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# Soil Resistivity Analysis and Earth Electrode Resistance Determination

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***Abstract—***A good grounding system is very important not only for safety reasons but also for preventing damages to industrial plants and equipment. At present, an earth electrode of the length 3.5 feet is in use in Sri Lanka, for domestic installations, which is readily available in the market and much popular among consumers and electricians. This may not comply with the maximum allowable earth resistance for the TT systems. Earth resistance depends on the earth resistivity, value of which depends on the soil structure of the location concerned. The intention of this work is to investigate the actual resistance of the said earth electrode's resistance at an identified location. Determination of soil resistivity is one of the key areas of this work, considering the earth as a homogeneous, two-layer and multilayer model for an identified soil entity, comprises with different type of soil layers. For each of these models the earth resistivity has been determined.

*CDEGS software has been used to determine resistivity of two -layer and multi-layer soil model. Voltage distribution on the surface of the earth has also been analyzed in the research. The actual values and values taken from analytical expressions have been compared with the standard value of the earth electrodes resistance*

***Index Terms—***Grounding system, earth electrode, multilayer earth model, soil resistivity

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## I. Introduction

A good grounding system is very important not only for safety reasons but also for preventing damages to industrial plants and equipment. A grounding system with high ground resistance provides unsafe path for a fault current, while making likelihood of severe injury to human beings and increased risk of equipment failure. If a fault current does not find any path to pass to the ground through a properly designed grounding system, its alternative path may be through some sophisticated equipment or in the worst case, through a human body. A high chance of Instrumentation errors and harmonic distortions in any electrical system is possible due to poor grounding systems [1], [2], [3].

To ensure sufficient electrical protection for humans and equipment available, it is very important to maintain the grounding resistance as per the specified limits which is 10 Ω or less for domestic installations. Sri Lanka, this is implemented with long term experience or through trial and error techniques. This may lead to over-design or under design grounding systems [2]. Over-design system brings

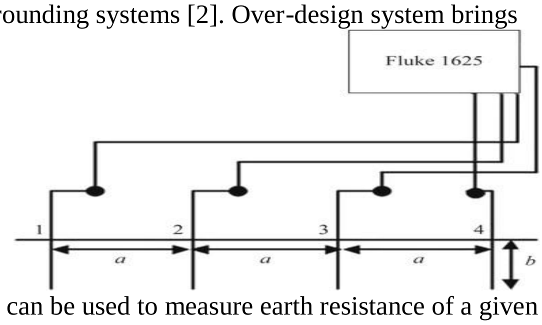


**Fig. 1.**Wenner 4-pole method can be used to measure earth resistance of a given location for homogeneous soil environment

waste of material and labor cost and under-design system causes situations with safety issues [2]. Therefore, it has become a necessity to evaluate the effectiveness of popular/ common earthing methodologies in order to come-up with an optimum solution.

Earth resistance depends upon many factors, such as Soil resistivity, Environmental effects, Materials used for earth electrode, length and diameter of earth electrode, shape of earth electrode, number of earth electrode and back filling material are some of them. By varying these factors, it can get optimum solution for achieve the particular range of earth resistance [1], [2], [3], [4], [5], [6], [7], [8], [9], [11].
Earth resistance is measured for various reasons in determining effectiveness of "ground" grids and connections can be done to protect personnel and equipment for prospecting for good (low resistance) "ground" locations, for obtaining measured resistance values may provide specific information about what lies some distance below the earth's surface (such as depth to a bed rock).
Several methods are available for the measurement of earth resistance. Wenner's four pole method is one of such methods. The measurements can be done using wenner four pole method as shown in Fig. 1 [1], [10]. In this method four equidistant probes are vertically inserted into the soil on a straight line and the distance "b" was maintained to be 10% of "a" where "b" is the depth of the probe and the value of "a" was varied. Fluke meter 1625 is used to inject a current
I, between probes 1 and 4 and potential V is then measured

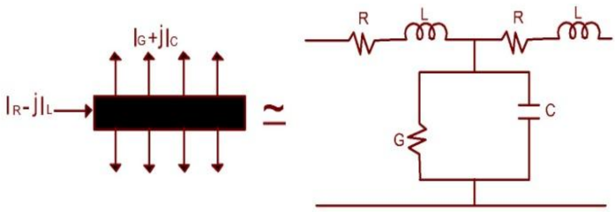


**Fig. 2**.Current components in the soil

between probes 2 and 3 and finally the soil resistance Re is measured by the meter [1]. The measured values can be theoretically calculated by using (1), for a>>b [10], [12].

