Integrated Geophysical Approach to Determine Engineering Parameters of Expansive Soils

Tesfaye Kassaye Libarge

February, 2009

Integrated Geophysical Approach to Determine Engineering Parameters of Expansive Soils

by

Tesfaye Kassaye

Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, Specialisation: (fill in the name of the specialisation)

Thesis Assessment Board

Dr. D.G. Rossiter	Chairman
Prof. Dr. J. van der Kruk	External examiner
Prof. Dr. F.D. van der Meer	1st supervisor
Dr. M. van der Meijde	2nd supervisor
Mrs. Fekerte Arega Yitagesu	Advisor (PhD student)
Drs. T.M. Loran	Program Director (observer)

INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION
ENSCHEDE, THE NETHERLANDS

Abstract

It is vital for geotechnical engineers to understand the in-situ behaviour of soil particularly the expansive soils which have profound effect on the damage of engineering works. Current practice of study of expansive soil is based on laboratory testing. These tests are expensive, time consuming and labour intensive; these tests use disturbed soil samples may not represent real ground conditions. Implementation of geophysical techniques such as EM and ER would be adopted in this paper to evaluate the capability of identifying expansive soils. These methods provide better understanding of the overall soil electrical properties in a manner that benefits engineering projects such as highway and construction. EM and ER methods are a fast, efficient, and cost effective geophysical tool for mapping spatial variations in soil conductivity beneath roadways.

EM and ER measurements were performed in Ethiopia, along the newly designed road from Addis Ababa to Nazareth on 22 transects / data points and soil samplings were grabbed from the center of each transect for determining soil moisture content. The geophysical survey has been performed in the location where soil samplings were already taken for engineering parameters determination. Inversion of soil ground conductivity and inversion of soil apparent resistivity were made using Tikhonov Regularization model and master curve matching with RESIT model respectively for characterizing the soil in different layer depth to associate the result with soil physical and chemical properties.

Strong correlations have been found between geophysical measurements (EM & ER) and soil moisture content. The soil moisture content could be estimated from soil ground conductivity with the relation expressed in equation Y=0.092 *X + 12.72, and correlation coefficient of R^2 =0.709. ER method was also established good correlation with soil moisture content and it could estimate soil moisture as explained in equation Y= -2.83 *X + 33.34, and correlation coefficient of R^2 =0.729. However the in-situ geophysical measurements, EM & ER were established weak correlation with engineering parameters. The geophysical method could differentiate the electrical properties of the two types of soil, the Andosols and Vertisols. It was distinctively differentiate the soil conductivity of Vertisols with conductivity higher than 89 mS/m and Andosols with conductivity of lower than 60 mS/m. The EM method also mapped the soil conductivity variation in laterally and vertically which would provide a qualitative characterization of the soil of the study areas.

Key words: Expansive soils, Electromagnetic (EM), Electrical resistivity (ER), engineering parameters, Tikhonov Regularization, Master curve, RESIST model etc.

Acknowledgements

First and above all I would like to extend my great thanks to the Almighty God who is my helper and refugee all the time, He gave me strength to undergone through to reach this far. The Netherlands government (Nuffic) is thanked for granted me a scholarship and provided all the necessary facilities to acquire the best knowledge and achieve my wish.

I want to acknowledge and express my heart felt thanks to my supervisors Prof. Freek van der Meer and Dr. Mark van der Meijde for their constant, valuable advice and comment. I have benefited from their supervision that helped me to complete my work with success. In addition, thank you for your encouragement, support and guidance from the beginning till the end of the research period. I would like to foreword my deepest gratitude to Mrs. Fekerte Arega for her support, advice, and showing her patient during repeated discussion and provided me soil data set to work on it.

I have undergone through many good and hard times, through all these time my Mama (Eyaya), brother Temesgen, aunt Bekelech and best friend Melaku had been there to support me being by my side. I would like to say thank you. You have cared for me and put everything what you can for my successful completion of my study. My younger brothers Alemayehu and Tamru, thank you very much for caring to Mama and the whole family you did a great job. I am greatly indebted to Mrs Yamrotsow for your wise advice; encouragement and showing me true friendship and concern visiting Mama. I met good friends, Bitti and Emiru I thank you very much, for being by my side when I needed help, your healing word advice and support were motivated and encouraged me so much.

My great acknowledgement forwarded to my organization Geological Survey of Ethiopia (GSE) for good cooperation and facilitating things to get permission the scientific instrument to be released from custom and gave me the organization materials to work with them. I would like to express my great appreciation and thanks to those persons involved through all these process, Deputy Minister of Mines Mrs. Sinkinesh, General Manager Mr. Tollosa, Chief Geologist Mr. Tibebu and others. My deep gratitude goes to Wogderes, Dereje, Getahun, Biruk, Gizaw and Girma for your help and assisting me during field work.

I am gratefully indebted to acknowledge Mr Getachew and Alain Frances for their advice and constant discussion about the subject matter and our good friendship. I have learned a lot from you, thank you very much. Last but not least my thanks goes to all class and cluster mates. I wish you the best of luck.

"Look deep, deep into nature, and then
You will understand everything better."
Albert Einstein

Dedicated to the three people who have put their great effort for my success
Mama “Eyaya”,
Temesgen Kassaye and
Melaku Yirdaw

Table of contents

List of figures

List of tables

GLOSSARY OF TERMS

Atterberg Limits	Tests measuring Liquid and Plastic Limits and consequently Plasticity Index
BCS	Black Cotton Soil (which are of high plasticity and expansiveness)
ECa	Apparent Electrical Conductivity
EM	Electromagnetic
ER	Electrical Resistivity
IP	Induced Polarization
LL	Liquid Limit (%)
MC	Moisture content (%)
PI	Plasticity Index
PL	Plastic Limit (%)
CEC	Cation Exchange Capacity (meq/100 g)
FEM	Frequency Domain Electromagnetic
TEM	Time Domain Electromagnetic
T_x	Transmitter
R_x	Receiver
DC	Direct Current

1. INTRODUCTION

1.1. Background

The engineering performance is very much affected in the presence of swelling clay soils which has a capacity of expansive and shrinkage due to the volume changes in dry and wet seasons. It may cause series cracking, rutting and deformation problems on foundation slabs, walls of small buildings, pipe lines and sewage systems. The study of expansive soils is required for good planning, designing, and to increase the performance of civil engineering infrastructure. To study swell/shrink parameters in conventional method by collecting soil samples and analyzing in the laboratory are expensive, time consuming, and labour intensive. There is a need to decrease costs associated with soil study. One way is to develop techniques for rapidly and non-invasively measuring soil physical properties across a field such as geophysical techniques. Electromagnetic (EM) and Electrical resistivity (ER) are electrical geophysical methods that measures bulk electrical properties of soil in situ in a rapid, non destructive and economical way. Using electrical methods, one may measure potentials, currents, and electromagnetic fields which occur naturally or are introduced artificially in the ground. However, the application of electrical geophysical methods to soil science problems are not straight forward because many soil physical and chemical properties may simultaneously influence in situ measured electrical parameters [1].The in situ measurement of electrical parameters can be done with a specific calibration and taking in to considerable electrode array lengths and arrangements to map different soil properties and to make the methods suitable for different application[2]. Several researchers have made an attempt to show the correlations of Electrical conductivity (EC) with soil water content [3, 4], soil organic matter [5, 6], salinity [7], and soil texture[5, 7].Pozdnyakova (1999) showed exponential relation ships between ER and CEC ; ER and soil water content with their strong correlation coefficient, in addition he studied the influence of various soil properties on the measured electrical conductivity in situ with the method of geostatistics. Kiberu (2002) and P.C Kariuki (2003) have made a quantitative estimation of CEC from chargeability values; water content, resistivity and clay amount using statistical regression model though they both used observations in laboratory under a certain controlled condition with IP techniques. Kiberu (2002)[8] made an attempt to describe a relation between clay content and IP [9] and other physical model.

The purpose of this paper is to establish the relationship between EC and engineering parameters of expansive soil and the result would be integrated with other geophysics techniques of Resistivity. In particular, the relationship between EC and Cation exchange capacity (CEC), EC and soil Moisture Content, and EC and other soil test parameters would be attempted to establish as well as with ER.

1.2. Statement of Research Problems

The presence of swelling clay beneath the surface poses a significant problem to engineering work design like roads and construction. Roads constructed over areas of expansive soils are generally subjected to potential differential settlement due to volume changes caused by swell/shrink of the clay resulting from dry and wet seasonal variation. If clay seams are not properly designed, a premature sub grade failure may occur and will also pose difficulties during and after construction resulting in lose of higher construction costs. So studying expansive soils is important for proper management and engineering design. Current engineering and geologic practices for characterization of expansive clays are time consuming and expensive because of extensive laboratory measurements needed and therefore the need to continue exploring new methods that would bring about identifying swelling soils rapidly and at low costs. There is spectroscopy technique used for supporting conventional geotechnical investigation for a rapid identification of constituent minerals in expansive soils at low cost and large scale [10-12]. However, for engineering work, the volume characterization of soils is required taking measurements on soil in situ [8].So there is still a need to utilize geophysical techniques to map clays beneath to the surface, fill the gaps between the soil sampling locations, and to see the variation in depth with a non invasive, non destructive method[13]. This geophysics technique is being applied quite new for the purpose of determining engineering parameters. The method has been used in the field of agriculture to evaluate soil salinity and hydrology to map ground water [14], [8], [15] in addition , for the purpose of characterizing and determining the thickness of clay soil [14]. In this paper more focus given to evaluate geophysical methods are capable to support the existed geotechnical methods for determining clay soil parameters.

1.2.1. Conventional method

Traditional approaches to subsurface field investigations to determine engineering parameters of soils commonly rely only upon the use of direct sampling methods such as:

- Borings for soil samples;
- Laboratory analysis of discrete soil,
- Extensive interpolation and extrapolation from a limited number of data points.

Conventional soil sampling and laboratory analyses are intensive, time-consuming and expensive. The accuracy and effectiveness of such an approach is heavily dependent upon the assumption that subsurface conditions are uniform. Numerous pitfalls are associated with this approach that can result in an incomplete or even erroneous understanding of site conditions. These oversights are the cause of many structural and environmental failures.

1.2.2. Properties of soils and Determination of soil parameters

A soil survey contains maps and a description of each major soil in the survey area. More important, the survey describes how soil properties affect a wide range of rural and urban land uses. One of these properties, shrink/swell potential, is of great effect in the construction industry [16, 17]. Shrink/swell potential is the relative change in volume to be expected with changes in moisture content, that is, the extent to which the soil shrinks as it dries out or swells when it gets wet. Shrinking and swelling of soils causes much damage to building foundations, roads and other structures. Extent of shrinking and swelling is influenced by the amount and kind of clay in the soil [18]. The estimates of soil properties include the range of grain-size distribution and Atterberg limits, the engineering classification, and the physical and chemical properties of the major layers of each soil[19]. Soils are classified according to grain-size distribution and according to plasticity index, liquid limit, and organic matter content. Clay as a soil separate, or component, consists of mineral soil particles that are less than 0.002 millimetres in diameter. The amount and kind of clay greatly affect the fertility and physical condition of the soil that is ability of the soil to adsorb cations and to retain moisture. They influence the shrink-swell potential, permeability, plasticity, the ease of soil dispersion, and other soil properties. The amount and kind of clay in a soil also affect tillage and earthmoving operations. Shrink-swell potential is the potential for volume change in a soil with a loss or gain in moisture. Volume change occurs mainly because of the interaction of clay minerals with water and varies with the amount and type of clay minerals in the soil. The size of the load on the soil and the magnitude of the change in soil moisture content influence the amount of swelling of soils in place. For others, swelling potential of soil was estimated on the basis of the kind and amount of clay minerals in the soil.

Clay minerals , Such as Kaolinite, Halloysite, Montmorillinite, vermiculite, chlorite and others, as explained by Keller and Frischknecht (1966)[9], have the property of sorbing certain anions and cations and retainable exchangeable state. The common exchangeable ions adsorbed on clay are Ca, Mg, H, K, Na and NH_3 in order of decreasing abundance. The exchange capacities of some clay are expressed in terms of the weight of ions in mill-equivalents absorbed per 100g of clay.

Table 1-1: *Exchange Capacity of Common Clays* (*Keller and Frischknecht)*

Clay	Exchange Capacity (meq/100g)
Kaolinite	3-15
Halloysite. 2 H_20	5-10
Halloysite. 4 H_20	40-50
Montmorillinite	80-150
Vermiculate	100-150
Illite	10-40
Chlorite	10-40
Attapulgite	20-30

There are two principle causes for Cation exchange properties in clays [9]. These are:-

- Broken bonds around the edge of the silica-alumina units in the crystal lattice contain unsatisfied ionic charges which are balanced by adsorbed ions.

- Trivalent aluminium may substitute for quadrivalent silicon in the tetrahedral sheet structure of a clay mineral, leaving unbalanced charge in the crystal. Ions of lower valence, such as magnesium, may substitute for aluminium in the lattice with the same effect.

In clay-water mixtures where there is more water than needed to make the clay plastic, the exchange ions may separate from the clay mineral in a process of resembling ionization.

The soil physical properties such as water content, influence of the mobility of electrical charges and chemical properties such as Cation exchange capacity (CEC), mineral composition are influencing the measured electrical properties[20].These physical and chemical properties of soil are described below.

1.2.3. Moisture Content Determination

Moisture content of the soil is the percentage of water present by mass of a given soil sample. Moisture content is one of the parameters used in classifying a given soil type for use in any engineering project. This is expressed by the water content (W) in percent.

$$MC\% = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

Eq. (1-1)

Where: W_1 = Weight of Container (g)

W_2 = Weight of moist soil + Container (g)

W_3 = Weight of dried soil + Container (g)

1.2.4. Soil Index Properties

Soil index properties are used extensively by engineers to discriminate between the different kinds of soil within a broad category. For instance, clay soil will exhibit a wide range of engineering properties that will depend on its mineralogical composition. The laboratory tests for the Atterberg limits (Swedish soil scientist A. Atterberg) are referred to as index tests outlines the procedure for the determination of the free swell of a disturbed soil on wetting. Soils that shrink or fail to saturate are usually dispersible. This might mask the extent of volume expansion thus a linear shrinkage test is recommended to indicate the likelihood of shrink-swell behaviour [21]. They serve as an indication of several physical properties of soils, including shrink and swell potential of clay minerals parameters shrinkage limits, plastic limits, liquid limits and plasticity indices. The consistency is often very much dependent on the amount of water in the soil.

Some index property tests that can be conducted in the soil mechanics laboratory are determination of plastic limit, shrinkage characteristics, and Liquid limit test depending on the soil type (e.g. clays); this test can be conducted by either using Casagrande method or cone penetration. The condition of a soil can be altered by changing the moisture content. The liquid limit is the empirically established moisture content at which a soil passes from the plastic to the liquid state. Knowledge of the liquid limit allows the engineer to correlate several engineering properties with the properties of soil. Liquid limit (LL) is the lowest water content at which the fine grained soil behaves like a viscous mud, flowing under its own weight. It is the transition water content between plastic and liquid states. At liquid limit, the soil has very little strength. Plastic limit (PL) is the lowest water content at which the soil exhibits plastic characteristics (i.e., the lowest water content at which the clay can be rolled into a 3 mm diameter thread). The range of water content, over which the soil remains plastic, is called the plasticity index (PI).

