ESTIMATION OF ACTUAL EARTH RESISTANCE OF A COMPLEX EARTHING NETWORK USING SOIL LAYER MODELLING IN THE FINITE ELEMENT DOMAIN

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Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
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Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree
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DECLARATION OF THE CANDIDATE & SUPERVISOR

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The above candidate has carried out research for the Masters Dissertation under my supervision.

Signature of the supervisor: Date:

Dr. Asanka S. Rodrigo

DEDICATION

To my beloved parents, siblings and my wife for
their endless guidance and support given throughout my life.

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ABSTRACT

Telecom infrastructure growth rate has been rapidly increased due to higher competition among operators for them to provide reliable and quality service to the customers. Rapid increase of telecom tower construction and usage of advanced equipment has been taken in place due to the recent development in telecom sector in Sri Lanka as well. The tower being a tall structure in the environment, act as a direct path for lightning to be grounded. Though it will protect low height buildings and people in the vicinity from direct lightning strikes, having a proper earthing system with low earth resistance is a must to avoid possible hazards by ground potential rise.

Given the smaller area of the tower premises proper earthing network should be incorporated to maintain the lower earth resistance at the tower. Operators have to maintain the earth resistance at tower sites as per the TRCSL guideline for antenna structures which is below 5 ohms [1]

To meet the TRCSL guidelines operators have incorporated complex earthing systems in tower sites. Typically, the tower earthing system includes copper tapes and multiple number of rods which have made a complex earth network to achieve the lowest possible earth resistance.

Measuring earth resistance is quite hard in a complex earthing network due to parallel conductors, intersections and subjected to many assumptions including specially the homogeneity around all directions. Site measurement is the key parameter of reflecting the earth networks effectiveness to surges and lightnings.

This thesis discusses specifically the reasons for deviations in measured and theorical values. Simulated earth networks thorough ANSYS Maxwell in the finite element domain to achieve earth resistance profile has been elaborated. Site earth resistance measurements has been taken along different directions. compared with the measurements in every direction of the sites. Validation has been done by the comparison between simulation and measurement.

Analysis has done for different types of soil conditions and limitations for study has been discussed. Thesis concludes with the mechanism to estimate the accurate earth resistance of a site for a particular accuracy which also includes the general assumptions.

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ABBREVIATIONS

TRCSL	- Telecommunication Regularity Commission Sri Lanka
GPR	- Ground Potential Rise
ART	- Attached Rod Technique
FEM	- Finite Element Method
DC	- Direct Current
AC	- Alternative Current
3D	- Three Dimensional

1 INTRODUCTION

1.1 Background

Telecommunication services has been an essential in today's world, where connectivity and content delivery playing vital role in telco services. In the Sri Lankan context where almost the mobile penetration is over 100 percent, operators are in a higher competition to full fill the customer needs and requirements. Different approaches have been taken by the telco operators to cater the higher demand and quality service.

Telecom tower has become more important as it is the main component and the foundation of the access network and also supports the transmission. These towers are taller as 60m to 100m and high chance of getting a lightning strike due to the height and the formation of tower. Proper grounding system and an earthing network is a must for a telecom tower to avoid damages to the tower equipment and surrounded environment and personnel. To ensure required protection to telecom tower and surrounded environment regulations are imposed. TRCSL, the main regulatory for telecommunication service providers in Sri Lanka has set guidelines for antenna structures for maintain the earth resistance below five ohms (5Ω) [1].

1.2 Problem Statement

Grounding system of a telecom tower is one of the most important in terms of lightning protection. Achieving lower ground resistance is a challenging task due to various conditions. Space limitations in the sites, soil conditions, climate changes and used material for earthing network are affecting maintain low resistances as per the regulatory requirements throughout the year.

The lightning protection system of the telecom tower is a critical property a must where periodic measurement of earth resistance of the telecom tower is essential to maintain safe and reliable network throughout the period. Figure 1.1 shows the typical earthing arrangement of a telecommunication station.

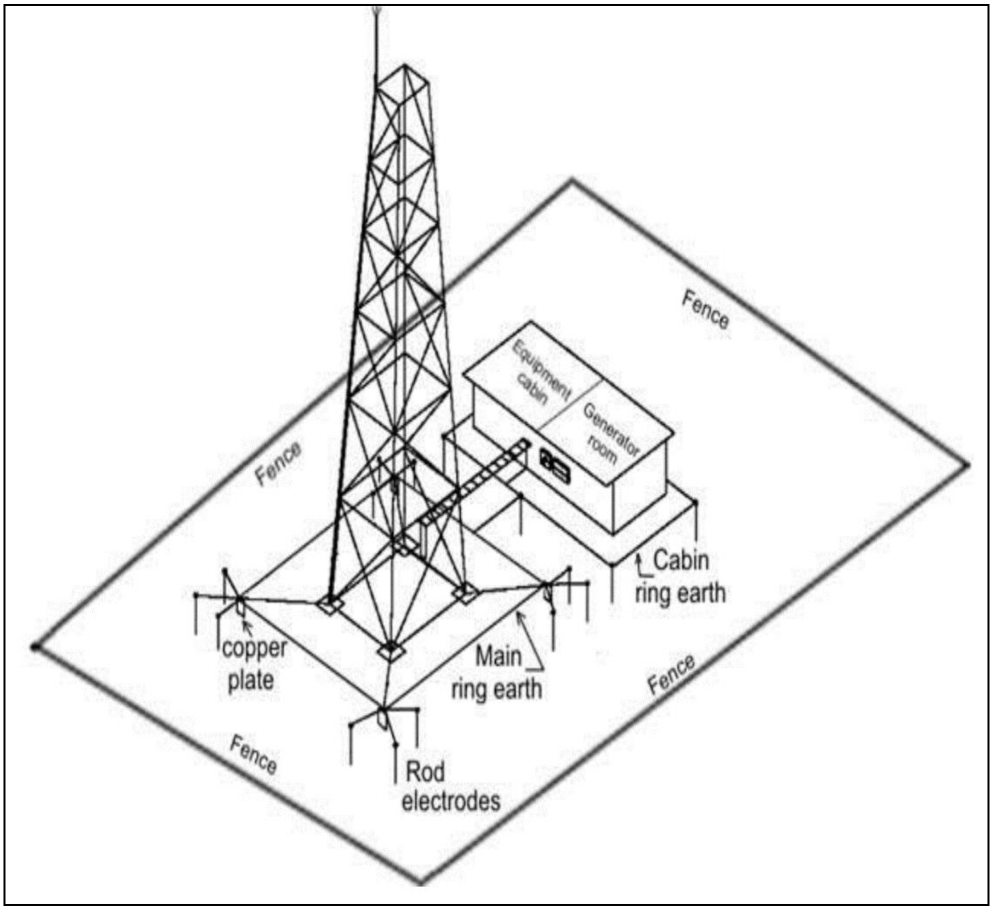


Figure-1-1.1 - General Arrangement of Telecommunication Tower Earthing System [2]

Typical telecom tower structures are in range of 40 m to 100 m height and perimeter around the basement of the tower is around 40 m. Normally a limited space is available for the earthing network. Air termination is equipped by a franklin rod made out of copper or aluminum and to ground the lightnings a down conductor is connected to air terminal which comes down along the tower to connect it with the earthing network. Figure 1.2 shows the telecommunication tower structure details.

The earth network is typically a complex design as it need to maintain a proper equipotential bonding around the tower and the equipment cabinet. The earthing network basically consists of copper cables, tapes and rods to achieve low resistance as required. The ring earth is connected to grounding bars inside power supplies and surge protective devices incorporated with both power and telecom equipment. From the base of the tower from the legs earthing network is extended outwards in crow foot arrangements and earth rods are connected in points as per the design to optimize the number of them. So, the earthing network is varying as per the site soil conditions and terrain and the foot print of the tower premises.

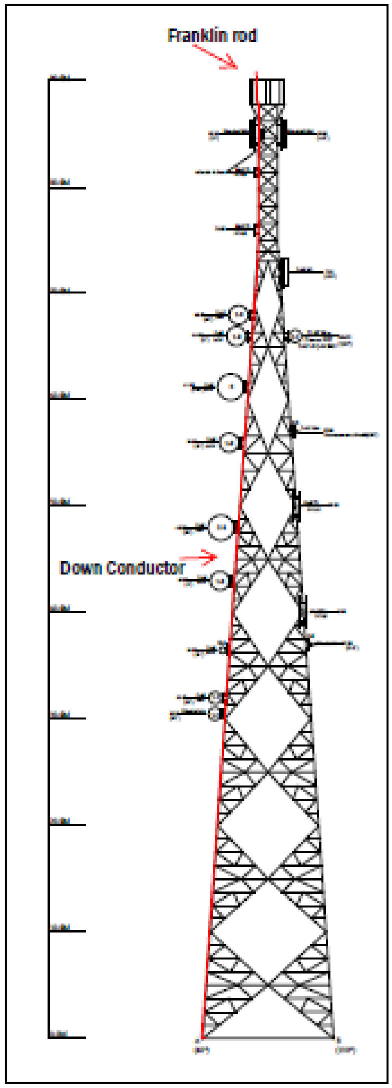


Figure-2 Air Terminal and Down Conductor Arrangement of a Tower Structure

Measuring earth resistance of the tower site is important as periodic measurements will ensure the safety of the site equipment and the surrounded vicinity. There are number of methods to measure earth resistance. Mostly used is fall of potential method [2] and still it's hard to find space for measurements due to lack of space and measurement alternations are occurring due to parallel conductors along the measurement probes.

In the practical scenario of earth resistance measurement of a particular site using fall of potential method it is practiced to use the probes in distances where as much as possible and taking measurements from different points of the earth network. Even though the earthing network act as an equipotential network when taking measurements from different end points of the earth network different earth resistance values are shown. Figure 1.3 elaborates the deviated measurement results of an earth network in a telecom site.

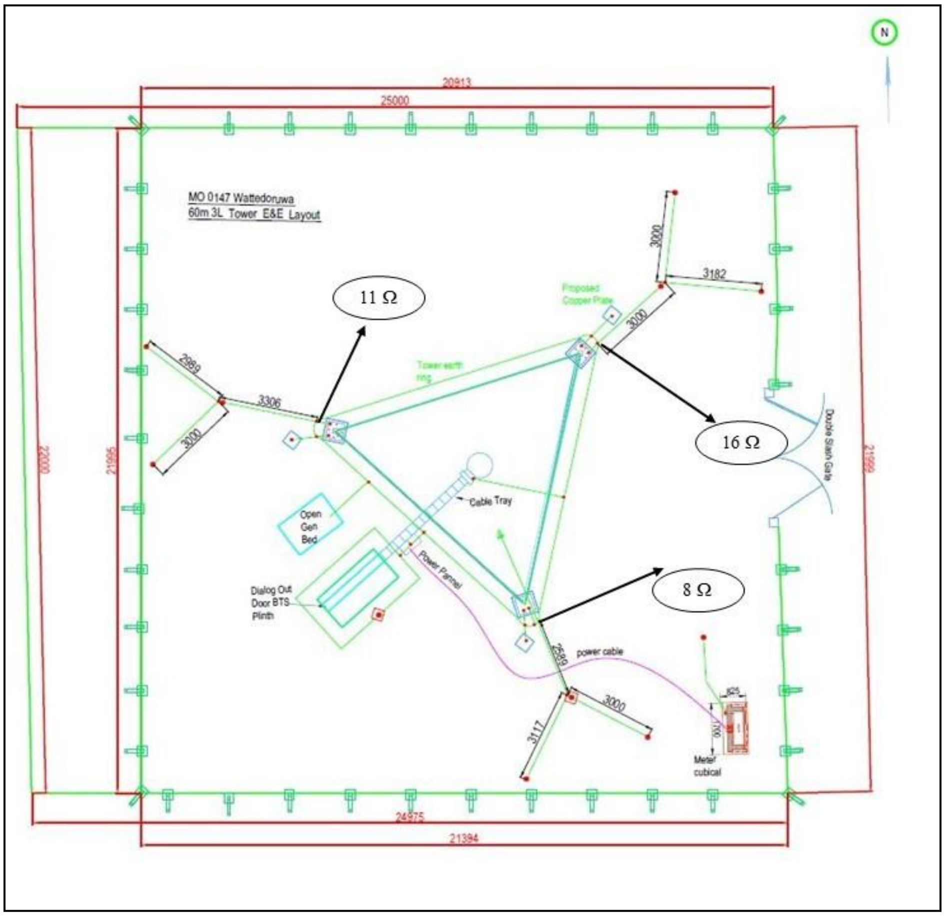


Figure 3 Deviated Earth Readings of a Telecom Site

The measured earth resistance against the used measuring technique has been the assurance to the regulatory compliance where huge costs are incurred when achieving such low resistances. The normal method is to take the average value of different points as the site earth resistance. The measuring method, practical difficulties and assumptions are mainly affecting for variation of earth resistance. Still by accurate methods there should be a way, actual resistance shown by the earth network. So, having a generalized method to estimate the actual earth resistance in such complex network has become a major need among telecom operators.

1.3 Earth Resistance Measuring Difficulties

- Non homogeneity of the soil at the sites are affecting to the earth measurement. But the methods of earth resistance measurement techniques developed with considering the soil having a homogenous structure. Voltage profiles may vary due to non-homogeneity of soil structure when injecting current to get earth resistance.
- Lack of space in urban sites to achieve measurements is another key challenge where space should be there to measurement probes to avoid overlapping. Measurements taken in a small length will be affected by the buried cables and results may be manipulated.
- Terrain constraints and slopes may deviate the earth resistance results. As measurement probes need to insert in different elevated points applying accurate measurement method is a difficult task.

1.4 Aim and Scope of the Thesis

The study will analyze and elaborate the reasons for variation in deviated earth resistances in different directions of complex earthing arrangements, specifically in telecom sites. Measurements covering different soil conditions and theoretical modeling will be compared for the similar earth arrangement in both practical and theoretical domain.

Ansys Maxwell software will be used for theoretical modelling in the finite element domain of the earth networks and to obtain relevant voltage and resistance profiles for further analysis.

Ultimately a method to estimate the actual earth resistance will be presented as a result of validated results and analysis.

2 LITERATURE REVIEW

2.1 Background

Earth resistance of a complex earthing network is governed by various factors. Basically, the earth network design, used material for earthing network and as built arrangement of the complex earthing network. Further, the soil resistivity of the site is another major factor and how deep the earthing network in installed.

Theoretically the built earthing network having a resistance towards the ground which should be a single value. Finding the resultant earth resistance is challenging in a complex earthing network which has used number of rods, meshes and interconnecting conductors. By currently most used measuring technique's results, earth resistance values are varying from point to point in a complex earthing network which has installed in telecom tower sites. In case of a single rod or a plate is used as the earthing arrangement, earth resistance is very much obvious and easily measured and calculated.

Analysis of earth resistance of a telecom tower site should carry basically the background studies of basics of earth resistance and earth resistivity, lightning protection system of the tower sites and earth resistance measuring techniques and mechanisms. Identifying the theories of earth resistance and resistivity basics and idea on how earth resistance is measured will be helpful for expand the existing theories towards a complex earthing network. Study of guidelines and standards involved in earth resistance has to take in to account as whatever the installation the maintained parameters should be accordance with the standard or the relevant guideline imposed by the relevant governing authorities. Specific arrangements of an earthing network in a telecom tower sites are mostly generic to sites footprint, soil resistivity and number of tower legs. Reviving existing earthing arrangement techniques and total sites lightning protection schemes are required for further studies. There are several techniques for earthing measurements in the field. Performance applicability and accuracy as per the site arrangements and conditions need to be considered for earth resistance analysis of a complex site.

Ground analysis methods will be further discussed as achieving resultant earth resistant of a complex network requires different analysis methods to involved in. It's a known factor that theoretical methods and practical measurements are having an error between them. Reviewing existing identified reasons will be useful for the study as to minimize those in the research.

2.2 Earthing of a Telecom Tower Station

2.2.1 Telecom tower station

A telecom tower station is the major element in the access network of a telecom operator specially in case of a mobile operator. As it acts as a two way communication station among users and the network side typically a tower station is called as a Base Transceiver Station (BTS) where the transceiver name implies the two way communication at the access network, transmitting and receiving. The station basically comprises of tower with antennas and other incorporated equipment and the ground level equipment cabin with a power supply. Reliable and uninterruptable service has to maintain through the BTS network to ensure 100 percent service delivery to customers. Downtime and vulnerability to faults has to be minimized in order to maintain the uptime of the network.

Figure 2.1 : Typical BTS with Tower and Equipment Cabin

Avoiding external hazards is important to telecom tower stations as direct impact to revenue loss is caused by such incidents. Major external hazards are caused by lightnings and surges to the system and the tower. Lightning and related incidents are one of the main reasons of effecting the failures of the telecom tower stations in countries like Sri Lanka where level of lightning incidents is higher within the region. Protective measures play a vital role in maintaining the tower sites safety to such occurrences and availability of protection from lightnings and surges is mainly considered when design and construction of telecom tower sites.

2.2.2 Earthing arrangement

For protection of tower sites form direct and indirect lightnings and surges earthing system plays a vital role and proper integrated earthing system is required and periodic maintenance is essential. Basically, requirement of an earthing need arises from two areas.

i. Power system earthing

ii. Earthing network for proper grounding of lightnings and surges

Both systems are essential in terms of personal and equipment safety of the BTS and those will ensure the reliable network operation. To avoid potential differences and circulating currents at the event of a lightning or a surge proper integration is incorporated.

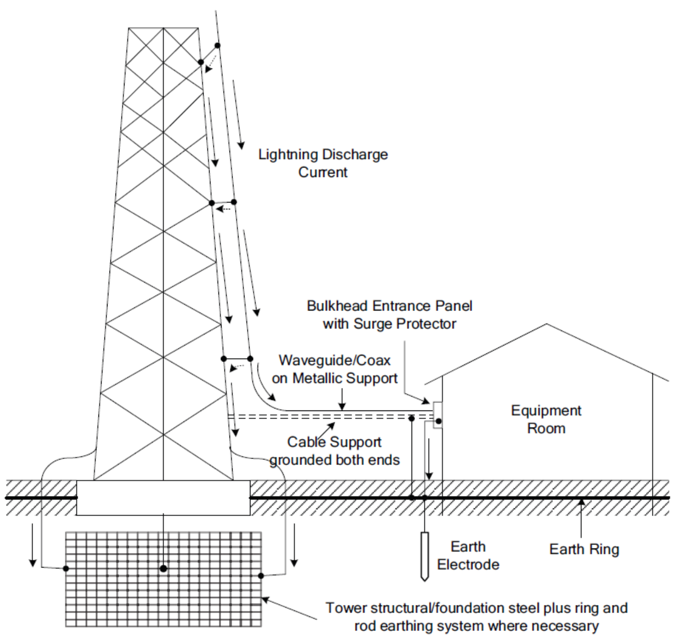


Figure 2.2 Integrated Earthing System

Figure 02 elaborates a telecom tower station with tower and its integrated earthing system. The towers air terminal connected to down conductor which will carry lightning discharge current. It will be connected to earth electrode and total tower and equipment room is covered with a buried ring conductor to provide equipotential bonding. All the surge protective devices connected to communication and power supply also connected to earth ring through conductors which designed to carry the surge impulses.

Design of the earthing is has done as per the earth resistivity of the site and to achieve required earth resistance to meet the regulatory compliance. Basic intentions of the earth network are to achieve followings at a telecom site.

- Prevention of people from electric shock
- provide electrical earth for power system
- As a good medium to discharge lightning current to earth
- Equipotential bonding
- Interception of the lightning current when propagating on the earth's surface

Typically, as the earthing network copper or aluminum is used in the industry. As per the standard IEC 62305 various materials are recommended with specific dimensions which used at the earthing network [3]

Material	Configuration	Dimensions		
		Earth rod diameter mm	Earth conductor mm^2	Earth plate mm
Copper Tin plated copper	Stranded		50	
	Solid round	15	50	
	Solid tape		50	
	Pipe	20		
	Solid plate			500 × 500
	Lattice plate[c]			600 × 600
Hot dipped galvanized steel	Solid round	14	78	
	Pipe	25		
	Solid tape		90	
	Solid plate			500 × 500
	Lattice plate[c]			600 × 600
	Profile	[d]		
Bare steel[b]	Stranded		70	
	Solid round		78	
	Solid tape		75	
Copper coated steel	Solid round	14[f]	50	
	Solid tape		90	
Stainless steel	Solid round	15[f]	78	
	Solid tape		100	

Figure 2.3 : Material, configuration and minimum dimensions of earth electrodes [3]

2.3 Earth Resistivity & Resistance

2.3.1 Earth resistivity

It is the parameter which indicates that how much soil or earth material resists or conducts an electric current through it [4].

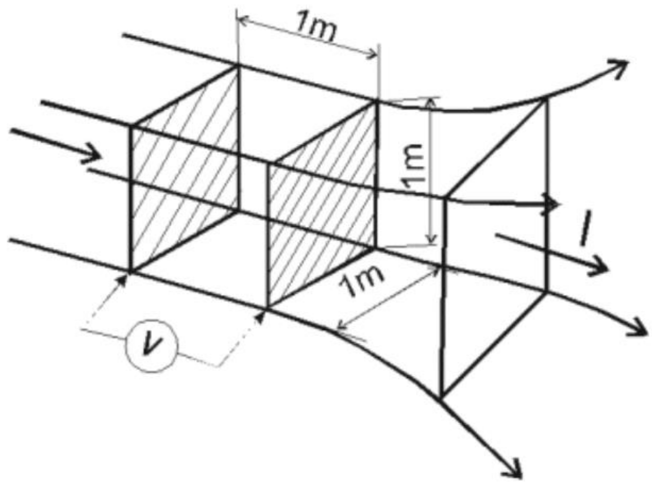


Figure 2.4 Explanation of the concept of soil resistivity (p=V/I)

Further it will be elaborated by measuring resistance of 1m X 1m X 1m soil cube from opposite sides as in above figure. Typically, the measurement units are in ohm meters(Ωm). Earth resistivity is variable due to following factors in a same soil.

- Moisture content
- Salt content
- Temperature

2.3.2 Earth resistance

It is the ohmic resistance shown between the earth electrode and a remote grounding electrode of zero resistance [4]. It is typically measured in ohms (Ω). So, for the earth resistance the intermediate media is making a considerably effect. The resistivity of the soil or intermediate material is governing the earth resistance of a particular rod to be high or low. (basic equations)

2.4 Earth Resistance & Resistivity measuring guidelines

Earth resistance measurement is the key parameter to the operator to understand the condition of the earth network performance. Measurement is the main parameter which gives the clear picture and idea of the unknown area.

Guidelines are important and much needed to industry for proper usage of measurements in order to obtain accurate performance. As the earth network arrangements and other parameters of the sites, measurement techniques may need to change. Measurement guidelines are needed to incorporate such conditions. Achieving accurate insights of the site conditions will be possible when having proper guidelines.

"IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System" is the prime standard used as the guideline for earth resistance and resistivity, measurements in the industry. Latest version is released at 2012 and it covers "*Practical test methods and techniques are presented for measuring the electrical characteristics of grounding systems. Topics addressed include safety considerations, measuring earth resistivity, measuring the power system frequency resistance or impedance of the ground system to remote earth, measuring the transient or surge impedance of the ground system to remote earth, measuring step and touch voltages, verifying the integrity of the grounding system, reviewing common methods for performing ground testing, reviewing instrumentation characteristics and limitations, and reviewing various factors that can distort test measurements"*[4] .

2.4.1 Objectives of testing

As per the IEEE 81 it has identified the objectives of the testing of earth or grounding impedance and potential gradients due to ground currents. It will help to verify the adequacy of a new grounding system, to detect changes in an existing grounding system, to determine hazardous step and touch voltages and to determine ground potential rise (GPR) in order to design protection for power and communication circuits [4].

2.4.2 Earth resistivity measuring guidelines

Further earth resistivity measurements guidelines are also explained by the IEEE 81 standard as mostly at the design of earth/ground networks earth resistivity is much needed and it is useful for the measurement, calculations and analysis of earth network related studies. So, it will be useful for:

- Estimating the ground resistance of a proposed substation or transmission tower
- Estimating potential gradients including step and touch voltages
- Computing the inductive coupling between neighboring power and communication circuits
- Designing cathodic protection systems

- Geological surveys

Earth resistivity values normally changes for different soils and rocks as per following table.

Earth Resistivity Ohmmeters	Quarternary	Cretaceous Tertiary Quarternary	Carboniferous Triassic	Cambrian Ordovician Devonian	Pre-Cambrian and Combinat. with Cambrian
1 Sea water					
		Loam			
10 Unusually low		Clay			
		Chalk	Chalk		
30 Very low					
			Trap		
100 Low			Diabase		
			Shale		
300 Medium				Shale	
			Limestone		
				Limestone	
1000 High			Sandstone		
				Sandstone	Sandstone
	Coarse Sand				
3000 Very High				Dolomite	Quartyite
	and Gravel				
					Slate
10 000 Unusally high	in surface				
					Granite
	Layers				
					Gneisses

NOTE — Table 1 is from reference [B38] of the Bibliography section.

Figure 2.5 Earth Resistivity of different soils with periods of geographical formation

As per the standard the impedance of a grounding system largely depends on the resistivity of the surrounding soil and the extent and configuration of the buried electrode. As per the buried electrodes material and mech structure and design the impedance will be changed. Earth resistance is considered when dealing with the power frequencies and for higher frequencies total impedance will be considered as inductance and capacitance will be affected. Isolated earths and small earth systems with typical soil resistivities are predominately resistive and large grounding systems, especially in low soil resistivity areas, will have a significant reactive component.

2.5 Earth Resistance & Resistivity Measuring Methods

2.5.1 Earth resistance measuring methods

There are different types of methods used in measuring earth resistance in industry as per the application. The typical methods are fall of potential method, two-point method and three-point method. Further there are methods called ratio method, staged fault test, single clamp earth resistance testing, double clamp earth resistance testing and attached rod technique which are being used as per the special scenarios.

