

## **Importance and Need of Accurate Modelling of Soil of High Voltage Substation for Optimal Designing of Grounding System**

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### **Abstract**

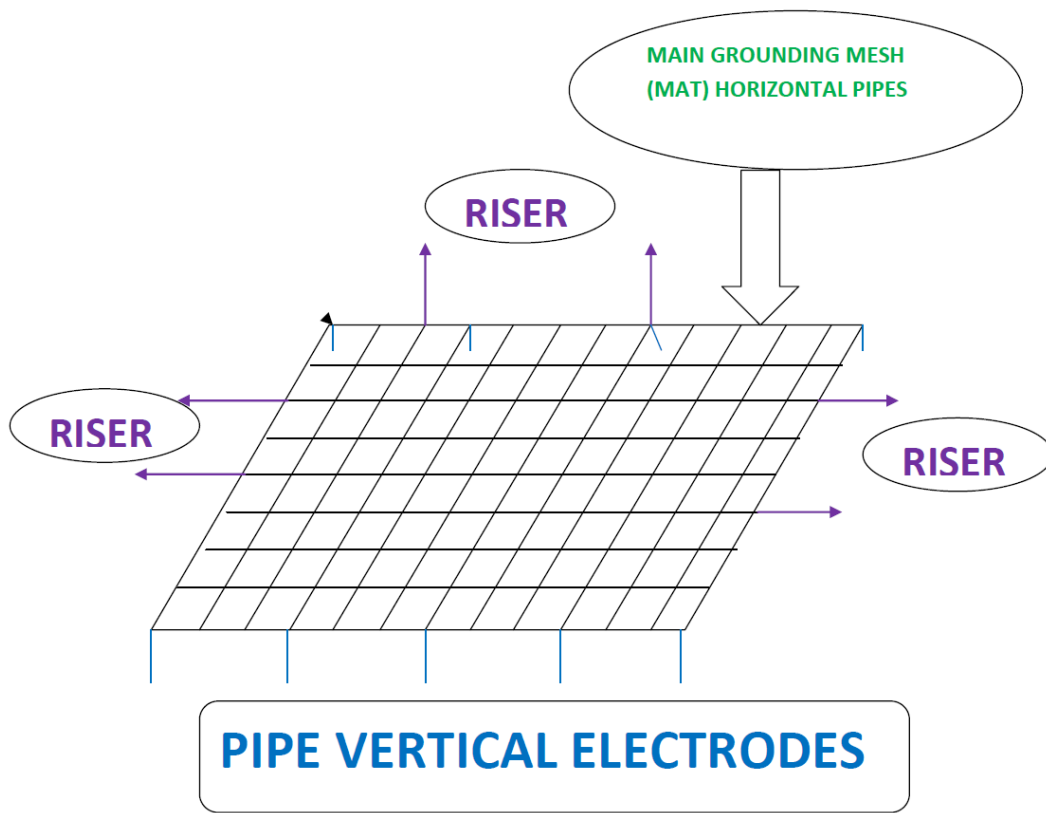
The main objective of grounding electrical systems is to provide a suitably low resistance path for the discharge of fault current which ultimately provide safety to working personnel and costly installed equipments in the substation. The flow of heavy fault current results in rise of potential in the substation area and with respect to remote ground. There is need to ensure that the ground potential rise, and touch and step voltages are within permissible limit, an accurate soil model is required to design grounding system of the substation that ensures that the resistance of the grounding grid through the earth is sufficiently low. Soil resistivity data is of fundamental importance in performing grounding system analyses. Reliable data is required to achieve good correlation between design and measured grounding system performance. This soil model is derived from the accurate soil resistivity measurement structure at the proposed grid location. This paper provides a overview of 4 pin method for measurement of resistivity & provide the method of single and two layer soil modelling of substation area with help of MATLAB GUI software and provides an example to understand the modelling procedure.