Table 1-2: *Definition of Atterberg limits with respect to the various states at which clay soil exist with varies moisture content*

Phases of Soil and the Atterberg Limits

Phase	Solid State	Semi-Solid State	Plastic State		Liquid State	Suspension
Water	← Water Content decreasing					
Limits	Dry Soil	Shrinkage Limit SL	Plastic Limit PL	Sticky Limit	Liquid Limit LL	
			Plasticity Index = PI			
Shrinkage	Volume Constant	← Volume Decreasing				
Moisture content	0	SL	PL ← PI → LL			

The Plasticity Index (PI) is simply the numerical difference between the liquid limit (LL) and the plastic limit (PL) for a particular material and indicates the magnitude of the range of moisture content over which the soil remains plastic. It gives some indication of the amount of swelling and shrinkage that will result in the wetting and drying of that fraction tested.

$$PI = LL - PL \qquad \textbf{Eq. (1.2)}$$

1.2.5. Cation Exchange Capacity (CEC)

A clay particle in nature can attract ions to neutralize its net charge. These ions are weakly attracted on the particle surface and therefore easily be replaced by other ions. Cation exchange capacity (CEC) of soils is a measure of easily influenced by the mineralogical content and specific surface area of soil grains [22] . It is also a measure of the number of cations that are required to neutralize the clay particle as a whole. Methylene blue adsorption test is conducted for determination of Cation exchange capacity of the soil samples [22] . The methylene blue adsorption is calculated in grams of methylene blue adsorbed by 100 gm of samples as

$$MAB = \frac{(C * p)}{\left(A/100\right)\left(g/100g\right)} \qquad \textbf{Eq. (1.3)}$$

Where: MAB= methylene blue adsorption value

C= concentration of the methylene blue solution (g/ml)

P =Amount of MB adsorbed (ml) and

A= weight of soil (g)

The adsorption is calculated in mill-equivalents per 100 g of the soil samples as follows:

$$M_f = \frac{(100 * N * P)}{A\left(\frac{meq}{100g}\right)}$$

Eq. (1.4)

Where: N=Normality of the MB solution (meq/l)

M_f is regarded as equivalent to the Cation exchange capacity of the soil Samples

1.3. Geophysical Measurement

Surface geophysical methods allow subsurface features to be located, mapped, and characterized by making measurements at the surface that respond to a physical, electrical, or chemical property. These non-invasive measurements can be effectively used to provide reconnaissance to detailed geologic information, guide subsurface sampling and excavation, and provide continuous monitoring. Surface geophysical methods provide data at a variety of scales, from the regional geologic setting to site-specific geotechnical forensics. The applications of geophysical methods that focus primarily on the engineering include determining the engineering properties of rocks and soils before construction is planned. Surface geophysical methods can be used to assess soil and rock properties and for the non-destructive testing of man-made structures. This research adopted the most commonly employed geophysical methods in the applications of surface geophysical methods. These are electrical resistivity and electromagnetic method. Integrated geophysical methods used in this study have advantage to get a reliable and more coherent relationship with the expansive soil parameters. The physical and chemical properties of soils are influenced the electrical geophysical measurement in-situ.[9] The electrical geophysical method such as electromagnetic and resistivity are influenced by porosity; moisture content, concentration of dissolved electrolytes, temperature and phase state of the pore water, and amount and composition of colloids[23, 24].

The density of mobile electrical charges, reflected in measured electrical properties, would be related to many soil physical and chemical properties[20] . The chemical properties of soil are humus content, base saturation, Cation exchange capacity, soil mineral composition and amount of soluble salts which could be related to the total amount of charges in soils. The physical properties of soils are water content and temperature these are influenced by the mobility of electrical charges in soils.

Of these properties of soils, the engineering parameters of soils like plasticity limit, liquid limit, plasticity index and Cation exchange capacity would be considered in this research to see the relation they have with the measured electrical properties of soils. However, the in-situ geophysical measurements would be proposed to do conductivity and resistivity test in laboratory test under a certain controlled condition by taking soil samples of different and known swelling potential.

1.3.1. EM

Electromagnetic methods provide a means to measure subsurface electrical conductivity and to identify subsurface conductive materials. Electrical conductivity is a function of soil and rock type, porosity and permeability, as well as the composition of fluids that fill the pore spaces [23, 25], it may be related to groundwater properties such as specific conductance or total dissolved solids. Electromagnetic conductivity values are given in units of mill-Siemens/meter (mS/m), it is the spatial variations in conductivity values that are significant. The electromagnetic techniques have the broadest range of different instrumental systems. They can be classified as either time domain (TEM) or frequency domain (FEM) systems [26].

FEM: use one or more frequencies
TEM: Measurements as a function of time

Frequency domain electromagnetic instruments EM31, EM34, and EM38 manufactured by Geonics, Ltd measure the electrical conductivity of soil and rock by measuring the magnitude and phase of an induced electromagnetic current. For this study, Geonics ground conductivity meter EM 31 instrument was used for measuring apparent conductivity values integrated over a volume of the subsurface to a maximum depth of 2.75m and 5.5m in horizontal and vertical dipole orientation respectively. The merit of using EM 31 instruments are to make relatively easy and quick measurements, provide excellent lateral resolution with profiling and do not require ground contact [25] .

Geonics™ EM-31 has two coils on a 3.66 m long bar and frequency 9.8 KHz , One being transmitter (Tx) introduced an alternating current and generates primary magnetic field (Hp) that propagates in the soil and induces very small electrical currents. These currents generate a secondary magnetic field (Hs) that is sensed; together with Hp by the Receiver (Rx).

The ratio of the two magnetic fields is proportional to the electrical conductivity (σ_a) of the soil under the assumption of homogeneity, and normalizing all spatial dimensions with respect to s.

$$\sigma_a = \frac{4}{\omega\mu_0 s^2}\left(\frac{H_s}{H_p}\right) \quad \textbf{Eq. (1.5)}$$

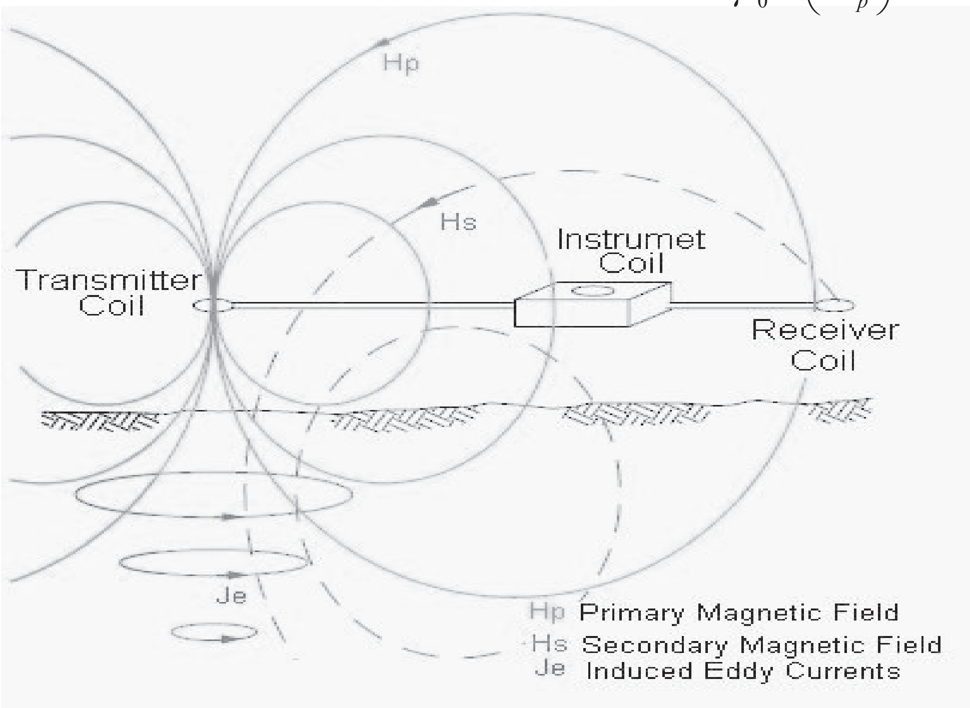


Figure 1-1: *EM Principle of Operation*

The basic principle of operation of the EM method is illustrated in Figure 1-1; a transmitter coil radiates an electromagnetic field which induces electrical currents (termed eddy currents, Je) in the earth below the coil. These eddy currents in turn generate a secondary magnetic field (Hs). The receiver coil detects and measures this secondary field. The instrument output, calibrated to read in units of terrain conductivity (apparent conductivity), is obtained by comparing the strength of the quadrature phase component of the secondary field to the strength of the primary field. The apparent conductivity measurement represents a weighted average of subsurface conductivity from the ground surface to the effective depth of exploration of the instrument.

The estimation of ground conductivity is carried out using an approximation formula that relates the quad phase measurement to the conductivity of the ground. The formula is valid for the so-called "low induction number" situation; that is, when the coil spacing is much smaller than skin depth of EM signals at the frequency being used. The EM-31 provides a good approximation for true ground conductivity when that conductivity is less than roughly 1000 mS/m. As the true conductivity of the ground becomes larger than 1000 mS/m, the value provided by the EM-31 becomes more of an underestimate.

The relationship between the vertical distributions of the soil ECa and the response of the EM ground conductivity are expressed quantitatively by depth response functions which determine the EM response to changes of ECa with depth. In analyzing the response of the EM-31, McNeil defined the induction number (N_B) as the ratio of the intercoil spacing (r) to the skin depth (δ), under the assumption that induction number N_B << 1 which can be used to predict the response of the instrument at different height (h) above a soil with depth varying conductivity [25] [27].

$$N_B = r/\delta = r\sqrt{\mu_0 \omega \sigma / 2} \qquad \textbf{Eq. (1.6)}$$

Where: angular frequency $\omega = 2\pi f$, and f: instrument operation frequency

Under the assumption of homogeneity, and normalizing all spatial dimensions with respect to σ_a, McNeill (1980) described the sensitivity ϕ of the instrument to conductivity at depth z, for both vertical and horizontal modes

$$\phi^V(z) = \frac{4z}{(4z^2+1)^{3/2}} \qquad \textbf{Eq. (1.7)} \qquad\qquad \phi^H(z) = 2 - \frac{4z}{(4z^2+1)^{1/2}} \qquad \textbf{Eq. (1.8)}$$

As seen in figure 1-2, horizontal mode $\phi^H(Z)$ configuration is more sensitive to contributions from materials at the very near surface while the vertical mode $\phi^V(Z)$ configuration better discriminates contributions at lower depth, with a maximum value at about 0.4 times the distance between the coils.

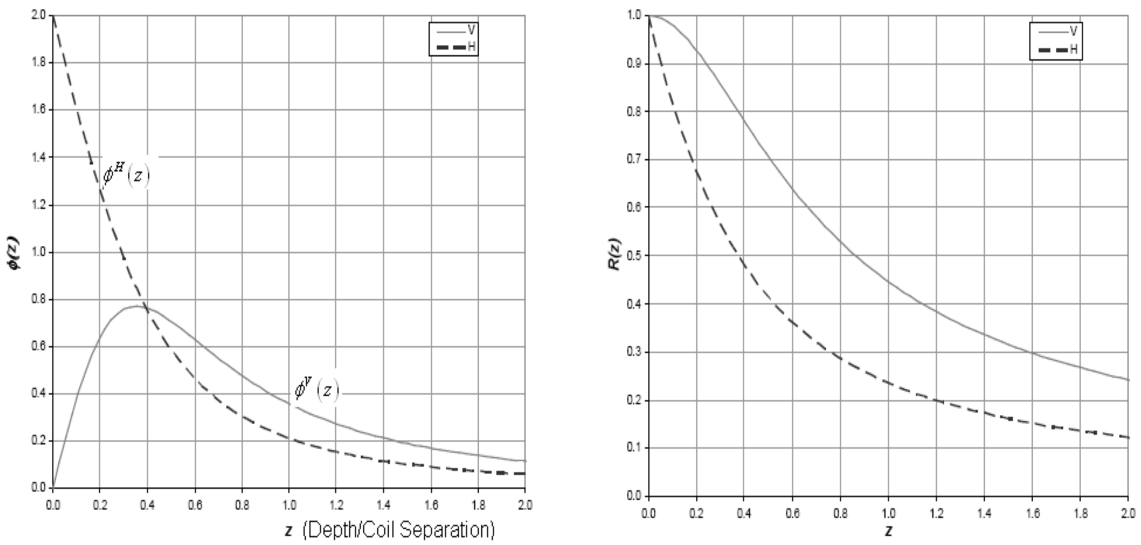


Figure 1-2: *Instrument sensitivity curves a) the relative response curve b) the cumulative response curve for both vertical (V) and Horizontal (H) dipole configurations*

Finally, after carried out inversion, Conductivity (ECa) can provide quantitative estimates of the subsurface conductivity at different depths.

1.3.2. ER

Electrical resistivity measurements are made by placing four electrodes in contact with the soil, a current is caused to flow in to the earth between one pair of current electrodes while the voltage across the other pair of potential electrodes is measured. The depth of measurements is related to the electrode spacing; smaller the spacing the higher resolution but lower depth of penetration. Resistivity measurements include profiling and sounding with fixed electrode spacing in 1-Dimensional by increasing electrode spacing at a fixed location using four-electrodes. ER measurements are widely applied for determining the depth and thickness of geologic strata; detecting lateral changes and locating anomalous geologic conditions; Measuring soil resistivity and determine fracture orientation. Resistivity measurements use electrodes that are in direct contact with the ground to inject a Direct Current (DC) and to measure the resulting voltage difference. This method is effectively used in a wide variety of environments to provide resistivity soundings, profiles, and cross-sections of the subsurface.

The DC ER method was applied for this study to measure the apparent resistivity averaged over a volume of the earth determined by the soil along with the electrode geometry and spacing. The electrical resistivity will be conducted using ABEM Terrameter (resistivity meter) by injecting current through two current electrodes resulting in a potential difference (ΔV). This is measured between two potential electrodes intermediate of the current carrying electrodes. The electrodes are separated by equal distance spacing (a) using Wenner array configuration. The ratio $\Delta V/I$ is measured and thus the apparent resistivity ρ_a is calculated Where: $K = 2\pi a$ is a geometrical factor as

$$\rho_a = K\frac{\Delta V}{I}$$ **Eq. (1.9)**

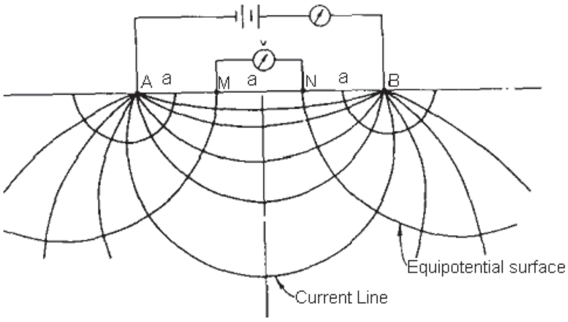


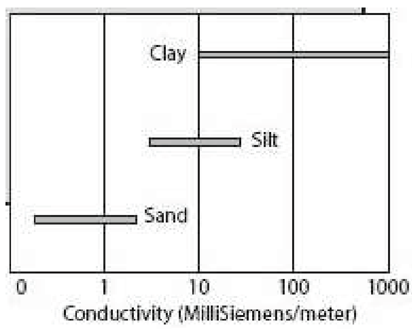
Figure 1-3: *Equipotentials and current lines for a pair of current electrodes A and B on a homogeneous half-space*

The mathematical demonstration for the derivation of the equation (1.9) may be found in text books on geophysics[9]. The equipotentials represent imagery shells, or bowls, surrounding the current electrodes, and on any one of which the electrical potential is everywhere equal. The current lines represent a sampling of the infinitely many paths followed by the current, paths that are defined by the condition that they must be everywhere normal to the equipotential surfaces.

Table 1-3 shows some typical ranges of resistivity values for manmade materials and natural minerals and rocks, similar to numerous tables found in the literature [9, 24, 26]. The ranges of values shown are those commonly encountered but do not represent extreme values. It may be inferred from the values listed that the user would expect to find in a typical resistivity survey low resistivities for the soil layers, with underlying bedrock producing higher resistivities.