Analytical calculations are used for derivation of three-point method and the ratio method which are related to the fall of potential theory. The two-point method and clamp method of measuring earth resistance should be limited to small earthing systems [5].

2.5.1.1 Fall of potential method

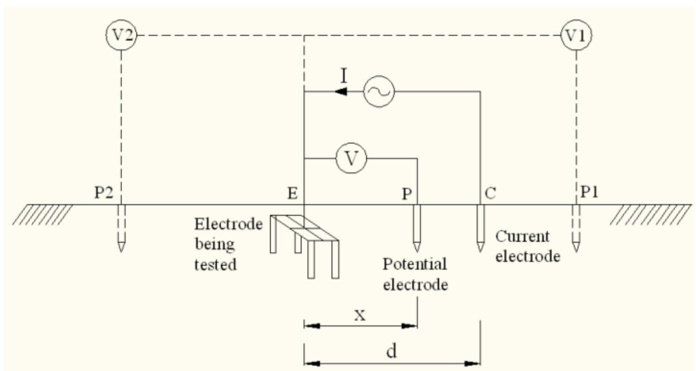


Figure 2.6 Fall of potential method

This method is involved a current probe and a potential probe to measure voltage. Earth electrode whose resistance is to be measured is taken to inject current between it and far most distance placed current electrode C. Resistance is measured in terms of potential between earth electrode under test and potential electrode P as shown in above figure. Normally before taking a measurement earth electrode is disconnected from the earthing system to not being affected by leakage currents by the system.

When current is injected between earth electrode under test and current electrode voltage will be distributed as the current flows along the earth. The potential will be measured along the distance between rods. The ratio V/I = R will be resistance measured and will be plotted against the distance of the measurement. As the potential probe moves away from the electrode under test in steps a value of resistance will be obtained for each distance. The plotted graph will be used for obtain the true or apparent resistance of the earth electrode under test.

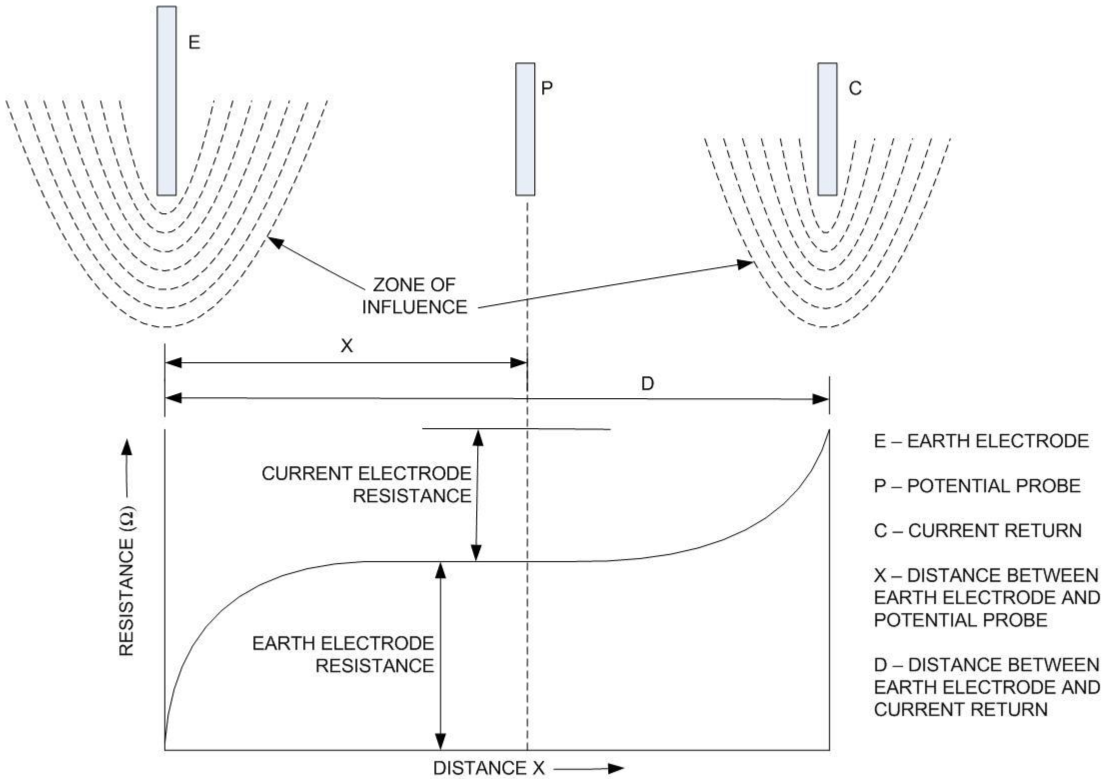


Figure 2.7 Resistance variation along the distance [5]

To obtain a flatten curve its needed to current electrode to place outside the influence area of the electrode under test as per above figure. When using fall of potential method large spacings are required as current probe has to place in a distance to avoid influence of electrode under test.

The accurate distance has to maintain when achieving correct results from a measurement. When the earthing arrangement is complex placing of probes has to done with excess care. The most reasonable resistance will be obtained when probe spacing x between potential and electrode under test placed between current probe and electrode under test when the x/d =62% [6] where d is the distance between electrode under test and current probe.

To obtain 62% distance and get an accurate result following factors has to be maintained.

a. Soil has to be uniformed
b. Large spacing should maintain between E & C.

2.5.1.2 Two Point method

This method is used for measure earth resistance of single rod driven earth. There has to be an auxiliary earth which can be used as a reference. Normally metallic water pipes in vicinity is used [5].

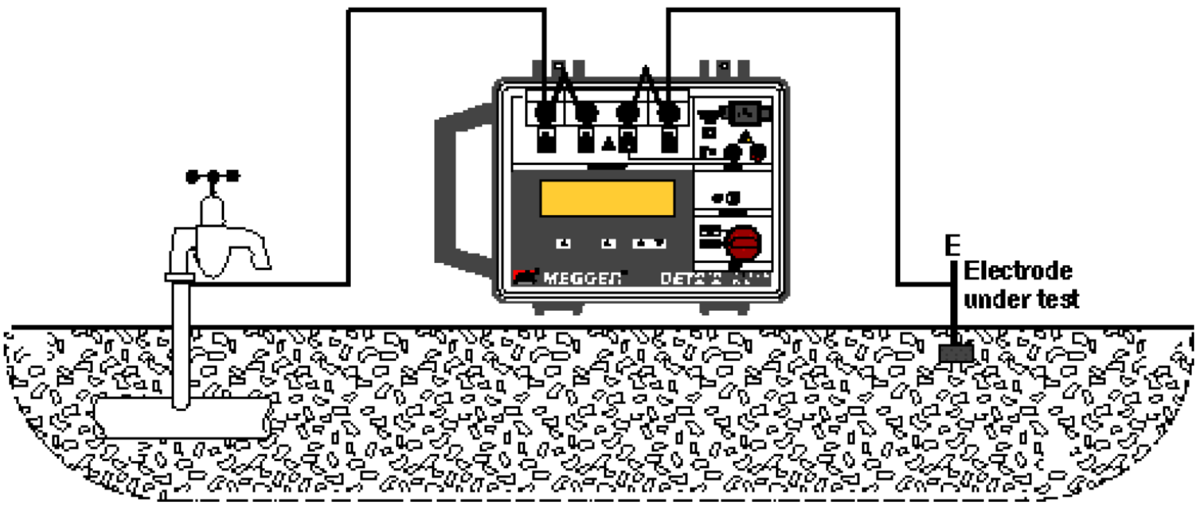


Figure 2.8 Two Point Method Illustration

The resistance of the metallic pipe assumed to be negligible compared to electrode under test. The measured value is taken directly as the resistance of electrode under test and for rough estimations this method is used and for low resistance value measurements this method cannot be used.

2.5.1.3 Three Point method

The three point method is using two electrodes where the resistance of them are taken as R_2 and R_3 . The electrode needs to test will be taken as R_1. The resistance measured between each pair of electrodes are being measured and denoted as follows.

R_{12} – Resistance between earth electrode and test electrode 2

R_{13} – Resistance between earth electrode and test electrode 3

R_{23} – Resistance between test electrode 2 and test electrode 3

$$R_1 + R_2 = R_{12} \text{ ----------------1}$$

$$R_1 + R_3 = R_{13} \text{ ----------------2}$$

$$R_2 + R_3 = R_{23} \text{ ----------------3}$$

By solving above three equations we can get following equation to obtain R_1

$$R_1 = \frac{R_{12} + R_{13} - R_{23}}{2}$$

So, in this way measuring series resistance of each pair of electrodes and using above equation the resistance of electrode under test can be found. Accurate results will be given by this method when the resistance of the two electrodes not comparatively large than the electrode under test. This method is recommended for small area of earthing systems and spacing between electrodes has to be kept more than 5 meters for accurate results [5].

2.5.1.4 Ratio method

In this method a comparison is done between the electrode under test and a known resistance. The electrode configuration is similar to the electrode configuration in the fall of potential method. The resistance values are independent of the test current as the method is using comparison between a known resistance. The test current is placed high enough to achieve required sensitivity of the reading [5].

2.5.1.5 Staged fault test

The staged fault test is the most representative measurement of the earth impedance of an installation [5]. Realistic fault current magnitudes are being produced by this test and rise of earth potential and earth impedance can be calculated by using remote voltage reference. This test is performed seldom as per the economic barriers and the constraints aroused by the operation.

2.5.1.6 Single clamp earth resistance testing method

In this method like in fall of potential method current probe to inject current and potential measurement probes are not needed for measure earth resistance. Disconnection between earthed body and electrical system is not required. This method is based on Ohm’s Law (R=V/I) [7].

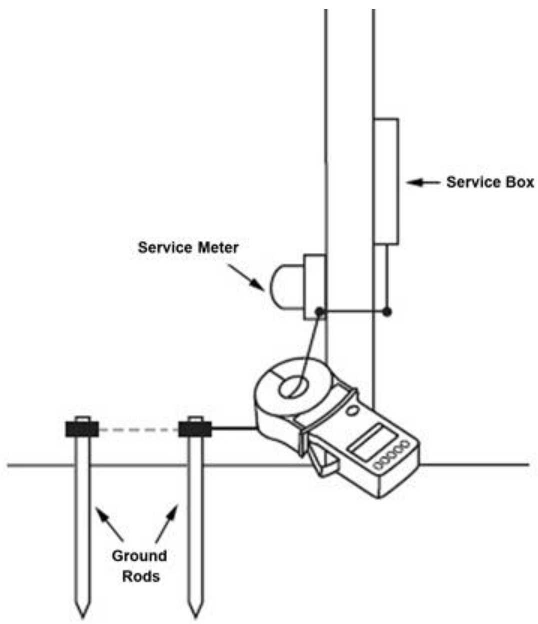


Figure 2.9 Clamp on method

As illustrated in above figure with the help of the source coil inside the clamp of the earth tester a known voltage is applied inductively to a complete circuit. The induced voltage by the clamp will be applied. There will be a current induced in the earthing circuit due to that voltage and it will be measured by the same clamp inside the earth tester which induced the voltage. Resistance calculation will be done by dividing the current flowed in the earthing circuit by the induced voltage in it. Verification should be done to ensure that the earthing system is included for the circulation current loop. By the induced current flowed path, clamp on earth tester measures the resistance. The basic assumption is, by the resistance of the total loop, earth system under test contributes significantly for the resistance measured.

The clamp on method is fast to measure resistance as it does not involve earth probes in measurement and the earthing system does not need to be isolated. Also, the reading may indicate the high resistance value as the grounding conductor is used as part of the return. Following disadvantages are explained by the manufacturer [7].

- The accuracy of the readings is seriously affected when frequency of the injected current in to the earth by the tester is same as the disturbance current in the earth.
- This method will be only applicable in situations where multiple grounds are in parallel as a return path is required. So, for isolated of single rod earthing arrangements it cannot be used as there won't be any return path and also due to the same reason for installation checks and commissioning this method cannot be used.
- For applications such as cellular towers or substations it cannot be used if an alternate lower resistance return exists not involving the soil.
- Measurement accuracy will be having effects due to mutual inductance between the voltage and the current loops of the clamp tester.
- The operator must be having a thorough idea of the earthing arrangement as a return path is required for complete the current loop and operator must have a clear idea of the method of using the clamp on test method for earth resistance measurement.
- Like in fall of potential method this do to have a built in proof method to verify the results shown like varying the probe spacing. The user has to accept the results shown by the clamp on tester when using it.

2.5.1.7 Double clamp earth resistance online tester

In this method there are two clamps being used to avoid effect of mutual coupling in the clamp where both coils are in it which having a slight difference than in single clamp method. In this method also isolation of earth conductor from the system or power isolation is not required. The tested equipped with a variable low frequency AC voltage generator, two clamps and the online earth tester [8].

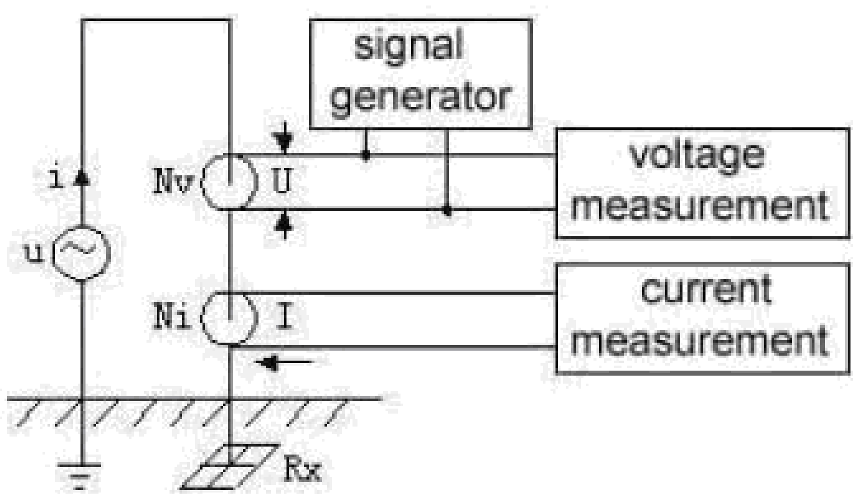


Figure 2.10 Double clamp earth tester

2.5.1.8 Attached rod technique (ART) by Megger

This tester combines advantages for both fall of potential method and clamp on testing method. It remains true to the theory and methodology of fall of potential method and does not need to disconnect the ground electrode from the system. Similarly, to the fall of potential method it used a current electrode and a potential electrode for voltage measurement while using a clamp for additional leakage measurement. When the fall of potential method is used without disconnecting the earth electrode from the attached power system it will be showing the resistance including interconnected systems. When it needs to obtain the currents carried by individual earthing system during the test additional clamp meter will be useful which will be used in this attached rod technique [7].

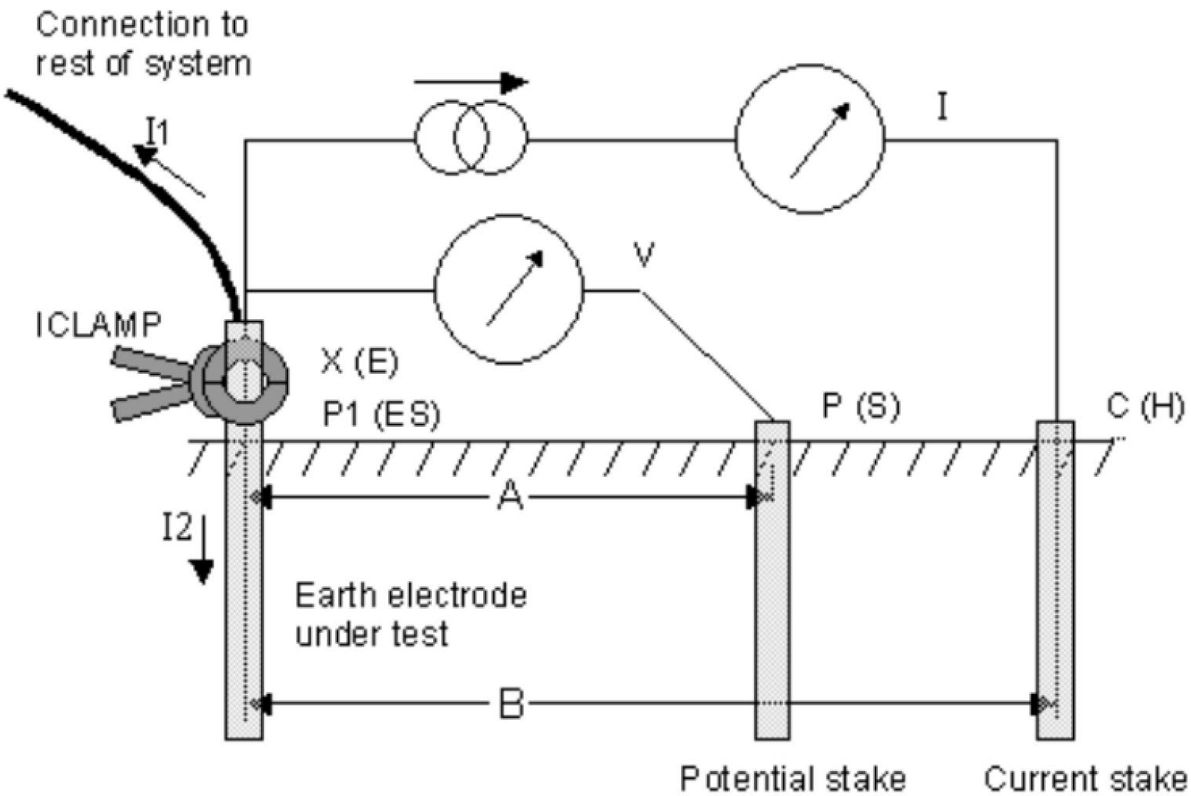


Figure 2.11 Attached rod technique (ART) measurement

The attached rod technique is followed by three steps

I. As in fall of potential method it will measure the effective resistance of the earthing system by the applied voltage - V
II. Measurement of total current being injected to the system- I
III. Measuring the current flowed to the interconnected system other than the electrode under test – I_1

The difference between total current and current flowed to interconnected systems will give the current flowed through the electrode under test- I_2. That can be used for calculate the earth resistance of the electrode under test by using following equation.

$$R = \frac{V}{I_2}$$

2.6 Earth Resistivity Measuring Methods

2.6.1 Wenner method

For measurement of earth resistivity four terminal method is used and most common method used is known as Wenner Method.

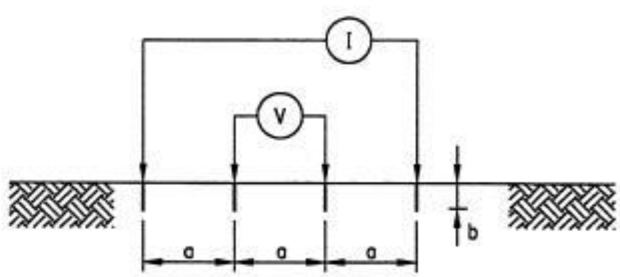


Figure 2.12 Wenner Method of Earth Resistivity Measurement

The measuring method is as shown in above figure and apparent resistivity is given by following equation.

$$\rho_E = \frac{4 \cdot \pi \cdot a \cdot R_W}{1 + \frac{2 \cdot a}{\sqrt{a^2 + 4 \cdot b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

$\boldsymbol{\rho_E}$ = measured apparent soil resistivity (Ωm)

$\boldsymbol{a}$ = electrode spacing (m)

$\boldsymbol{b}$ = depth of the electrodes (m)

$\boldsymbol{R_W}$ = Wenner resistance measured as "V/I" in ohms.

If $\boldsymbol{b}$ is small compared to $\boldsymbol{a}$, as in the practical scenario where penetrated distance of the electrode is negligible compared to inserted distance equation will be deduced to following.

$$\rho_E = 2 \cdot \pi \cdot a \cdot R_W$$

2.6.2 Schlumberger method

This method also using four electrodes similarly in Wenner method. The voltage probe distance and current probes are taken as ***a, c***.

$$\rho_E = \pi \frac{c \cdot (c + a)}{a} R_S$$

P_E = measured apparent soil resistance
a = electrode spacing
b = depth of the electrodes
c = electrode spacing
R_S = Schlumberger resistance measured as "V/I"

2.7 Methods Used in Ground Analysis

2.7.1 Grounding system size-based analysis

In this method grounding systems are categorized in to three sub systems depend on the size of the earthing grid arrangement as follows [9].

I. Small grounding systems - 40mx60m
II. Medium grounding systems - 280mx140m
III. Large grounding systems - 440mx280m

Further three approaches are used for analysis of ground for above three grounding systems. In the first method it is most commonly used and it is based on the method of images and assumes that the grounding system as a equipotential structure. The results will be accurate for non-extensive grounding networks at low frequencies [9].

Second one is the method where voltage drop along the grounding network taken in to account. Then the assumption made as grounding system to be an equipotential structure is eliminated. It is capable of computing potentials at every point in the grounding system and it does not account for inductive and capacitive interactions between conductors in the grounding system.

In the third method of grounding analysis field theory approach has been used and its is not most commonly used. Not like in other two methods it does not consider the grounding system as a equipotential structure and it consider not only the self-impedance but also the interactions due to capacitive and inductive components of the grounding conductors.

When analyzing different sizes of grounding systems using the above three different approaches results will be as follows [9].

- Small & Medium grounding systems – Almost equal GRP values for all 3 approaches
- Large Grounding systems – lower ground impedance for Approach 1, Approaches 2 and 3 has an angle, implying an inductive component
- Commonly used grounding analysis algorithm with the assumption of equipotentiality of grounding systems gives satisfactory results for small and medium-sized grounding grids consisting of copper conductors.

2.7.2 Computing techniques used for ground analysis

2.7.2.1 Integral approach

In this method of analysis is done by using integral equations to analyze electric potentials [10].

2.7.2.2 Differential approach

Differential approach is using Finite Element Method (FEM) for analysis of ground potential. Commonly for analysis computer based software are used such as MATLAB, ANSYS, etc.[10]

In here three kinds of elements are used to model ground systems. First one is unidimensional elements to model conductors and rods. Second is bidimensional elements to model thin layers and final one is tridimensional elements to model the soil [11].

2.8 Variations in Theoretical and Practical Values in Earth Resistance

Variations may happen between practically measured values and the theoretical values due to serval reasons as follows [4].

- Inadequacy of the analytical methods used in the calculations of the resistance.
- As per the soil condition varies, earth resistivities at the time of the resistance measurement being different from those assumed in the calculations.
- Non accurate or insufficient extent of the resistivity survey. As an example, number and dispersal of tests, probe spacing, and inadequacy of the instrumentation used.
- Availability of buried metallic structures and ground wires in the proximity of testing site, which can divert a substantial amount of the test current through them.
- Clamp-on meter readings might contain a large error if the reactance in the test circuit is significant compared to the resistance of the test circuit or if the filters are inadequate to filter out 50 Hz/60 Hz frequencies caused by stray currents. [12]

2.9 Literature Review Summary

From the above literature referred, as the most suitable and widely used earth resistance measurement technique, fall of potential method was identified and will be using in at practical measurements at tower sites. Similarly, for the resistivity measurement Wenner method will be using and those measurement data will be using in theoretical modeling. In both cases the general assumption of taking the soil layer under study as a homogeneous will be practiced. The ground analysis will be done using computing techniques which accommodate finite element method for ground potential analysis using ANSYS Electromagnetics.

3 METHODOLOGY

The research methodology will be elaborated from following steps as explained below. It will flow from initial data collection to theoretical modeling, analysis, comparison and reasons for deviations.

3.1 Collection of Earth Resistance Data

The initial step was to gather earth resistance data of telecom tower sites having multiple leg towers. Operator maintained annual data and measurements were taken for multiple leg towers and telecom stations having a complex earth arrangement which not only having a single earth point.

When earth resistance data gathered for a particular earth network significant deviations of earth resistance from each other points were considered for further analysis. Those were taken as sites having deviated directional earth resistances and other sites having insignificant deviations were not considered for analysis.

Site Name	R1	R2	R3	R4	Average
Erauwala, Pannipitiya	1.25	7.24	7.13	7.32	5.7
Kapugala	9.7	8.9	9.9	N/A	9.5
Maha Induruwa	3.62	4.42	7.85	9.32	6.3
Kuruwita	8.52	10.21	12.58	16.8	12.0
Parakaduwa	4.23	5.32	13.89	14.3	9.4
Aththidiya	5.87	5.12	5.62	5.81	5.6
Rathgama	4.56	3.26	5.63	3.51	4.2
Atthidiya	5.12	4.91	N/A	N/A	5.0
Deraniyagala	12.8	9.8	10.52	22.5	13.9
Akuressa	12.24	12.2	11.52	8.8	11.2
KARANDENIYA	9.31	6.31	7.81	8.34	7.9
Kalegana	5.63	15.63	12.3	14.5	12.0
Batuwandara	6.6	6.62	6	5.78	6.3
Watagedara	11.8	9.05	16.67	N/A	12.5
Hiralugama	0.68	0.65	0.63	0.69	0.7
Pothegama	0.45	0.5	0.37	N/A	0.4
Idama	4.56	4.63	N/A	N/A	4.6
Awissawella	13.6	13.18	13.2	12.99	13.2
Aluthgama	3.7	3.23	8.42	8.64	6.0

Table 3.1 Earth Resistance Data of Operator 1

Above table shows sample earth resistance data of one of the telecom operators in Sri Lanka. Yellow highlighted sites show considerable variation of the average value and the individual legs earth resistance values.

Below table shows another data sample of another telecom operator which extracted from the earth resistance measurements which are having deviated earth resistances.