$$\rho = 2\pi a R_e \qquad (1)$$

The current tends to flow near the earth surface for small probe spacing, but for larger spacing more of the current penetrates deeper soil. Therefore, it is approximated that, the resistivity measured for a given probe spacing "a" indicates the apparent resistivity of the soil to a depth of "a" when soil layer resistivity contrasts are not excessive [13]. Since the application of 1 agrees with the above conditions, they were used to determine the apparent resistivity $\rho$ at a depth of "a".

## II. Determination of Earth Electrode's Resistance

In determining the earth electrode's resistance, it is essential to know the electric potential of the atmosphere where it is to be placed – here some points randomly selected in the corresponding soil, as well as that of on the surface of the earth-electrode. As the resistivity of the corresponding soil type is going to be found out, it is very important to know 'the composition/ type of the soil' in which the earth rod is to be placed.

According to [14], the ac current which is injected to the earth electrode is distributed through the soil as per Fig. 2. But for domestic leakage currents except lightning, only the resistive component is effective and those capacitance and inductance are considered to be negligible [14]. Therefore, the soil can be considered as a pure resistive structure. Hence, the voltage distribution in the soil is calculated as a direct current that flows through the earth electrode. Then, the electrode resistance is ratio of voltage and current (V/I).

## III. Determination of Earth Resistivity in Multilayer Soil Model

Uniform soil model (single-layer soil model) and the two-layer soil model are the most commonly used soil models for resistivity analysis. When there is a little variation in apparent resistivity, that model can be considered as a homogeneous/ uniform soil model. For homogeneous soil conditions, the uniform soil model may be reasonably accurate. If the variation of the soil model is considerably high, there will be erroneous situations in the results, if it has been considered as a single-layer entity. Therefore, for more complex soil conditions, multilayer soil models are much popular.

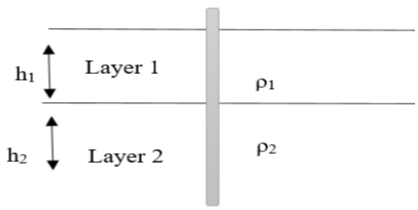


**Fig. 3.** Two-layer soil model

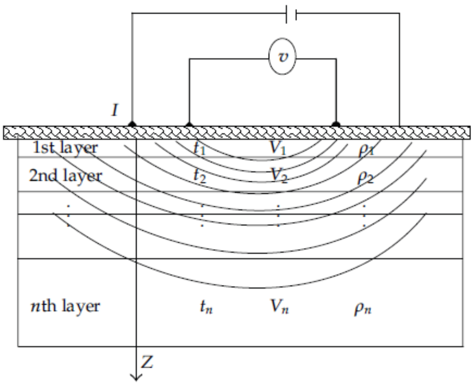


**Fig. 4.** Multi-layer soil model

Out ofthese, two-layer soil models are often a good approximation for many soil structures. Soil resistivity measurements can be obtained either manually or by the use of computer analysis techniques [15], [16], [17]. For more accurate representation of the actual soil conditions, two-layer model with finite thickness of upper layer, infinite thickness of lower layer and two different resistivity can be used. The instant change in resistivity at the boundary of each soil layer is described by reflection factor K [15], [18].

$$K = (\rho_2 - \rho_1)/(\rho_2 + \rho_1) \qquad (2)$$

Where, $\rho_1$ and $\rho_2$ are the upper layer and lower layer soil resistivity in $\Omega m$. respectively.

Sunde's technique is a graphical method to determine the resistivity and the depth of each layer of two-layer model: that could be obtained from the reading (which is the apparent resistivity) of the wenner four pole method. The apparent soil resistivity of the total soil entity (two-layer model) shows the characteristics of the two-layer structure/model as in equations (3) and (4) [19]. For a negative reflection coefficient K

$$\rho_{a=}\frac{\rho_1}{\left(1+\left[\frac{\rho_1}{\rho_2}-1\right]\times\left[1-e^{\frac{-1}{-k(h+2H)}}\right]\right)} \qquad (3)$$

For a positive reflection coefficient K

$$\rho_{a=\rho_2}\left(1+\left[\frac{\rho_2}{\rho_1}-1\right]\times\left[1-e^{\frac{-1}{k(h+2H)}}\right]\right) \qquad (4)$$

Where h is the depth of layer 1 and H is the grid depth.