**Key Words:** Grounding, Soil Resistivity, Substation, Resistance, Single and Two Layer soil Model

## 1. INTRODUCTION

Grounding/ Earthing means making a connection to the general mass of earth. The use of grounding is so widespread in an electric system that at practically every point in the system, from the generators to the consumers' equipment, earth connections are made.[3,4]

Earlier, the design criterion was to achieve lowest earth resistance, However, the modern design criterion for grounding system is to achieve low earth resistance and also to achieve safe 'step-potential', 'touch potential' and voltage gradient during an earth fault between conductor and any of the earthed bodies in the substation.



**Fig 1 Grounding Mat of the Substation**

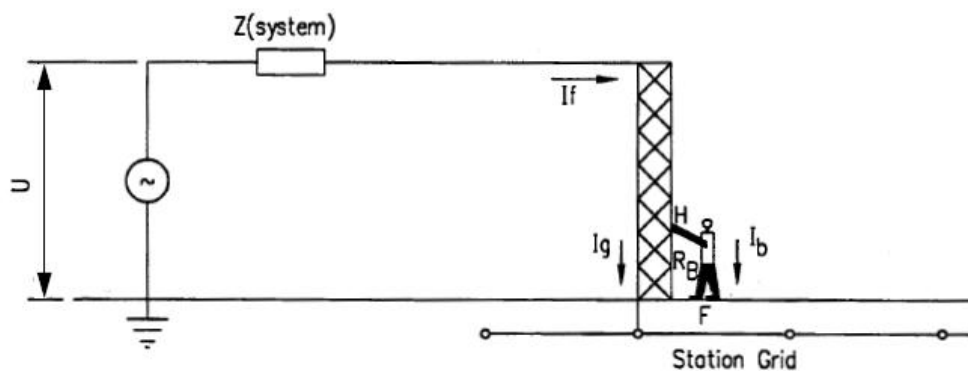
## 2. Step Potential And Touch Potential

During an earth-fault in the substation the earth fault current flows from the fault-point to earth via the metallic path having certain total resistance  $R$ . This flow of fault current ( $I_f$ ) flowing through resistance  $R$  causes a voltage drop  $V = I_f R_0$ . This voltage drop results in a voltage-gradient along the substation floor during the earth faults. This voltage gradient should be held in safe limits by proper design of station grounding system.[3]

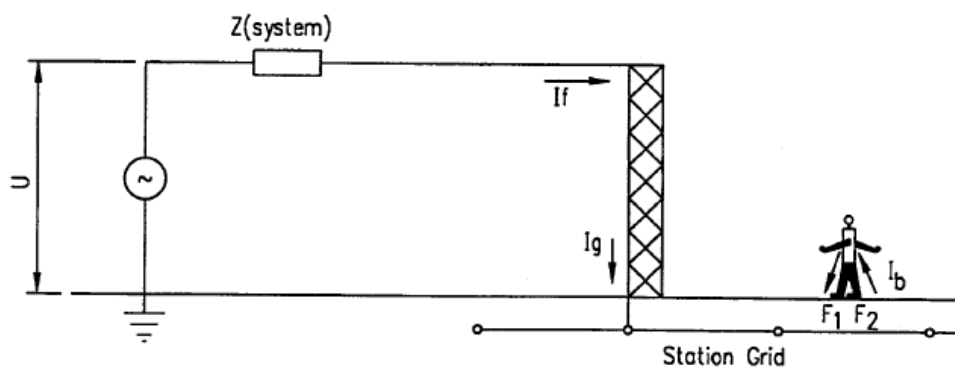
A operation maintenance person is subjected to 'step potential' and 'Touch Potential' during an earth-fault in the substation. The '**Step-Potential**' is defined as the potential difference between two steps of a person standing on the substation floor during the flow of earth fault current. The '**Touch Potential**' is defined as the potential difference between a step and the tip of the raised hand touching a substation structure during the flow of the earth fault current through the latter [1].