Site Name	R1	R2	R3	R4	Average
Kotabowa	6.41	6.31	7.45	N/A	6.7
Alawathugoda Town	7.6	14.2	N/A	N/A	10.9
Kelimune	19.5	13.4	Cannot measure. Rocky area		16.45
Kahadamodara	2.4	6.7	3.6	N/A	4.2
Nagarawewa	3.5	7.6	4.5	N/A	5.2
Athimale west	12.6	8.5	5.6	N/A	8.9
Pinwatta Station	15.2	7.3	6	N/A	9.5

Table 3.2 Deviated Earth Resistance Data of Operator 2

Almost all the sites above are having deviated earth resistance values which extracted from the earth resistance reports of telecom operator 2. All these measurements were taken using fall of potential method with the assumption soil as homogeneous.

From the sites having deviated earth resistance values of each other for better comparison sites having similar earthing configuration were selected for further studies. Following figures illustrates earth configurations of the telecom sites.

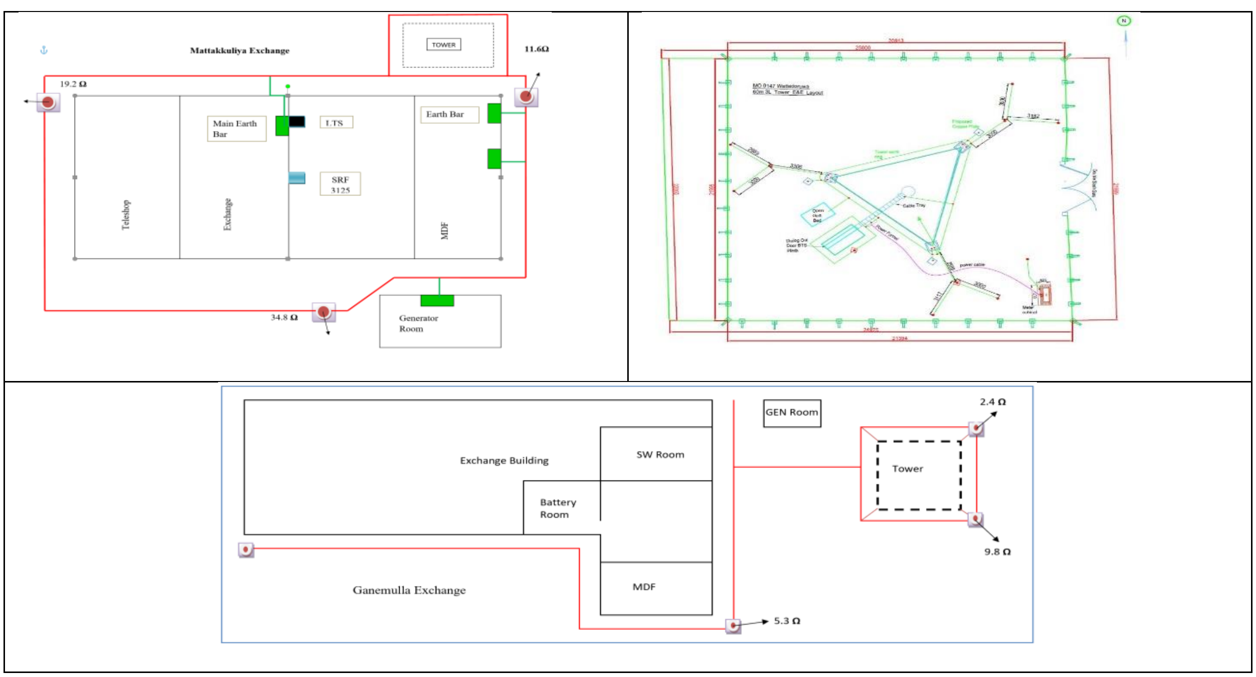


Figure 13 Typical Earth Configurations of Telecom Sites

From the earth configurations existing in telecom sites, as 3 leg towers are mostly common to each other earthing arrangements are also similar to each other in sites. So, for further study 3 leg tower sites were selected.

3.2 Gathering Earthing Data of Selected Sites

As 3 leg tower sites are selected for further study, earth network data were gathered for those type of sites. Sites were selected to represent different soil conditions from different parts of the country. Following table shows measured data of sample telecom site and study will be done comparing sites located in different parts of the country.

Site Name	**Pinwatta Station**
Site Area	Western
Type of Tower	3 Leg
Earth Resistivity	500 Ωm
Earth Resistances	15.2 Ω /7.3 Ω /6 Ω

Table 3.3 Selected Site Earth Data

For selected sites earth network data were gathered and those were as follows.

Earth Grid Specifications	
Material	Cu
Earth Tapes	3x25 mm
Earth Rods	Cu bonded mild steel Diameter-16 mm Length – 3 m
Earth Plates	600x600x3 mm
Connections	Cad Welded

Table 3.4 Earth Network Specifications

Different lengths of Cu tape and rods were used as per the initial design of the earthing for each site.

3.3 Modeling Selected Sites

Modeling was done based on the measurements and assumptions made of sites by using Ansys Electromagnetics Software. Site earth map was used for modeling of the earthing arrangement as per the actual dimensions and soil conditions. Buried earth ring was modeled including the conductor which connects the air terminal. Following is the site earth configuration.

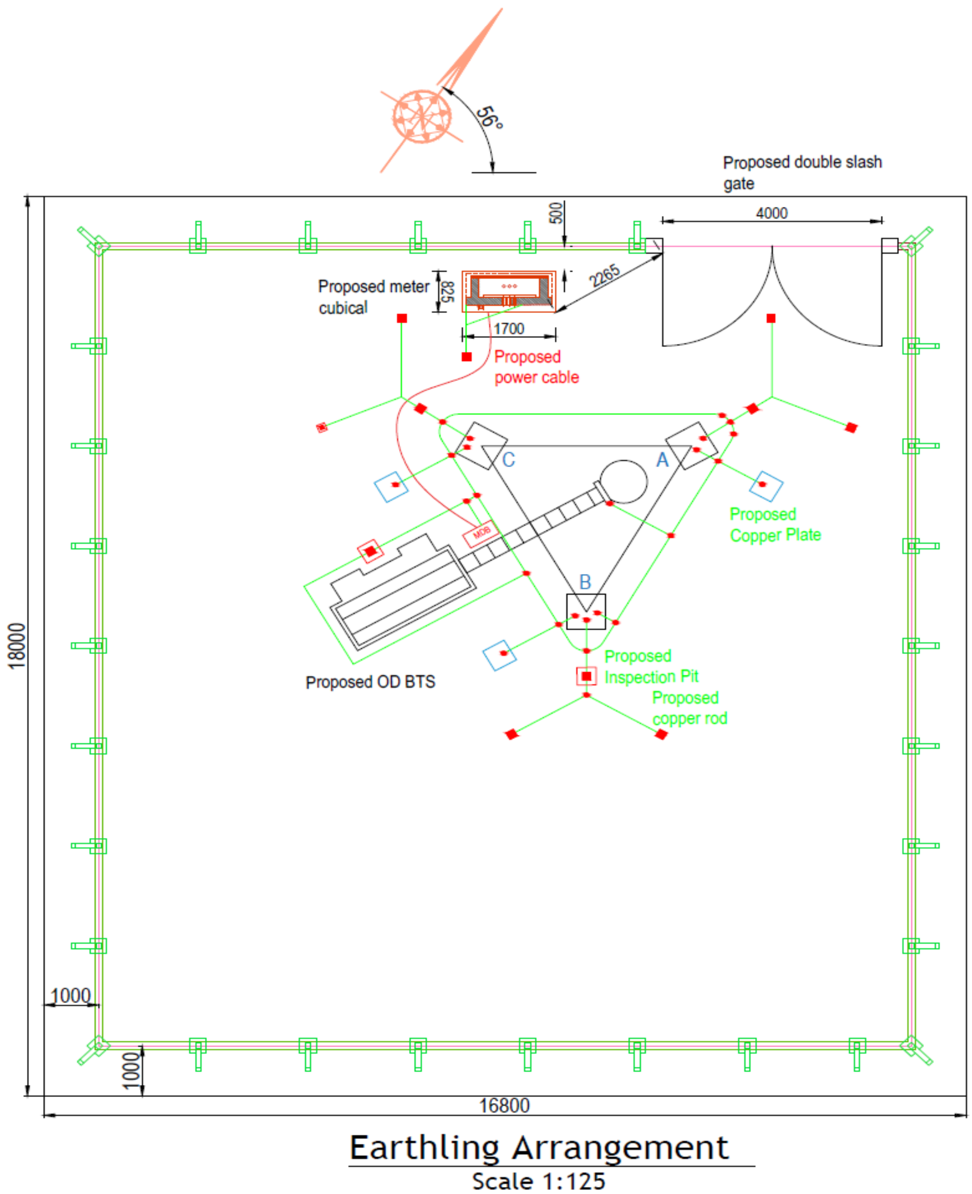


Figure 14 Pinwatta Station Earth Map

3.3.1 Soil modeling of selected telecom site

Soil area was selected as per the site boundary and depth was selected in accordance to the soil resistivity measurement taken which was 10 m depth while keeping assumption soil volume as homogeneous. Soil depth was considered as per maximum effectiveness towards earth resistance of the earth network of the telecom site.

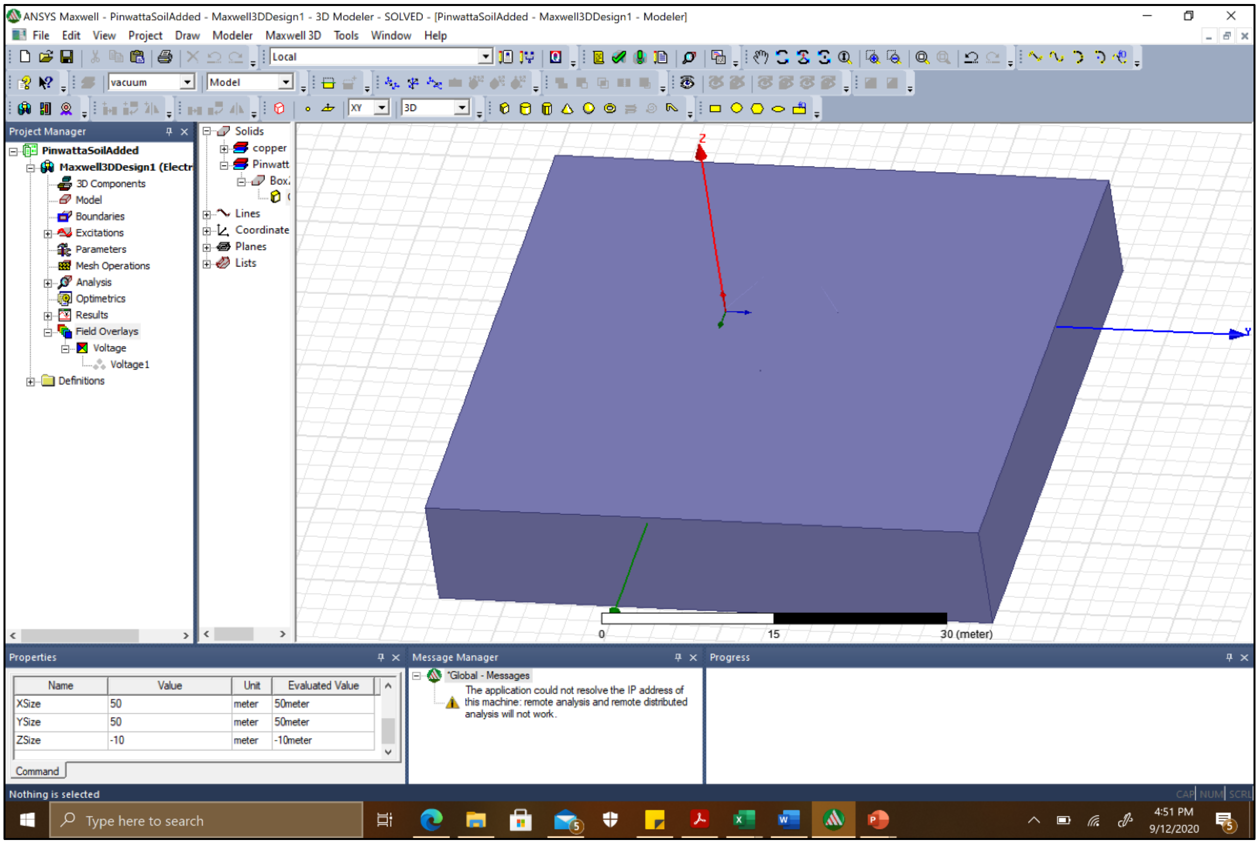


Figure 15 Modeled Soil for Simulation

Following are the soil data which modelled for a particular site as per the site boundary and resistivity.

Soil Dimensions:	L – 50 m
	W- 50 m
	H- 10 m
Soil resistivity:	500 Ωm (Homogeneous)
Thus, conductivity:	0.002 S/m

3.3.2 Earth Network Modeling

Earth map of the telecom tower site was modeled inside the soil as it actually lies. Typically an earth network is under the soil from 300mm~600m in depth. As per the drawing data earthing network is placed under the top soil surface according to the specified as built drawing.

All the metal connections between copper tapes and earth rods are being made through it and for the simulation it will act as a one common continuous conductor without any open circuits.

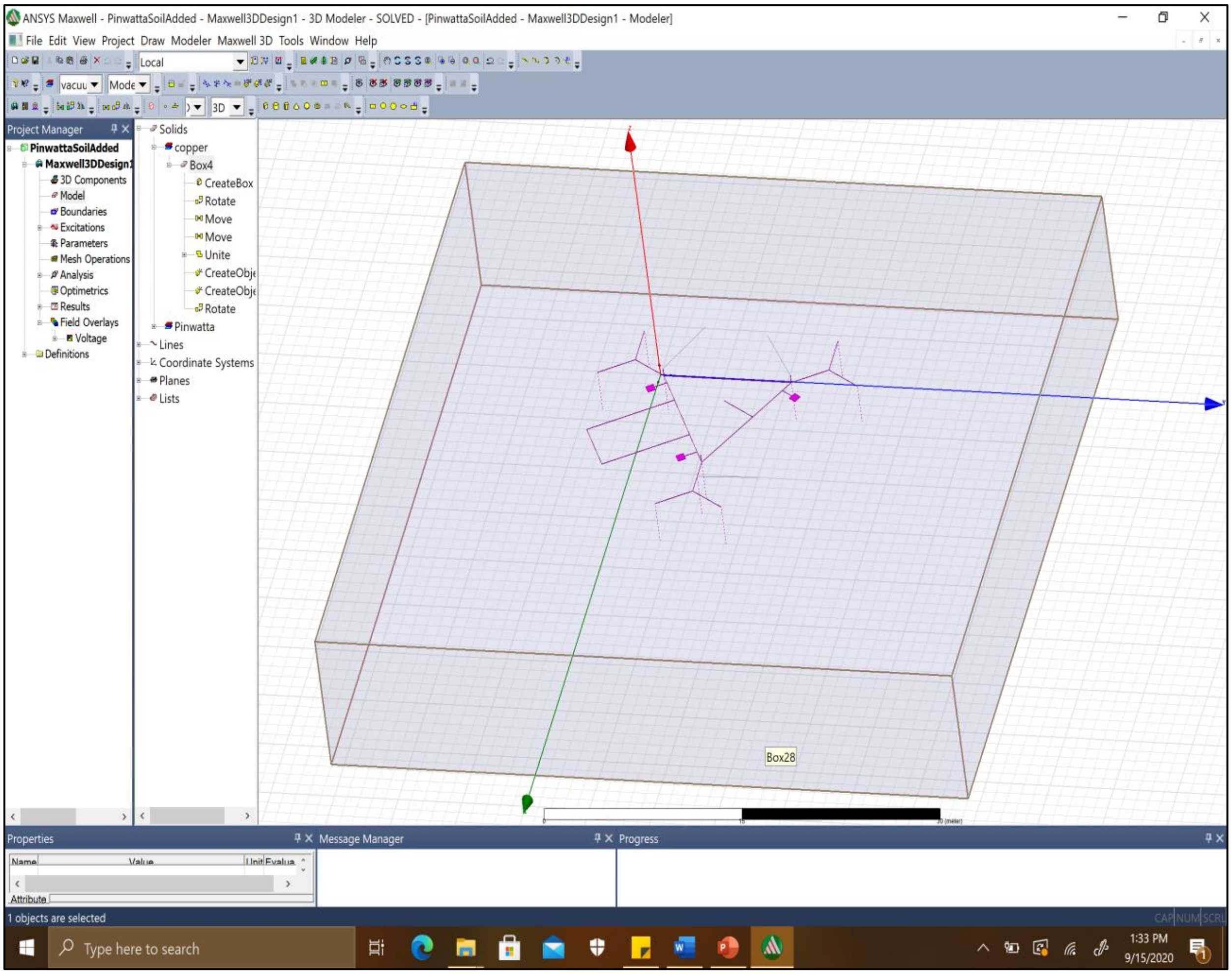


Figure 16 Modeled Earth Network with Soil

3.3.3 Electrical modeling

Down conductor coming from the air termination is modeled from the earthing network to soil surface. It is needed for inject the current/voltage to the earth network for simulation and current carrying path of the earth network will begin through that. For the simulation purpose as it is considered only the soil depth of 10 m where resistivity is measured for that depth bottom layer of the soil is considered to be zero volts or the sink.

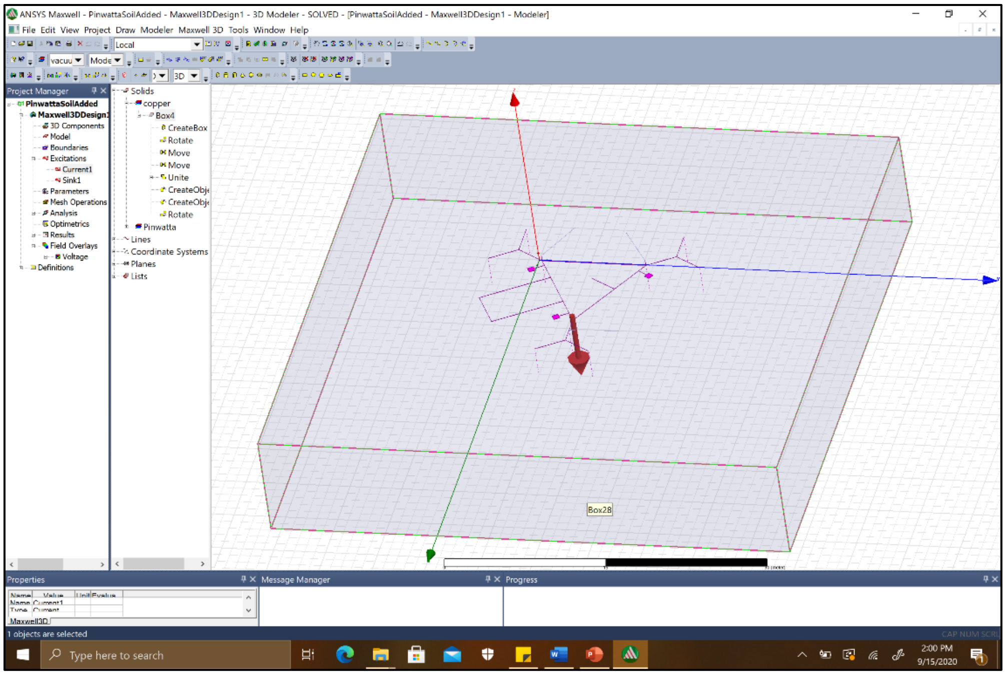


Figure 17 Current Injection Point at Top Surface

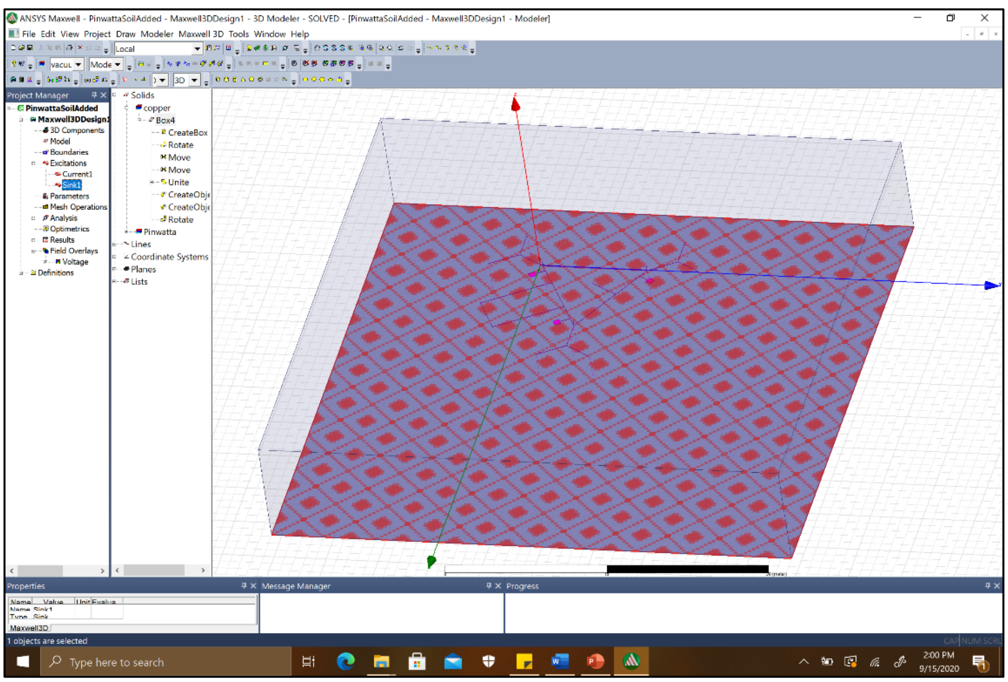


Figure 18 Sink at Soil Bottom Surface

3.3.4 Obtaining voltage and current profiles

For the simulation purpose a test current of 10 kA was injected and the simulation done to obtain the voltage and current profiles. Following figure illustrates the voltage profile at the soil volume after simulation.

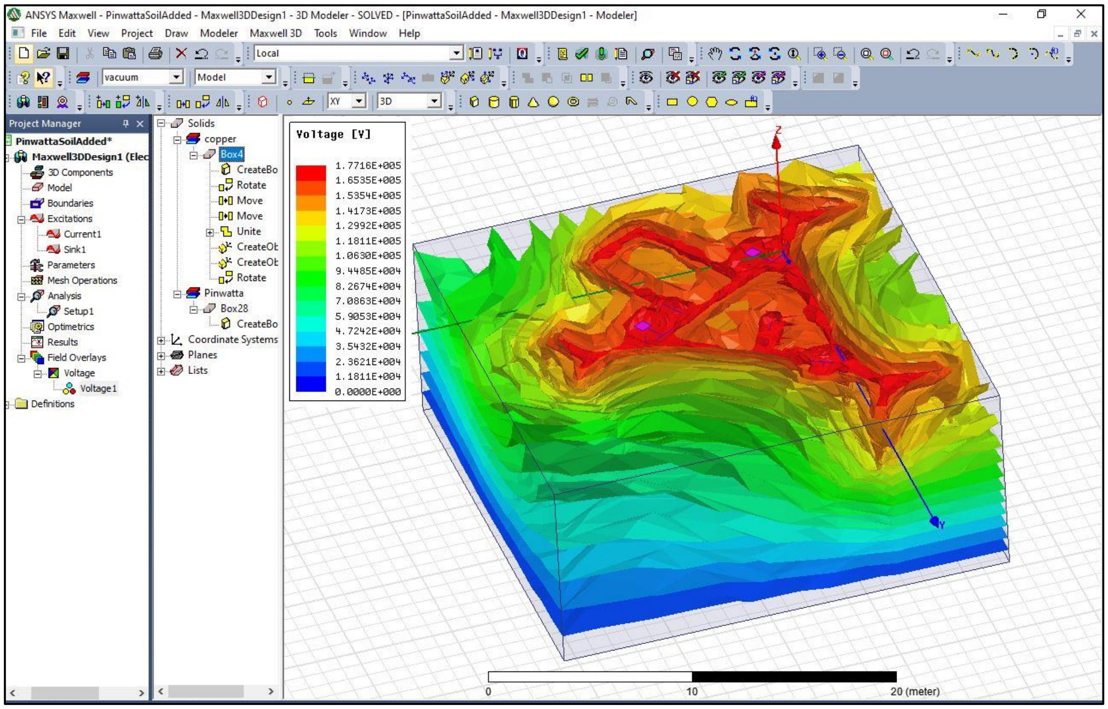


Figure 19 Simulated Voltage Profile of the Soil

Voltage at the earth network is at higher levels and with the distance outwards it voltage reduces in all directions on the surface and along the depth. To obtain voltage and current profiles along the directions where measurements being made, non-model lines were used and voltage and current densities were obtained.