For multilayer soil resistivity analysis, the earth is considered to be horizontally stratified as demonstrated in Fig. 4. Through the surface voltage and current injected measured using wenner 4 pole method, it can be investigated the resistivity in each layer [17]. The potential (Ua) created on the soil surface by a point-wise current source located on the soil surface, can be calculated using (5)

$$U(a) = \frac{\rho_1 I}{2\pi}\int_0^\infty [1 + 2B(\lambda)]\, J_0\,(\lambda a)d\lambda \qquad (5)$$

Where a is the distance between source and calculation point, I is the point current, $\rho_1$ is the soil resistivity of the upper layer, $J_0(\lambda a)$ the Bessel function of first kind and zero order and $B(\lambda)$ is the so called kernel function which depends on the number of layers. For a five-layer soil model, considering the deepest layer of infinite extension, the kernel function reads as below equations.

$$B_5(\tau) = \frac{K_{51}e^{-2\lambda h_1}}{1-K_{51}e^{-2\lambda h_1}} \qquad (6)$$

$$B_{51} = \frac{v_{12}+K_{52}e^{-2\lambda h_2}}{1+v_{12}K_{52}e^{-2\lambda h_2}} \qquad (7)$$

$$B_{52} = \frac{v_{23}+K_{53}e^{-2\lambda h_3}}{1+v_{23}K_{53}e^{-2\lambda h_3}} \qquad (8)$$

$$B_{53} = \frac{v_{34}+v_{45}e^{-2\lambda h_4}}{1+v_{34}v_{45}e^{-2\lambda h_4}} \qquad (9)$$

$$v_{ij} = \frac{(\rho_j-\rho_i)}{(\rho_j+\rho_i)} \qquad (10)$$

where $\rho_i$and $h_i$ are the resistivity and the thickness of the$i^{th}$layer, respectively [17], [20].

## IV. Methodology and Results

In order to investigate the soil resistivity of a selected soil model, which comprises different soil types, a location with borehole logs was identified. All model tests were conducted at the Institute of Technology, University of Moratuwa, Diyagama, Sri Lanka, on the 07th September 2018, which can be considered as a dry day. The earth resistance measurements were taken with 'Fluke 1625 earth tester' which follows Wenner four pole method (as per the fig.1). Measurements were taken with randomly selected points on earth surface in such a way three readings per each spam. Their average value was calculated for further calculations and analysis, as shown in Table I.

The research work was carried out based on 4 off study cases for convenience of analysis as presented in Fig. 5.

For this analysis, an earth electrode was selected which is readily available in the market and popular among consumers and electricians. It was a copper plated mild steel rod of the length 1.066m, and average diameter of 1.0127cm.

*A. Study 1*

Considering the soil is a homogeneous entity the analysis was carried out under the study 1. The apparent resistivity for different spams were calculated using (1). Correspondingresults are tabulated in Table 1Sample calculation,