**The Step Potential and touch Potential depend upon the following aspects :**

1. Earth fault current  $I_f$
2. Duration of earth fault
  - (a) Whether short time (less than 3 sec.)
  - (b) Whether sustained (more than 3 sec.)
3. Fault current flowing through body  $I_b$
4. Values of body resistances in the path of  $R_b$



**Fig 2 Touch Potential [1]**

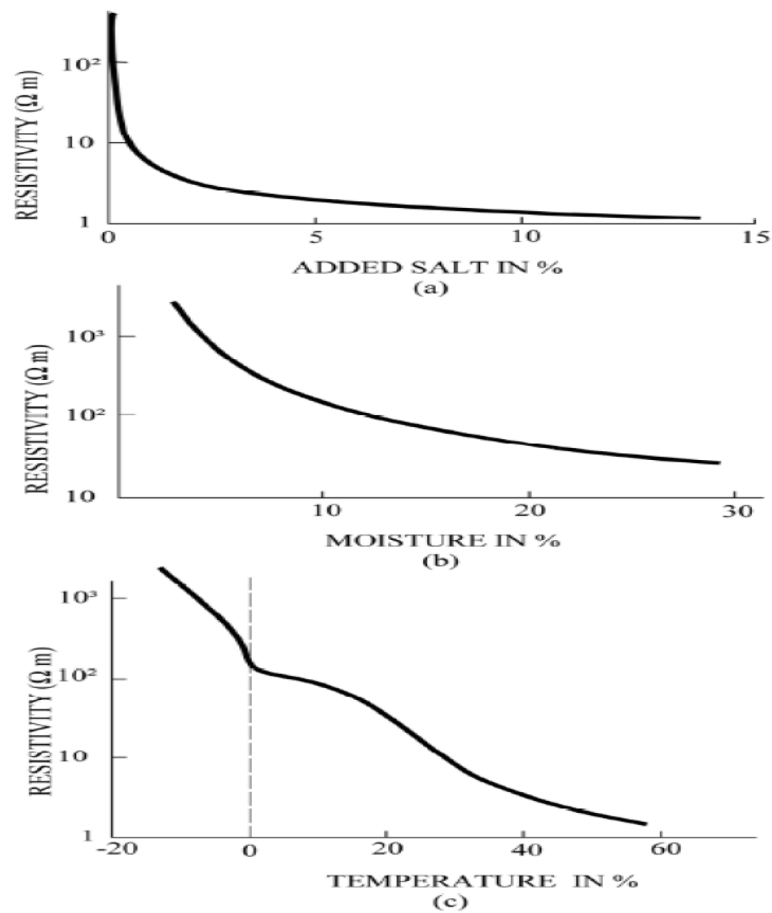


**Fig 3 Step Potential[1]**

### 3. Concept of Soil Resistivity

Soil resistivity can be defined as the resistance between the opposite sides of a cube of soil with a side dimension of one meter. Soil resistivity values vary widely, depending on the type of terrain; e.g., silt on a riverbank may have a resistivity value around  $1.5 \Omega\text{-m}$ , whereas dry sand or granite in mountainous country may have values higher than  $10,000 \Omega\text{-m}$ . The factors that affect resistivity may be summarized as follows [5,13]:

1. Type of earth (e.g., clay, loam, sandstone, granite).
2. Stratification of layers of different types of soil (e.g., loam backfill on a clay base).
3. Moisture content: resistivity may fall rapidly as the moisture content is increased, but after a value of about 20%, the rate is much less. Soil with moisture content greater than 40% is rarely encountered.
4. Temperature: above the freezing point, the effect of temperature on earth resistivity is negligible.
5. Chemical composition and concentration of dissolved salts. Presence of metal and concrete pipes, tanks, large slabs, cable ducts, rail tracks, or metal pipes. Figure 1 shows how resistivity varies with salt content, moisture, and temperature. It is found that earth resistivity varies from  $0.01$  to  $1 \Omega\text{-m}$  for sea water, and up to  $10^9 \Omega\text{-m}$  for sandstone. The resistivity of the earth increases slowly with decreasing temperatures from  $25^\circ\text{C}$ , while for temperatures below  $0^\circ\text{C}$ , the resistivity increases rapidly. In frozen soil, as in the surface layer in winter, the resistivity may be exceptionally high.