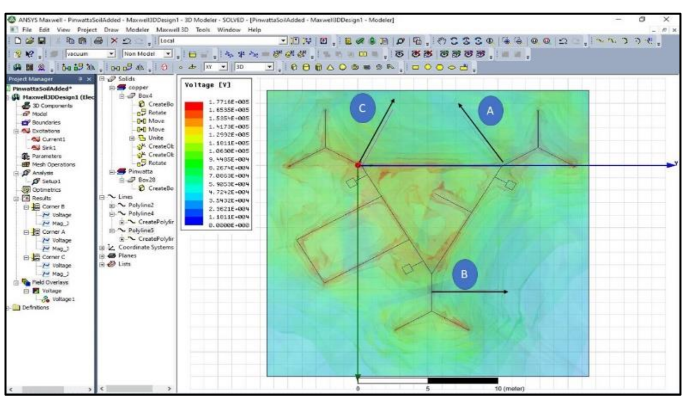
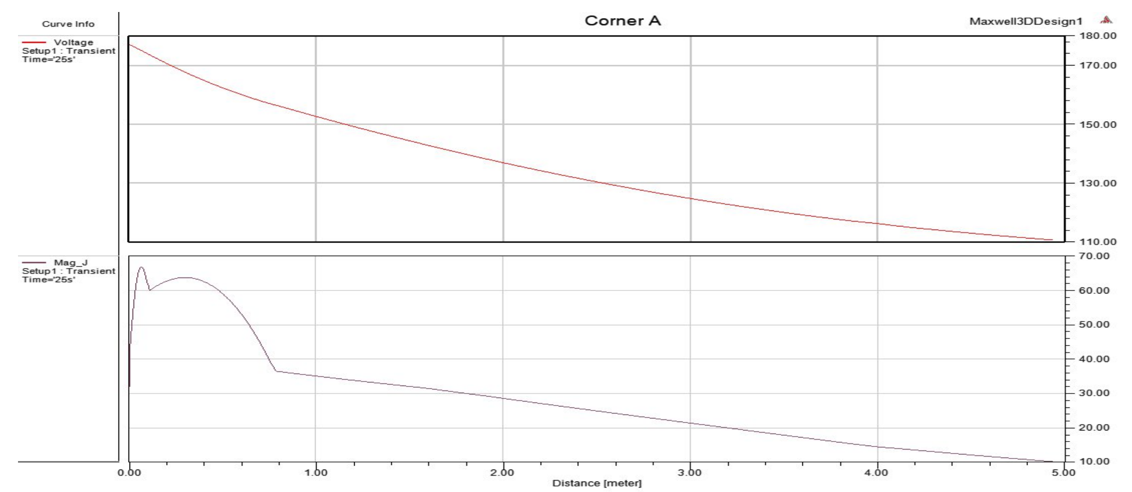


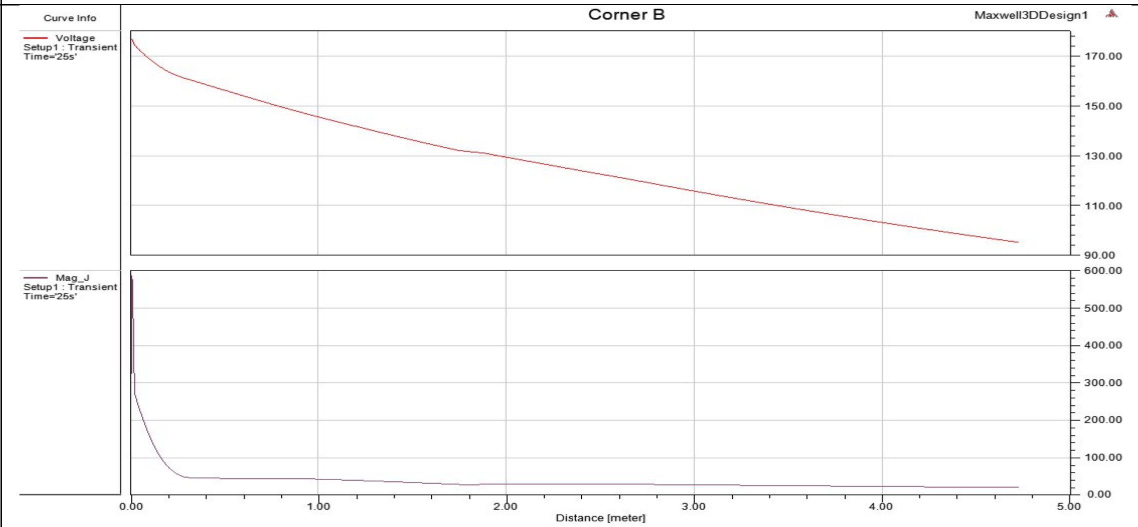
Figure 20 Non-Model Lines for Directional Voltage and Current Profiles

The obtained voltage and current profiles were as follows.

A



B



C

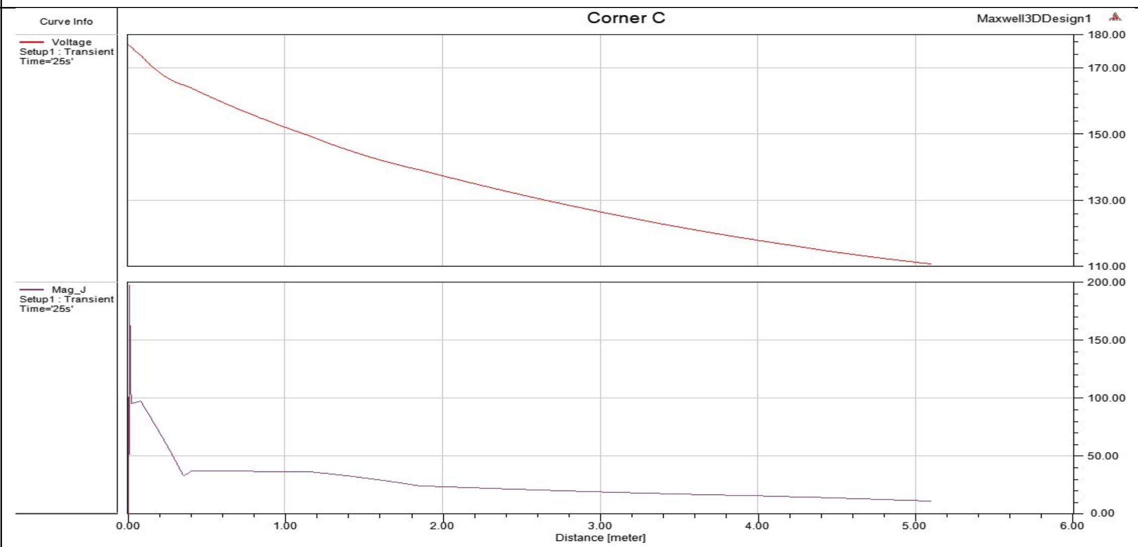


Figure 21 Directional Voltage and Current Profiles

3.3.5 Analyze the behavior of the profiles

Analysis is done based on the results received by the voltage profile of the telecom site and directional voltage and current profiles. The voltage profile is compared with similar telecom sites having similar earthing arrangement and different soil resistivity.

Further voltage profiles were compared from each direction of the site and between different sites having same earthing arrangement. It is to obtain a common simulated model for a typical telecom tower site and for reliable comparison between measurements and theoretical model.

Simulation for different types of current injections will be done and compared to observe deviations of voltage profiles as per the current being AC or DC.

3.3.6 Estimate the Earth Resistance Profiles

From the simulations as voltage profiles are being obtained, derivation of resistance profile is done from those voltage profiles. From a directional voltage profile, individual data points will be gathered from the simulator. Those data will be used to generate the inverted voltage profile.

Inverted voltage = $V_{max} – V_i$

Individual voltage points along the distance outward the earthing network will be deducted from the maximum voltage observed along the line.

As $V \alpha R$,

Inverted voltage or voltage drop will be equal to the trend of directional resistance. Resistance estimation will be done using that method.

3.3.7 A Method to Estimate Actual Earth Resistance

To estimate the actual earth resistance from the complex earthing network directional voltage profiles or obtained resistance profiles has to be compared with measurements.

In order to that directional earth resistances have to be measured and comparison will be done for achieve relationships and through a validated model further comparison will be done to obtain a method for estimation.

3.3.8 Reasons for deviations

Reasons for deviations will be considered based on the literature and assumptions made. From the sites having equal configuration, directional profiles will be considered for sites having irregular behaviors on each other. Deviations from each other sites will be discussed.

4 THEORETICAL ANALYSIS

4.1 Introduction

The theoretical analysis is based on the ANSYS electromagnetics in the finite element domain simulations on selected sites and obtained voltage and current profiles.

4.2 ANSYS Simulations on Selected Sites

Sites were selected from different parts of the country and among them with the availability of earth maps on selected sites. Summary of sites data are as follows.

Earth resistances were measured and selected sites were having deviations from each other legs. These sites are to be modeled using ANSYS electromagnetics to obtain voltage and current profiles.

Site Name	**Pinwatta Station**	**Kelimune**	**Nagarawewa**
Site Area	Western	North Western	Southern
Type of Tower	3 Leg	3 Leg	3 Leg
Earth Resistivity	500 Ωm	900 Ωm	150 Ωm
Earth Resistances	15.2 Ω /7.3 Ω /6 Ω	19.5 Ω /13.4 Ω	3.5 Ω /7.6 Ω /4.5 Ω

Table 4.1 Simulated Site Data

Earth network data was gathered as per the specifications of the material used in the sites. Almost all the sites had same earth grid specifications as follows.

Earth Grid Specifications	
Material	Cu
Earth Tapes	3x25 mm
Earth Rods	Cu bonded mild steel Diameter-16 mm Length – 3 m
Earth Plates	600x600x3 mm

Table 4.2 Earth Grid Specifications

4.2.1 Simulation of Pinwatta Station site

The site is at western coast of Sri Lanka and the earth map was as follows.

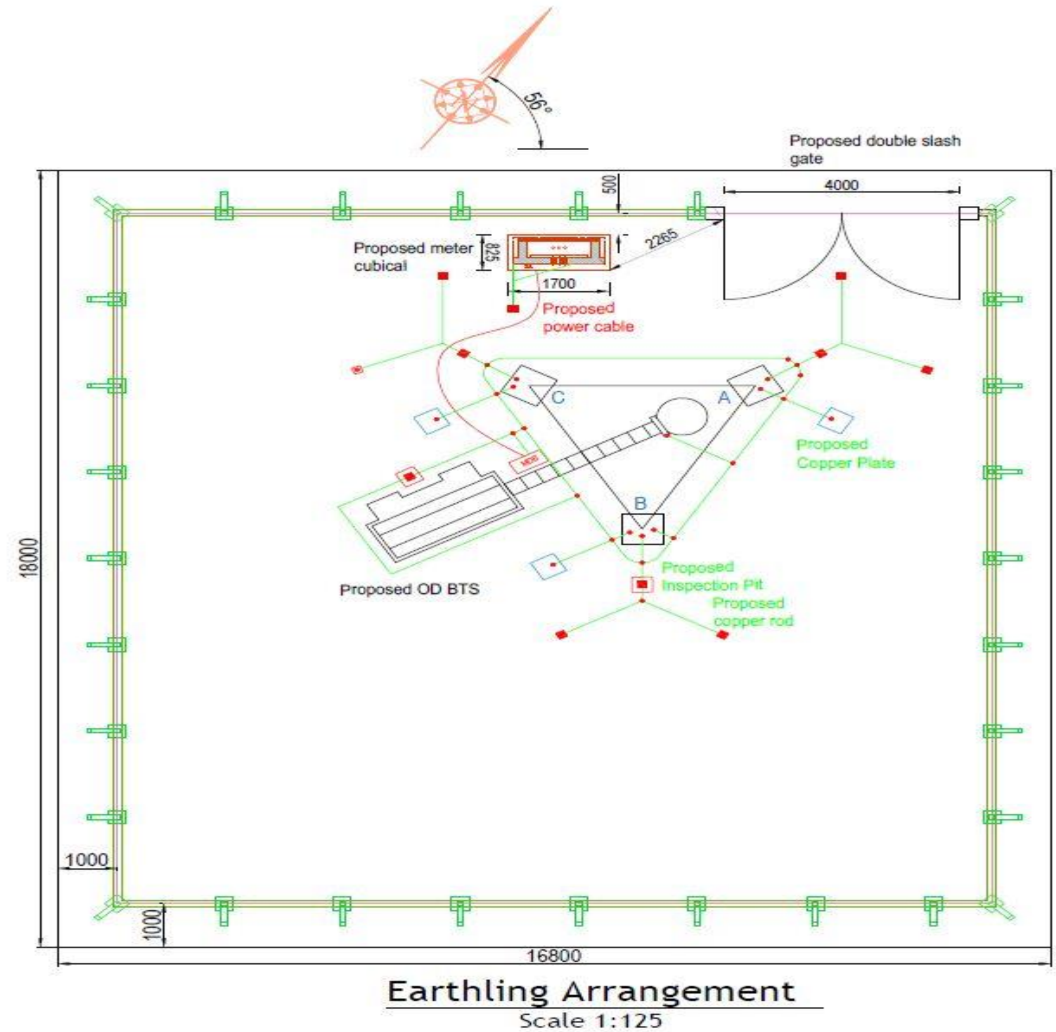


Figure 22 Pinwatta Station Site Earth Map

The site having earth rods, tapes and plates incorporated in the earthing network. Site modeling done using ANSYS by feeding soil data as follows.

Soil Dimensions: L – 50 m

W- 50 m

H- 10 m

Soil resistivity: 500 Ωm, Thus, conductivity: 0.002 S/m

Assumptions : Soil taken as homogeneous.

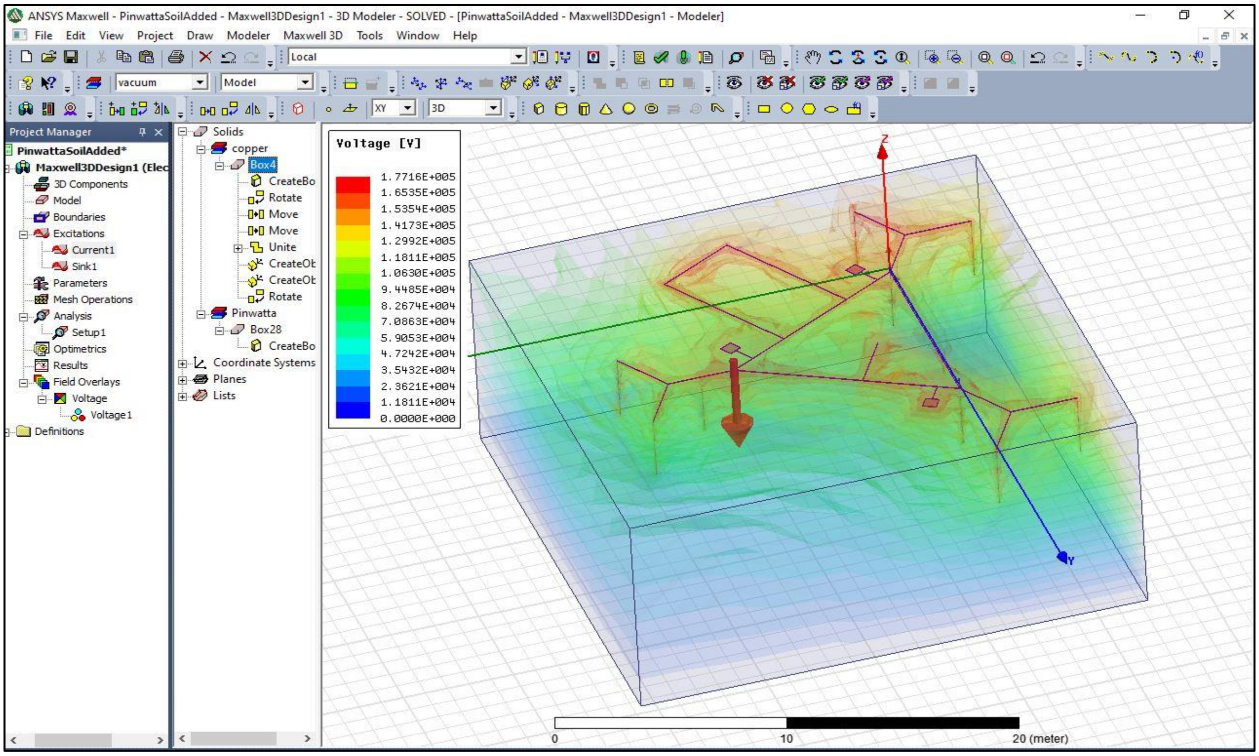


Figure 23 Modeled Site of Pinwatta Station

Initially a test current of 10 kA was used from the down conductor connecting point and below surface of the soil was assigned as the sink where voltage as zero.

4.2.1.1 Results of Pinwatta Station Site

Voltage distribution obtained was as follows.

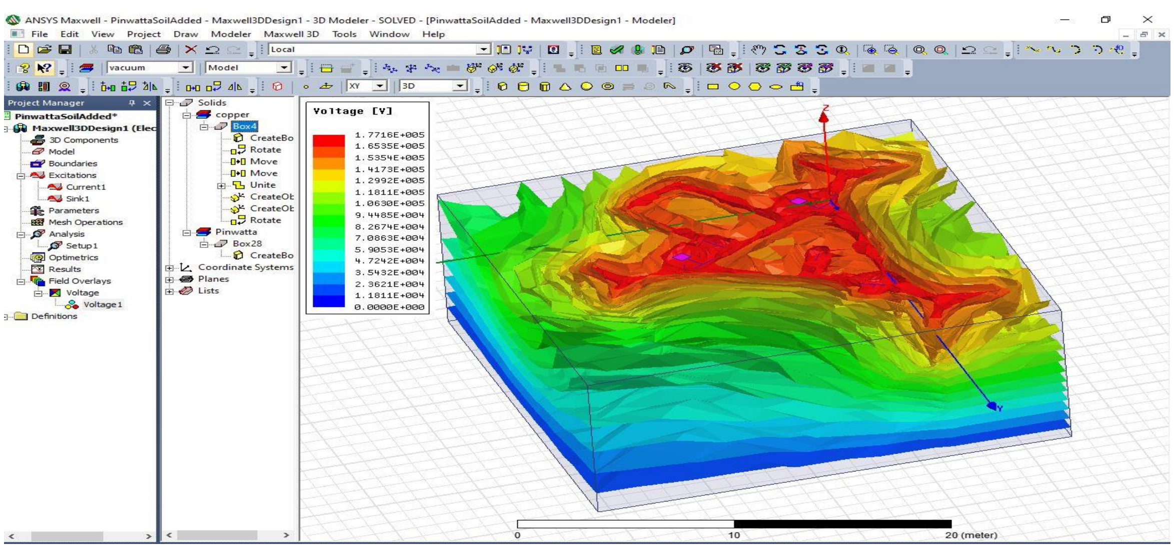


Figure 24 Voltage Distribution of Pinwatta Station Site

By the voltage distribution it can see that higher voltage is built up near the earthing conductors and as the distance increases from the earth network voltage drops as per the resistivity of the soil. For further comparison voltage and current profiles were taken along the distance of earth resistance measuring directions.

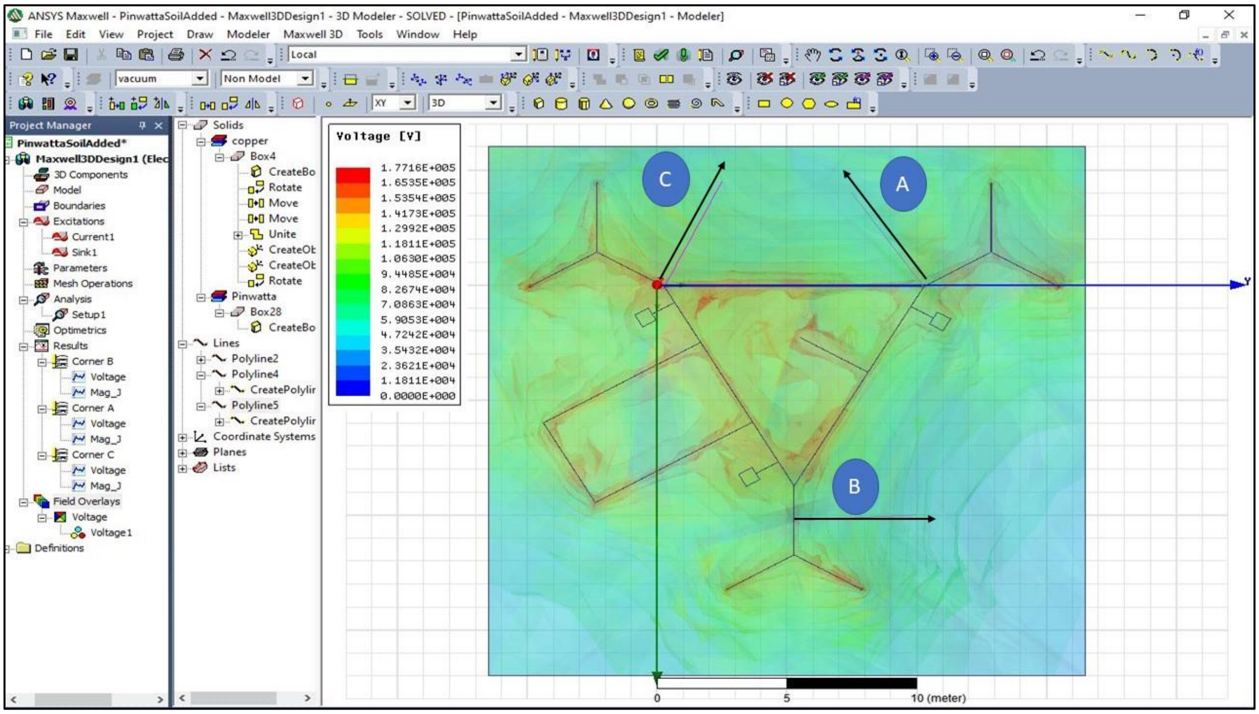


Figure 25 Directions of Pinwatta Station Site for Voltage Profiles

Obtained voltage and current profiles were as follows.

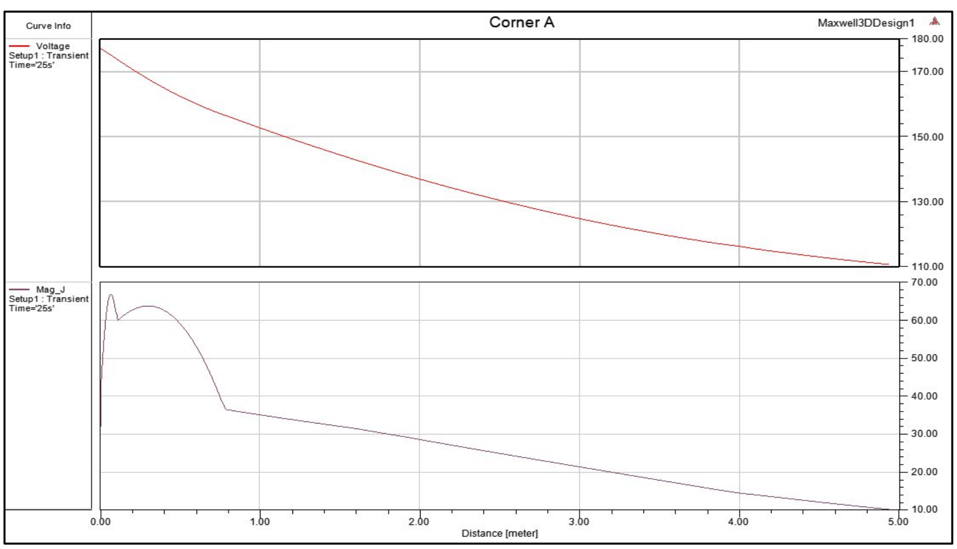


Figure 26 Corner A Profiles

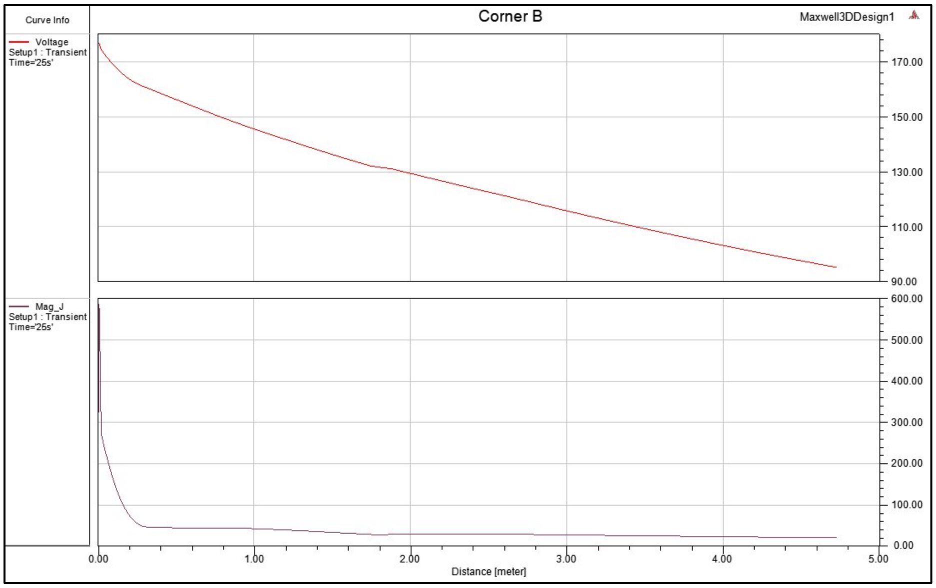


Figure 27 Corner B profiles

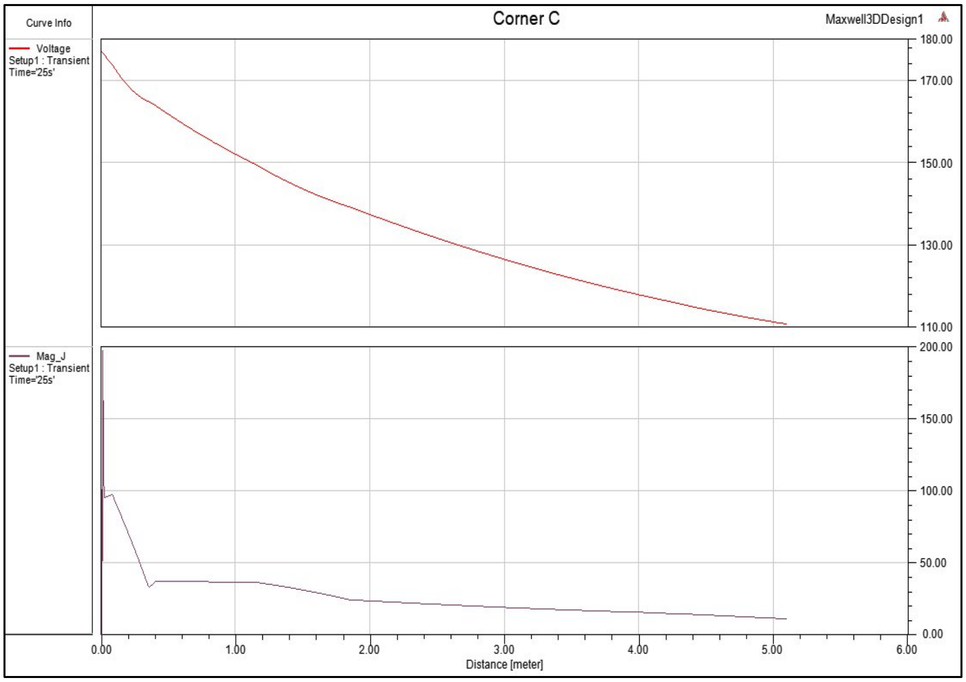


Figure 28 Corner C Profiles

At all the directions voltage and current pattern were same. With the distance it reduces to zero.