Spam – 1m, Measured Earth resistance average,

= (16.16+17.82+15.89)/3

= 16.62 Ω

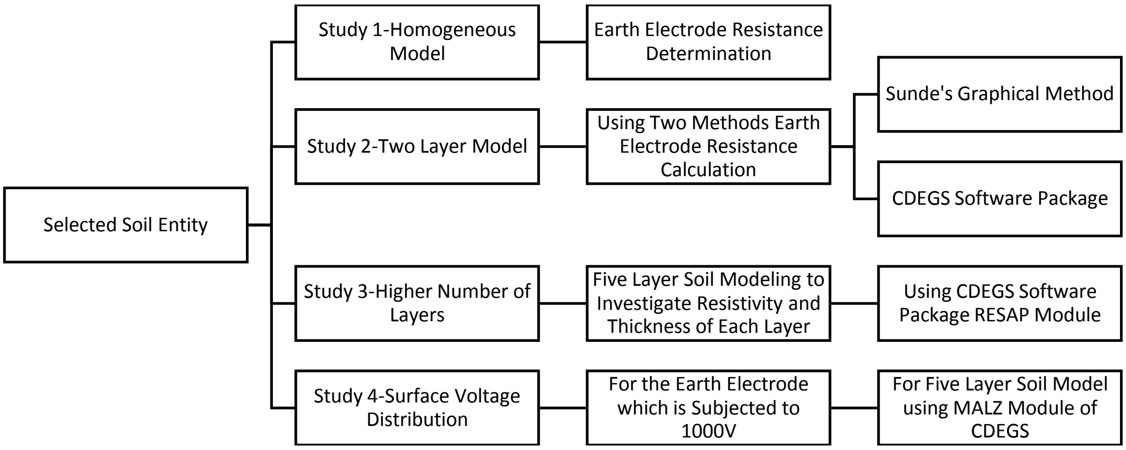


**Fig. 5**. Research work

**TABLE I**

EARTH RESISTANCE MEASUREMENTS FOR DIFFERENT SPAMS AND CALCULATED APPARENT RESISTIVITY

| Spam (m) | Earth resistance measured(Ω) | | | | Calculated earth resistivity ($\Omega m$) |
|---|---|---|---|---|---|
| | *reading 01* | *reading 02* | *reading 03* | *average value* | |
| 1 | 16.16 | 17.82 | 15.89 | 16.62 | 104.43 |
| 2 | 8.93 | 9.40 | 8.74 | 9.02 | 113.34 |
| 3 | 7.45 | 8.63 | 7.24 | 7.77 | 146.46 |
| 4 | 6.27 | 7.79 | 6.79 | 6.95 | 174.67 |
| 5 | 5.28 | 6.83 | 6.13 | 6.08 | 191.01 |
| 6 | 4.61 | 5.45 | 5.24 | 5.10 | 192.27 |
| 7 | 3.96 | 4.55 | 4.71 | 4.40 | 193.52 |
| 8 | 3.78 | 3.75 | 4.18 | 3.90 | 196.03 |
| 9 | 3.49 | 3.39 | 3.66 | 3.51 | 198.48 |
| 10 | 3.10 | 2.95 | 3.39 | 3.14 | 197.29 |

Therefor resistivity $\rho = 2\pi a R_e \rho = 2\pi * 1 * 16.62\ \rho = 104.43\Omega m$

For a homogeneous soil entity, the earth resistance of the electrode can be calculated using (11).

$$R = (\rho/2\pi L)\,(ln(4L/d) - 1) \qquad (11)$$

where, R = resistance of the single electrode in Ω, d= radius of electrode in m, $\rho$= soil resistivity in Ωm and L= length of electrode in m.

Since earth electrode is of the length of 1.06m, the resistance has been calculated for a depth of 1.06m. The graph in the Fig. 6 becomes constant in $195\Omega m$, which can be considered as the resistivity of the soil entity.

calculation of earth electrode resistance, $R_h$ for corresponding data

$R_h = (195/2\pi * 1.066)\,(ln\,((4 * 1.066/0.0127) - 1)$

$R_h = 140\Omega (\gg 10\Omega)$

This results shows that the earth electrode resistance is much higher than 10Ω.Because of the calculations were based on a homogeneous entity with reference to [15], [16] this cannot be taken as a much accurate value.