Table 1-3: *Typical Electrical Resistivities and Conductivity of some of Earth Materials (Keller, G.V. and F.C. Frischknecht)*

Material	Resistivity (ohm-m)
Clay	1-20
Sand, wet to moist	20-200
Shale	1-500
Porous limestone	100-1,000
Dense limestone	1,000-1,000,000



1.4. Literature Review

In order to get the merits of geophysical methods, these are lower cost, increased efficiency, and more timely results. In addition, the ability to obtain data at many more points with a sensor, as compared to sampling methods, means that overall spatial estimation accuracy can increase even if the accuracy of individual measurements is lower [28], Researchers have carried out investigation to formulate empirical relation or linear regression between soil physiochemical properties and Electrical conductivity of soil. In addition, it was proved that apparent electrical conductivity (ECa) of the soil profile is a sensor-based measurement that can provide an indirect indicator of important soil physical and chemical properties. Soil salinity, clay content, Cation exchange capacity (CEC), clay mineralogy, soil pore size and distribution, and soil moisture content are some of the factors that affect ECa [1, 25], the contributions of the soil properties affecting the ECa measurement are known or can be estimated in some cases, within-field variations in ECa due to one soil property predominate and ECa can be calibrated directly to that dominant factor [29, 30]. Examples of this direct calibration approach include estimating soil salinity and topsoil depth above a subsoil claypan horizon [31-33]. The ground conductivity meter commonly used is high frequency Geonics EM-38 and EM-31.The electrical properties of the basic soil types, such as Spaodosols, Alfisols, Histosols, Mollisols and Aridisols of Russia in situ were measured using non-contact electromagnetic, electrical profiling and electrical sounding methods as Pozdnyakov , [20] described in his paper he showed the relation between electrical properties and soil physiochemical properties however ,he explained the soil electrical properties depend on the simultaneously on many soil properties which made the relationship very complex and he drew conclusion the geophysical method do not measure individual charges in soils, but rather outlined places with different densities of electrical charges. One of Soil chemical property is soil exchange capacity that is related to the total amount of available charges in soils. The soil physical properties, such as water content and temperature, are also influence the mobility of electrical charges in soils [20]. Electrical characterization of soil was done by conducting surface electrical resistivity measurements and subsequently translating these data in terms of electrical properties of subsurface soil [34]. Various attempts have been made in literatures to integrate the ER and geotechnical data for characterization of subsurface soil [35]. The application of electrical resistivity for characterization of soil was reviewed [36].

The ground conductivity measurement or EM reading commonly used to predict soil electrical conductivity profile. To do this, McNeill (1980)[25] linear model used to present the ground conductivity meter. This model used to select linear combinations of measurements that maximized the response to conductivity within a depth of interest [37-39].The inverse procedure was developed on the basis of McNeil linear model and the basic principle of physics with second order Tikhonov regularization which does not require further field calibration. The linear and non linear model was verified by Hendrickx et al. (2002)[40] for inversion soil electrical conductivity profiles using electromagnetic induction measurements above the ground that combine with Tikhonov regularization. The thin layer thickness of soil electrical conductivity can be determined using the inversion models.

1.5. Objectives

The main purpose of this research is to study the techniques of integrated geophysical methods on its possible application for clay soil swelling potential parameters determination. More specifically, the overall objectives of this study are:

- To quantify the Cation Exchange Capacity (CEC) and acquire information about the nature of clay mineralogy in the soil samples by the Electromagnetic and Resistivity method.
- To determine the relationship between EC and CEC, and other soil test parameters.
- To integrate measured geophysical parameters with Atterberg Limits of Soils (e.g., PI, PL, LL,)
- To relate electrical conductivity and resistivity with the engineering soil parameters such as water content (%), and CEC (meq/100g).

1.6. Research questions

- Is there any relationship between the amount of water in the soil samples and Atterberg Limits (LL, PL, & PI) with the conductivity and resistivity data?
- Can the EM technique be used to differentiate major classes of clay type according to their response to geophysical properties?
- Can soil conductivity affecting factors like moisture (water) content, and minerals present in the soil be related to the engineering parameters?
- Can the analysis of the soil samples and values obtained from inversion geophysical measurement lead to parameters related?
- Is it possible to use the EM technique to quantify CEC, and water content?

1.7. Research Hypothesis

- Apparent electrical conductivity are measured using the Geonics™ ground conductivity meter EM-31 and Inversion is carried out to produce electrical conductivity of soil at required depth where the soil samples are taken. The clay minerals that adsorbed ions (CEC) can contribute and give an indication to soil conductivity appreciably. In addition, the amount of water content of clay minerals increases the conductivity of soils which can give also an indication to relate with the inverted conductivity values [15, 25, 41]. Thus the clay soil classification can be carried out in to major classes of mineralogical composition having the same or similar conductivity properties.

- The electrical geophysical methods (EM & ER) are measured the volume density of mobile electrical charges in soils which is proportional to the number of electrically charged particles in an elementary volume of media [18]. As surface charge in soils is formed by exchange cations and anions, the CEC is equivalent to the density of exchange surface charges. So soil engineering parameters can be related with the volume density of the mobile electrical charge in soils.

- The particle size distribution, moisture content, clay mineralogy ,clay content and Cation exchange capacity (CEC) are soil properties used to determine soils swelling potential characteristics [8]. The swelling capacity of soil increases with the proportion of clay in the soil or the amount of expansive clay minerals, notably Montmorillinite [42].The clay minerals related to their swelling potential influenced the electrical measurements .EC can be related with the parameters of soil properties.

1.8. Research Methodology

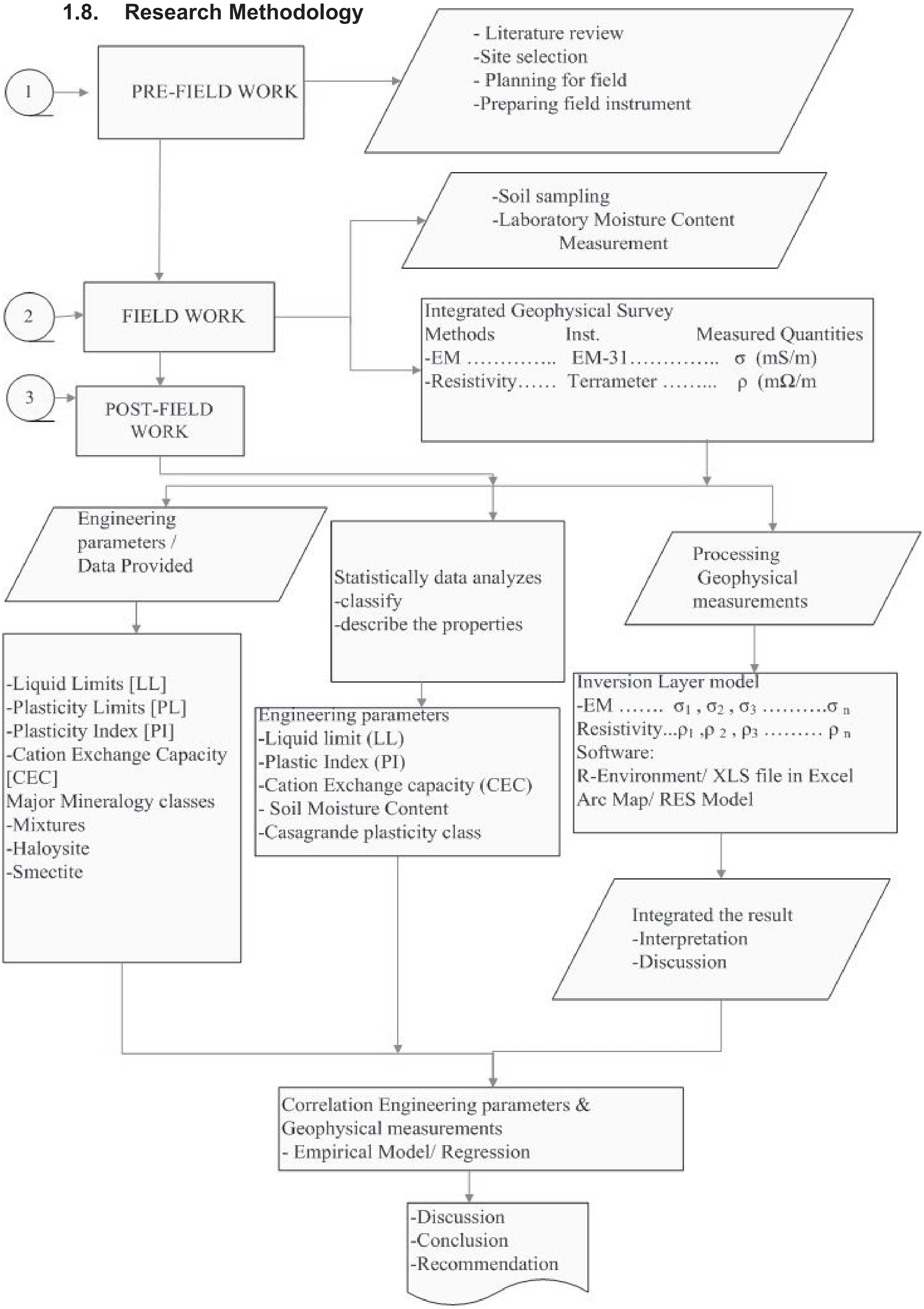


Figure 1-4: *Flow chart of the research approach*

2. DESCRIPTION OF THE STUDY AREA

2.1. General Setting

The study area is located in the horn of Africa, particularly Ethiopia, from Addis Ababa to Nazareth along the newly designed road which bounded in geographic coordinates of latitudes $38^0 50'$-39^0 20' and longitudes of $8^0 30'$-$8^0 50'$. Topography of the study area is elevated plain ranging between 1800 m-2200 m altitude above sea level (see figure 2-1) and the climate along the project road is largely governed by altitudinal variations that control rainfall distribution to some degree and temperature variation to a very large extent. The area is largely characterized by a wet climate in which the rainy season prevails from June to September the largest part of the area is represented by "Weina Dega" climate zone with mean annual temperature of 20ºc and rainfall of 1500 mm.

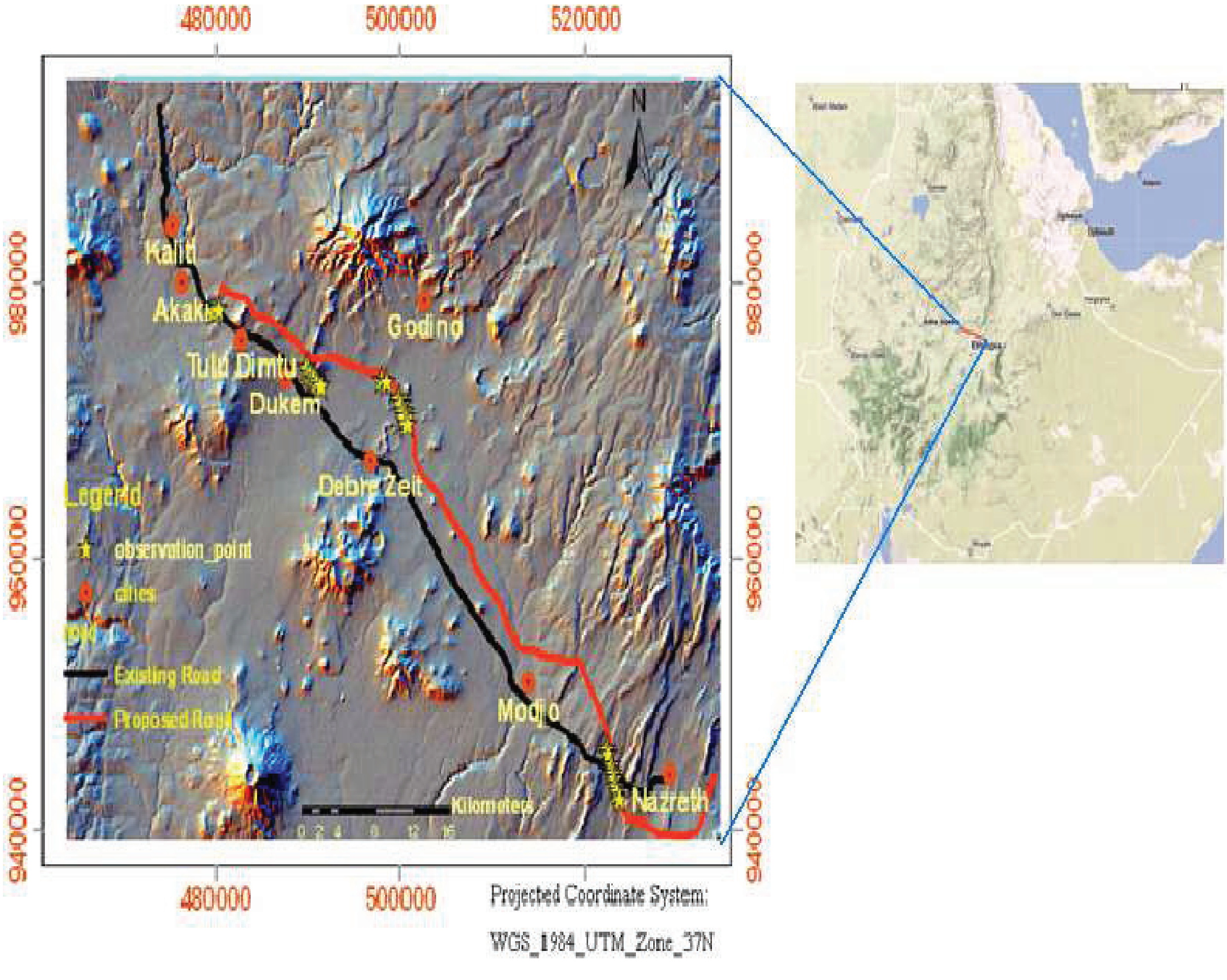


Figure 2-1: *Location map of the study area*

2.2. Geology

Geology of the study area is in general described by Quaternary to Tertiary volcanic rocks with minor sedimentary sediments. These volcanic rocks are group of Adama series (Nn), alkaline olivine basalt (Qb) and Bishoftu formation (NQtb), Tarmaber Megezez formation (Q), Chilalo formation (Nc) and Dino formation (Qd) (See Fig. 2-2).Rhyolite is found North of Dukem which characterized light grey to yellowish, fresh to moderately weathered, massive to widely jointed and weakly to moderately fractured. Conical shaped isolated hills of scoria are common between Debre-Zeit and Akaki area. The Bishoftu formation mainly consists of basalt and trachyte while the Adama series rocks include ignimbrite, pumice, ash and rhyolite with rare intercalation of basaltic flows. The basalt that found in the area is dark grey in colour, fine-grained, aphanitic to porphyritic in texture and located in hilly to flat lying topography which covered by thin to thick dark silty clay soil [43].

Between Tulu Dimtu and Dukem towns, basalts are being highly extracted for construction material from quarry sites. The highly expansive silty clay is derived from the weathered basalts formed alluvial or colluvial and lacustrine deposits. This alluvial or colluvial origin expansive soil is commonly known as Black cotton soil which comprises highly cultivable land, this places becomes swampy during rainy seasons. The area around Nazareth is comprises of thick succession of welded ignimbrites with pumice, ash, and rhyolite flows and domes with rare intercalation of basalt flows. see the apex , the general description of geology symbol.