4.2.2 Simulation of Kelimune site

This site is at north western province of Sri Lanka and having a higher soil resistivity at the site. Site earth map is as follows.

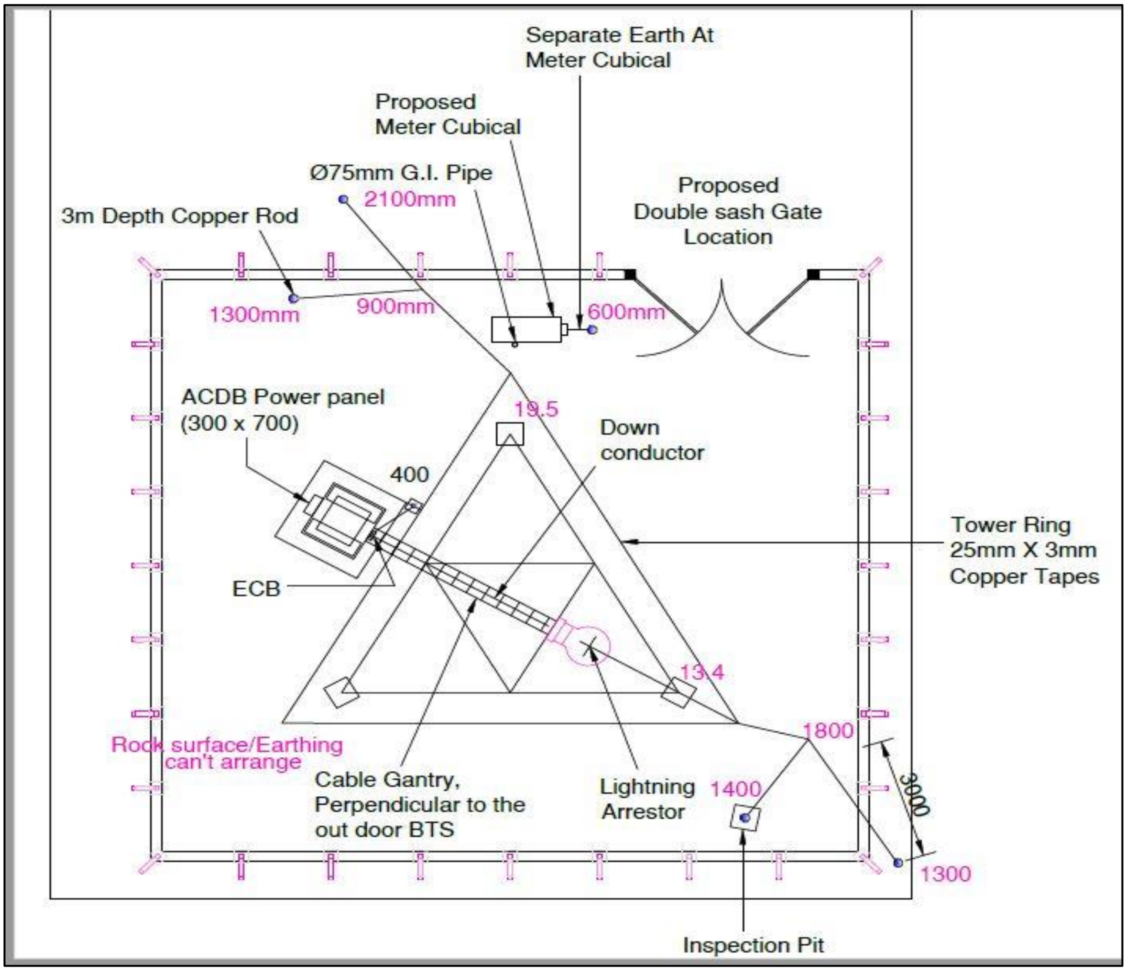


Figure 29 Kelimune Site Earth Map

For earth network simulation similar 10 kA was applied and soil data was as follows.

Soil Dimensions: L – 15 m

W- 15 m

H- 10 m

Soil resistivity: 900 Ωm, Thus, conductivity: 0.0011 S/m

Assumption: Soil taken as Homogeneous

4.2.2.1 Results of Kelimune site

The voltage profile obtained was similar to the Pinwatta Station site and it is as follows.

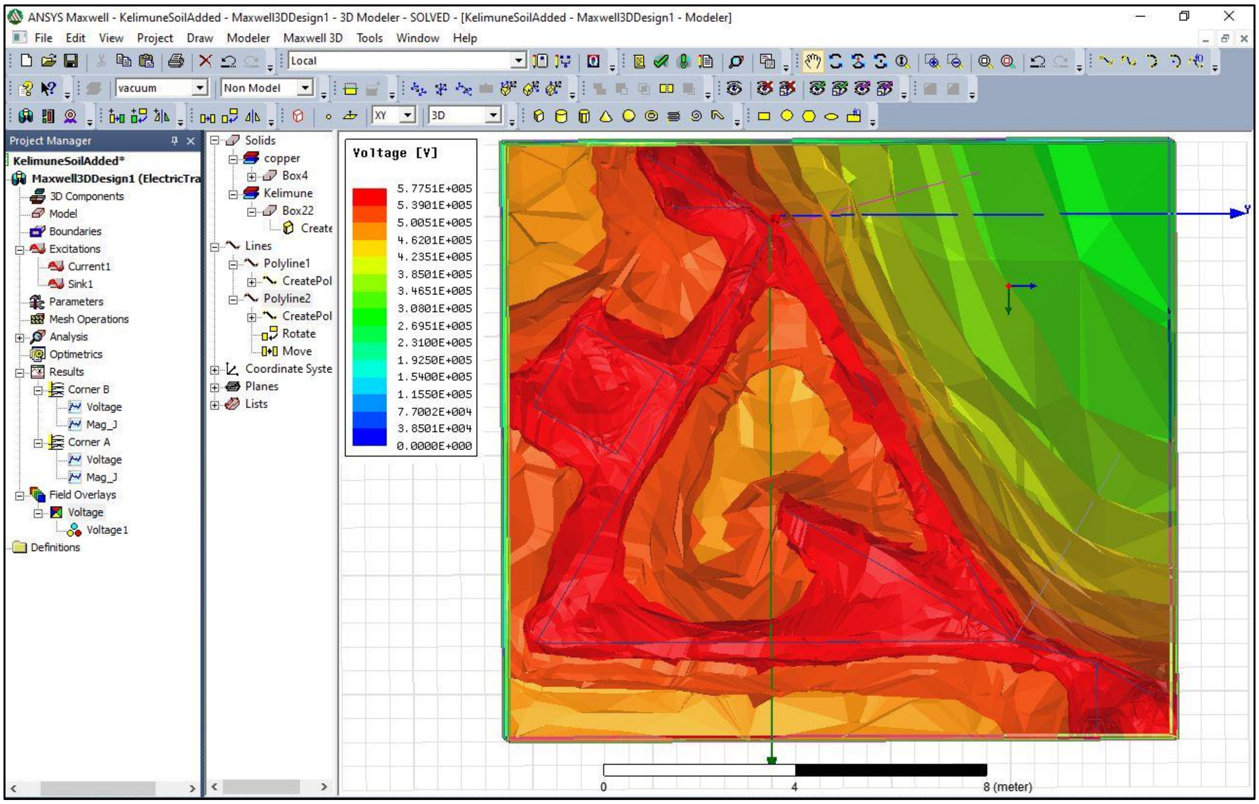


Figure 30 Voltage distribution of Kelimune Site

The higher voltage shown at the earth grid and its reducing with the distance increases from the earth network. Similar to previous voltage profiles were obtained in the direction of resistance measurements are taken.

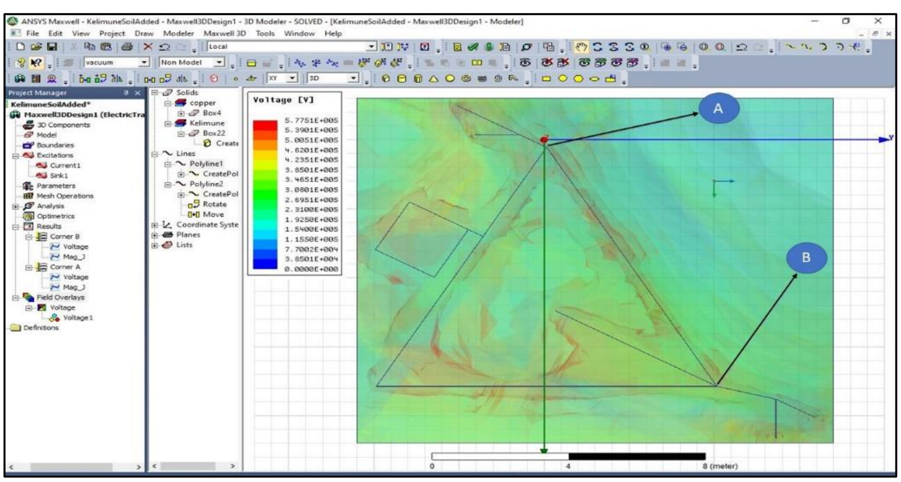


Figure 31 Directions of Voltage Profiles at Kelimune Site

Obtained voltage and current profiles were in similar pattern as in the Pinwatta Station site and illustrated below.

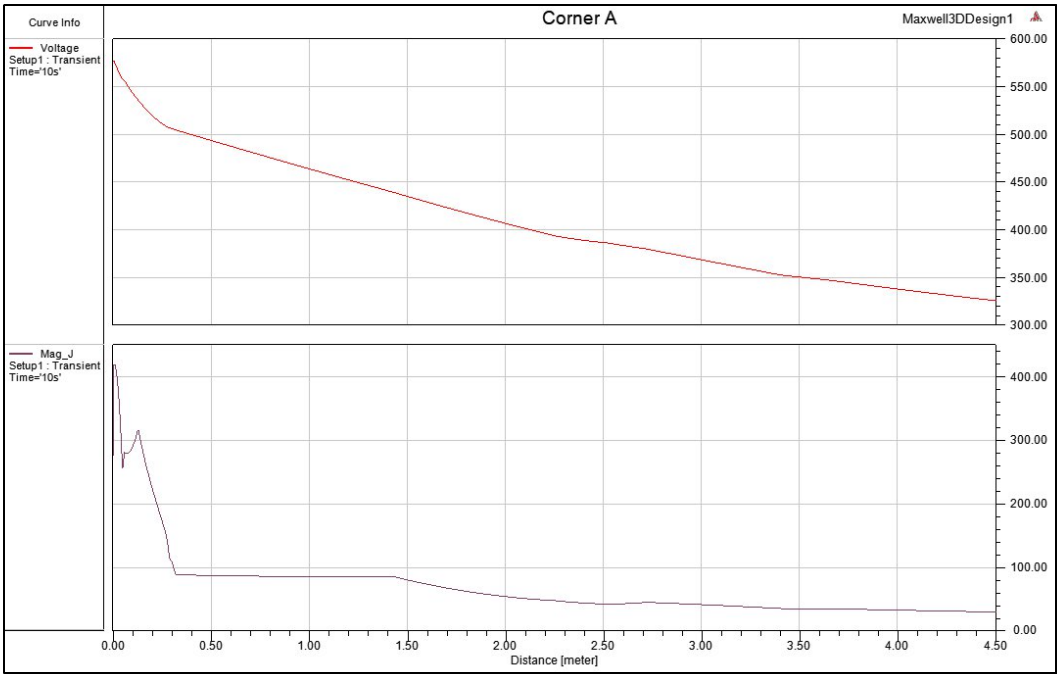


Figure 32 Corner A Voltage and Current Profiles

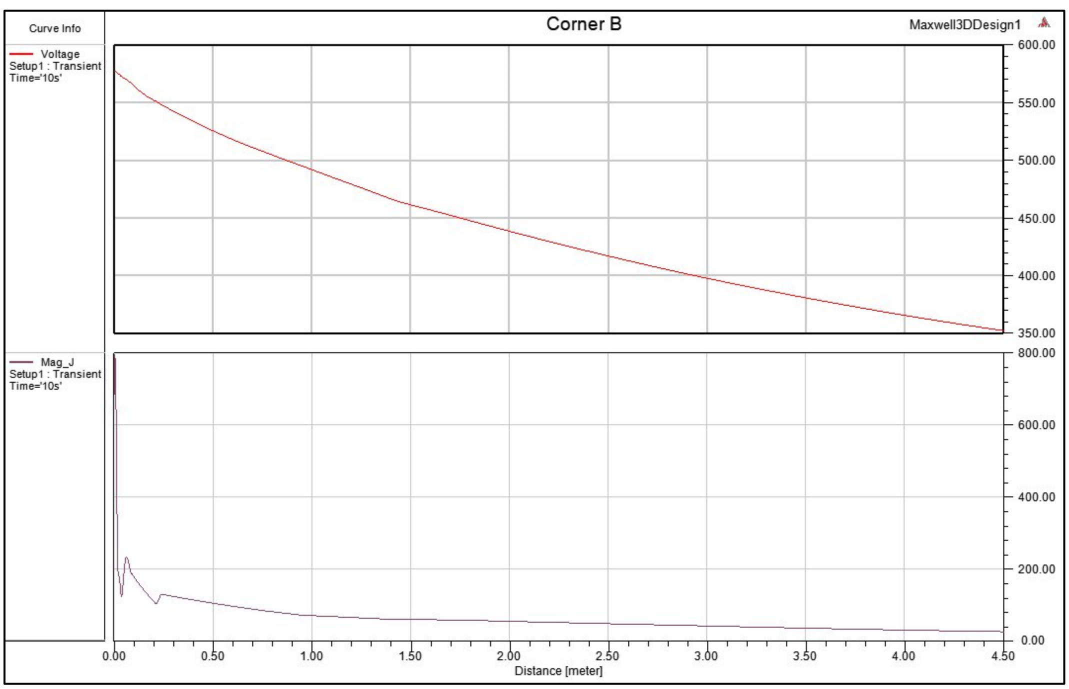


Figure 33 Corner B Voltage and Current Profiles

4.2.3 Simulation of Nagarawewa site

Being located at southern province of the country Nagarawewa site has lowest earth resistivity from the selected sites used for comparison. Site earth map is as follows.

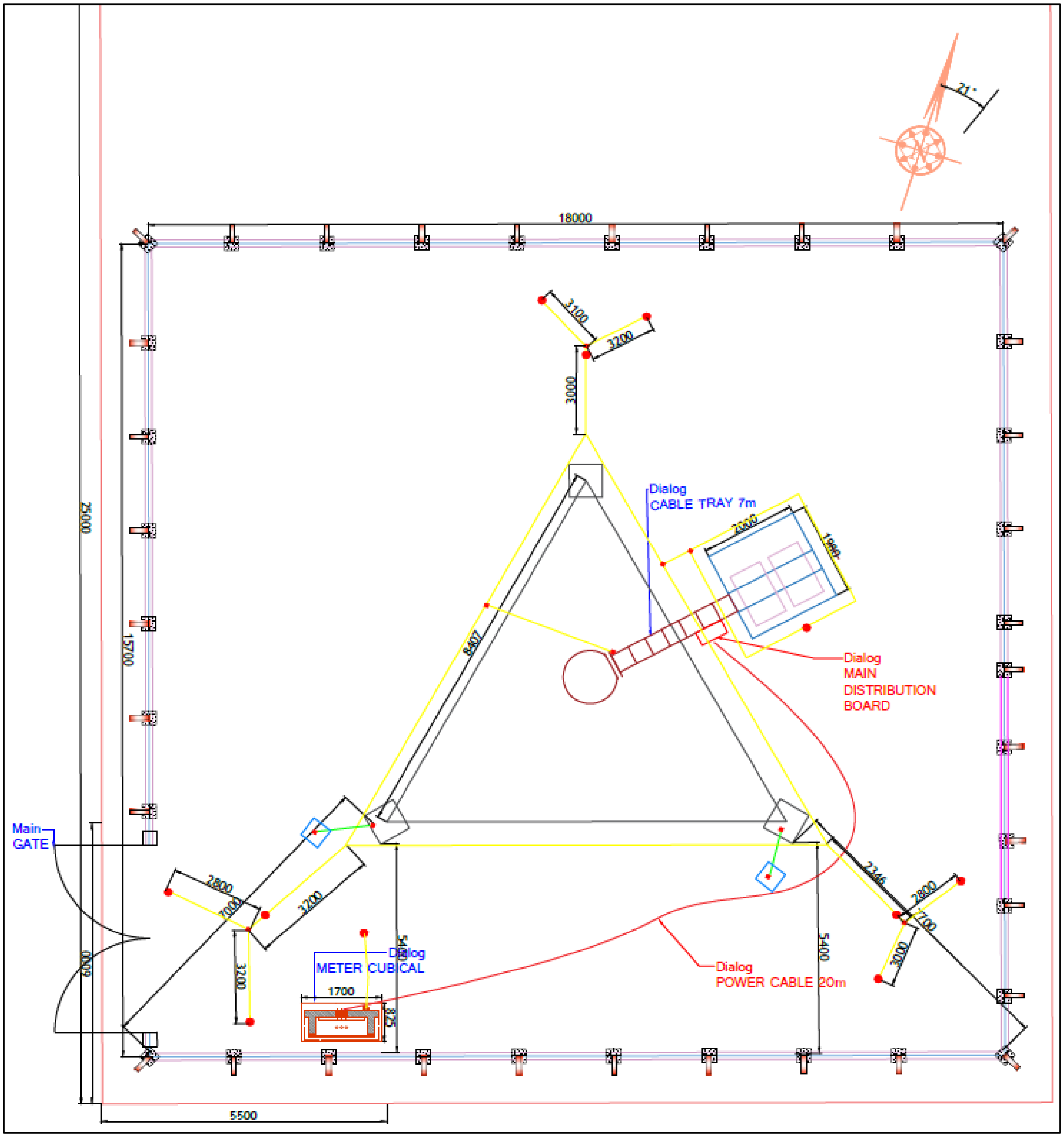


Figure 34 Nagarawewa Site Earth Map

Soil modeling was done as per the site boundary dimensions as follows and resistivity measured was used for soil modeling.

Soil Dimensions: L – 15 m

W- 15 m

H- 10 m

Soil resistivity: 100 Ωm,

Assumption: Soil taken as Homogeneous

Thus, conductivity: 0.01 S/m

4.2.3.1 Results of Nagarawewa Site

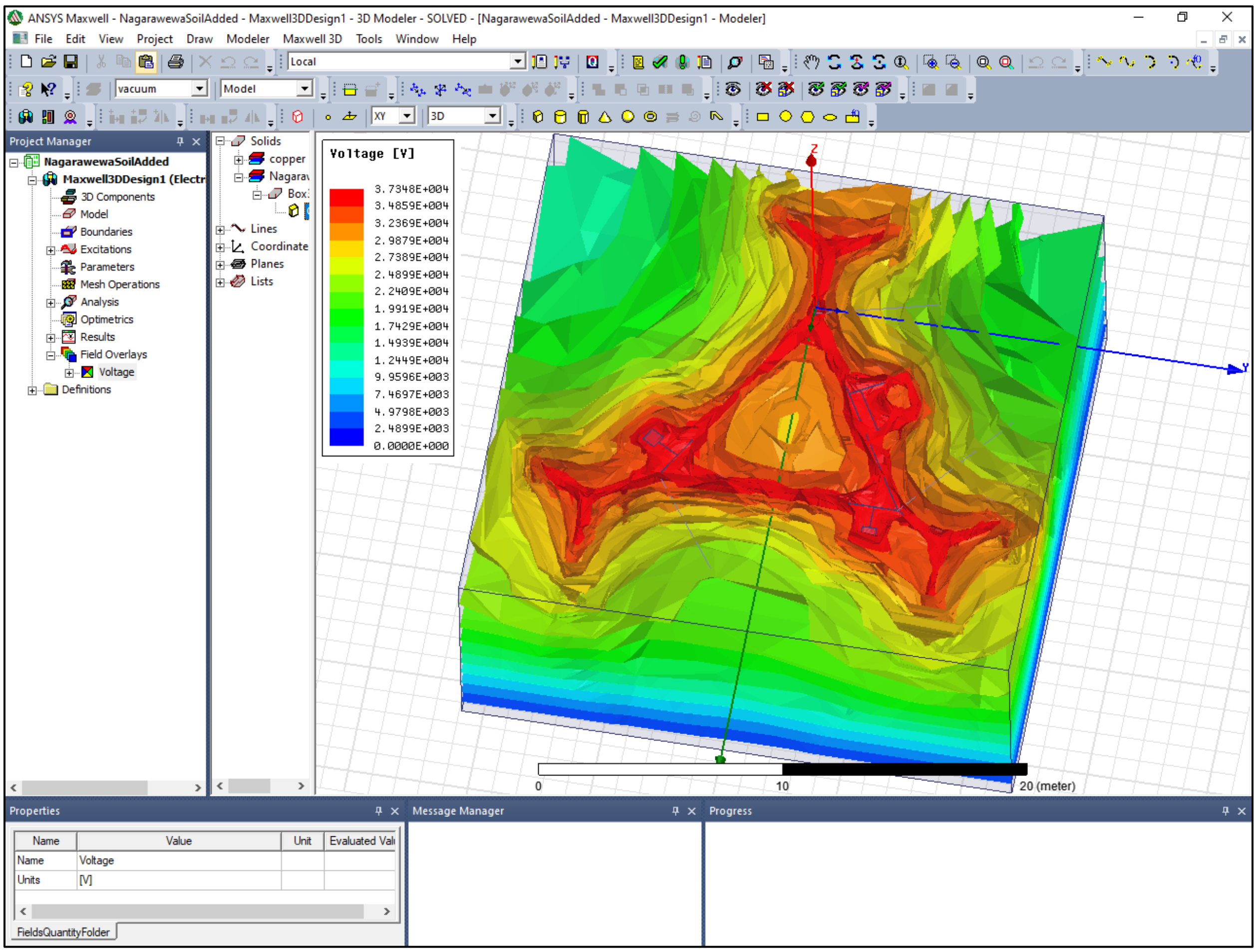


Figure 35 Voltage Profile of Nagarawewa Site

Directional voltage profile showing a similar pattern like in other two sites previously illustrated. The difference observed compared to other sites is voltage propagation to soil having longer distances as the resistivity is lower. Similar in other sites highest voltage was at the earth grid and reducing with the distance increases.

Directional voltage and current patterns along the three corners were obtained and as follows.