**Fig 4 Impact of Salt, Moisture and Temperature on Soil Resistivity**

Table 1 shows the resistivity values for various soils and rocks that might occur in different grounding system designs. The electrical properties of the soil are determined by the thicknesses of layers and their changes in resistivity, resistivity is dependent upon water and chemical content, as well as soil texture. Usually there are several soil layers, each having a different resistivity, in which case the soil is said to be non-uniform. Lateral changes may also occur, but, in general, these changes are gradual and negligible, at least in the vicinity of a site where a grid is to be installed. In most cases, measurements will show that the resistivity,  $\rho$ , is mainly a function of depth. The interpretation of the measurements consists of establishing a simple equivalent function to yield the best approximation of soil resistivity's to determine the layer model.

**TABLE 1 Typical Resistivity of Soil**

Type of Soil or Water	Typical Resistivity (ohm- meter)	Usual Limit (ohm- meter)
Sea water	2	0.1 to 10
Clay	40	8 to 70
Ground well and spring water	50	10 to 150
Clay and sand mixtures	100	4 to 300
Shale, slates, sandstone, etc.	120	10 to 100
Peat, loam, and mud	150	5 to 250
Lake and brook water	250	100 to 400
Sand	2000	200 to 3000
Moraine gravel	3000	40 to 10000
Ridge gravel	15000	3000 to 30000
Granite	25000	10000 to 50000
Ice	100000	10000 to 100000

#### 4 Method and Procedure of Resistivity Measurement

There are many methods being used worldwide for measurement of resistivity. Four point method of resistivity measurement is quite common.

##### **Four-point method [2]**

A good method for measuring the apparent resistivity of large volumes of undisturbed earth is the four point method. Four auxiliary probes are installed in the earth, all at depth  $b$  and spaced

(in a straight line) at intervals  $a$ . A test current  $I$  is passed between the two outer probes, and the potential  $V$  between the two inner probes is measured with a potentiometer or high-impedance voltmeter. Then, the  $V/I$  ratio gives the resistance  $R$  in ohms. Two different variations of the four-point method are often used, as follows:

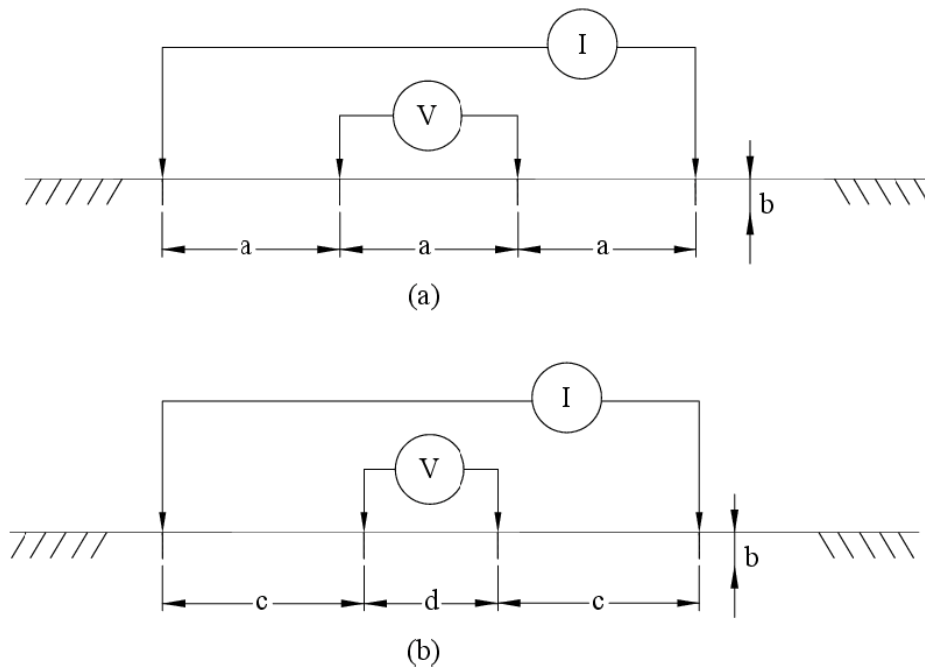
a) **Equally Spaced or Wenner Arrangement.** With this arrangement, the probes are equally spaced, as shown in Figure 5(a). Let  $a$  be the distance between two adjacent probes. Then, the apparent resistivity in the terms of the length units in which  $a$  and  $b$  are measured is

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

Theoretically, the electrodes should be point contacts or hemispherical electrodes of radius  $b$ . However, in practice, four rods are usually placed in a straight line at intervals  $a$ , driven to a depth not exceeding  $0.1 a$ . Then, the user can assume  $b = 0$  and

the equation becomes  $\rho = 2\pi aR$  and gives the approximate apparent soil resistivity to the depth  $a$ .