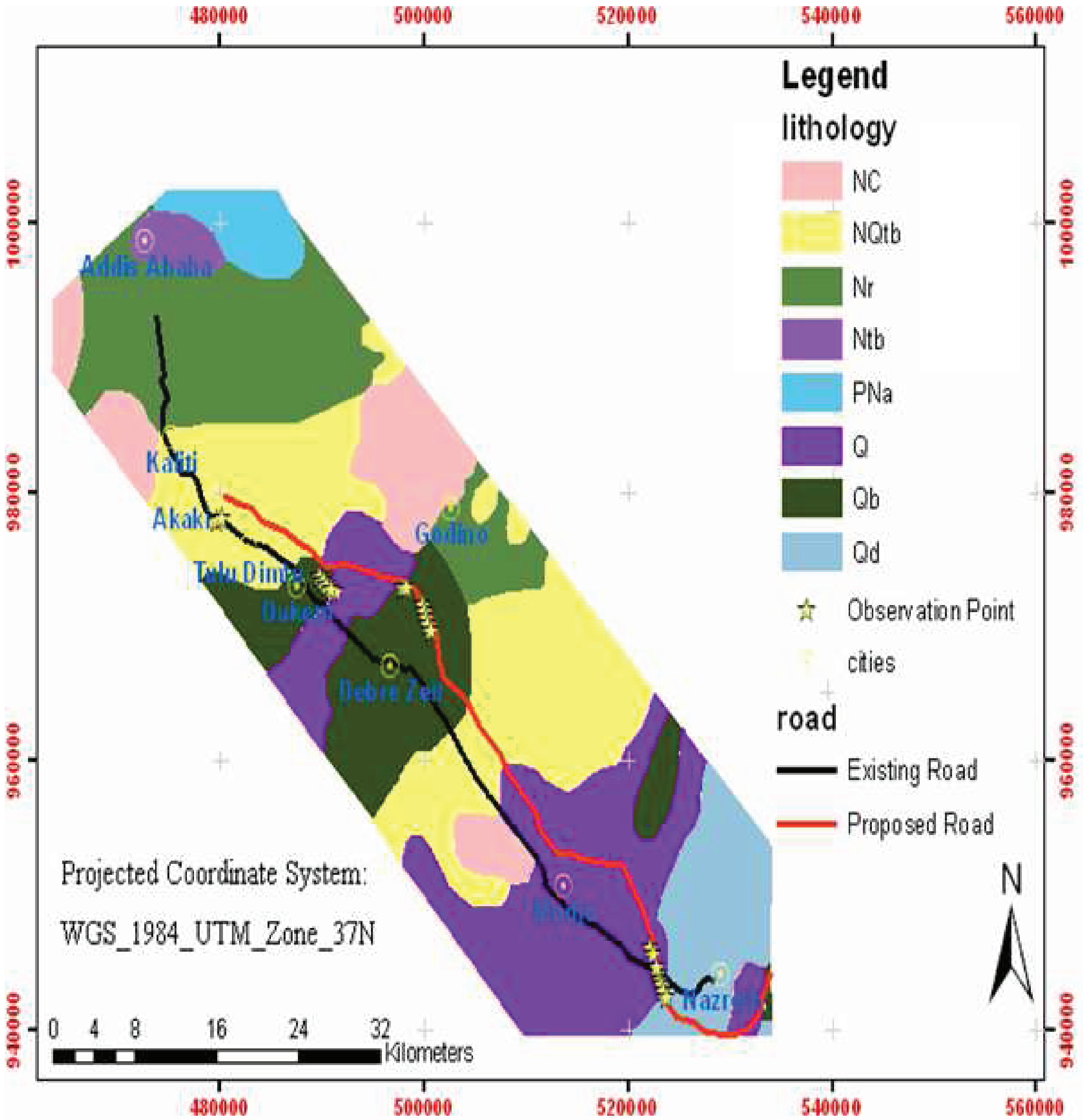


Figure 2-2: *Geology Map of the study area*

2.3. SOIL

From the parent rock and general formation of soils of the study area are characterized by quaternary alkaline basalt , trachyte , alluvial and lacustrine deposits i.e. sand, silt, clay, diatomite, limestone and beach sand [44]. The group of soil found in the area are mainly Vertisols, Luvisol and Andosols [7] of which Vertisols, commonly known as 'black cotton' clay soils covered large portion of the road corridor as seen in figure 2-3 [17]. This soil contains dominant swelling clay mineral grouped under smectite, mainly nontronite and Montmorillinite clays [45] . As several researchers described, the presence of expansive soils which are residual soils, derived from the weathering of basic volcanic rocks and invariably clays and silty soils. The expansive soil deposit in the field are characterized by the general pattern of cracks during the dry season of the year and causes vertical heaving of soil which may cause damage to an overlying structure during wet seasons [46], [47], [10].The soil group, Andosols, which is found around Nazareth area , is developed from parent material of volcanic origin, such as volcanic ash, tuff, and pumice ,It is characterized highly porous, low plasticity and stickiness, Because of the range of in characteristics of volcanic ash-cap soils, classified in two, Allophanic Andosols and non- Allophanic Andosols. Allophanic Andosols are generally rich inorganic matter and contain the clay minerals allophane and imogolite characterized having a tendency of expansive clay minerals[48]. Luvisol is covered small portion in the study area along the road corridor between Tulu Dimitu and Dukem towns. This soil is comprised from parental material of a wide variety of unconsolidated materials including alluvial and colluvial deposits.

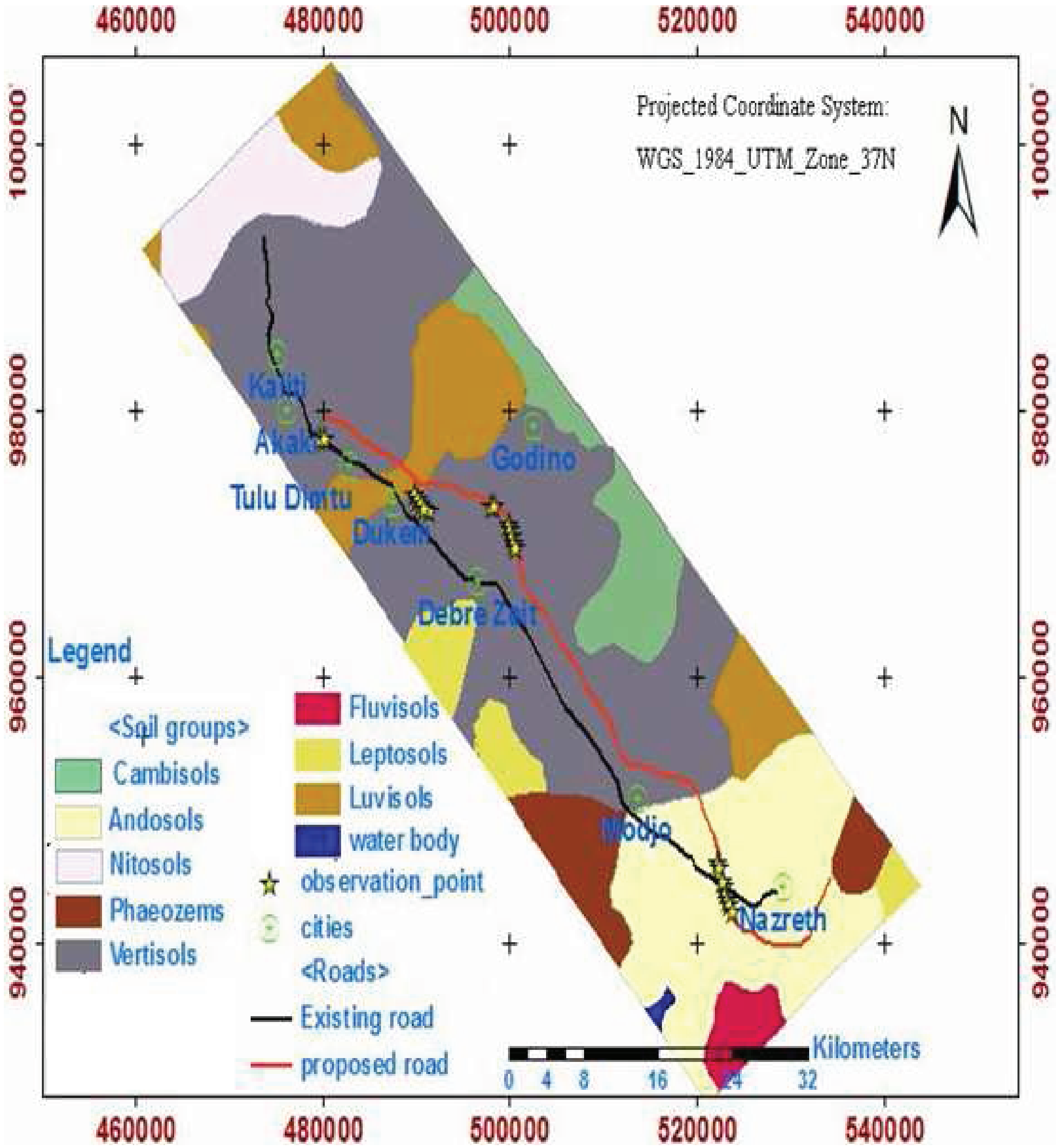


Figure 2-3: *Soil Map of the study area*

.

3. MATERIALS AND METHODOLOGY

The following data set were available and used for the research study , Atterberg limit (engineering parameters)that have been provided by PhD student Mrs. Fekerte Argaw and the maps used as supporting are listed below : These are

- Geological Map,
- Soil Map,
- Topographic Maps,
- Atterberg limit (PL, LL, PI) and Cation Exchange Capacity (CEC)

The following geophysical survey, and Soil sampling and Laboratory work have been done in November starting date 07/2008-16/2008 during field work.

- Electrical resistivity (ER)
- Electromagnetic Survey (EM)
- Collecting soil samples
- Determining moisture content in laboratory

3.1. Instrumentations

The following instruments were used for conducting geophysical measurements and soil sampling. These are:-

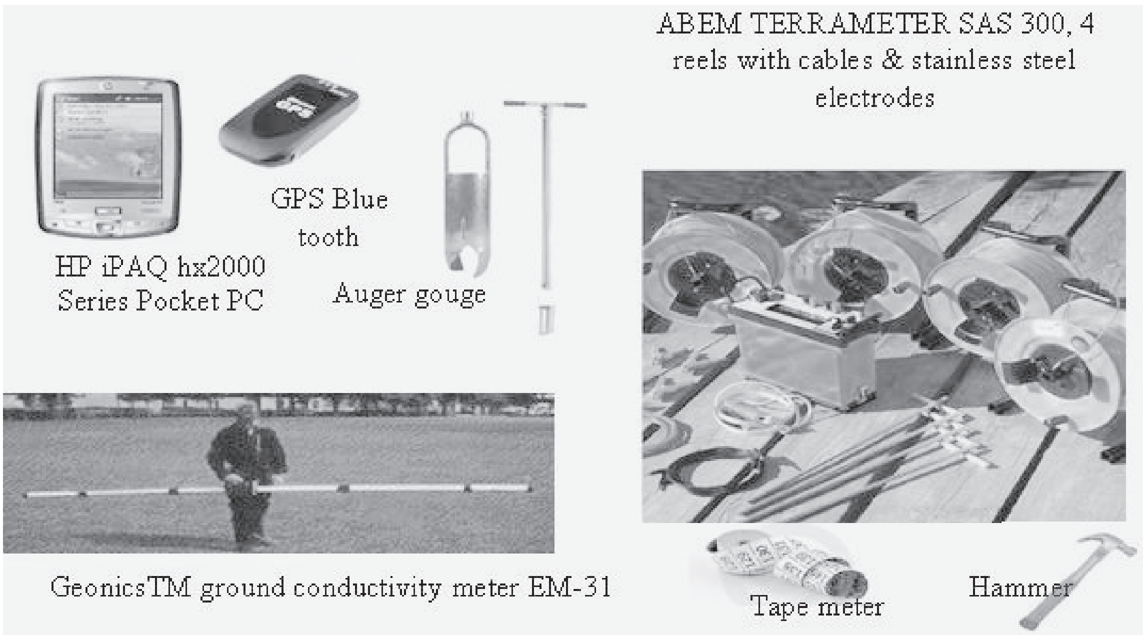


Figure 3-1: *Instruments used for data collection*

3.2. Data acquisition

The measurements were made in selected sampling locations along the newly proposed and designed high way from Addis Ababa to Adama by Ethiopia Road Authority (ERA). The selection of sampling locations were made taking in to account the accessibility and favourable condition for conducting geophysical survey since the field work was about end of rainy season and the beginning of spring. During such season most sampling position were harvested and covered by agricultural products. Among 32 sampling points which would be planned to do geophysical survey, only 22 sampling points, geophysical measurements were made due to accessibility for survey and the limited time constraints. In addition sampling of soil was taken for determination of moisture content in the laboratory from the top surface up to 80cm to 1m depth by digging using auger. Due to the reason mentioned above, the geophysical survey (EM and ER) have been conducted in radius of 25 meter from the location where the soil parameters taken for determining engineering parameters (LL, PL, PI and CEC) which were taken place about a year before.

3.3. EM-31 Surveys

For the conductivity measurements, the Geonics EM-31 ground conductivity meter was used to collect data at 1 m intervals along the transect, first holding the instrument at 0 (on the surface) and taking the reading in both vertical and horizontal dipole orientations, then the reading repeated at 0.5m and 1m instrument position above the ground for each point location (see figure 3-2).

Figure 3-2: *EM survey holding instrument position at different height*

The instrument reading range was set according to the conductivity of the soil which varies 30 mS/m; 100 mS/m and 300 mS/m .Readings were taken and recorded on data sheet by tuning the oper mode button, each reading at every point took few minutes, allowing to cover 15 and/or 16 m length with 1m spacing in 1hr. A total of 2125 measurements at the 22 transects in a total of 6 measurements for every survey location were made. The instrument was calibrated after every 8 data points readings during the survey progress to check consistency of the reading and to adjust the reading at zero, and to monitor ECa sensor drift during each field survey. The vertical dipole configuration of the equipment is most sensitive to material at a depth of 0.45 times the two coils spacing, and can penetrate depths about 1.5 times the transmitter-receiver spacing[25]. The maximum depth of information could be obtained 2.75 m and 5.5 m in horizontal and vertical dipole orientation.

3.4. ER Survey

ABEM TERRAMETER SAS 300 (Resistivity Meter) was used for resistivity measurement at 22 transects. Reading was being taken injecting a Current (DC) in to the ground through a pair of current electrodes by pushing the current switch provided in the instrument. The apparent resistance of the soil was read from the resistivity meter in unit of ohm-m which was determined by measuring the electric potential between two potential electrodes and dividing by the injected current and then by multiplying the resistance with a geometric factor of Wenner array depending on the distance between the electrodes.

Figure 3-3: *ER Instrument set up and measurement taken during field work*

The instrument was set up by deploying four electrodes in to the ground in equal spacing using Wenner array configuration, first at the smallest electrode spacing of 0.5 m, and taking a resistivity reading (see Figure 3-3). Then the electrode spacing was increased successively to 1m, 2m, 3m, 4m, 5m, and /or 6m and the procedure was repeated. The measured resistivity values against electrode spacing were plotted in logarithmic scale sheet while recording the data so as to see the general trend of the resistivity curve. The same procedure followed to be carried out the resistivity measurements to all 22 transects. The total depth of soil could be reached was about 3m.

3.5. Collecting Soil Samples

After conducting geophysical survey, Soil samples were dug from top surface to 0.8m - 1m depth regarding the condition of capability to dig by auger due to wetness and occurrence of intercalated course sand and gravel. The sampled were taken from the middle of each transects at point survey location 8. The soil profile description was written and the samples were put in plastic bag; Care was taken not to lose the moisture due to exposed to the air.

4. DATA PROCESSING

Proper organisation, inspection and integration of the collected data have been done in the first step for the further data analysis purpose. In order to carry out Inversion of EM-31 data, in McNeill layered model and Tikhonov regularization were used, a number of computer scripts have been understood and rewritten according to proper way to use the inversion model. The model algorithm was developed by Vervoort and Annen [41] in R-language as a programming platform. The measured apparent resistivity was inverted using master curve matching and RESIST program.