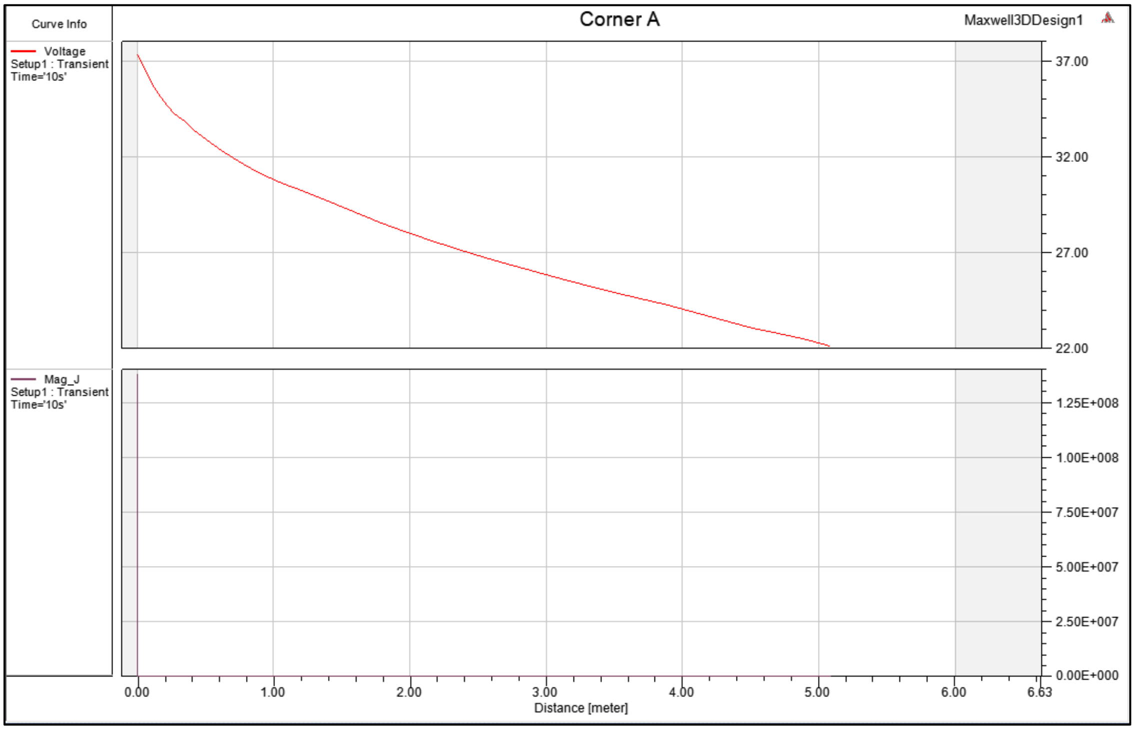


Figure 36 Corner A Voltage and Current Profile

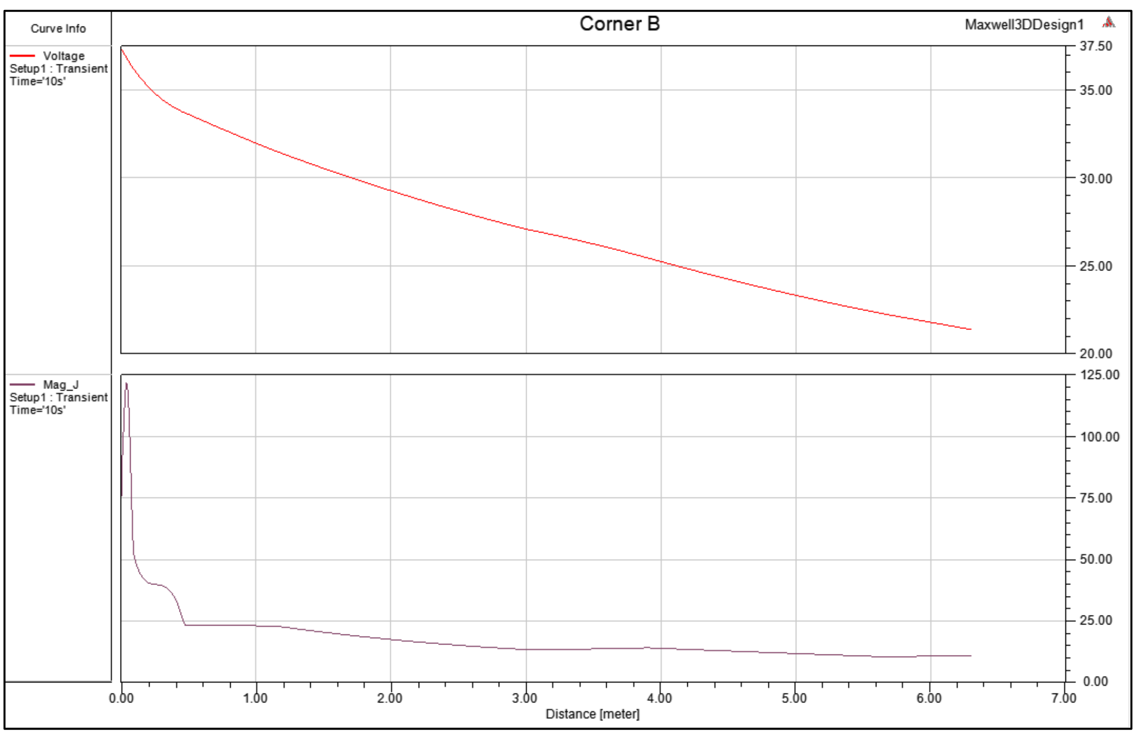


Figure 37 Corner B Voltage and Current Profile

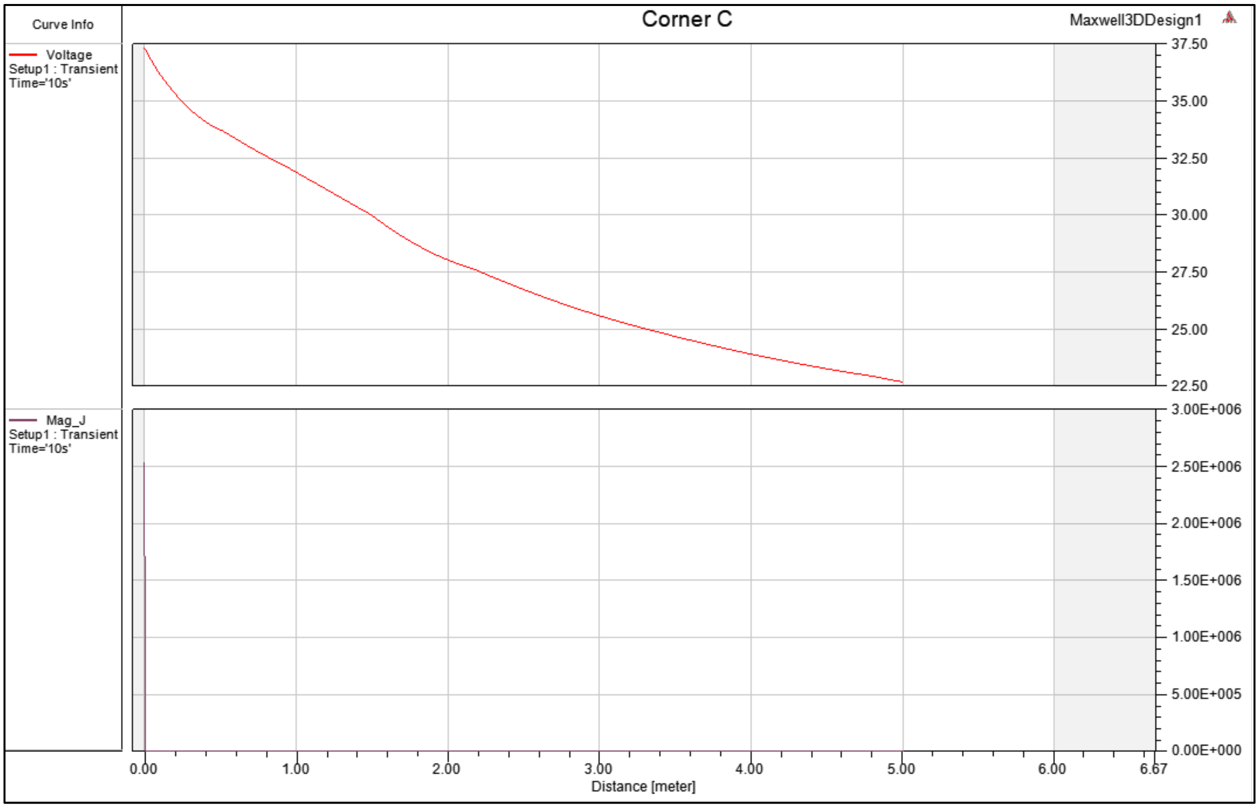


Figure 38 Corner C Voltage and Current Profile

4.2.4 Analysis by varying currents injected

As almost all three sites showed similar patterns of 3D voltage patterns of the soil cubes it was decided to further check with varying the type of current injected to the earth grid and results were analyzed for better comparison.

The selected site data for different current injection is as follows.

Site Name	**Kelimune**
Site Area	North Western
Type of Tower	3 Leg
Earth Resistivity	900 Ωm
Earth Resistances	19.5 Ω /13.4 Ω

Table 4.3 Selected Site Details for Different Current Injection

The two simulation scenarios are as follows.

- Scenario 1

Excitation Type	DC Continuous
Value	100 V
Soil volume	12.5 x 14 x 10

- Scenario 2

Excitation Type	Impulse
Value	10 kA
Soil volume	12.5 x 14 x 10

The results obtained for two scenarios were compared as to consider new simulation methods and to verify the obtained voltage distributions from the current injection. The observed voltage profiles were as follows. In both cases practical and theoretical modeling done with the assumption taken as soil as homogeneous.

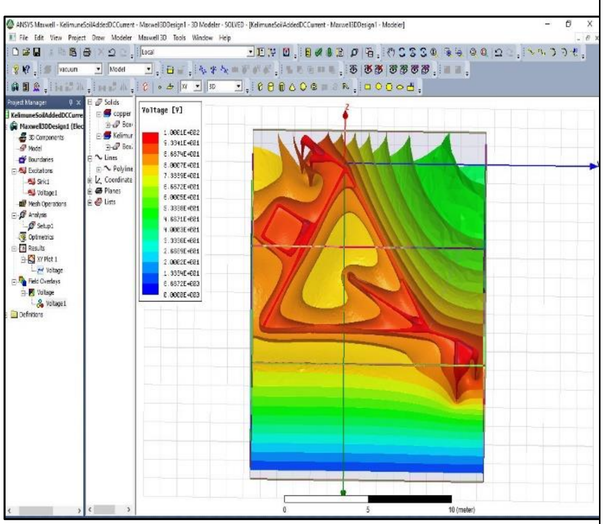
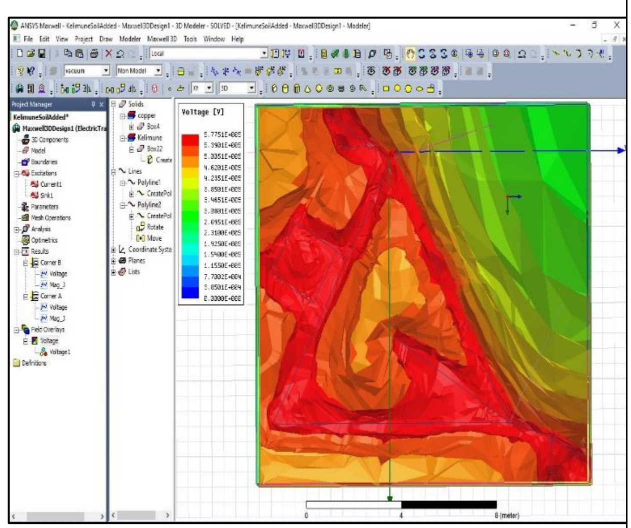
Scenario 1	**Scenario 2**
	

Table 4.4 Comparison of Two Excitation Scenarios

So, by the 3D voltage profiles it can be seen that in both scenarios the voltage distributions are similar to each other and for further analysis any type of excitation can be used. Directional voltages were also obtained through non model lines constructed along the direction of earth resistance is measured. Following table elaborates comparison of directional voltage profiles.

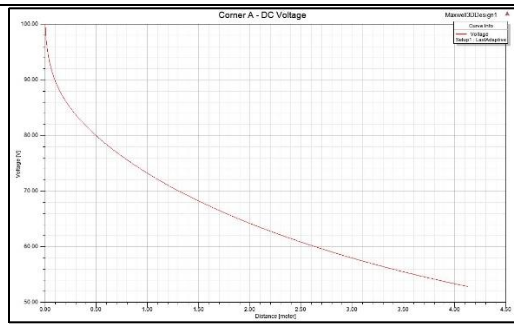
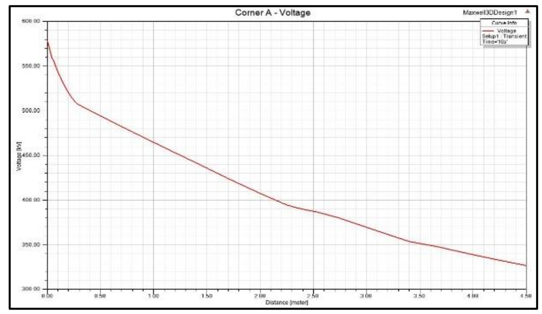
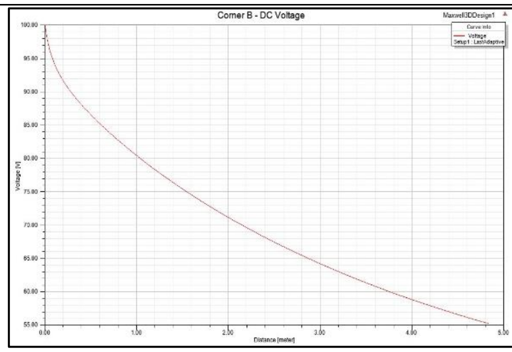
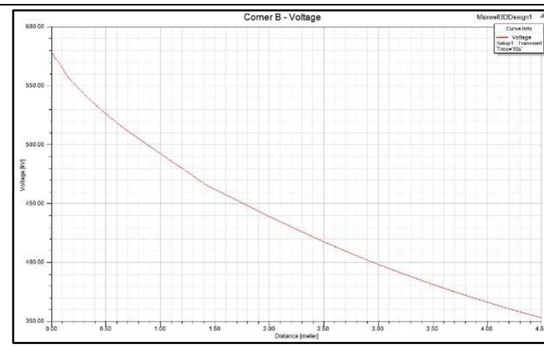
Scenario	**1**	**2**
Direction A		
Direction B		

Table 4.5 Directional Voltage Comparison Between Two Excitation Types

So, above table further verifies that either impulse current injection of DC voltage applying is giving similar results on 3D voltage distribution of sites and directional voltage profiles are in same pattern. So, for modeling and for study, excitation selection for obtaining 3D voltage profiles and directional voltage profiles both impulse current and DC voltage can be used.

4.2.5 Summary of results on selected sites

Three typical telecom tower sites have been modeled and analyzed for comparison. Obtained directional voltage and current profiles and compared. Two excitation types were tested and compared to verify and accurate usage of 3D voltage profiles and directional voltage profiles. As a result, for theoretical modeling typical three leg site can be used with excitations of impulse current or DC voltage for further study of the research.

5 EXPERIMENTAL RESULTS

Practical measurements on earth resistance and resistivity were taken in selected telecom sites using a selected method as per the literature survey. The measurement technique used is fall of potential method with the assumption soil as homogeneous.

5.1 Method of Earth Resistance Measurement

All the resistance measurements were done using fall of potential method as it has higher accuracy when correct probe spacings are used and due to most used technique in the telecom industry personals. The fall of potential method is done as per following figure.

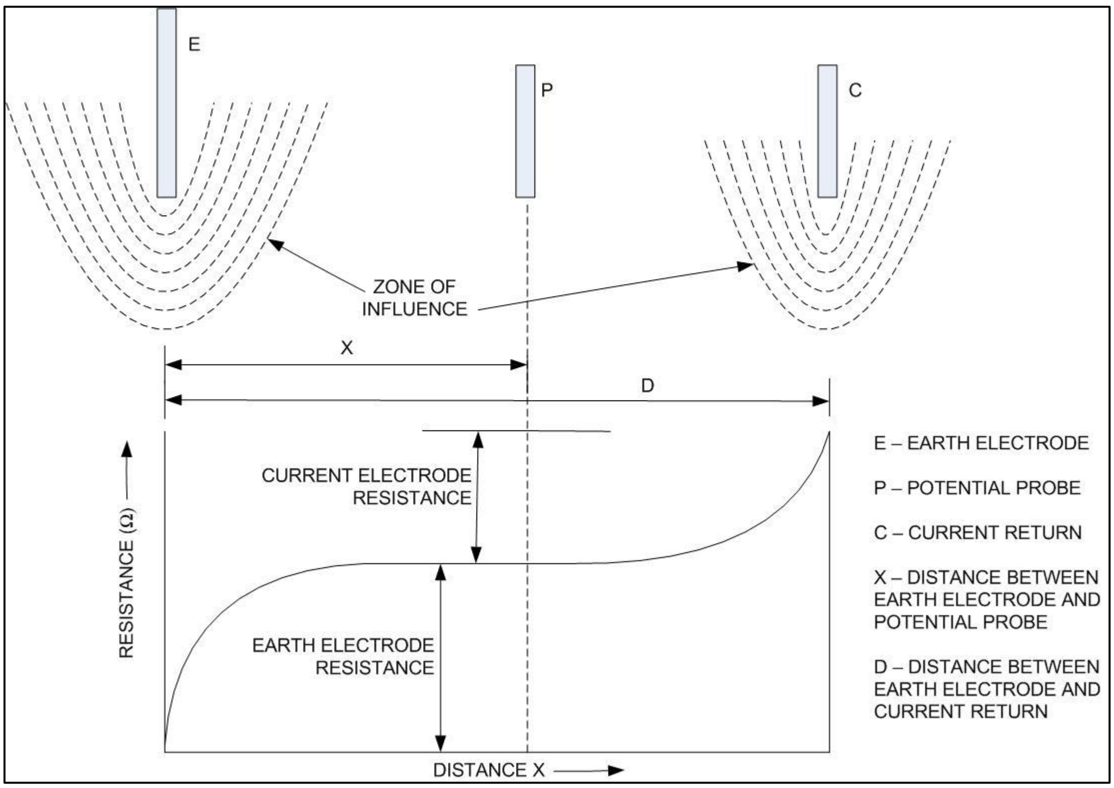


Figure 39 Fall of Potential Method [5]

There are 3 points connected to earth measuring equipment. Those are current and potential probes at predefined distance ratio of 62% =x/d and earth electrode. For accurate measurement correct spacing has to be placed and normally the earth electrode is at the earth grid, at which point the measurement need to be taken. Those points are typically the three corners of a 3-leg tower. The method used for earth resistance carries assumption where soil in which the earth network is build is having uniform soil resistivity.

5.2 Equipment Used for Measurement

The earth resistances of the sites were measured by following earth megger.

Figure 40 : Equipment used for earth resistance measurement

5.3 Measurement Setup

When measuring the earth resistance at telecom tower sites initially only one measurement was taken keeping current electrode in random distance and maintain the ratio with potential probe to be as per 62% rule. But to get the directional variation of the earth resistance of the corner point of measurement total measurement length has to vary as per the following diagram.

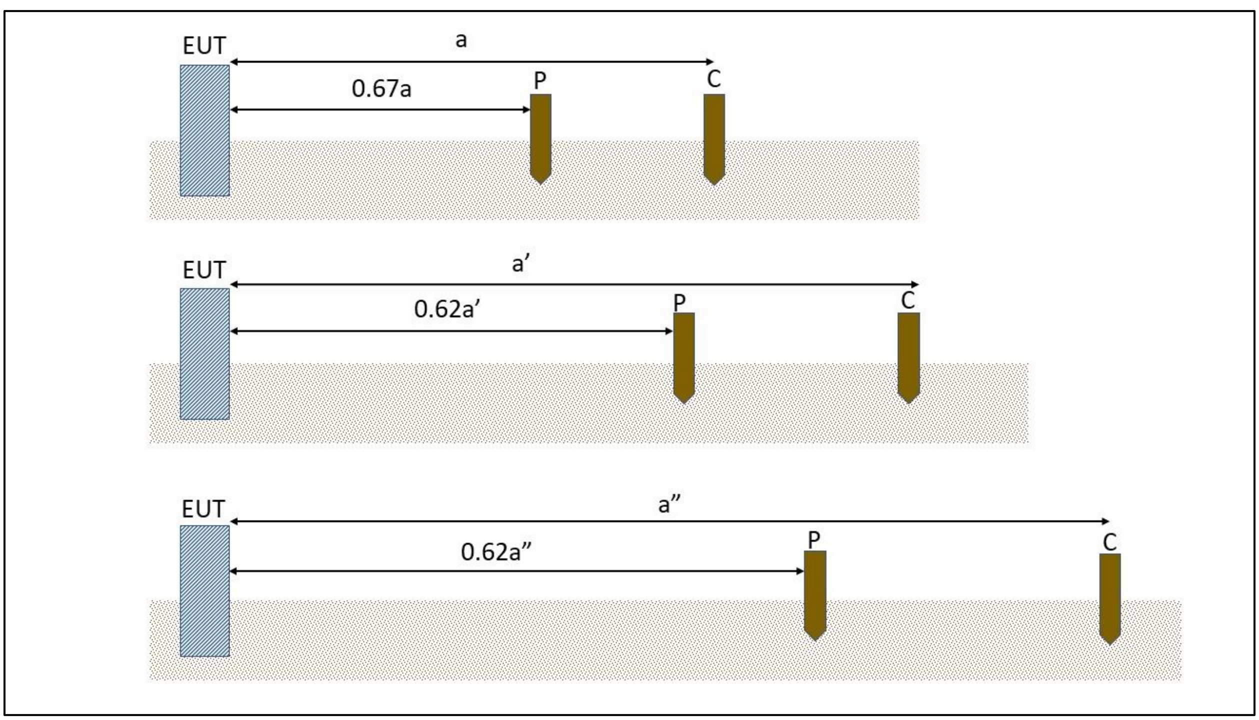


Figure 41 Setup for Directional Earth Resistance Measurement

In the above diagram electrodes are as follows.

EUT – Earth electrode/Earth grid point under test

P- Potential Electrode

C- Current Electrode

As per the above diagram for directional measurement distance has to increase in equal steps to get the data for better comparison. For do that practically measurement distances have to maintain accurately and recorded. A meter tape was used and laid along the direction of measurement as follows.

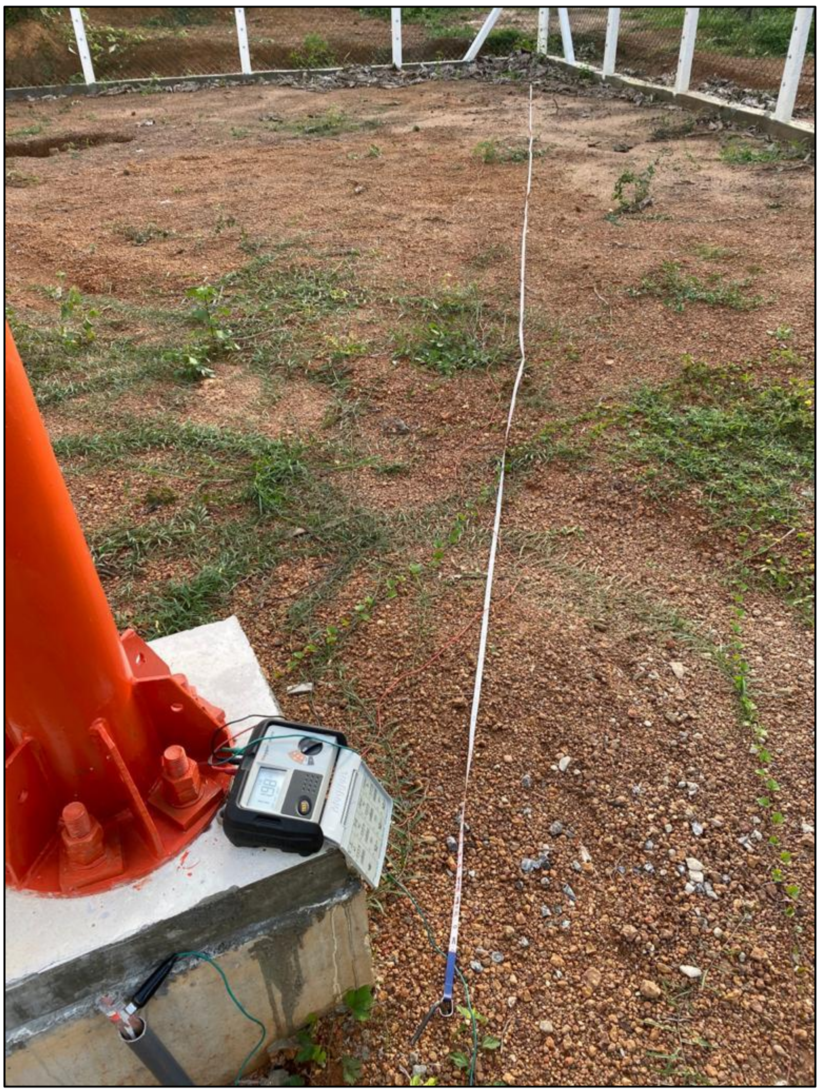


Figure 42 Site Measurement Arrangement

In this way initially four sites were selected in the same area for comparison of directional earth resistance measurement. One leg per each site was selected initially where having the provision for earth measurements for a long distance where comparison between each other site will be easy and accurate. Following table is the data gathered for each measurement distance of the site legs selected.

Distance (m)	***Earth resistance at selected tower legs***			
	Dunkannawa	***Bibiladeniya***	***Thawala***	***Pilakatumulla***
1.5	95	118.4	111.2	61.4
2	61	81.6	81.7	58.6
2.5	31	66.6	74.6	55.8
3	27	54.2	62.3	47.3
3.5	25.8	39.2	44.3	41.8
4	23.5	29.5	42.6	35.9
4.5	18.6	14.69	40.4	34.1
5	25.8	11.33	38.7	33.9
5.5	17.5	9.65	34.8	33.2
6	11.6	7.31	28.7	32.8
6.5	8.8	5.05	24.1	35.4
7	8.4	4.56	21.1	31.4
7.5	6.1	3.27	17.1	24.9
8	5.3	2.45	14.8	24.3
8.5	5.1	1.94	13.9	21.9
9	5.2	1.56	14.1	21.1
9.5	5.58	1	13.7	17.58

Table 5.1 Field Measurements Taken at Different Site Legs

The earth resistance measurement results obtained for variable measurement length were plotted against the measured distance and illustrated below.