A set of readings taken with various probe spacing gives a set of resistivity that, when plotted against spacing, indicates whether there are distinct layers of different soil or rock and gives an idea of their respective model.



**Figure 5 Wenner Method and Schlumberger-Palmer Method**

**b) Unequally Spaced or Schlumberger–Palmer Arrangement.**

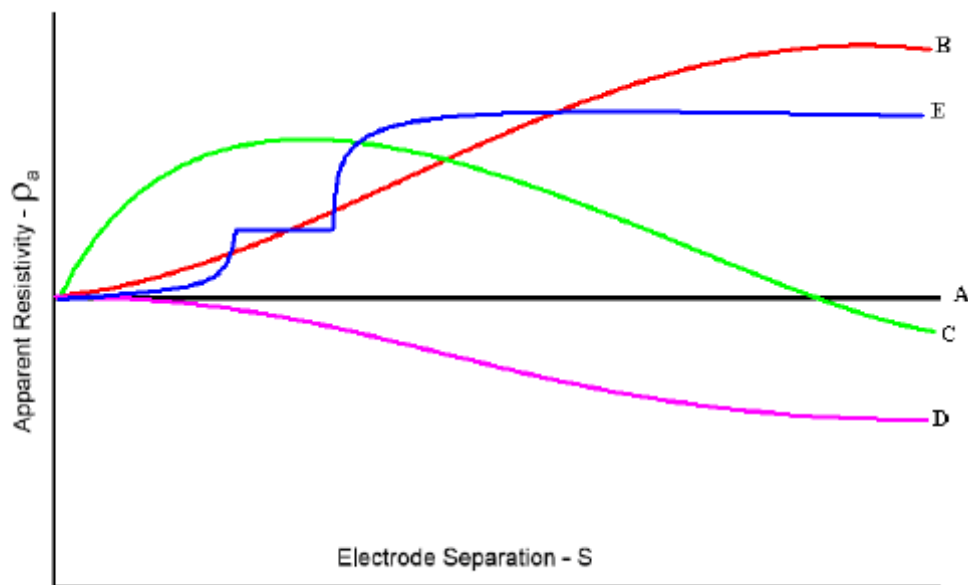
One shortcoming of the Wenner method is the rapid decrease in magnitude of potential between the two inner electrodes when their spacing is increased to relatively large values. Historically, instruments were inadequate for measuring such low potential values, although improved sensitivity in modern testers mitigates this disadvantage to some extent. Another disadvantage with the Wenner method is the requirement to reposition all four probes for each depth to be measured. The arrangement shown in Figure 5(b) can be used to measure soil resistivity successfully when current probes are separated by a large distance or to expedite testing for multiple current probe locations. With the Schlumberger method, the inner probes are placed closer together and the outer probes are placed farther apart. Unlike the Wenner method, which requires all probes to be moved to calculate soil resistivity at different depths, the Schlumberger method only required the outer probes to be

repositioned for subsequent measurements. Reducing the number of probes to be repositioned for each test makes the Schlumberger method a faster choice for testing at different depths. The equation to be used in this case can be easily determined. If the depth of burial of the electrodes  $b$  is small compared to their separation  $d$  and  $c$ , and  $c > 2d$ , then the measured apparent resistivity can be calculated as follows:

$$P = \pi(c+d)R/d$$

### 5.0 Different Soil Models

Uniform soil model is seldom found in the field. Grounding design engineers usually come across the following types of soil models.[19]



**Fig 7 Soil Resistivity Vs Electrode Separation Curve for Non- Uniform Soil**

- Curve (A) represents homogenous resistivity
- Curve (B) represents a low resistance layer overlaying a higher resistivity layer
- Curve (C) represent a high resistivity layer between two low resistivity layer
- Curve (D) represents a high resistivity layer overlaying a lower resistivity layer
- Curve (E) represents a low resistivity layer over a high resistivity layer with vertical discontinuity.