4.1. Inversion of EM

As described in section 1.3.1 about the principle of electromagnetic induction that are generally used to determine lateral variations of apparent electrical conductivity, can provide quantitative estimates of the subsurface conductivity at different depth. EM geophysical data recorded in the field were inverted to obtain models of the subsurface which often reproduce the observations with a high degree of fidelity. Thus, the measured data can be used to predict the quantities of soils. The prediction is not straight forward so that the measured EM-31 data needs to be calibrated for inversion processing.

I used the explanation made by Mc Neil (1980) [25] for illustrating the inversion model, he presented the linear model of the ground conductivity meter. Many researchers have used this model of the ground conductivity meter's response to select linear combinations of measurements that maximized the response to conductivity within a depth range of interest.

Borchers et al. (1997)[38] describe and discuss a more general linear model for the instrument response, which can be extrapolated from the model under the following assumption:

1) The subsurface model represents a horizontally stratified medium in which the current flow is entirely horizontal.

2) The current flow at any point of the subsurface is independent of the current flow at any other point, since the magnetic coupling between all current loops is negligible. With the two coils in vertical mode, assuming the instrument at a given height (h) above the soil, σ_a^V takes the form

$$\sigma_a^V(h) = \int_0^\infty \phi^V(Z+h)\sigma(z)\,dz$$
Eq. (4.1)

Where: $\sigma(z)$ is the conductivity at depth z. The sensitivity function $\phi^V(z)$ is described by eq. (1.7).

Similarly, for the horizontal orientation, the apparent conductivity $\phi^H(z)$ is written as follows:

$$\sigma_a^H(h) = \int_0^\infty \phi^H(Z+h)\sigma(z)\,dz$$
Eq. (4.2)

With $\phi^H(Z)$ given by eq. (1.8). Collecting measurements of σ_a^V and σ_a^H recorded at different elevation, h_1, h_2,…, h_N, above the soil surface, the two integral eq.(4.1) and eq. (4.2) provide the linear forward model to invert, from which the electrical conductivity profile $\sigma(z)$ can be estimated.

Assuming a stratified medium model (Figure 4-1) the subsurface is divided into M layers with specified thickness dzj, electrical conductivity σ_j and magnetic permeability μ_j equal, in this context, to that of the free space: $\mu_j = \mu_o$ for j = 1, 2, …, M.

Let dT(σ) = [$\sigma_a^V(h_1)$, $\sigma_a^V(h_2)$, ..., $\sigma_a^V(h_N)$, $\sigma_a^H(h_1)$, $\sigma_a^H(h_2)$,…, $\sigma_a^H(h_N)$]

T denote the vector gathering data relative to apparent conductivity measurements

$$\mathrm{d}(\sigma) = \begin{bmatrix} d^V \\ d^H \end{bmatrix}$$
Eq. (4.3)

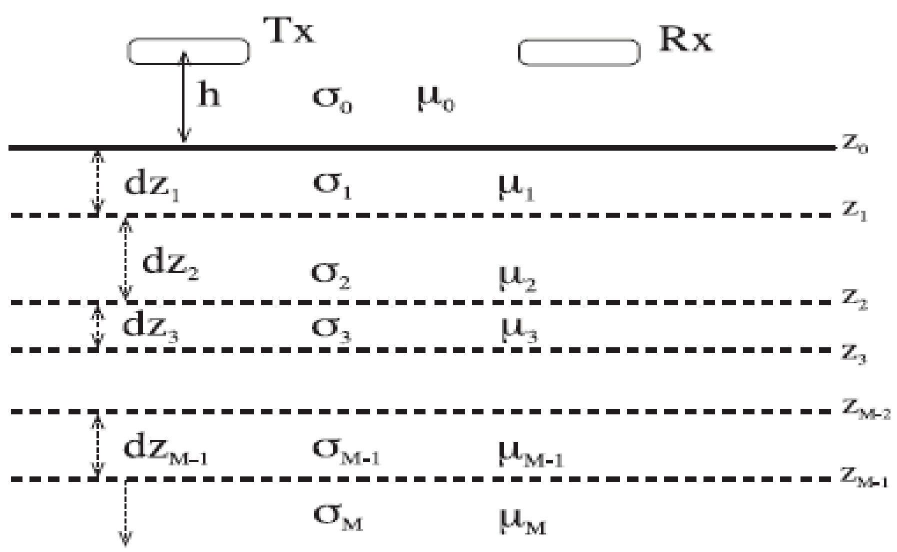


Figure 4-1: Schematic diagram of M-layer Model

T_x and R_x represent transmitter and Receiver coil electromagnetic ground conductivity meter. T is the thickness of the soil layer; σ is apparent electrical conductivity of each layer, μ is the magnetic permeability and h is instrument height above the ground.

Using the instrument response model described by eq.(1.7) and eq.(1.8), the following system of linear equations establishes a correspondence between the subsurface conductivity profile and the apparent conductivity measurements: The system matrix K is constructed as follows: The detail explanation of the matrix and the inversion model is found in McNeill (1980)[25, 49].

$$\mathrm{d}(\sigma) = K\sigma \qquad \text{Eq. (4.4)}$$

Where: $K = \begin{bmatrix} V \\ H \end{bmatrix}$ the elements of V and H are, respectively

$$K = \begin{bmatrix} 1 - R(z_1)_1 & R(z_2)_1 - R(z_1)_1 & \cdots & R(z_n)_1 - R(z_{n-1})_1 \\ \vdots & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \vdots \\ 1 - R(z_1)_n & \cdots & \cdots & R(z_n)_n - R(z_{n-1})_n \end{bmatrix}$$

Where Rv(z)i and RH(z)i is the vertical and horizontal cumulative response function of the instrument respectively.

$$R^{v}(z)_i = \int_0^{\infty} \phi^{v}(Z + h_i)dz \qquad \text{Eq. (4.5)} \qquad \text{and} \qquad R^{H}(z)_i = \int_0^{\infty} \phi^{H}(Z + h_i) \qquad \text{Eq. (4.6)}$$

For i = 1, 2, …, N and j = 1, 2, …, M.

The above inversion used to estimate the conductivity under the following assumption [25, 38]: 1) the subsurface model represents a horizontally stratified medium in which the current flow is entirely horizontal. 2) The magnetic coupling between all current loops is negligible. The electrical conductivity profile can be estimated by solving least square problem through optimization of the σ solution. The Tikhonov regularization introduced equation 4.7 that biases the least square problem toward a smooth σ solution.

$$mim\left\|\sigma_{a.pred} - \sigma_a\right\|^2 \qquad \text{With } \sigma \geq 0 \qquad \text{Eq. (4.7)}$$

In general,

$$mim\left\|\sigma_{a.pred} - \sigma_a\right\|^2 + \alpha^2.\left\|L_i.\sigma\right\|^2 \qquad \text{with } \sigma \geq 0 \qquad \text{Eq. (4.8)}$$

The component L_i. σ quantifies the regularity of the solution and the term α balances the smoothness of the solution with the misfit, allowing an optimal tuning on the sensitivity of the solution to input data errors.

On the basis and facts of the above inversion model, the techniques used for the measured EM-31 data are McNeill Auto, Mc Neil User Def. and Tikhonov regularization approach. The six layer conductivity model was assumed in increasing of 1m, 2m, 3m, 4m, 5m and 6m depth, it is for McNeillUserDef. as indicated in table 4.1. For McNeil Auto: thickness of layers is derived from the instrument depth penetration minus height of measurements. For McNeillTikh: fixed discrete thickness layer used.

Table 4-1: *parameters for the input layered subsoil model for McNeillUserDef*

Layers	1st	2nd	3rd	4th	5th	6th
Thickness (m)	1	1	1	1	1	∞
Cumulative thickness (m)	1	2	3	4	5	∞

After running the program in R-environment, the conductivity of each layer and its depth with RMSE value were obtained. Plots, graphs and conductivity against thickness maps were made for all 22 transect. The result obtained from each approached were carefully analyzed and determined which most described the first 1m depth soil conductivity. The Tikhonov solution has been selected for the top clay soil conductivity estimation since the Tikhonov inversion, has given more coherent and consistent results comparing the others inversion approaches even though the solution shows higher root mean square error (RMSE) (See figure B-2 in appendix). It was also indicated by previous researcher Vervoort 2006[41] that from the different inversion methods, Tikhonov methods appeared to represent more accurately than the McNeill inversion method.

Based on the model result, the values of first layer conductivity at 1m depth were selected for further analysis of each transect with others engineering parameters. The conductivity was determined the average of the values of all data points and data points 4 to 10 that around the point location where the soil sample was taken for moisture content determination in laboratory. In addition the conductivity value that exactly where the soil sample taken that is data point 8 was examined. After the analysis of the variation of the result, the average conductivity of all data points were taken since the small change was observed from averaging.

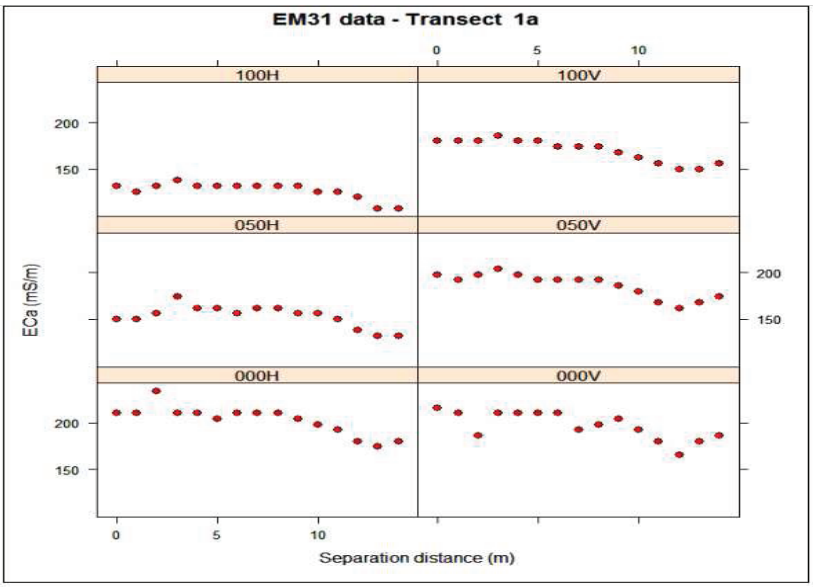


Figure 4-2: Profile plots of EM data for transect 1a

After carried out Inversion model, the EM-data profile plots have been obtained. Figure 4-2 shows the data values of transect 1a along the profile line every 1m separation. It also indicates the measured EM data in horizontal and vertical dipole orientation and EM data values at 0, 0.5m and 1m instrument height position above the ground for both orientation. 00H, 050H and 100H and 00V, 050V and 100V represent the instrument height position at 0, 50cm and 100cm for horizontal dipole orientation (H) and vertical dipole orientation (V) respectively. In horizontal orientation of the plots follow similar trend and it is also similar trend follow for vertical orientation for all 22 transects (see figure B-5, B-6, B-7 & B-8 in apex).

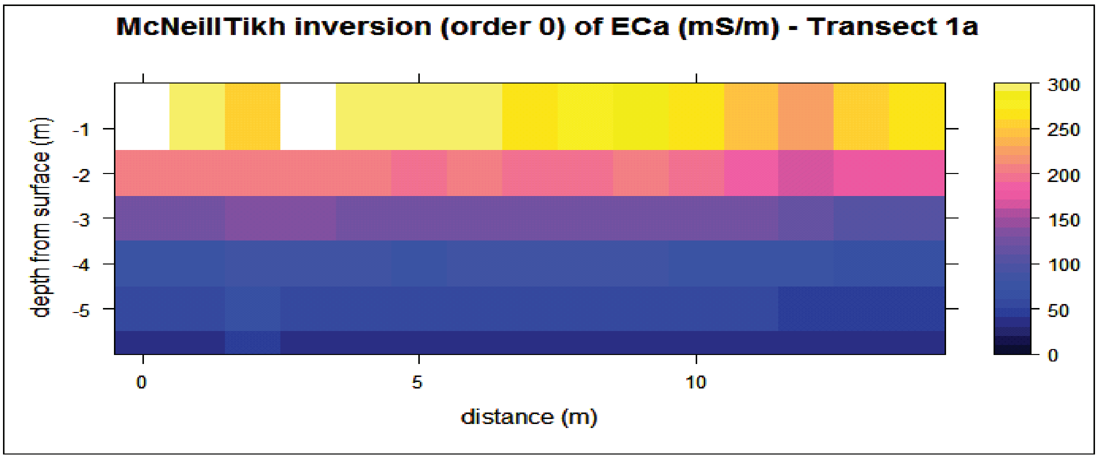


Figure 4-3: Soil Conductivity map of transect 1a

Figure 4-3 was obtained from inversion EM data of transect 1a, it is a conductivity map that indicates the conductivity value at six layer in 1m thickness each and the variation of conductivity along the profile line . In most transects the conductivity map depicts the soil conductivity variation is small laterally but it is decreasing vertically. Figure B-1 & B-2 in apex exhibit the conductivity map for 22 transects their conductivity variation laterally and vertically.

4.1.1. Measurement precision

The variation of the measured value might be caused by various possible sources of errors which occur during the measuring process. The possible source of errors during measuring geophysical survey using EM-31 instrument could be imperfection of person holding the instrument at the same height above the ground in both dipole orientation all the time and the recorder who registered in to the note book, the scale of the reading range that varies 3 mS/m to 1000 mS/m which magnifies the error when multiplying its by two decimal number of the reading. The precision of measurement of the instrument is +/- 2 % of the full scale which mean there would be a possibility the data observed imprecision of +/- 0.6 mS/m, +/-2 mS/m, +/- 6 mS/m and +/- 20 mS/m in the range 30,100, 300 and 1000 of reading respectively and the instrument accuracy of the measurement is +/- 5 % at 20 mS/m in addition the noise contribution is less than 0.1 mS/m [50]. EM data reading were taken the first 9 transects instrument reading range of 300; transects 10-11, 15, 17, 20-22 data were taken instrument reading range of 100 ; transects 16 and 18 data were taken instrument reading range of 10 and transect 19 data was taken instrument reading range of 30.

The inspection of the measurement was done by calculating the standard error and plotting the profile and Error bar taking in to consideration of the imprecision of the reading interval. The error bar was used for visualize the data distribution and indicated the dispersed of the data (see Figure 4-4).

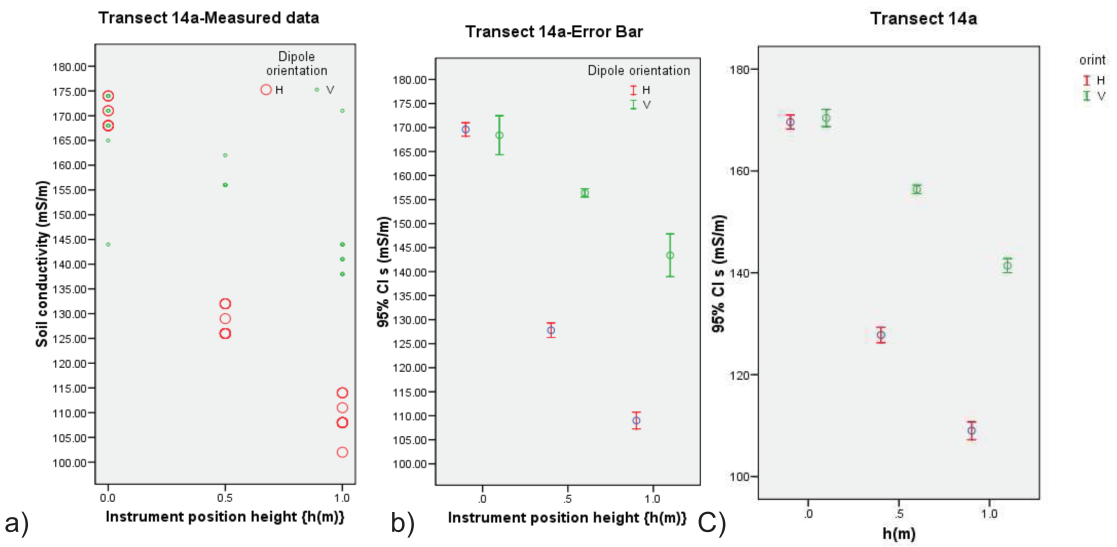


Figure 4-4: *scatter plot of the profile respect to instrument position height and dipole orientation and Error bar; a) and b) are before correction and c) after correction.*

After inspection and analysis, the raw data has been examined and thus some values were found extremely high and low values. It was probably made mistake while recording and entering to the computer and contribution of other factors. Among 2125 EM reading, 25 of which have been shown values extremely high and low measured values. These data were carefully reviewed and made some correction. The uncertainty of the measurement was estimated to see the general precision of the measurement applying the statistical techniques [51], the precision is defined by coefficient of variation C,

$$c = \frac{100 \times s}{\bar{x}} \qquad \text{Eq. (4.9)}$$

Where: s is standard deviation

$\bar{x}$ is the mean

After calculating the precision of the measurement, it was found in between 2 mS/m to 8 mS/m of coefficient of variation. It is about 2 % to 8 % precision of EM data measurement including the precision of instrument measurement precision 2 % in full scale.