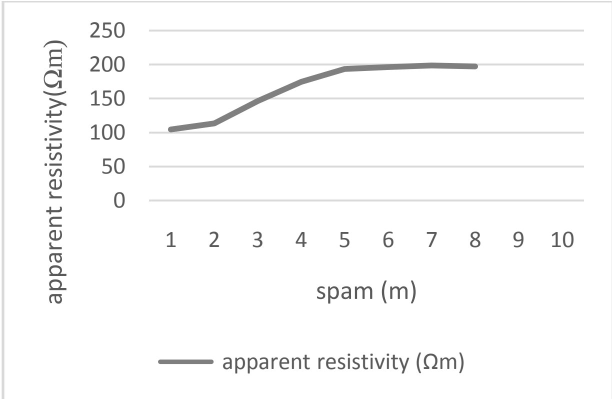


**Fig. 6.**Apparent resistivity Vs spam

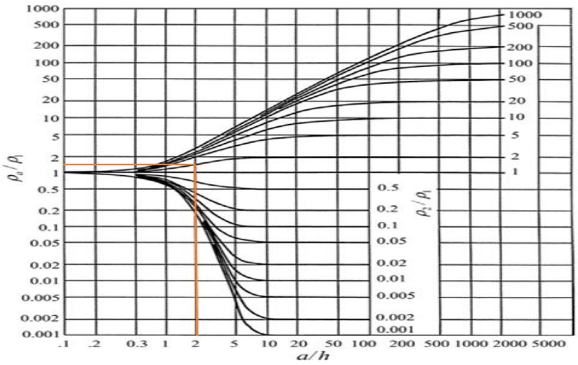


**Fig. 7.**Sunde curve

***B. Study 2***

For many applications, the representation of a ground electrode based on an equivalent two-layer earth model rather than a homogeneous entity, can be considered for designing a safe grounding system [15]. Fig.4 demonstrate such a two-layer soil model which bases this study 2 analysis. There, two approaches were practiced. They are Sunde's graphical method (method 1) and CDEGS software analysis (method2).

*1) method 1:* Sunde's graphical method

(Please refer to the graph demonstrates in Fig. 6) Assumptions made, $\rho_1 = 100\Omega m$, $\rho_2 = 200\Omega m$,

$\rho_2/\rho_1 = 200/100 = 2$

By selecting curve which $\rho_2/\rho_1$=2 on the graph of fig.7, a point was selected as $\rho_a/\rho_1 = 1.5$,

where, $\rho_a$is apparent resistivity

since $\rho_1 = 100\Omega m$, $\rho_a = 1.5 * 100 = 150\Omega m$

Referring to the graph demonstrated in Fig. 6, this $150\Omega m$ corresponds to a spam of 3.13m.

Therefore, the spam, a=3.13m

from Fig. 7, $\rho a = 150\Omega m$ a/h = 2, a = 3.13, then h = 1.5m-thickness of the soil layer 1 With the calculated results the model can be illustrated as given in Fig. 8.

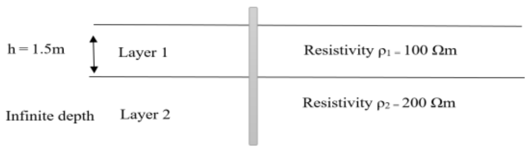


**Fig.8.** Two-layer soil model

In order to find the resistance of the electrode, apparent resistivity of the model is needed to be calculated, From (2),

K= $(\rho_2 - \rho_1)/(\rho_2 + \rho_1))$

= (200-100)/ (200+100)

= 0.33

Using (4) for the depth of 1.06m (3.5 feet) electrode,

$$\rho_{a=\rho_2}\left(1+\left[\frac{\rho_2}{\rho_1}-1\right]\times\left[1-e^{\frac{-1}{k(h+2H)}}\right]\right)$$

$$\rho_{a=200}\left(1+\left[\frac{200}{100}-1\right]\times\left[1-e^{\frac{-1}{0.33(1.5+2*1.06)}}\right]\right)$$

$= 313.4\Omega$m

Earth resistance of the earth electrode, From (11),

$$\mathrm{R}=\frac{\rho}{2\pi L}\left(ln\frac{(4L)}{a}-1\right)$$

$$\mathrm{R}=\frac{313.4}{2\pi * 1.066}\left(ln\frac{(4 * 1.066)}{0.0127}-1\right)$$

R = 225.36 Ω

*2) method 2:* Two-layer modeling using CDEGS

CDEGS facilitates computations required for determination of an equivalent earth structure model based on measured soil resistivity data, with its RESAP (Soil Resistivity Analysis) facility. Apparent resistance (the reading given by earth tester), Methodology used to measure the earth resistance (Wenner) and Space between probes have been considered as input parameters. Resistivity and thickness corresponded to each soil layer in two layer have been received as computational outputs. Two-layer soil modeling is demonstrated in Fig. 9. Based on data from RESAP, the soil entities with two layers could be demonstrated as in Fig. 10. Considering Fig. 10,

$\rho 1$ = 94.04 Ω*m*, $\rho 2$ = 232.64 Ω*m* Thickness of 1$^{st}$ layer (h) = 1.43 m