### 6. Estimation of Two Layer Soil Parameters

When the measured apparent resistivity at a site is not uniform, the data can be interpreted to obtain the best fit two layer equivalent. The process basically involves an iterative search for such values of two layer parameters  $\rho_1$ ,  $\rho_2$ , and  $h$  as make the appropriate theoretical apparent resistivity expression for the two layer soil fit the measured data by the least squares criterion. Either the infinite series expression of apparent resistivity as given by (A) or one of the finite term expressions evolved in the previous section can be used. However, use of the latter makes the search for unknown parameters much faster with insignificant loss in accuracy. The present development is based on the finite formulae as given in equations (B) and (C). The objective function to be minimized in the search process is formulated as [5,9,10]

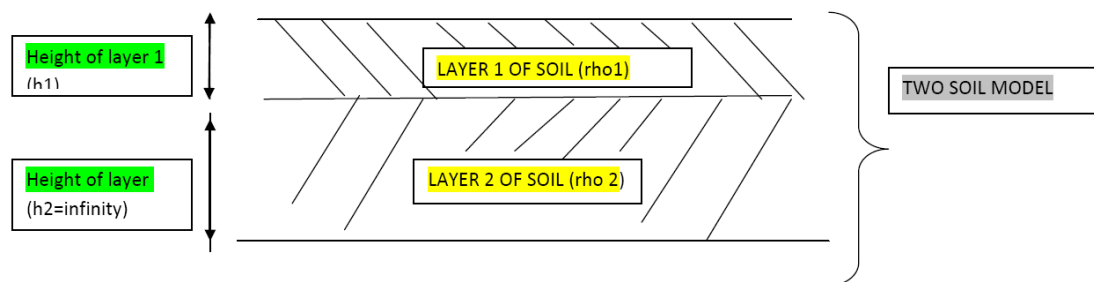
$$f(\rho_1, \rho_2, h) = \sum_{j=1}^n \frac{[\rho_{m(j)} - \rho_{c(j)}(\rho_1, \rho_2, h)]^2}{\rho_{m(j)}}$$

**Where,**

$n$  = number of electrode spacing for which apparent resistivity measurements are made.

$\rho_{m(j)}$  = measured apparent resistivity for  $j$ th electrode spacing.

$\rho_{c(j)}$  = apparent resistivity at the  $j$ th electrode spacing computed by using finite expression (13) or (17) depending on whether lower layer has higher or lower resistivity than the upper layer



**Fig 6 Two Soil Model**

### **1. Expressions for apparent resistivity for two layer soil with infinite series expression [5]**

$$\rho_a = \rho_1 \left[ 1 + 4 \sum_{n=1}^{\infty} k^n \left( \frac{1}{\sqrt{1 + \frac{(2n h)^2}{a^2}}} - \frac{1}{\sqrt{1 + \frac{(2n h)^2}{a^2}}} \right) \right] \text{-----(A)}$$

**Where,**

$\rho_a$  = Apparent Resistivity Ohm- meter

$\rho_1$  = Resistivity of the upper layer soil in Ohm- meter

$\rho_2$  = Resistivity of the lower layer soil in Ohm- meter

$h$  = depth of the upper layer in meter

$k$  = reflection factor  $(\rho_2 - \rho_1) / (\rho_2 + \rho_1)$

$a$  = Separation of electrode in meters

### **2. Expressions for apparent resistivity for two layer soil with finite series expression $\rho_2 > \rho_1$ [5]**

$$\rho_a = \rho_1 + 4 \rho_1 k \left[ \frac{1}{\sqrt{a^2 + 4 h^2}} - \frac{1}{\sqrt{4a^2 + 4 h^2}} \right] + 4\pi V_b a \left[ \frac{1}{c + (a/h)^\beta} - \frac{1}{c + (2a/h)^\beta} \right]$$

**Where,**

$V_b = \rho_1 [-k - \ln(1-k)] / (2\pi h)$

$c = x_1 \ln(\rho_2 / \rho_1)^{X_3}$  &  $\beta = 2.0 - x_2 \ln(\rho_2 / \rho_1)$