4.2. Inversion of ER

The apparent resistivity data were inverted to create a model of the resistivity of the subsurface using Master Curve matching and RESIST Models. RESIST models uses an iterative smoothness-constrained least-squares method as defined by Van Vander Velpen 1988 [52, 53].

All the measured apparent resistivity data against electrode spacing were plotted on a logarithmic coordinate sheet so as to permit a wide range of values for the variables to be presented on a single graph. The reason is to compute that the theoretical curves with the resistivity of the over burden and its thickness to plot using equation 4.9 with its logarithmic scale. As V. Keller and C. Frischknecht explained, the apparent resistivity over horizontally stratified layered earth is expressed in their book [9] as:

$$\rho_a = \rho_1 \left[1 + 2\sum_{n=1}^{\infty} \frac{K_{1,2}^n}{\left[1 + \left(\frac{2nh}{r} \right)^2 \right]^{3/2}} \right] \quad \text{and} \quad K_{1,2} = \frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} \qquad \text{Eq. (4.9)}$$

Where: ρ_1 is resistivity of the first layer

h_1 is thickness of the first layer

$K_{1,2}$ is reflection coefficient and r is half electrode (AB/2) separation

After all field data were plotted on the sheet of logarithmic paper, two layer resistivity model was chosen based on the shape of the field apparent resistivity against current electrode spacing curve. Following the steps that noted below, resistivity and its thickness were determined to be as input for RESIST model.

- The field sounding curve was drawn on a transparent paper and smoothen from logarithmic paper
- The transparent paper containing the field curve was put the master curve sheet and moved the sheet respect to the other, keeping the axes parallel, until the field curve matched with one of the curves. Minor interpolation was made to get the best fit.
- Traced the "cross" of the master curve and also the two resistivity marked and then thickness ratio value was made by matching the field curve.
- The first cross on the sheet has given the resistivity ρ_1 and thickness h_1 of the first layer and the resistivity of the second layer ρ_2 were determined by multiplying the resistivity ratio by resistivity of the first layer.

For processing and interpretation of resistivity data, a processing package for use on IBM PC or compatibles, RESIST was offered by Vander Velpen B.P.A (1988)[52]. This RESIST Model was used to process the raw resistivity data in the package so as to get the final smoothed Resistivity and thickness of the subsurface. The RESIST program run by providing the two layer resistivity and thickness that obtained from curve matching as input to the model. The model would give us the plot of resistivity against half of current electrode spacing (AB/2) with the description of parameters, Resistivity and thickness of the layer, with its RMS error.

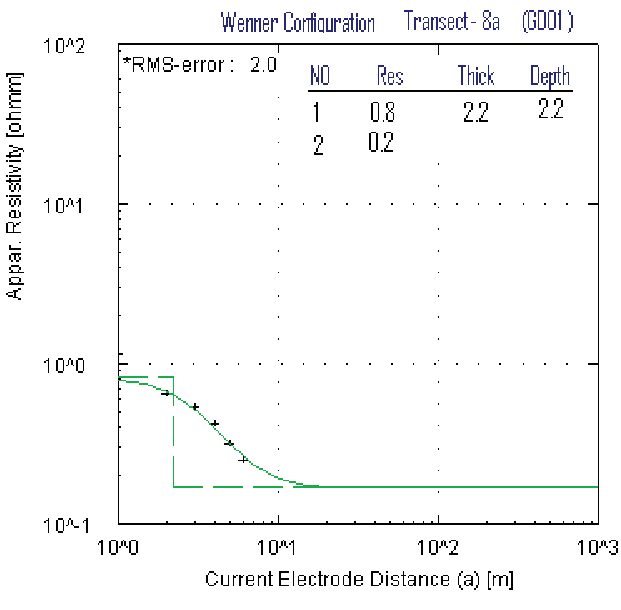


Figure 4-5: *Graph of resistivity against electrode spacing for Transect 8a*

Figure 4-5 shows the result of the inversion model for transect 8a which has resistivity value 0.8 ohm-meter for the first 2.2 m depth and the second layer resistivity is 0.2 ohm-meter. The RMS error is 2 which explain the fitness of the resistivity value with the RES model. From the RES inversion model, the graphs of resistivity against electrode separation with the inverted resistivity value for two layers were obtained for 22 transects (See in figure B-3 & B-4 in apex). The inverted resistivity value varies from 0.8 ohm-meter to 12.5 ohm-meter, it is not big variation observed for comparison, and it might be due to the presence of moisture content and clay mineral.

4.3. Analysis of Soil Parameters

The laboratory test result of soil data set has been provided by Mrs. Fekerte Argaw, the data set consist of LL, PL, PI, CEC, degree of plasticity and spectra of soil mineral composition with at which location and depth the samples were taken for the 22 transects. The geophysical survey has been done within 25m radius from the soil samples grabbed locations for engineering parameters determination about a year before.

In addition, the soil samples have been dug using auger at the middle of each transect line for determination of moisture content of the soil during the geophysical measurements has been taken place. Ethiopia Road Authority soil laboratory was used to determine the amount of water in the soil sample and the measurement was done following a standard operating procedure. This involved weighing empty, clean and dry container varies their mass 38.3g and 40.5g using a Mettler top pan balance (dynamic range =400g) to the nearest 0.01g. Select a representative quantity of moist soil that is ¼ of the total amount collected samples which varies from 150 g to 200 g weight. The sample was placed in the weighing container and weighted the container and contents to the nearest 0.01 g (W_2). The wet soil samples were weighted and then the soil was put in an oven at 105 ^{0}C for 24 hr to be completely dried. Then the dry soil samples were weighted and the water content of the soil was determined using the equation (1.1). The measurement was done for each soil samples twice to see the consistency of the measurements. The result of soil moisture content indicates the value varies from 11% to 38 % (See table A-2 in apex shows result of the laboratory moisture content).

The data set that include the engineering parameters and soil types are as seen in table A-1 in apex for 22 transects /data points. Transect 1a-15a of soil samples represent the Vertisols soil type but the rest transects 16a-22a representative soil samples taken from Andosols soil type.

For the better understanding of Plasticity characteristics, The result of liquid limit against plasticity indices of soil samples was plotted as seen in figure 4-6 on the famous plasticity chart of Casagrande to show their respective plasticity characteristics and classes with respect to the "A-line ".

The plastic properties of clays are identified by using their Atterberg 'plastic limit' and 'plasticity index' values as parameters for Casagrande Plasticity Chart. An empirical boundary between soil types is called the 'A' line, with a slope expressed by the equation (4.10) that separates inorganic clays from inorganic silts and organic soils. Soils that lie above the "A-line "are clayey and those that lie below it are Silty, these division is depends on the particle size of the soils.

$$PI = 0.73 \times (LL - 20), \qquad \textbf{Eq. (4.10)}$$

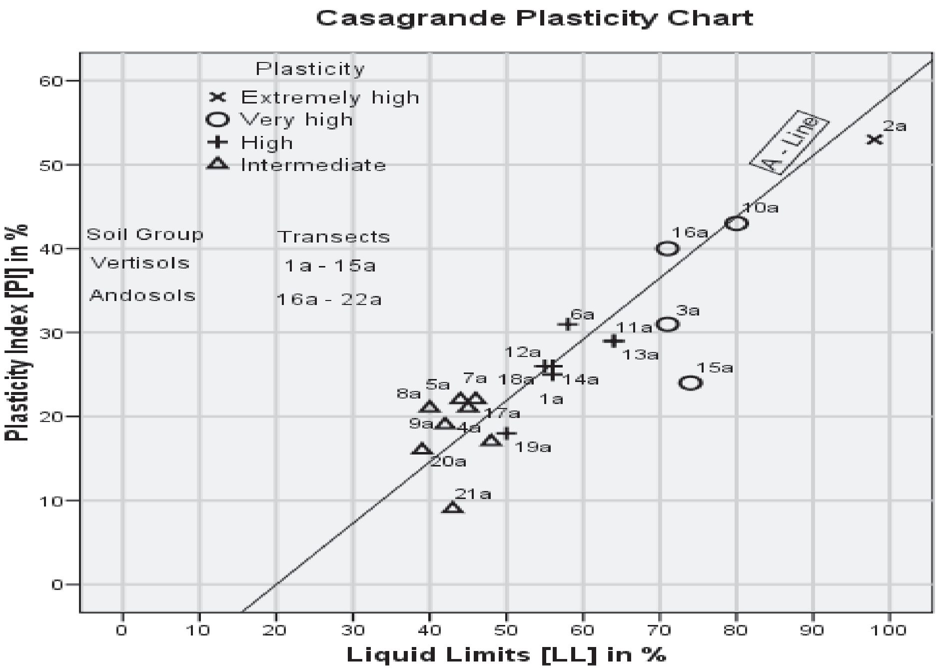


Figure 4-6 : *Casagrande plasticity chart with "A" line showing the empirical division between clayey and silty soils (Clay and silt referring the particle size)*

According to the classification of Casagrande Plasticity Chart shows the wide variability of characteristics of soil plasticity as seen the results obtained from the analysis of soil samples. The liquid limit (LL) percentage that is less than 35 % is grouped low plasticity, the values between 35 %< LL<50% is grouped under Intermediate, 50 %< LL<70% grouped under High, 70% < LL<90%

grouped under Very High and LL>90% is grouped under Extremely High Plasticity whereas LL between 0 and 20% is non plastic. Soil samples of transect 22a is non plastic class soil in addition it has not been identified its mineralogy group due to the dominant presence of quartz result in the dark appearance of soil spectra. This sample has zero liquid limits represent that it is impossible to determine the liquid limit of the given sample and is reported as Non Plastic (NP).The rest all soil samples are classified according to the degree of plasticity as seen the plasticity chart graph in figure 4-6 and table 0-1 in apex.

The soil spectra described the mineralogy group according to the spectral characteristics of soil samples that listed in table A-1 in apex. The spectral interpretation of each soil samples were grouped in to three major classes of mineralogical composition namely; Halloysite, mixture and smectite.

5. GEOPHYSICAL SURVEY RESULTS

The geophysical survey result has been plotted and mapped in stratified layer for 22 transects (see Figure B-1 & B-2 in apex). The result shows small variation of conductivity of soils in transects profile horizontally whereas the variation is significantly big enough to distinguish the conductivity value of all transects. The inverted resistivity value is exhibited by small different in all transects. In this section each geophysical survey result would be discussed and interpreted according to the soil types, moisture content, and other soil properties.

5.1. EM survey Result

The EM result obtained from Tikhonov inversion could be explained the soil conductivity of the six layers model in every 1m thickness which nearly seems the same value in stratified layer along the 15 m profile line for each transects (see figure 5-1).Remark: white colour shows the conductivity value out of range.

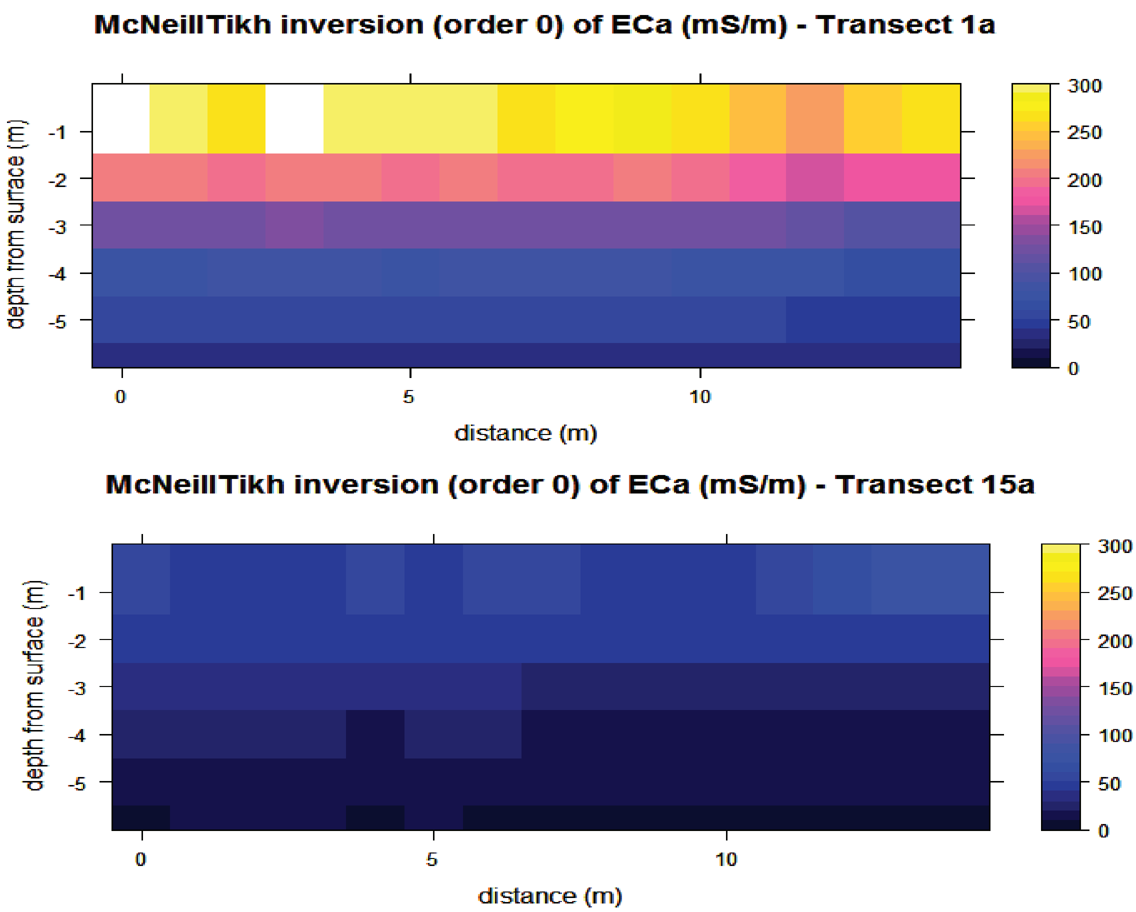


Figure 5-1: *Conductivity map of transect 1a and 15a*

As seen the map of transect 1a and 15a above, which are group of different soil types, clearly shows very big variation of conductivity between them. In general the conductivity is likely uniform along the profile but decreases in depth almost in all transects. (See the apex figure B-1 & B-2 and table A-3)

After calculating the average conductivity of the first 1m depth layer of all data points; some of nearest data points (from data points 4 -10) and exactly the data point (data point 8) where the soil samples taken were carefully analyzed of the variation, it was within 1mS/m -5 mS/m difference, finally the average conductivity value of the whole profile was taken for further analysis which would be described in soil conductivity range between 15 mS/m and 276 mS/m. The two soil type's conductivity values are clearly distinguishable for comparison, the EM result reveals the Vertisols group of soils have high conductivity values of between 89 mS/m and 276 mS/m (see figure 5-2) whereas the Andosols soil type characterizes by low conductivity values between 15 mS/m and 54 mS/m. The horizontal line in the graph is to show the boundary of conductivity of the two types of soils. The result of conductivity value difference observed in two soil types due to the moisture content that measured relatively low in Andosols whereas relatively high in Vertisols soil type.