The apparent resistivity of the model $\rho a$,

K= $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$

= (232.64-94.04)/ (232.64+94.04)= 0.42

Using (4) for the depth of 1.06m (3.5 feet) electrode,

$$\rho_{a=\rho_2}\left(1+\left[\frac{\rho_2}{\rho_1}-1\right]\times\left[1-e^{\frac{-1}{k(h+2H)}}\right]\right)$$

$$\rho_{a=232.64}\left(1+\left[\frac{232.64}{94.04}-1\right]\times\left[1-e^{\frac{-1}{0.43(1.43+2*1.06)}}\right]\right)=400.18\Omega\mathrm{m}$$

∴ The earth resistance, R, from (11):

$$\mathrm{R}=\frac{\rho}{2\pi L}\left(ln\frac{(4L)}{a}-1\right)$$

$$\mathrm{R}=\frac{400.18}{2\pi * 1.066}\left(ln\frac{(4 * 1.066)}{0.0127}-1\right)$$

R = 287Ω (<<10 Ω)

Hence, for a two-layer soil entity, compared to CDEGS method,

Percentage error with Sunde technique = [(287-225.36)/287] x100%

= 21.47%

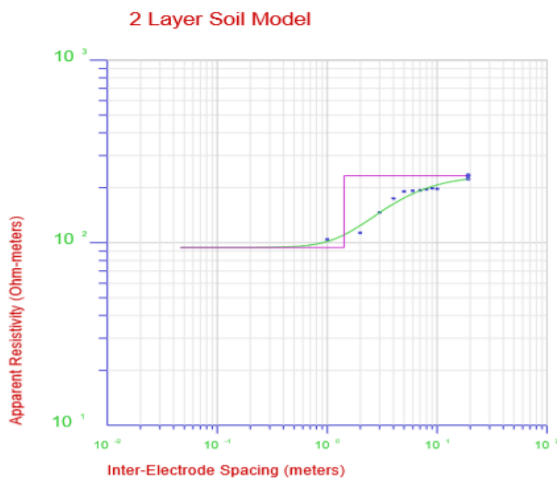


**Fig. 9.** Two-layer soil modelling result

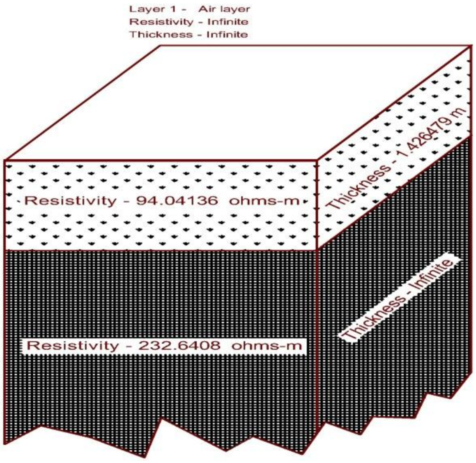


**Fig.10.**Two-layer soil modelling 3D representation

Earth resistance variation with Sunde CDEGS methods and error percentages with reference to CDEGS calculations against different depths are shown in Fig. 11.

*C. Study 3*

Under this study the same soil entity has been considered as a multi-layer (5- layers) model. In reality the earth consists of number of layers having different earth resistivities. Referring to RESAP, this study was done for a 5-layer entity. For this analysis, in order to do the soil resistivity calculations, Apparent resistance, Methodology used to measure the earth resistance (Wenner) and Space between probes have been considered as input parameters same as in Study-2. Resistivity ($\rho_{i,}$i = 1, 2, ..., 5) and thickness ($t_i$, i= 1, 2,...,5) corresponding to each soil layer have been received as computational outputs. The soilentity with five layers could be modelled as demonstrated in Fig, 12.