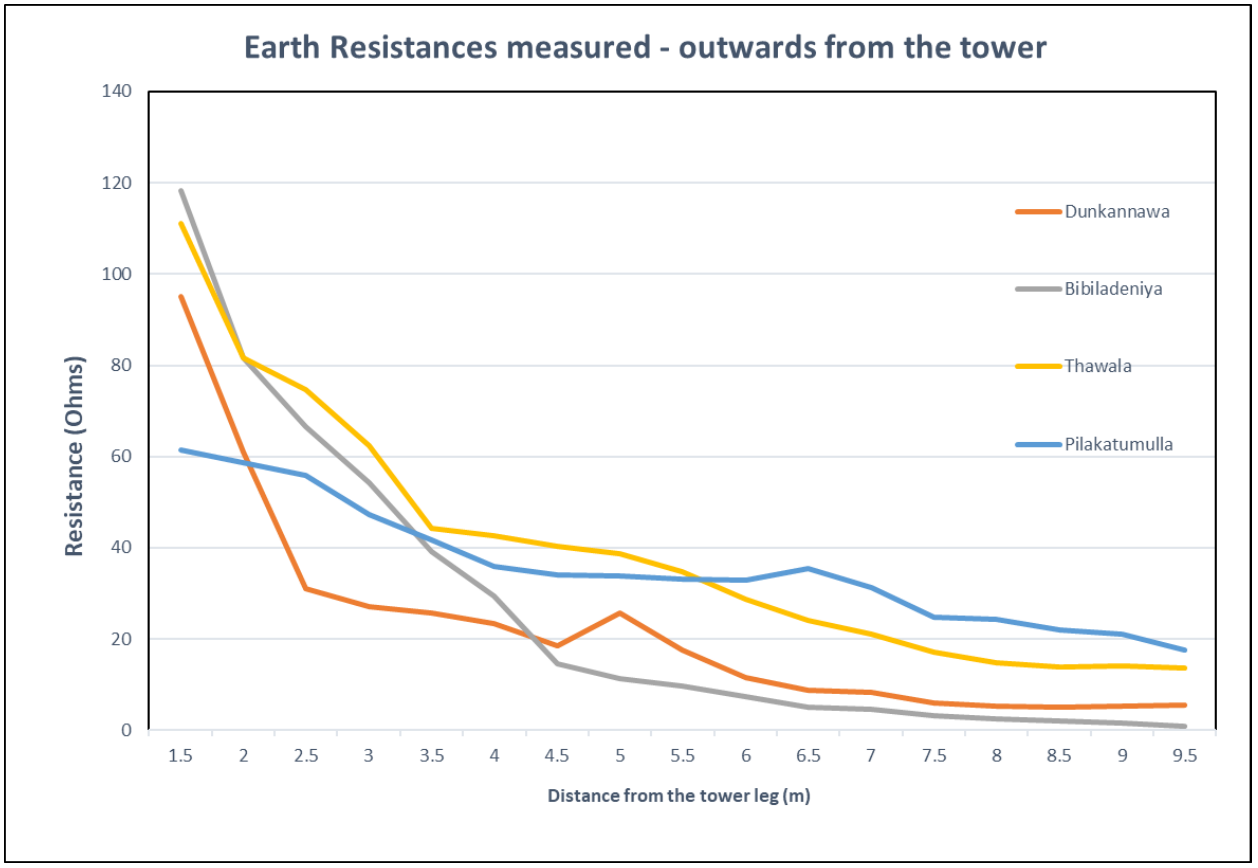


Figure 43 Results Comparison of Site Measurements

So, by the above graph it can see that almost all the sites having similar earth resistance pattern with the measurement distance increased. Initially for short distances it shows a higher value which is highly varying and decreasing fast with the distance increased. With the distance is increasing earth resistance value settling somewhat and every site showing the same pattern on it as well. At the higher distance from the earth network resistance values are becoming same for each distance point in each site.

6 RESULTS VALIDATION

Validation of simulation results were done by comparing the voltage results by achieved model of a particular telecom site and measured resistance value of the same site under the basic theory, where voltage is proportional to the resistance.

6.1 Selected Site Data

For validation of results following site was selected as per the results of theoretical modeling and the site data is as follows.

Site Name	**Thawala**
Site Area	North Western
Type of Tower	3 Leg
Earth Resistivity	173 Ωm
Earth Resistances	12.2 Ω /8.1 Ω /16.6 Ω

Table 6.1 Selected Site Data for Validation

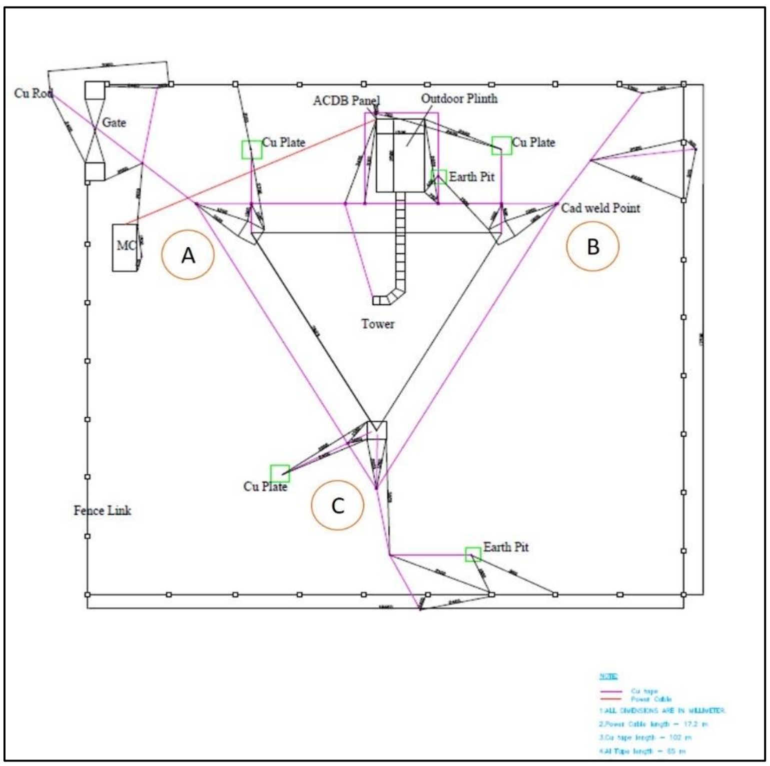


Figure 44 Selected Site Map for Validation

6.2 Modeling of Selected Site

Ansys modeling of selected site done using soil data and site boundary conditions.

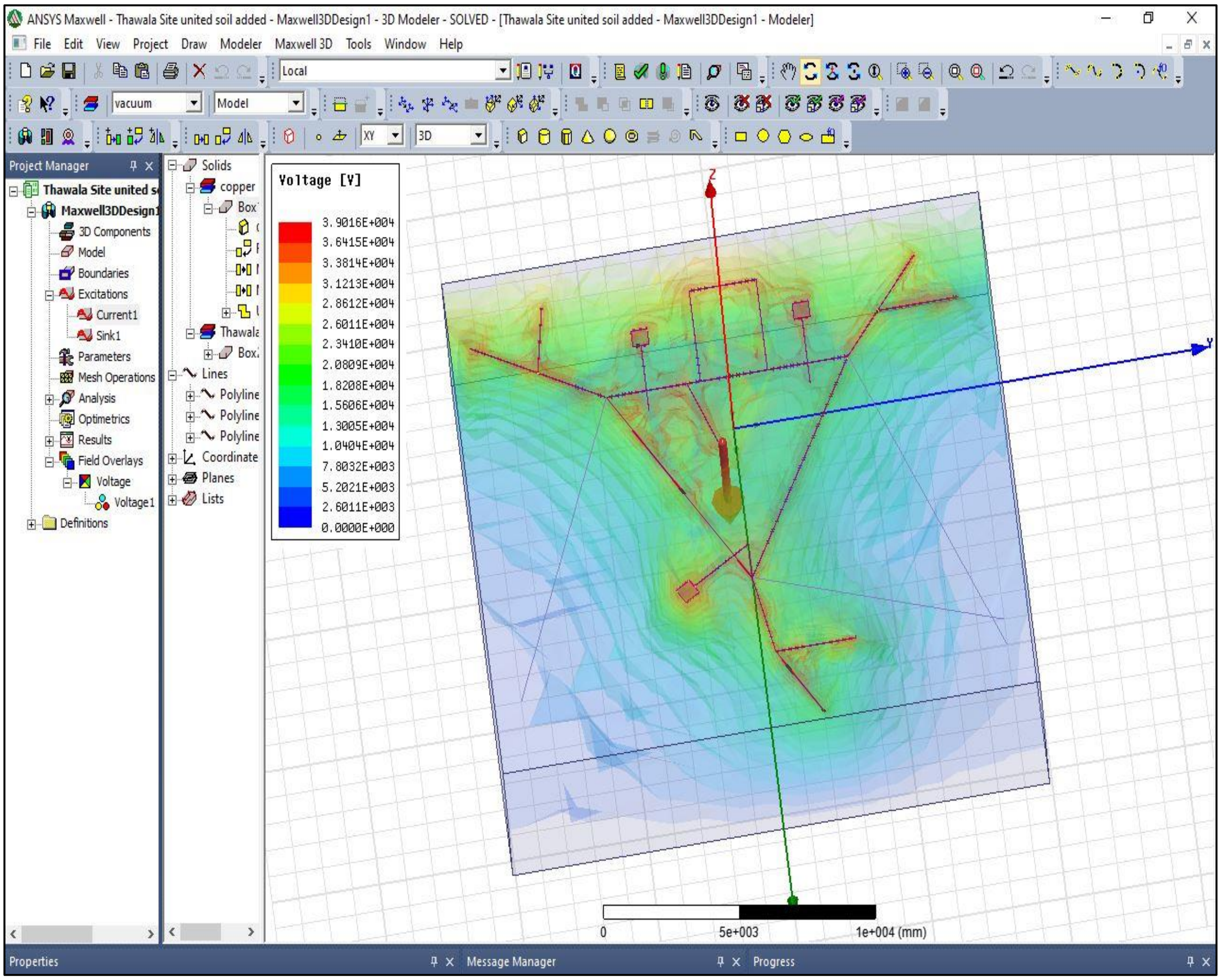


Figure 45 Modeling of Selected Site

Current injection was selected as a impulse current of 10 kA as it was already verified as a generalized excitation method to obtain the voltage distribution. Sink plane or zero voltage plane was selected as the below surface of the soil cube. Boundaries for soil model was selected as per the site dimension and resistivity measurement done for 5m depth. Conductivity was assigned for the ANSYS model using the soil resistivity data as follows.

Soil Dimensions : 19m x 20m x 5m

Resistivity : 173 Ωm taken as Homogeneous

Conductivity : 0.00578035 S/m

6.3 Simulation Results

Simulation was done for the selected site and obtained voltage distribution is as follows for site corners and for total soil volume.

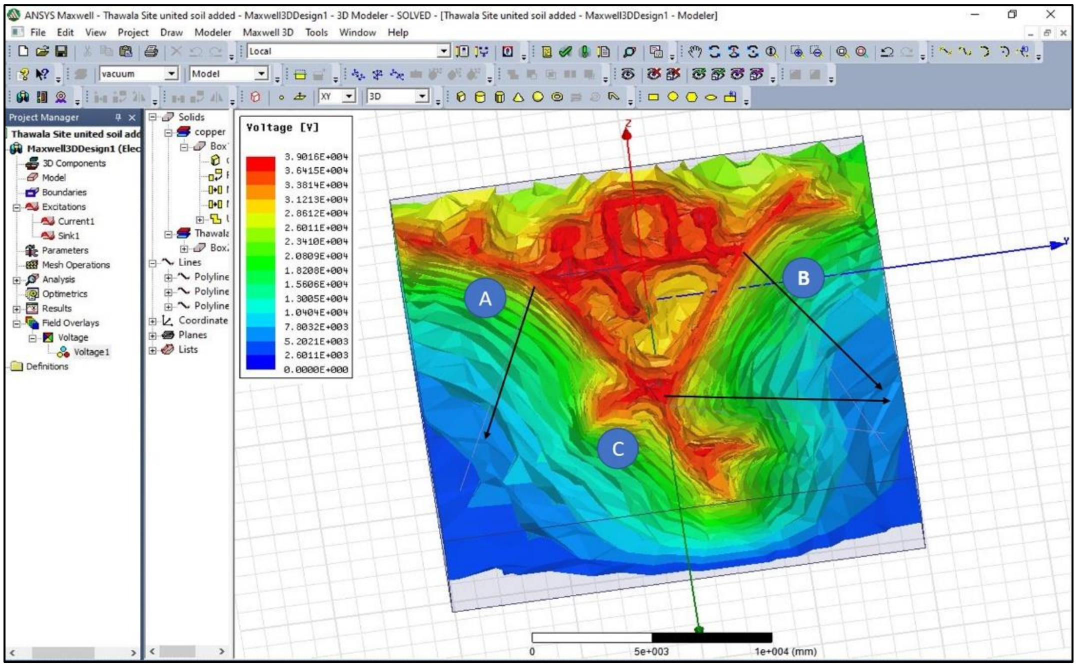


Figure 46 Simulation Results

Directional voltage profiles were obtained by non-model lines in the direction of voltage measurement. Data tables were obtained for each plot and attached as Annex 1.

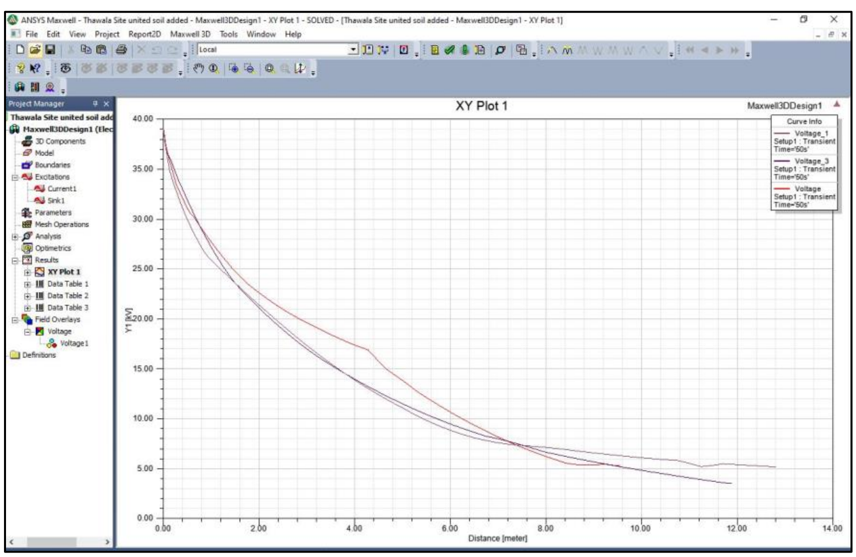


Figure 47 Directional Voltage Profile of Simulated Site

6.4 Comparison of Measured Values and Modeled Results

Measurements were taken at all three directions by varying distance of measurement and earth resistance results were compared with the voltage results obtained by the theoretical model for all three directions, as voltage is proportional to the resistance.

6.4.1 Comparison at 3 legs

Following is the data table for measured resistances and simulated voltage relevant to each distance point of Leg A, B &C

Distance (m)	***LEG A***		***LEG B***		***LEG C***	
	Resistance (Ohms) Measurement	***Voltage (kV)from Simulation - Leg A***	***Resistance (Ohms) Measurement***	***Voltage (kV)from Simulation - Leg A***	***Resistance (Ohms) Measurement***	***Voltage (kV)from Simulation - Leg A***
0.50	-	31.98	-	-	-	-
1.00	-	27.24	151.7	25.91	168.70	27.76
1.50	96.5	23.61	111.2	23.60	130.50	24.80
2.00	72.7	21.12	81.7	21.41	101.40	22.63
2.50	62.8	18.93	74.6	19.32	86.00	20.98
3.00	53.4	17.02	62.3	17.34	77.30	19.63
3.50	49	15.41	44.3	15.53	64.00	18.44
4.00	46.3	13.99	42.6	13.89	56.20	17.39
4.50	40.9	12.69	40.4	12.41	45.50	15.80
5.00	31.2	11.52	38.7	11.09	39.40	13.84
5.50	24.8	10.45	34.8	9.85	35.60	12.14
6.00	21.6	9.47	28.7	8.86	29.50	10.69
6.50	21.2	8.62	24.1	8.10	26.70	9.36
7.00	21.9	7.98	21.1	7.59	23.10	8.18
7.50	22.7	7.36	17.1	7.33	19.70	7.14
8.00	20.1	6.64	14.8	7.13	18.70	6.22
8.50	17.4	6.15	13.9	6.86	17.90	5.49
9.00	15.18	5.68	14.1	6.58	16.60	5.37
9.50	14.78	5.24	13.7	6.32	-	-
10.00	13.88	4.84	12.8	6.10	-	-
10.50	12.64	4.46	10.6	5.90	-	-
11.00	12.2	4.09	8.1	5.53	-	-

Table 6.2 Comparison of Measured and Modeled Results

Above data is used for graphically interpret the comparison at each leg as follows.

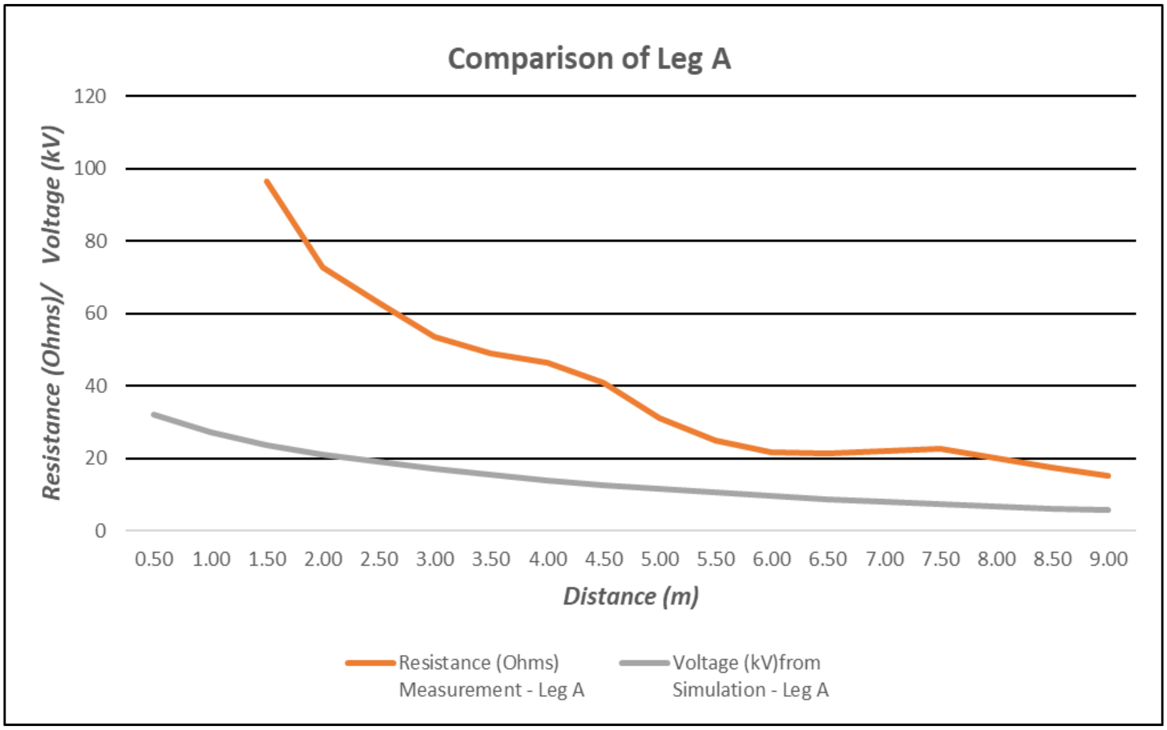


Figure 48 Comparison at Leg A

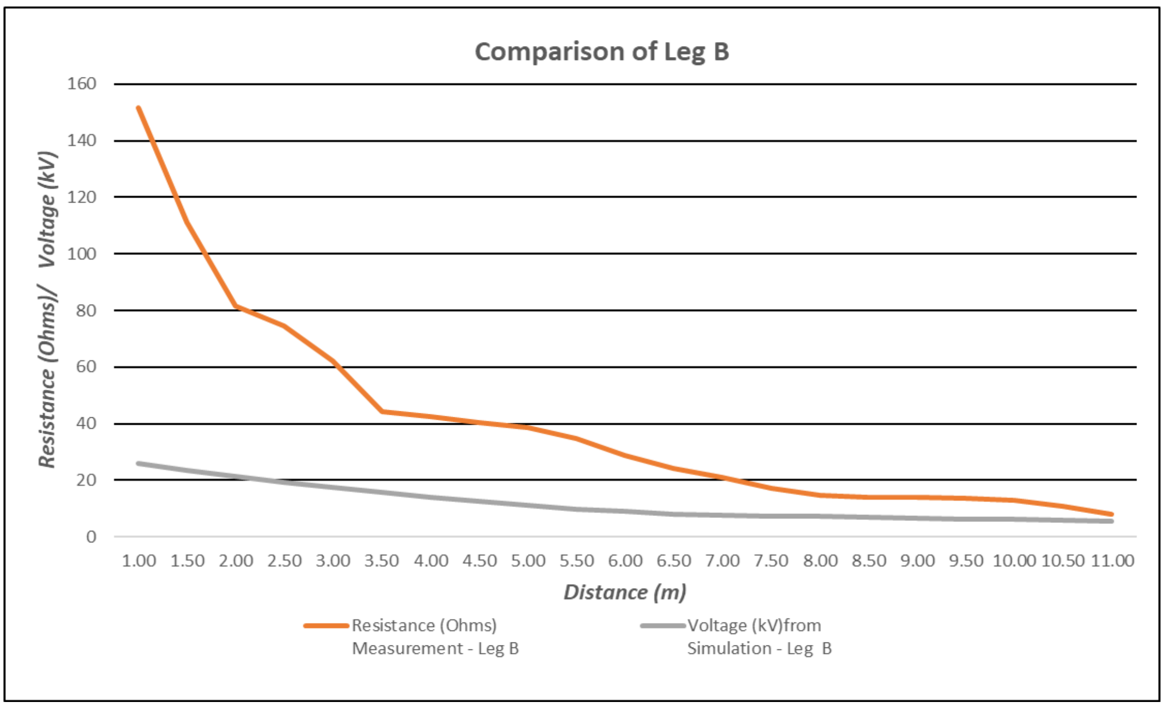


Figure 49 Comparison at Leg B

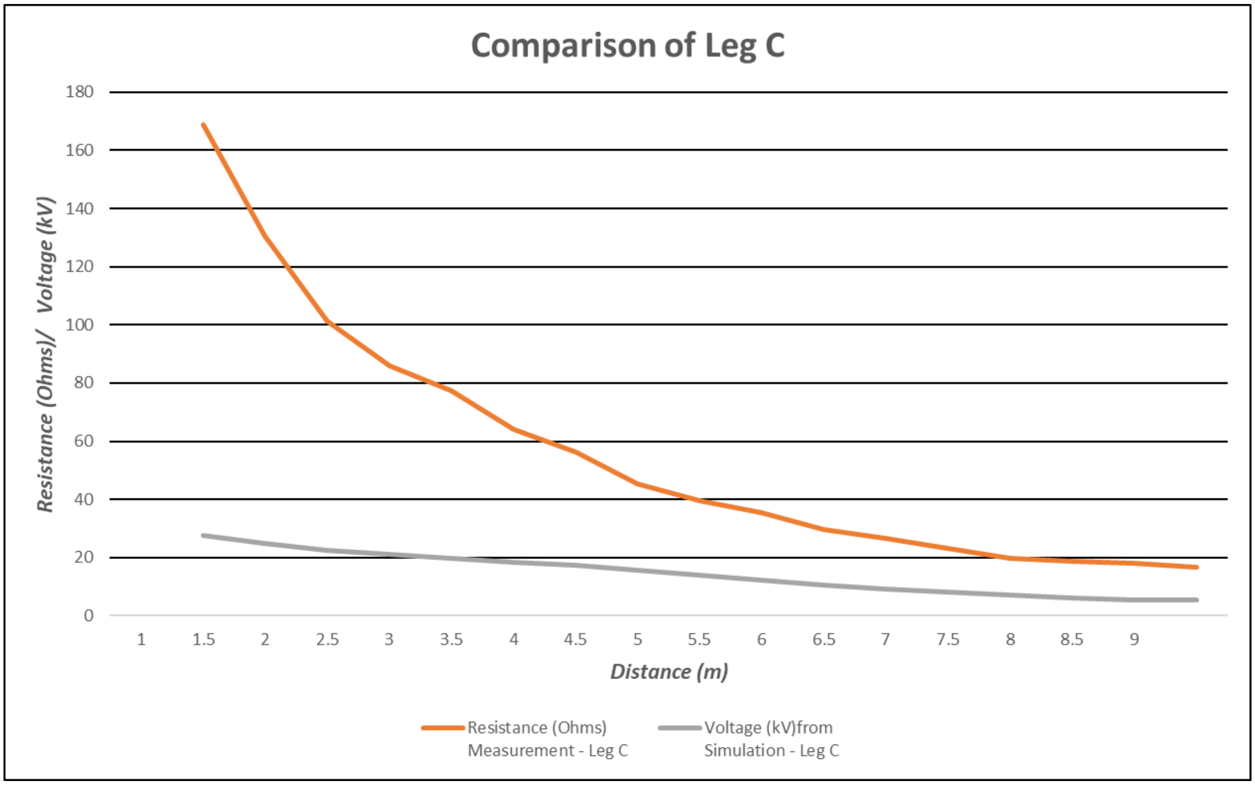


Figure 50 Comparison at Leg C

So as per the graphs at each leg it can see that with the distance increases voltage trend becomes equal to the measured resistance trend. For short distances both trends decreasing and with the distance increases both are in same patterns. Therefor measurements got for longer distances are in proportional to results from theoretical model. So, the model is theoretical model is validating at longer distances from the measurement point.

7 ANALYSIS OF RESULTS

Further analysis was done to find a method to estimate the actual earth electrode resistance of a earthing network. For this comparisons and analysis continued for the telecom site used at the validation. Voltage drops and resistance drops along the measurement distance were in detailed compared for analysis.

7.1 Comparison of Percentage Drops in Voltage and Resistance

As voltage is proportional to the resistance,

$$V \propto R$$

Percentage voltage drop and the resistance drop should be equal between the validated model and the practical measurements. For each side of the legs in the simulated telecom site percentage drops in voltage and earth resistances were calculated. The equations for percentage drops are as follows.

$$Percentage\ Voltage\ Drop = \frac{V_{max} - V_i}{V_{max}} \times 100\%$$

$$Percentage\ Resistance\ Drop = \frac{R_{max} - R_i}{R_{max}} \times 100\%$$

Data obtained were tabulated and graphically interpreted. Error between two percentage drops were calculated for further analysis.

7.1.1 Percentage drop comparison in leg A

Calculated data table for leg A is as follows.