$X_1 = 16.4133$ ;  $X_2 = 0.136074$ ;  $X_3 = 0.393468$

### **3. Expressions for apparent resistivity for two layer soil with finite series expression $\rho_2 < \rho_1$ [5]**

$$\rho_a = \rho_2 + (\rho_1 - \rho_2) [2 e^{-b(a)} - e^{-b(2a)}] \text{-----(C)}$$

**where**

$b = [b_m - (b_m \cdot x_1) e^{-x_2 a/h}] / h$  and  $b_m = x_3 - x_4 (\rho_2 \cdot \rho_1)^{x_5}$

$x_1 = 0.673191$ ;  $x_2 = 0.479513$ ;  $x_3 = 1.33335$ ;  $x_4 = 0.882645$ ;  $x_5 = 0.697106$

The above written equations can be used to get two soil model of any substation area.

### 7. Example of Soil Resistivity Measurement and Soil Modelling

In order to get clarity or understand the impact of soil modelling, an arbitrary data of soil resistivity measurement for three different locations within the premises of the HV substation is considered as follows:

#### LOCATION1

SEPARATION OF SPIKES (S) Meter	N	NE	E	SE	S	SW	W	NW	AVG RESISTIVITY
0.5	33.45	14.38	17.67	30.77	11.52	8.44	9.63	40.66	20.82
1	36.73	17.96	21.47	19.84	9.54	6.84	10.99	34.79	19.77
2	6.65	14.06	17.2	12.43	6.02	2.26	6.28	12.05	9.62
3	7.34	9.04	9.79	8.85	5.08	1.884	3.39	8.47	6.73
5	0.94	7.85	7.53	6.9	6.59	3.14	2.19	6.59	5.22
10	1.25	10.04	6.28	6.28	9.42	7.53	3.24	5.65	6.21
15	1.88	5.65	3.76	6.59	5.65	4.56	2.13	4.57	4.35
AVG RESISTIVITY	12.61	11.28	11.96	13.09	7.69	4.95	5.41	16.11	

#### LOCATION2

SEPARATION OF SPIKES (S) Meter	N	NE	E	SE	S	SW	W	NW	AVG RESISTIVITY
0.5	227.96	39.59	46.22	36.48	39.72	34.1	15.26	241.46	85.10
1	71.59	40.94	37.42	24.61	38.55	27.5	17.39	20.09	34.76
2	30.14	26.37	20.72	20.09	22.85	2.51	19.34	2.51	18.07
3	16.95	12.81	16.2	16.39	8.85	0.75	9.23	15.07	12.03
5	25.12	7.22	12.56	15.38	6.59	4.39	7.53	9.4	11.02
10	12.56	6.28	10.67	13.18	8.16	2.51	6.28	12.56	9.03
15	9.42	4.71	8.93	11.3	3.76	18.84	3.76	9.42	8.77
	56.25	19.70	21.82	19.63	18.35	12.94	11.26	44.36	

#### LOCATION3

SEPARATION OF SPIKES (S) Meter	N	NE	E	SE	S	SW	W	NW	AVG RESISTIVITY
0.5	39.25	49.8	49.07	21	194.68	45.93	18.87	149.15	70.97
1	61.6	30.58	11.86	53	63.42	19.40	23.55	153.23	52.08
2	20.84	19.71	4.39	4.14	16.32	6.40	5.52	3.39	10.09
3	8.85	8.28	3.23	3.95	13.18	7.72	5.46	5.65	7.04
5	0.62	5.43	3.12	2.45	12.56	5.96	4.39	6.28	5.10
10	11.3	4.32	2.21	2.34	12.56	1.88	3.14	6.28	5.50
15	10.8	3.51	2.09	2.01	6.28	5.65	4.71	9.42	5.56
AVG RESISTIVITY	21.89	17.38	10.85	12.7	45.57	13.28	9.377	47.63	
	N	NE	E	SE	S	SW	W	NW	AVG RESISTIVITY
location 1	12.60	11.28	11.95	13.09	7.68	4.95	5.40	16.11	10.39
location 2	56.24	19.70	21.81	19.63	18.35	12.94	11.25	44.35	25.54
location 3	21.89	17.37	10.85	12.69	45.57	13.27	9.37	47.62	22.33
AVG RESISTIVITY	30.25	16.12	14.88	15.14	23.87	10.39	8.68	36.03	19.42

From the above data, it is clear that if single soil model is considered the grounding system is designed based on the average resistivity of the soil as shown above and this value in this comes out to be 19.42 ohm-meter.