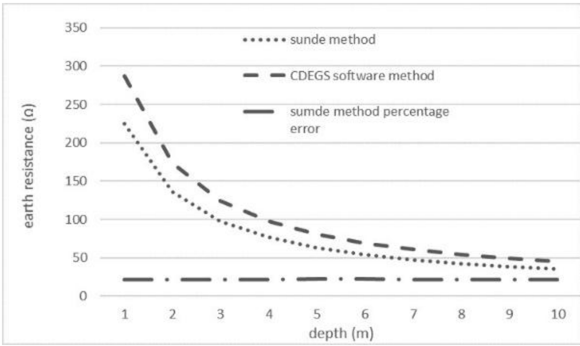


**Fig. 11.** Earth resistance variation with Sunde CDEGS methods and error percentages

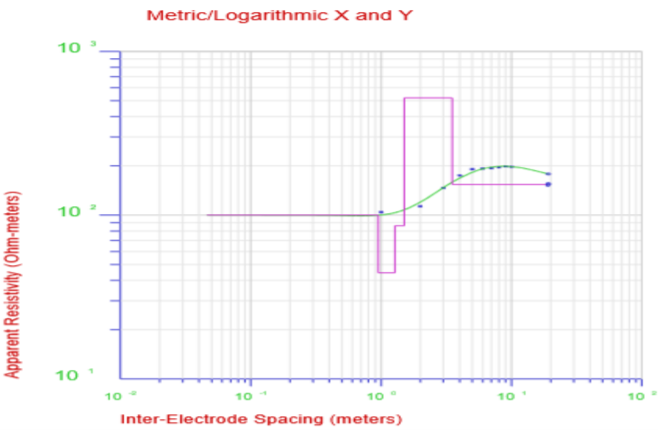


**Fig.12.**Five-layer soil modelling result

The soil layer distribution with corresponding $\rho$ and t values is shown in Fig. 13. The $\rho$ values obtained from RESAP analysis and real bore hole test were compared. The error with the RESAP computational results have been calculated with reference to the real bore hole test results. The corresponding values are tabulated in

Table III. The variation of percentage error with thicknesses have been plotted against the layer number which is demonstrated in Fig. 14.

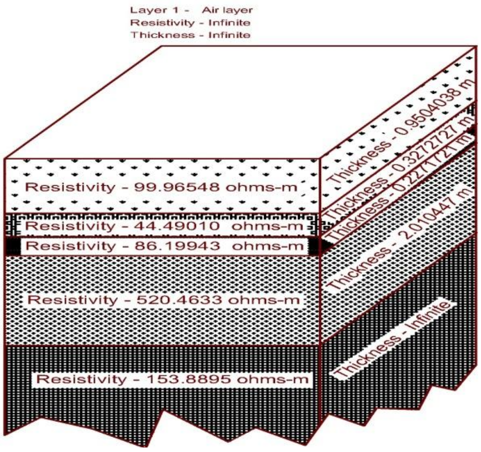


**Fig. 13.**Five-layer soil modelling 3D representation

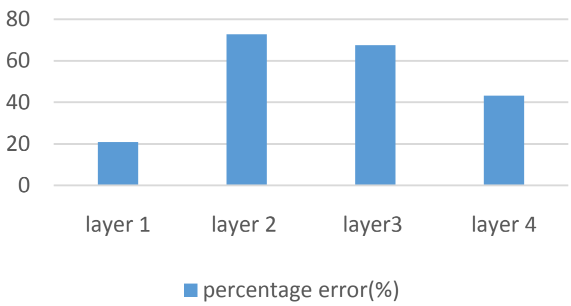


**Fig. 14.** Percentage error between thickness obtained from RESAP and Bore-hole

**TABLE II**
FIVE-LAYER MODEL RESULTS IN RESAP ANALYSIS COMPARISON WITH REAL BOREHOLE LOGS

| Soil Layer Number | Resistivity From the Results of RESAP Analysis of CDEGS($\Omega m$) | Thickness From the Results of RESAP Analysis of CDEGS ($m$) | Thickness From the Bore-hole logs($m$) |
|---|---|---|---|
| 1 | 99.96548 | 0.9504038 | 1.2 |
| 2 | 44.49010 | 0.3272727 | 1.2 |
| 3 | 86.19943 | 0.2271721 | 0.7 |
| 4 | 520.4633 | 2.010447 | 1.4 |
| 5 | 153.8895 | Infinite | Infinite |

***D. Study 4***

The potential distribution around a driven rod in an identified soil entity can be achieved either through a set of analytical equations or simulation demonstrations. In this study the latter option was selected, which is facilitated by the MALZ computation module of the CDEGS. The voltage distribution received as a computational result of the above shows the influence on the surface of the earth by potential distribution. The non-uniformity of the soil greatly affectsthe potential distribution on the surface of the earth [21]. Hence, it is essential to consider the non-uniformity of the soil entity in concern, in computing its potential distribution.

As per the diagram demonstrated in Fig. 15, the test setup was arranged. The electrode was subjected to 1000V. Considering the electrode coordination as the origin, for 5cm intervals along the X and Y axis, voltage calculationswere done. The relevant voltage distribution contours and surface voltage distribution obtained are shown in Fig. 16 and Fig. 17 respectively.