Distance (m)	***Resistance (Ohms) Measurement - Leg A***	***Voltage (kV)from Simulation - Leg A***	***% R drop***	***% V drop***	***Error***
0.50		31.98		0.00	0.00
1.00		27.24			0.00
1.50	96.5	23.61	0.00	0.00	0.00
2.00	72.7	21.12	24.66	10.53	14.13
2.50	62.8	18.93	34.92	19.81	15.11
3.00	53.4	17.02	44.66	27.93	16.73
3.50	49	15.41	49.22	34.74	14.48
4.00	46.3	13.99	52.02	40.76	11.26
4.50	40.9	12.69	57.62	46.24	11.38
5.00	31.2	11.52	67.67	51.21	16.45
5.50	24.8	10.45	74.30	55.73	18.57
6.00	21.6	9.47	77.62	59.88	17.73
6.50	21.2	8.62	78.03	63.47	14.56
7.00	21.9	7.98	77.31	66.19	11.12
7.50	22.7	7.36	76.48	68.82	7.65
8.00	20.1	6.64	79.17	71.86	7.31
8.50	17.4	6.15	81.97	73.97	8.00
9.00	15.18	5.68	84.27	75.94	8.33
9.50	14.78	5.24	84.68	77.79	6.89
10.00	13.88	4.84	85.62	79.51	6.11
10.50	12.64	4.46	86.90	81.11	5.79
11.00	12.2	4.09	87.36	82.69	4.67

Table 7.1 Percentage Drop Calculated Data Table for Leg A

Initially individual percentage drops of voltage and resistance were plotted for comparison.

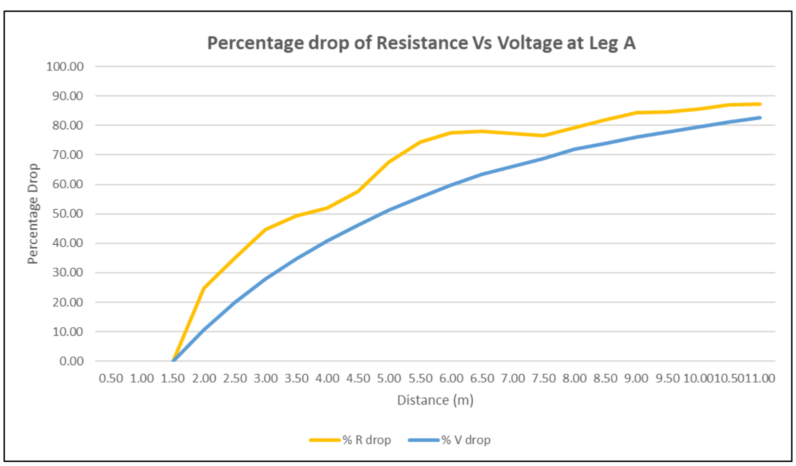


Figure 51 Percentage Drop of Resistance Vs Voltage at Leg A

By the comparison of percentage drops it can see that both of the percentage drops in leg A are in the same increment and follows most nearly the same pattern. Voltage drop percentage and measures resistance drop percentage along the distance are getting closer at the longer distances. To get a clear idea on that percentage error between theoretical modeled and measured value's percentage drops were calculated as in the data table and plotted as below.

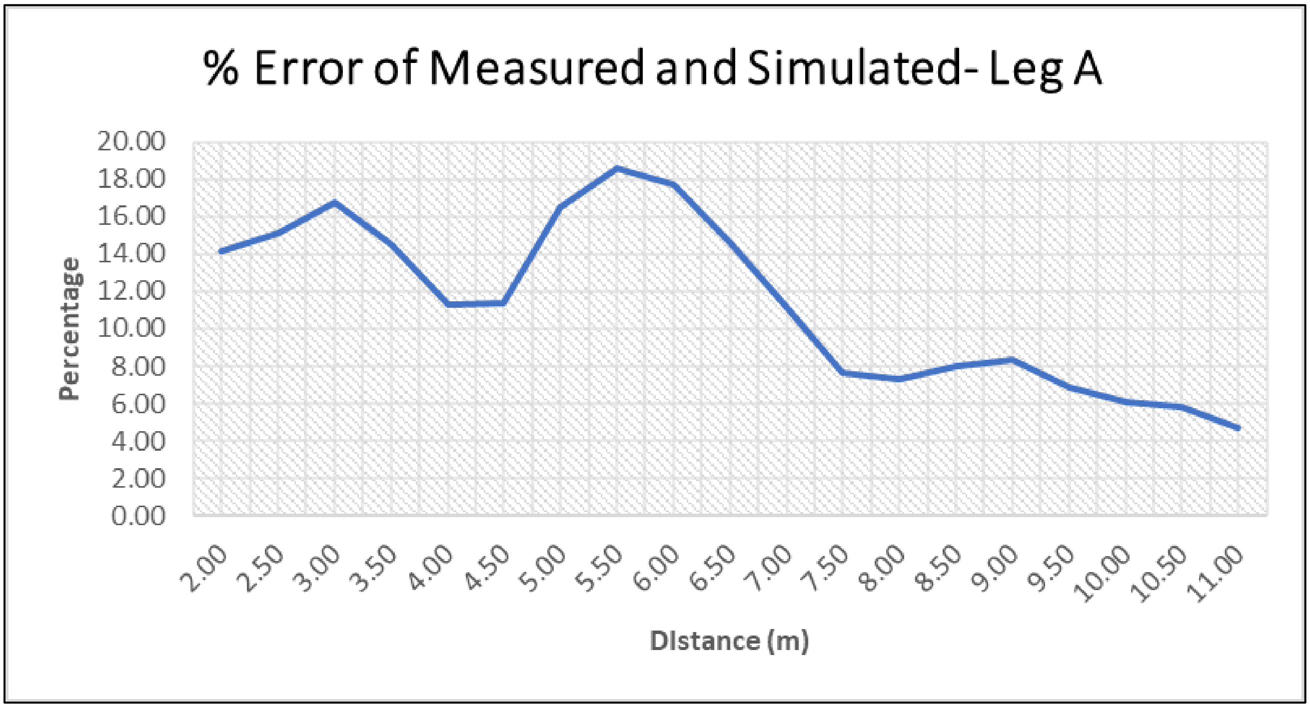


Figure 52 Percentage Error of Measured and Simulated- Leg A

By the error graph it can see that with the distance increases, error is reduced and similar calculations and graphical interpretations for percentage drops and error calculations were performed for leg B and Leg C as follows.

7.1.2 Percentage drop comparison in leg B

Distance (m)	***Resistance (Ohms) Measurement - Leg B***	***Voltage (kV)from Simulation - Leg B***	***% R drop***	***% V drop***	***Error***
1.00	151.7	25.91	0.00	0.00	
1.50	111.2	23.60	26.70	8.94	17.76
2.00	81.7	21.41	46.14	17.39	28.75
2.50	74.6	19.32	50.82	25.44	25.38
3.00	62.3	17.34	58.93	33.07	25.86
3.50	44.3	15.53	70.80	40.06	30.74
4.00	42.6	13.89	71.92	46.40	25.52
4.50	40.4	12.41	73.37	52.11	21.26
5.00	38.7	11.09	74.49	57.19	17.30
5.50	34.8	9.85	77.06	61.98	15.08
6.00	28.7	8.86	81.08	65.83	15.25
6.50	24.1	8.10	84.11	68.73	15.38
7.00	21.1	7.59	86.09	70.69	15.40
7.50	17.1	7.33	88.73	71.71	17.01
8.00	14.8	7.13	90.24	72.50	17.74
8.50	13.9	6.86	90.84	73.53	17.31
9.00	14.1	6.58	90.71	74.62	16.09
9.50	13.7	6.32	90.97	75.60	15.37
10.00	12.8	6.10	91.56	76.48	15.09
10.50	10.6	5.90	93.01	77.24	15.77
11.00	8.1	5.53	94.66	78.67	15.99

Table 7.2 Percentage Drop Calculated Data Table for Leg B

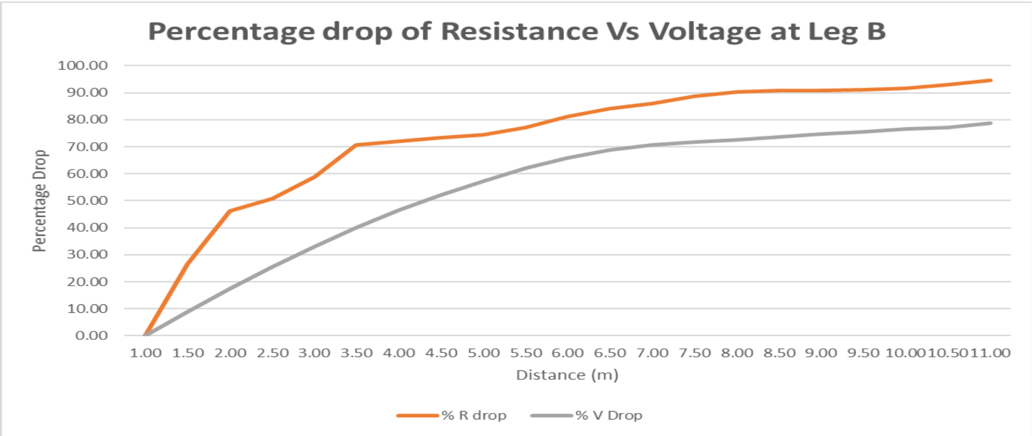


Table 7.3 Percentage Drop of Resistance Vs Voltage at Leg B

Error between percentage voltage drop and resistance drop is as follows for leg B.

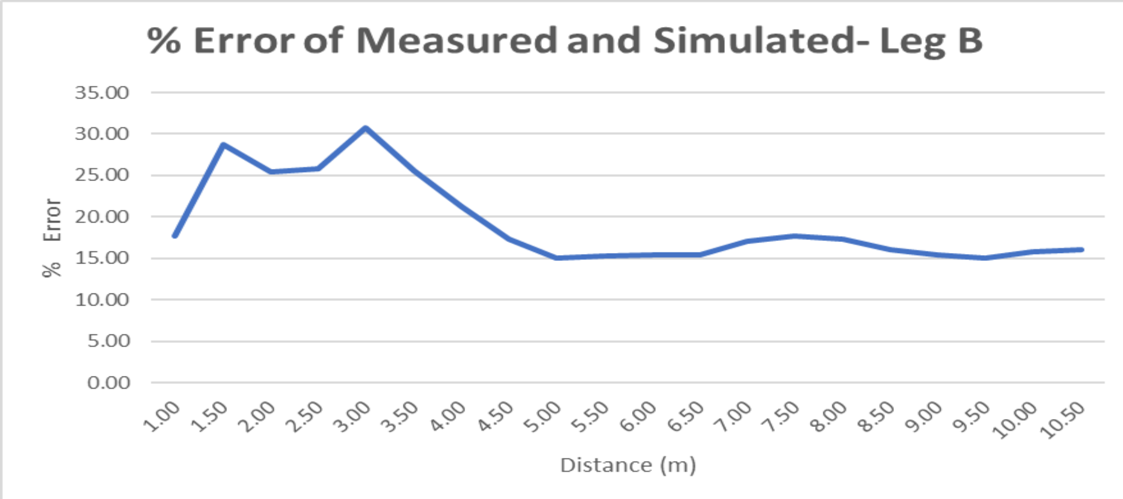


Figure 53 Percentage Error of Measured and Simulated- Leg B

7.1.3 Percentage drop comparison in leg C

Distance (m)	***Resistance (Ohms) Measurement - Leg C***	***Voltage (kV)from Simulation - Leg C***	***% R drop***	***% V drop***	***Error***
1.00	168.70	27.76	0.00	0.00	0.00
1.50	130.50	24.80	22.64	10.65	12.00
2.00	101.40	22.63	39.89	18.47	21.42
2.50	86.00	20.98	49.02	24.43	24.59
3.00	77.30	19.63	54.18	29.29	24.89
3.50	64.00	18.44	62.06	33.58	28.48
4.00	56.20	17.39	66.69	37.36	29.32
4.50	45.50	15.80	73.03	43.06	29.97
5.00	39.40	13.84	76.64	50.15	26.49
5.50	35.60	12.14	78.90	56.28	22.62
6.00	29.50	10.69	82.51	61.48	21.03
6.50	26.70	9.36	84.17	66.30	17.88
7.00	23.10	8.18	86.31	70.53	15.78
7.50	19.70	7.14	88.32	74.27	14.05
8.00	18.70	6.22	88.92	77.59	11.32
8.50	17.90	5.49	89.39	80.21	9.17
9.00	16.60	5.37	90.16	80.67	9.49

Table 7.4 Percentage Drop Calculated Data Table for leg C

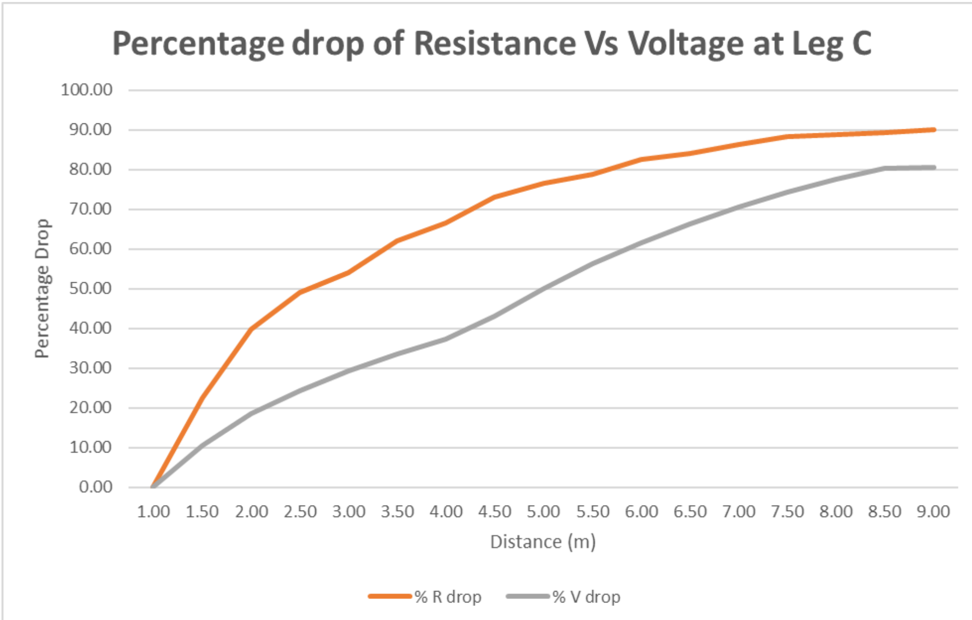


Figure 54 Percentage Drop of Resistance Vs Voltage at Leg C

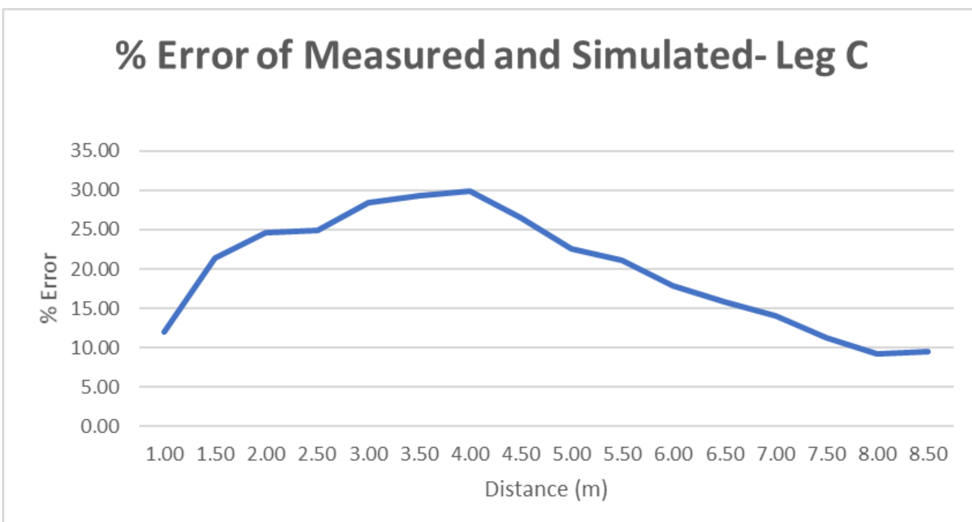


Figure 55 Percentage Error of Measured and Simulated- Leg C

For leg C also like in leg A& Leg B percentage drops and error between measured and modeled are in same pattern. But in leg C the error is not reducing much as others. Reasons may be human errors done during the earth resistant measurement.

7.2 Percentage Error Comparison of Measured and Modeled

For all three legs error between voltage data obtained by the ANSYS model and the measurements came from the earth resistance measurement by fall of potential method was compared and illustrated in below graph indicating values for all three legs in the same graph.

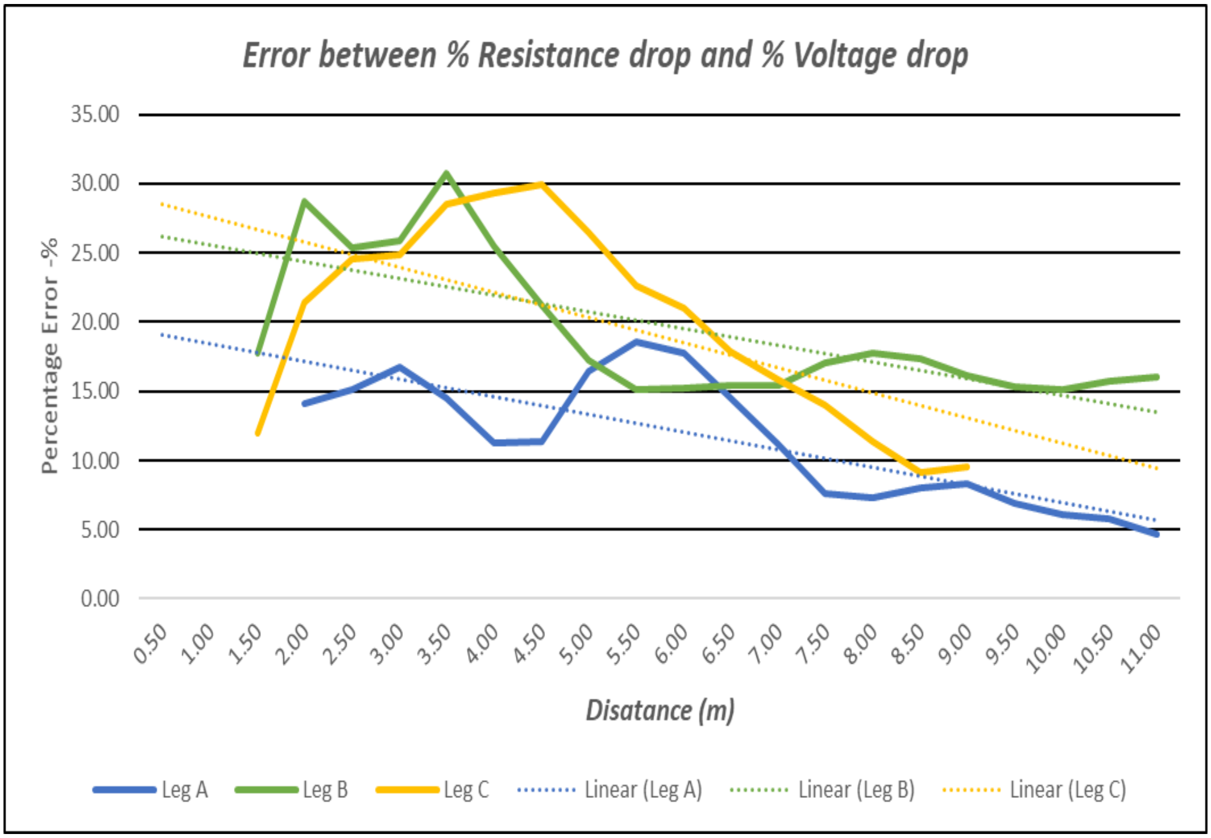


Figure 56 Error Between % Resistance and % Voltage Drop for all Three Legs

As all three legs follows the same pattern best fit curves were introduced to get a better idea on the accuracy level of measurements. By considering the measurement error less than 10% for leg A at a distance more than of 7.5 m it has reached. For leg B it should be more than 10.5 m and for leg C by the trend it can derive for measurement error less than of 10% measurement distance should be more than 14.5 m. To get an overall idea or error of the all three measurements, from the measurement distance 7.5m to 11 m at 0.5m intervals average percentage error was obtained from the above graphs best fit curves.

7.3 Average Percentage Error Calculation

Example: For measurement done at 7.5 m for all three legs,

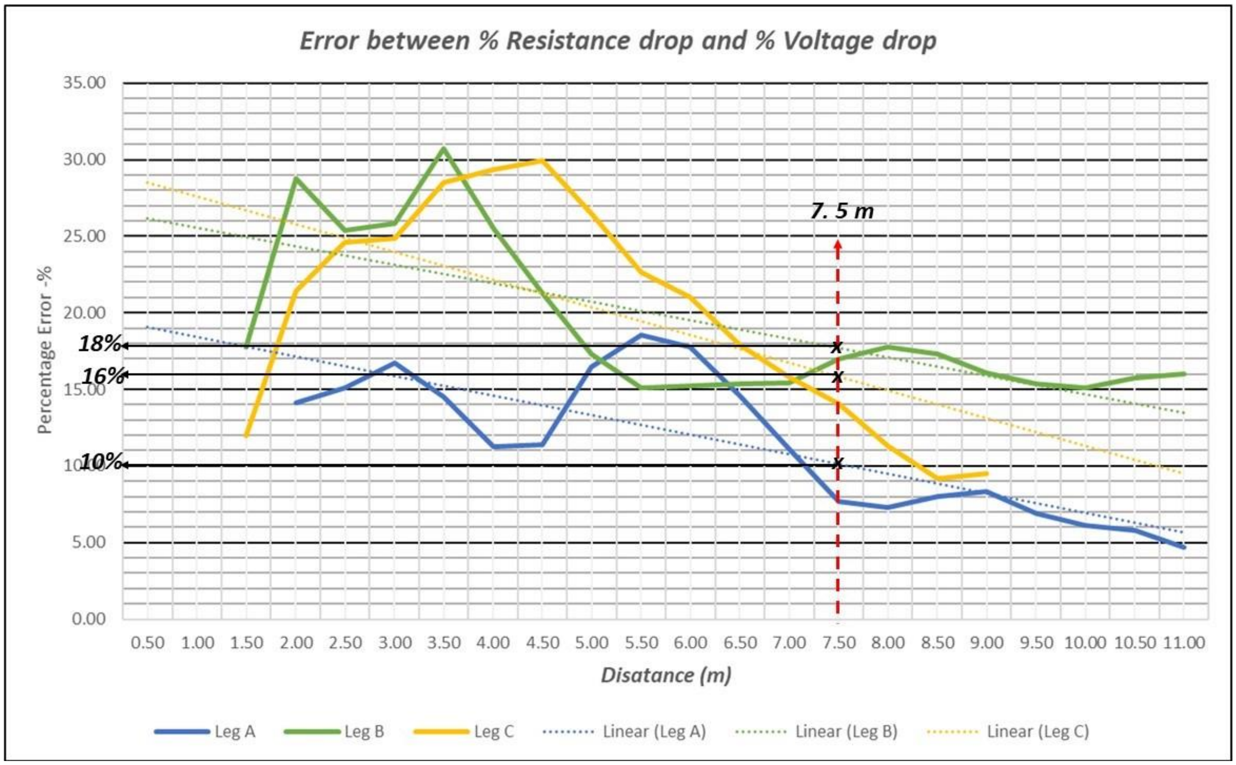


Figure 57 Average Error Calculation Data

Error percentages for individual Legs,

A-10% B-16% C-18%

There for average = 14.67 %, Similarly for distances more than 7.5m average error was calculated.

Distance (m)	Error at Leg A	Error at Leg B	Error at Leg C	Average Error
7.5	10%	16%	18%	14.67%
8.0	9%	15%	16%	13.33%
8.5	9%	14%	16%	13.00%
9.0	8%	13%	16%	12.33%
9.5	7%	12%	15%	11.33%
10.0	7%	11%	15%	11.00%
10.5	6%	10%	14%	10.00%
11.0	6%	10%	13%	9.67%

Figure 58 Average Error Calculation at Each Distances

There for it can be seen that from the previous analysis for an error less than or equal to 10% measurement distance shall be more than or equal to 10.5m under the assumptions and following of correct measurement mechanisms.

8 CONCLUSIONS AND RECOMMENDATION

8.1 Summary of Conclusions of the Study

In the conclusions of the study, a method realized by the analysis to measure earth resistance for a particular error percentage and limitations of the study are discussed.

8.2 Recommendation for Earth Resistance Measurement

The study has shown that when measuring earth resistance by commonly used measurement methods such as fall of potential method, placement of electrodes in the ground has to do with extensive care. The correct ratio has to be maintained if the measurement is done by fall of potential method and 62% rule has to be correctly followed where ratio between distance from earth electrode to current electrode and potential electrode should be 62% for correct reliable reading.

For better accuracy of the reading which will more equal to the actual the measurement can be achieved when measurement distance is higher. But due to practical constraints of the site premises it is unknown up to which accuracy level the measurements are taken. The research has shown for a reading which estimates the actual earth resistance having an error less than of 10% will be given by a measurement taken more than 10 m away from the earthing network to be measured.

The measurements have to be performed avoiding interference from the earthing network elements such as tapes and rods. Further general practices have to be incorporated when taking measurements such as placing of electrodes in the line of perpendicular to the earth network.

8.3 Limitations of the Study

The earth resistance theoretical modeling was done using the relationship between voltage and resistance. As ANSYS Electromagnetics is electromagnetics simulator where not a purpose-built simulator for earthing, voltage profiles were used to derive earth resistance patterns. It was hard to find a simulator for earthing which uses finite element method for analysis.

The soil was assumed as uniform and having uniform resistivity. Resistivity measurements were taken considering the total soil volume having similar resistive material. Actual resistivity of different soil layers will be different and for simulation different soil layer resistivities are not considered. In both practical measurements and theoretical modeling

Finding actual as built drawings of telecom sites were hard and study was done based on existing site drawings. When improvements and alternations done at the earthing sites were not updated by the operators sometimes.

Measuring earth resistances at sites were hard with the constraints coming from site premises. Flat terrain sites are considered for analysis and sites having rocks were not taken as directional measurements in all directions will not be possible.

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