### **Two Soil Modelling Data Obtained from Above Single Soil Data**

Using the above data of soil resistivity measurement for two soil modelling with the help of computer program developed in the MAT LAB GUI, the following results are obtained.

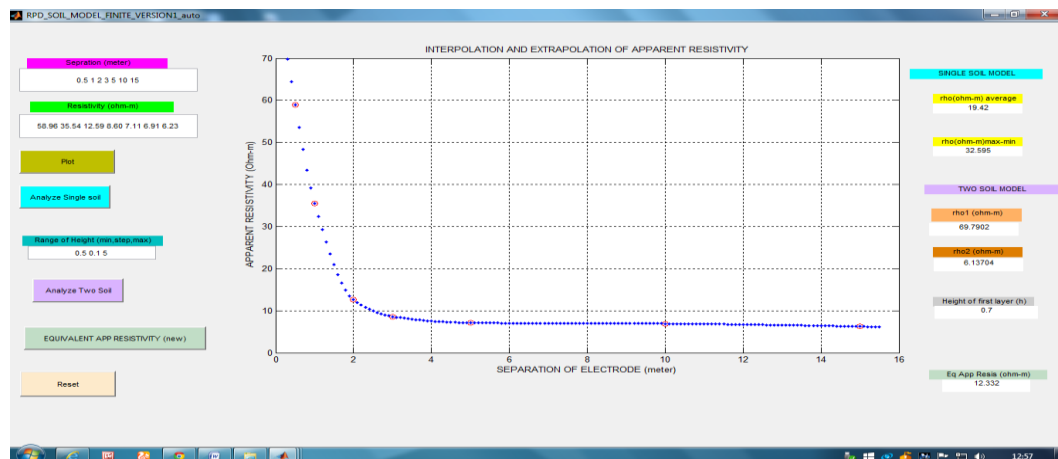
<b>AVERAGE RES FOR LOCATION AT GIVEN SEPARATION</b>	<b>0.5</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>5</b>	<b>10</b>	<b>15</b>		
<b>location 1</b>	20.81	19.77	9.61	6.73	5.21	6.21	4.34		
<b>location 2</b>	85.09	34.76	18.06	12.03	11.02	9.02	8.76		
<b>location 3</b>	70.96	52.08	10.08	7.04	5.10	5.50	5.55		
<b>AVG RESISTIVITY</b>	<b>58.96</b>	<b>35.54</b>	<b>12.59</b>	<b>8.60</b>	<b>7.11</b>	<b>6.91</b>	<b>6.23</b>	<b>19.42</b>	<b>AVERAGE VALUE</b>

### **RESULTS:**

Final results of the two soil model for above resistivity measurement data is as follows:

Resistivity of Top layer (ohm-meter)	69.79
Resistivity of Top layer (ohm-meter)	6.13
Height of Top layer (meter)	0.7

The screen shot of the MATLAB GUI program showing the results for the above data is given below.



From the above it can be observed that with single soil model the resistance of the substation grounding system which depends on resistivity of soil in the above case (case of Negative K, reflection factor ) is less as compare with two soil model. It further reduces the calculated GPR, Step Potential and Step Potential for the substation.

## **7. Conclusion**

This paper highlights the importance of accurate measurement of the soil resistivity and proper interpretation of the data for modelling of soil structure. A both infinite & finite expression for Wenner apparent resistivity calculation for two layers have been used to develop the two layer soil model of the H.V. substation in MATLAB GUI and has been tested for a number of combinations of soil resistivity measurement data.

The computed apparent resistivity depends on resistivity of top layer, depth of the upper layer, reflection factor (K) and distance between electrodes of earth tester/ resistivity measuring device.

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