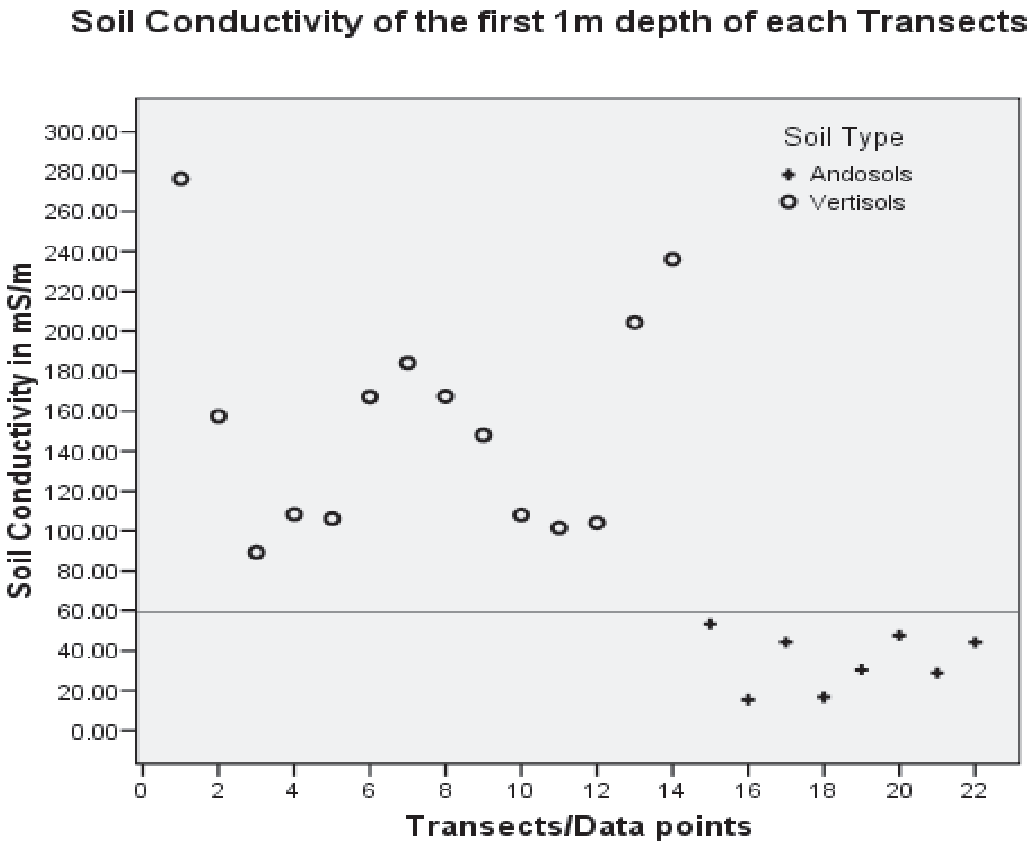


Figure 5-2: *Conductivity values of all transects in the first 1m depth*

5.2. ER survey result

ER survey result would be characterized two layers of soil resistivity values. The value recorded from inversion RES model varies from 0.8 ohm-m to 12.5 ohm-m of the first layer resistivity. The depth of each transects are different, it is not like EM result that all exactly shown 1m depth but the resistivity values are characterized different depth that is varies from 0.8 m to 2.2 m. In general the resistivity result reveals low, which could be because of the conductive properties of clay minerals and high moisture content of soil. The comparison of the two types of soils Andosols have high resistive than Vertisols. The Vertisols soils have low resistivity value of 0.8 ohm-m to 5.1ohm-m. The Andosols group of soils reveal high resistivity in comparison which is between 6.7 ohm-m and 12.5 ohm-m with few exception of soil transect 15a and 17a (indicated in figure 5-3 in circle) have relatively low resistivity i.e. 3.2 ohm-m and 4.2 ohm-meter respectively this is likely due to the presence of Allophanic minerals in the soil that derived from volcanic ash and particularly transect 15a has a characteristics of high plasticity and mineralogy group of smectite that differ it from the Andosols group of soil samples. The horizontal line in the figure 5-3 has drawn to indicate the resistive boundary between the two soil types.

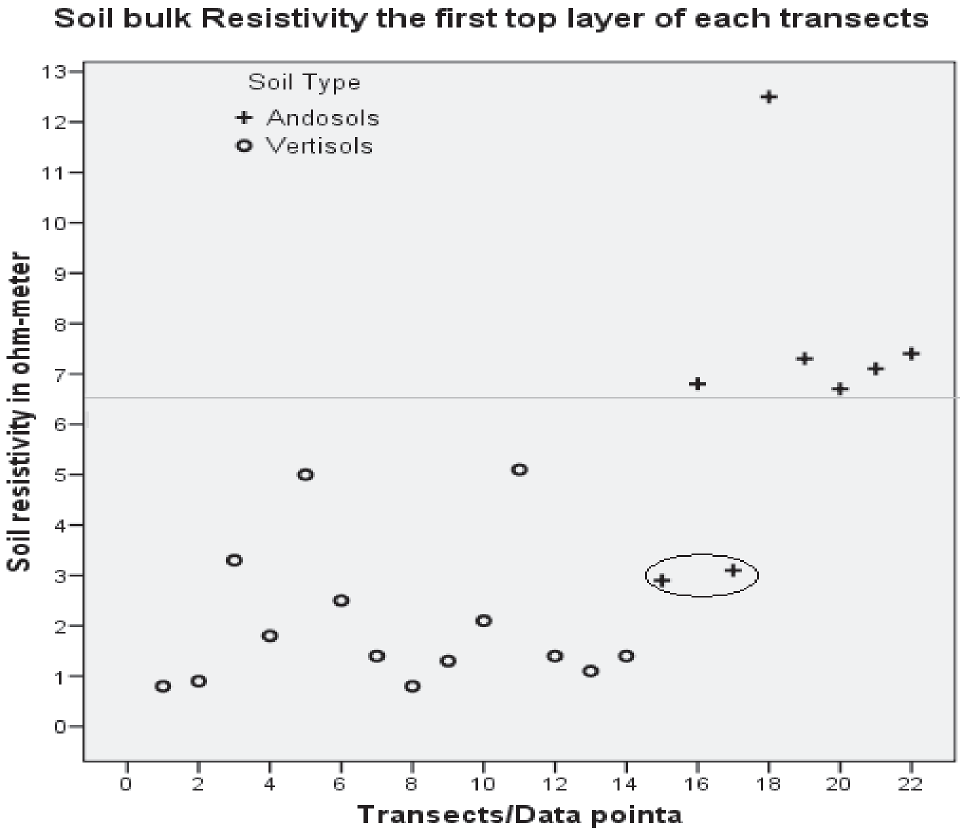


Figure 5-3: *Restivity values of all transects*

6. ANALYSING RELATIONS OF SOIL ENGINEERING PARAMETERS VERSUS GEOPHYSICAL ELECTRICAL PARAMETERS

In this section, Statistical distribution of the data set would be explored and explained the relation they have between engineering parameters and geophysical electrical parameters. To have understanding about the soil data distribution as well as the geophysical parameters, each variables are explored in numerical and graphically. SPSS and R- commander software package were used to prepare numerical and graphical statistical analyses. Plots were also used for detecting outliers, unusual observations, and influential cases.

6.1. Soil Engineering parameters

The numerical summary of soil data set would be presented in table 6.1 below. The soil engineering parameters include liquid limit (LL), Plastic Limit (PL), Plasticity index (PI), Cation exchange capacity (CEC) and soil moisture content.

Table 6-1: *Descriptive statistics summary of the five soil engineering parameters*

		Moisture Content	LL	PL	PI
Total	Mean	22.48	57.14	30.29	26.10
	Minimum	12	39	19	9
	Maximum	38	98	45	53
	Std. Deviation	8.297	15.157	6.428	9.879
	Variance	68.835	229.729	41.314	97.590

Box plots of each variable are plotted below in figure 6-1 to compare the distribution on the five–number summary which describes the median, the quartiles and the smallest and largest values of the variables would be seen so as to identify the suspected outliers. The median is marked within the box that describes the centre. The box plot graphs are also sketched in terms of their soil type. This would help to understand the variation of values respect to their soil type to compare the plasticity and the degree of expansive potential according to their soil parameters.

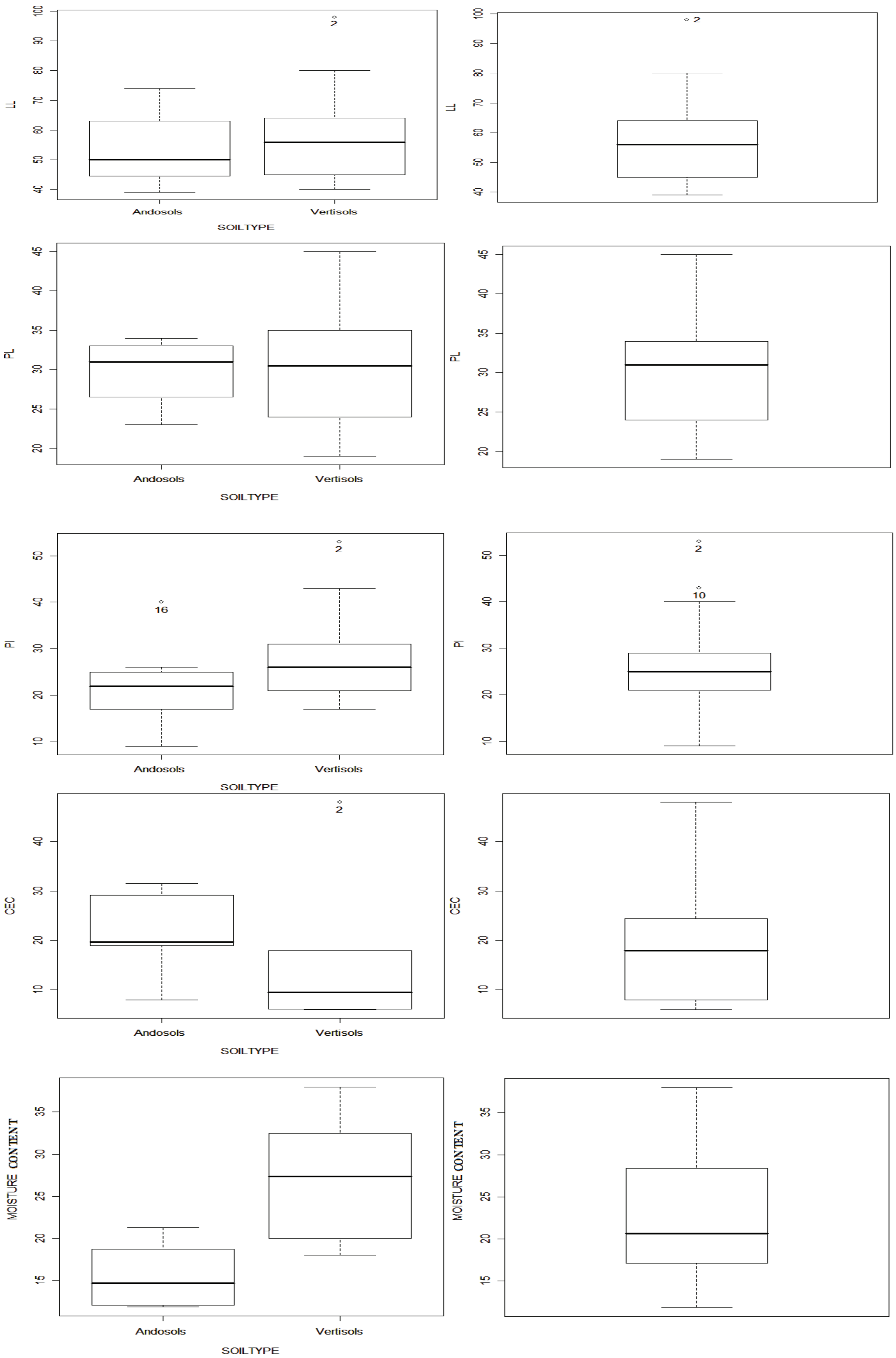


Figure 6-1: *Box plots of soil engineering parameters, Liquid limits (LL), Plasticity limits (PL), Plasticity Index (PI), Cation Exchange Capacity (CEC) and soil moisture content*

Visual inspection of box plots of soil engineering parameters as shown in figure 6-1 the values varies in range 40 % to 74 % for liquid limits; 19 % to 34 % for Plasticity limits; 17 % to 40 % for Plasticity index ; 6 meq/100 g to 31 meq/100 g for Cation exchange capacity and 12 % to 38 % for soil moisture content.

The extreme and outliers values are observed from box plots of liquid limits, plasticity index and Cation exchange capacity variables. In all three cases the extreme value observed the soil samples taken from transect 2a that be outliers. The soil sample obtained from Akaki area i.e. transect 2a is a less decomposed and silty clay residual soil. This is a fact that this sample is exhibited a high liquid limit value (98 %) indicates the expansive potential property of active clay minerals in its composition. It is also revealed a high Cation exchange capacity value (48 meq/100 g) which confirms the presence of active clay minerals in the sample [10]. This sample is extremely high plasticity and grouped smectite clay mineral. In addition the Box plot of plasticity index is showing outliers of soil samples of transect 10a, it is also consisting of less decomposed and silty clay minerals and characterized by high liquid limit (80 %) and very high plasticity. The mineral composition of this sample is group of smectite.

The distributions of almost all soil engineering parameters are approximately normal except plasticity index is not as seen from box plot and normality test. To check the normality of the distribution of soil engineering parameters Numerical Normality test (Kolmogorov-Smimov), histogram and Q-Q plots have been made. It would be useful to see the normal distribution of the variables and then those variables do not show normal distribution they were transformed using appropriate transformation method (mostly logarithmic transformation) to fulfil the linear model assumption.

