td>2.4</td>
<td>1150</td>
<td>2886</td>
</tr>
<tr>
<td>3.1*</td>
<td>1100*</td>
<td>3328*</td>
</tr>
</tbody>
</table>

* Values used for Projection

The procedures of the calculations are given in the following step:

First

- The extrapolation of the actual preliminary earth rod test data has been done by selecting two known values within the first few meters of depth.

- Then, Projecting the resistivity and resistance values to a factor of up to 8 times the known depth values

Second

- Determine \( k \) from Equation (2), where:

\[
\rho_1 = 975 \text{ ohm.m} \quad \rho_2 = 3328 \text{ ohm.m}
\]
Then,

$$
k = \left[ \frac{3328 \times 1200 \times 1.6}{974 \times 1100} \right]^{-1} = 0.168.
$$

Third

- Determine $C_\rho$ from Equation (3), where:

$$
L_1 = 0.6 \text{ m}, \quad L_2 = 3.1 \text{ m}.
$$

Then,

$$
C_\rho = \frac{975 - 3328}{0.168 + \ln 2.5} = \frac{-2353}{1.08} = -2179.
$$

Fourth

- Solve for $\rho_x$ at $L_x = 24.4$ m from Equation (1)

$$
\rho_x = 975 - (-2179)[0.168 + \ln x]
$$

$$
x = L_x - L_i = 24.4 - 0.6 = 23.8 \text{ m}.
$$

$$
\rho_x = 975 - (-2179)[0.168 + \ln 23.8] = 8248 \text{ ohm.m}
$$

- Solve for $R_x$ at $L_x = 24.4$ meters using the equation

$$
R_x = \frac{\rho_x}{2\pi L_x} \left[ \ln \left( \frac{8L_x}{d} \right) - 1 \right]
$$

where $d$ (diameter) = 0.016 meters

$$
R_x = \frac{8248}{2\pi (24.4)} \left[ \ln \left( \frac{8(24.4)}{0.016} \right) - 1 \right] = 452 \Omega
$$

- The actual resistance field test at this depth = 450 $\Omega$

RESULT AND DISCUSSIONS

The main function of this paper is to suggest a technique to extrapolate a limited preliminary earth test data up to eight times the known test rod depth and within reasonable accuracy. The preliminary test is limited to three meters in depth.

Table 2 summarizes resistance and resistivity measured at various depths as well as the calculated resistivity and resistance values using the proposed technique. In this table, the resistivity decreases with depth. It is shown that the degree of imprecision introduced is negligible.

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Table 2: A comparison between the average predicted and average actual values
(Soil resistivity decreased with depth)

<table>
<thead>
<tr>
<th>Depth</th>
<th>Predicted (Average Value)</th>
<th>Actual (Average Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>ρ</td>
</tr>
<tr>
<td>3.0</td>
<td>68</td>
<td>272</td>
</tr>
<tr>
<td>4.6</td>
<td>46</td>
<td>252</td>
</tr>
<tr>
<td>6.1</td>
<td>34</td>
<td>238</td>
</tr>
<tr>
<td>7.6</td>
<td>27</td>
<td>228</td>
</tr>
<tr>
<td>9.1</td>
<td>23</td>
<td>219</td>
</tr>
<tr>
<td>10.7</td>
<td>21</td>
<td>212</td>
</tr>
<tr>
<td>12.2</td>
<td>19</td>
<td>207</td>
</tr>
</tbody>
</table>

Table 3 summarizes a comparison of the resistivity and resistance of the projected values with the actual field test results obtained with the one 21.3 meter deep rod. From this table, it is shown that the soil resistivity increases with depth. In this case the lower soil layer had a high soil resistivity value, and thus there is no meaning for installing deep ground electrodes. From the obtained results, the technique can be used to predict the practical limits for driving deep rods, and thus eliminate the many extra rods and valuable construction time spent installing deep rods.

Table 3: Comparison of the Actual and Projected Values
(Soil resistivity increased with depth)

<table>
<thead>
<tr>
<th>Depth</th>
<th>Predicted</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>ρ</td>
</tr>
<tr>
<td>4.6</td>
<td>24</td>
<td>136</td>
</tr>
<tr>
<td>6.1</td>
<td>22</td>
<td>157</td>
</tr>
<tr>
<td>7.6</td>
<td>20</td>
<td>173</td>
</tr>
<tr>
<td>9.1</td>
<td>19</td>
<td>185</td>
</tr>
<tr>
<td>10.7</td>
<td>17</td>
<td>196</td>
</tr>
<tr>
<td>12.2</td>
<td>16</td>
<td>205</td>
</tr>
<tr>
<td>13.7</td>
<td>15</td>
<td>213</td>
</tr>
<tr>
<td>15.2</td>
<td>15</td>
<td>220</td>
</tr>
<tr>
<td>16.8</td>
<td>14</td>
<td>226</td>
</tr>
<tr>
<td>18.3</td>
<td>13</td>
<td>232</td>
</tr>
<tr>
<td>19.8</td>
<td>13</td>
<td>237</td>
</tr>
<tr>
<td>21.3</td>
<td>12</td>
<td>242</td>
</tr>
</tbody>
</table>

Using the technique to predict rod resistance, a comparison between the measured resistance for a group of earth rods and the calculated resistance for different types of soils is shown in Figures 1-3. The reference points used for projection are indicated by arrows. The comparison has been shown that the technique gives accurate prediction. The analysis has been shown that the relatively constant ratio of change of the soil resistivity is important for an accurate prediction. As resistivity change per meter becomes more constant there is better agreement between the predicted values and the measured values. However, small rates of change of soil resistivity yield more consistently accurate results than very large rates of change. In Figure 3, the rate of change between 5 meters and 10 meters is a factor of several times greater than the rate of shown above 10 meters and below 5 meters. Thus, the values above 10 meters and below 5 meters will yield a reasonably accurate projection.
Fig. 1. A comparison of actual and projected values (sand soil)

Fig. 2. A comparison of actual and projected values (clay soil)

Fig. 3. A comparison of actual and projected values (rock soil)
CONCLUSION

The paper presents a technique for accurate evaluation of soil resistivity and earth rod resistance values for deep ground electrodes based on preliminary test earth rods. It provides the effect of depth variations in soil. The preliminary test earth rods were limited to there meters or less in depth. The technique has been shown to accurately predict the effectiveness of installing deep earth electrodes and the predicted results are compared to actual earth field test results. The degree of imprecision introduced is negligible. A relatively constant ratio of change of the soil resistivity is important for an accurate prediction. The predicted resistance is well within an acceptable limit for designing an earth electrode system.

REFERENCES