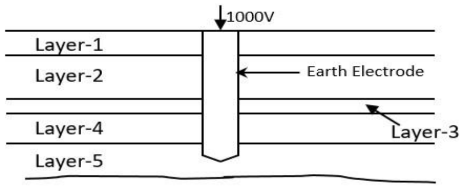


**Fig. 15**.Test set-up for surface voltage measurement

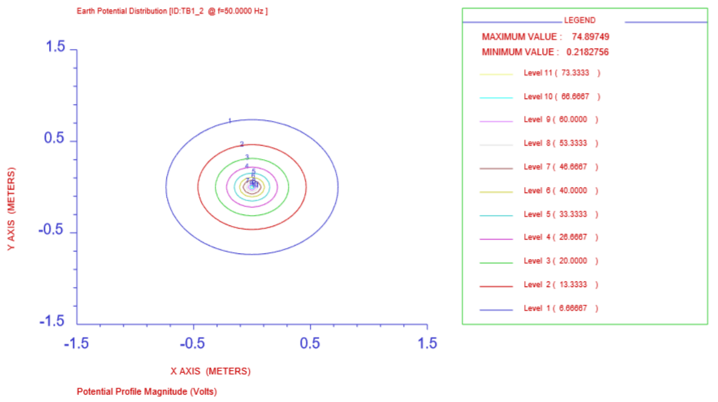


**Fig. 16.**Contour map of voltage distribution

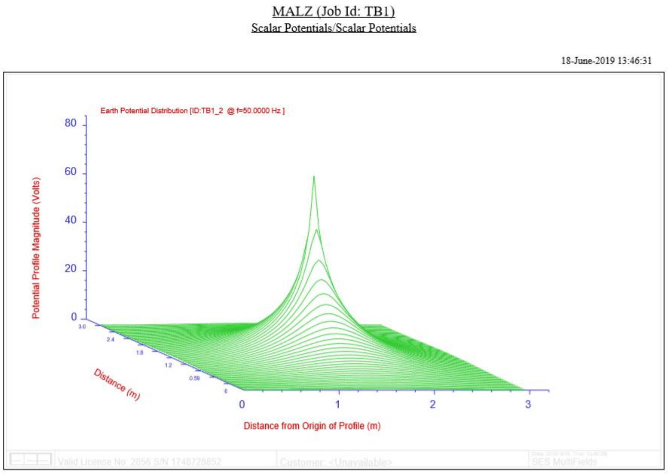


**Fig. 17.** 3D map of surface voltage profile distribution

## V. Conclusion

This research study was carried out referring to a soil entity in an identified location, to calculate R, and voltage distribution following different methodologies. Considering the soil entity as a homogeneous, two-layer and five-layer model in an identified location, the analysis were conducted. The results obtained (for R and $\rho$) based on Sunde and CDEGS methods, (Study-2 and Study-3: Case-1) showed much high values than that of Study-1. It can be considered that these results are with higher accuracy compared to the results of Study-1.

The results given by bore-hole test do not agree for a homogeneous soil entity. The bore-hole test shows that soil structure is not uniform even within a 2m depth. Hence it was decided that, finding the earth electrode's resistance considering the earth as a homogeneous entity is with aconsiderable error. This error may impose a large impact on safety and preventing damage to equipment through installation earthing in various locations all over the country. The results obtained through different methodologies show that the calculated value of earth electrode's resistance is much higher than the maximum allowable value, which is 10Ω. Therefore, the standard height and electrical properties of the electrode are needed to be revised.

With reference to the study-2, since the earth resistivity values obtained (for case-1 case-2) were based on assumptions and approximations it can be considered that the resultsare with a considerable error.

Reference to the results of the Study-3, since

(1) the five-layer model of RESAP analysis gives 99, 44 and 86$\Omega m$as the earth resistivity for Layer-1, 2 and 3 respectively, which falls within a 2m depth (this confirms the soil entity is not homogeneous),
(2) the resistivity values are less than the single layer model (104.43$\Omega m$), it can be decided that the real earth resistivity found in single layer model using Wernner method is not sufficiently accurate. Hence the earth resistivity value can only be accepted for approximate calculations for domestic installations.

## Acknowledgment

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