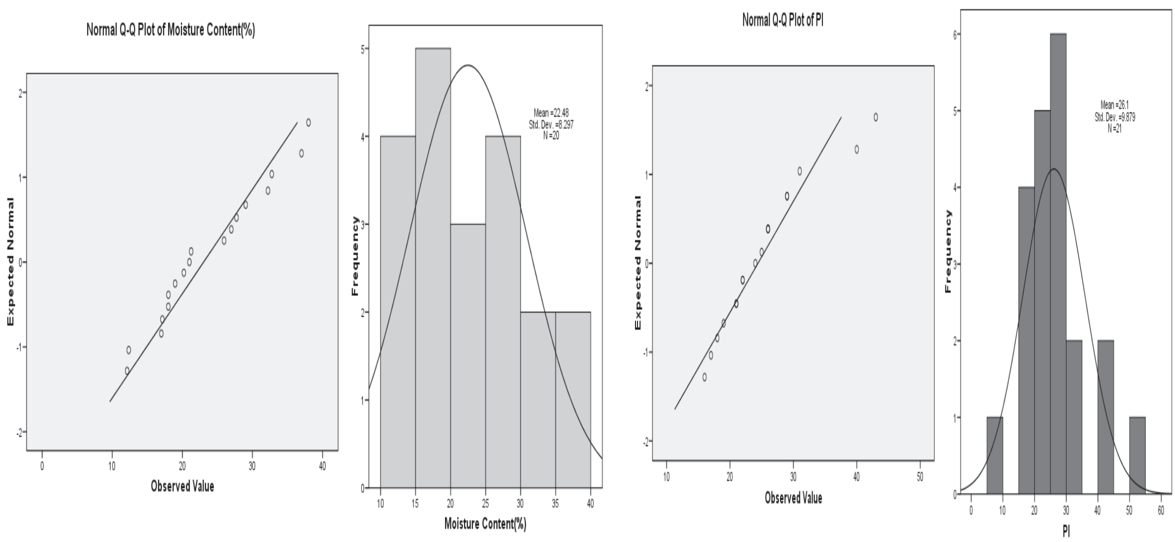


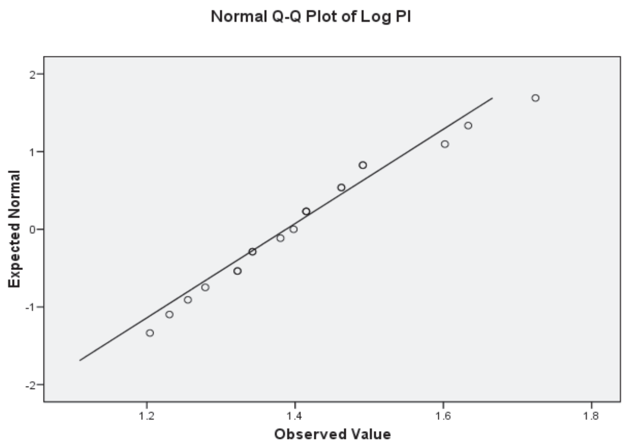
Figure 6-2: *Histogram and Q-Q plots of Moisture content and Plasticity index*

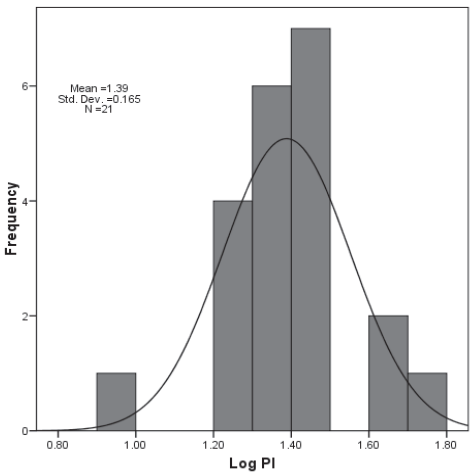
Table 6-2: *the normal test of all soil engineering parameters*

	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
LL	.149	21	.200(*)	.913	21	.063
PL	.122	21	.200(*)	.973	21	.790
PI	.171	21	.113	.921	21	.091
CEC	.191	11	.200(*)	.871	11	.081
Moisture content	.132	20	.200(*)	.960	20	.546

* This is a lower bound of the true significance.
a Lilliefors Significance Correction

The histogram of plasticity index is skewed and the Q-Q plot shows deviation from the normal. The K-S (Kolomograv-Smirvoy) statistic normality test is significant implying rejection of the assumption that the data distribution is approximately normal. The appropriate transformation method was applied to transform the data so as to fulfil the assumption of normality.





Tests of Normality

	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Log PI	.122	21	.200(*)	.962	21	.566

* This is a lower bound of the true significance.
a Lilliefors Significance Correction

Figure 6.3: *Histogram, Q-Q plots and Normality test results of Plasticity index after applying an appropriate transformation method*

The logarithmic transformation that has been applied for plasticity index variable fulfils the assumption of the data distribution approximately normal.

The plasticity characteristics of soil samples are classified in to four groups (intermediate, high, Very high and extremely high) according to increasing the extent of plasticity of soils whereas the mineralogy soil composition that obtained from spectra analyses are grouped in to three (Halloysite, Mixture and Smectite) . To have a better understanding about the plasticity and Mineralogy of soil samples, the bar graph was plotted respect to transects/data points where the soil samples obtained and represented in numbers as follows.

Plasticity

1-Intermediate

2-High

3-Very high

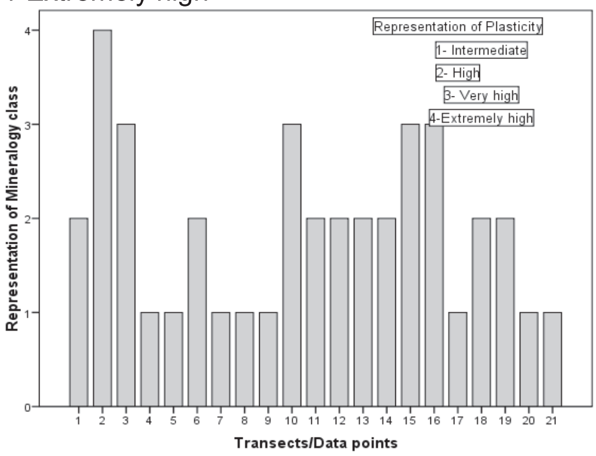
4-Extremely high

Mineralogy

1- Halloysite

2- Mixture

3-Smectite



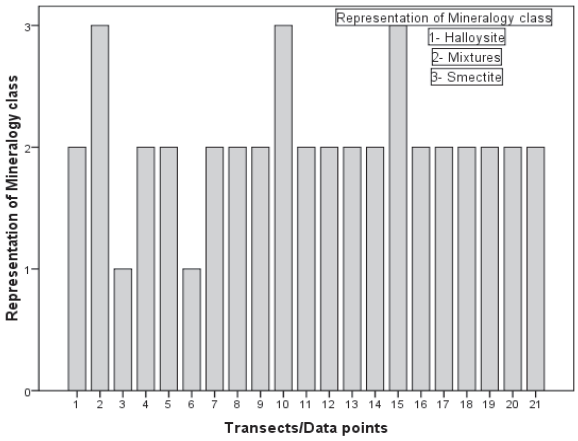


Figure 6-3: *Bar graph of plasticity and Mineralogy of soil samples Correlation analysis of soil engineering parameters*

The relation ships between different soil engineering parameters are seen in the table 6.3 that helps to understand the linear relationships between them selves.

Table 6-3: *Table showing correlation coefficients of soil engineering parameters*

	Clay fraction	LL	PL	PI	CEC
Clay fraction	1.000				
LL	.702**	1.000			
PL	.607**	.845**	1.000		
PI	.653**	.895**	.599**	1.000	
CEC	.604*	.939**	.795**	.828**	1.000

*. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The coefficient of correlation in general shows soil engineering parameters have fairly high correlation between themselves. However the soil engineering parameters are governed by the mineral composition and the amount of clay fractions [11, 17, 54] that can be present in the soil samples. Soil samples are constituent inhomogeous mixture of different amount of sand, silt and organic matter etc. This might have influence on the overall relationships between the soil engineering parameters.

6.2. Correlation between soil engineering parameters and in-situ geophysical Measurement

The physical and chemical properties of soil have an influence on the conductivity and resistivity of soil that measured in-situ. To see the extent of electrical measurements that are depend on the soil engineering parameters which have been discussed in section 6.2. Soil engineering parameters against the conductivity and resistivity of soil were plotted and the correlation coefficient would be calculated.

First let us see the relationship between conductivity and resistivity of soil that measured in-situ. It is well known that the conductivity is the inverse of resistivity which means they are negatively related.

6.2.1. Electrical conductivity and Resistivity

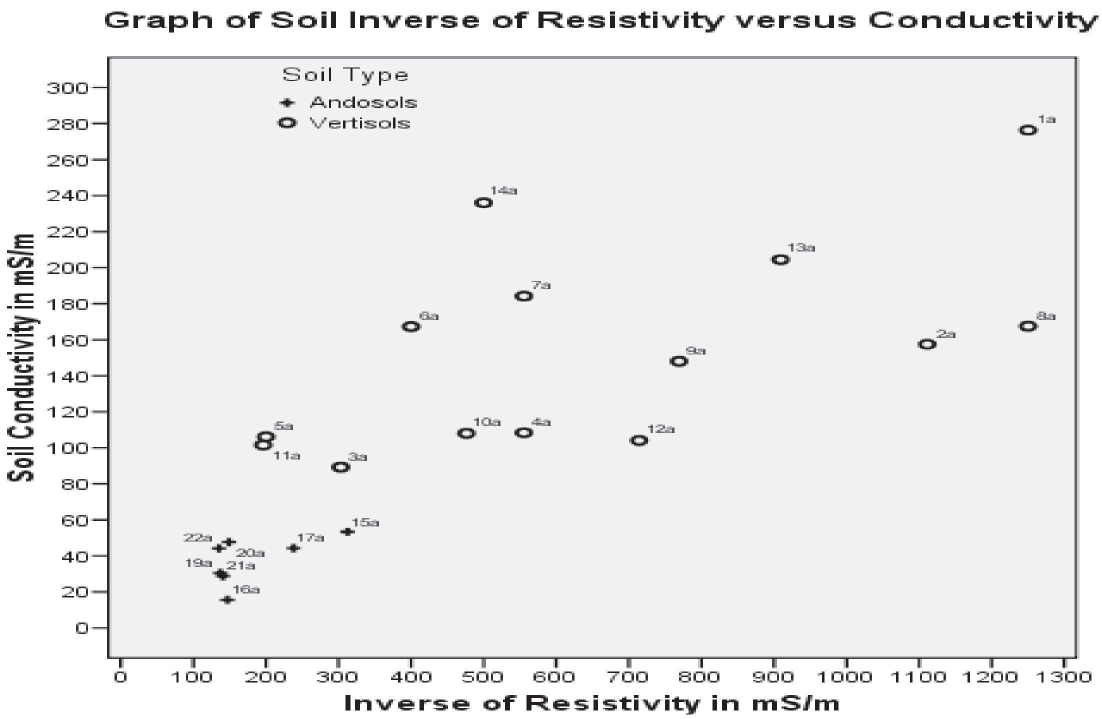


Figure 6-4 : *Inverse Resistivity versus conductivity graph*

The two soil type of Vertisols and Andosols of the study area are clearly shown the distinct value boundary for both resistivity and conductivity measurements. The relation shown in figure 6-4 depicts high conductivity (89 mS/m-276 mS/m) corresponding to low resistivity value (1 ohm-m -3 ohm-m except soil sample transect 11a shows relatively high 5.1 ohm-m) for Vertisols. Where as the conductivity is low (15 mS/m-53 mS/m) and resistivity is relatively high (6.7 ohm-m-12.7 ohm-m) for Andosols soil type. The resistivity value that observed relatively very high 12.7 ohm-m and conductivity very low (16.7 mS/m) confirmed relatively low electrical properties of sand[9] since the measurement was done at plateau of the mountain which contains more of sand that observed scattered gravel scoria in the area. The difference the geophysical result may be the effect of the physical and chemical properties between the two soil types however the primary reason could be the moisture content that observed from laboratory result indicated Vertisols contains relatively high moisture than that of Andosols during measurement taken place. Pearson correlation coefficients were calculated between Resistivity and Conductivity of soil and obtained -0.796. The linear correlation coefficient simply showing, they are negatively related and they are statistical significantly correlated (i.e. $p < 0.01$). It is well known one is the inverse of another and highly correlated but Soil apparent electrical properties are influenced by a number of factors, including soil moisture, clay content, salinity and others physical and chemical properties . The correlation between conductivity and resistivity might be influenced by these factors since the measurement were done in different areas of soil which reflects many different properties of soil even if soil group is the same type, the properties may differ.

6.2.2. Geophysical result and soil engineering parameters

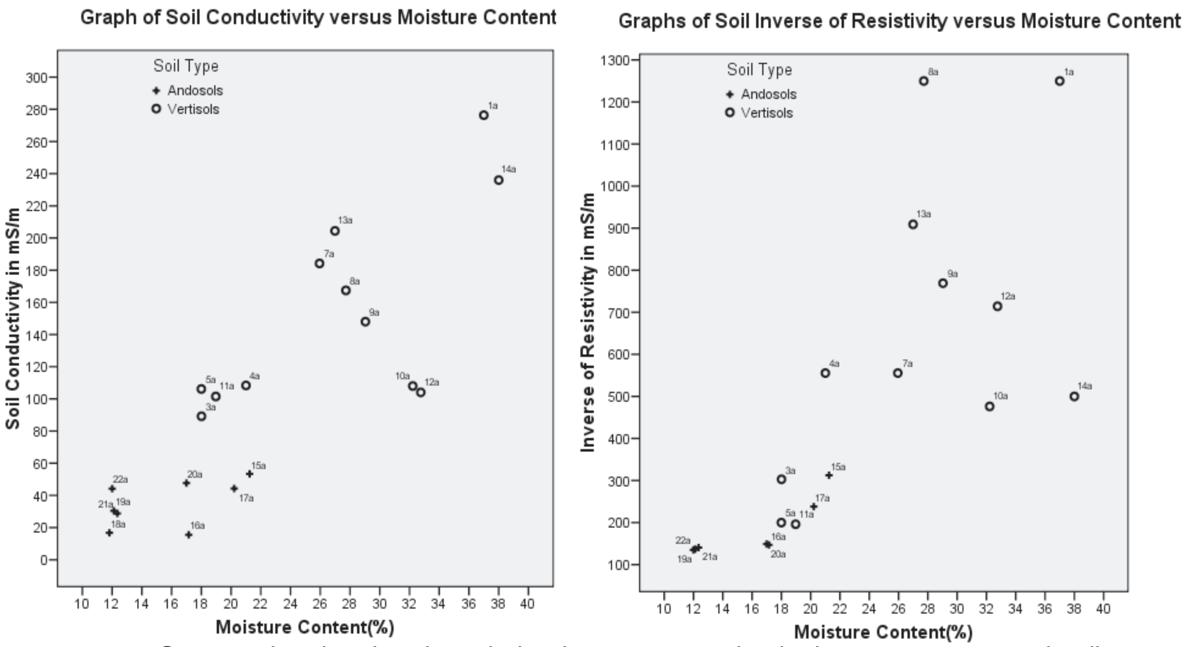


Figure 6-5: *Scatter plot showing the relation between geophysical measurement and soil moisture content*

Figure 6-5 shows the relation between geophysical measurement (conductivity and resistivity) and soil moisture content. As the moisture content increases, the conductivity of soil also increases whereas it has negative effect on resistivity measurement. This shows electrical measurement is influenced by the soil moisture content [9, 26]. In case of the two soil type, the percentage of moisture in Andosols is relatively less than that of Vertisols. Moisture content in soil could be contributed the increase of conductivity value and decrease of resistivity value. The correlation coefficient is also evident that soil conductivity has positive relation with its moisture content but negative relation with soil resistivity. Table 6.4 below shows the correlation coefficient of conductivity and resistivity versus soil moisture content is high that is 0.842 and -0.854 respectively. These confirm the geophysical measurements are significantly correlated with soil moisture content and highly influenced by soil water content.

Table 6-4 : *Table showing correlation coefficient of geophysical parameters and soil engineering parameters*

	Conductivity	Resistivity	Moisture Content	Clay fraction	LL	PL	PI	CEC
Conductivity	1.0							
Resistivity	-.796**	1.0						
Moisture Content	.842**	-.854**	1.0					
LL	.046	-.217	.139	.702**	1.0			
PL	-.032	-.048	-.063	.607**	.845**			
PI	.158	-.299	.288	.653**	.895**	.599**	1.0	
CEC	-.072	-.142	-.017	.604*	.939**	.795**	.828**	1.0

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

As can be seen the scatter plots of geophysical measurements and soil engineering parameters below in figure 6-6, it would explain that they are weakly related, the data are found widely spread in the plot. The correlation coefficient in table 6.4 depicts this fact that they have relatively very small values (i.e. CEC, LL, PL, PI have 0.072, 0.046, -0.032, 0.158 with conductivity and -0.142, -0.217, -0.048, -0.299 with resistivity respectively). The conductivity and resistivity survey result are not showing any relation with engineering parameters of soil (i.e. CEC, LL, PL, and PI).

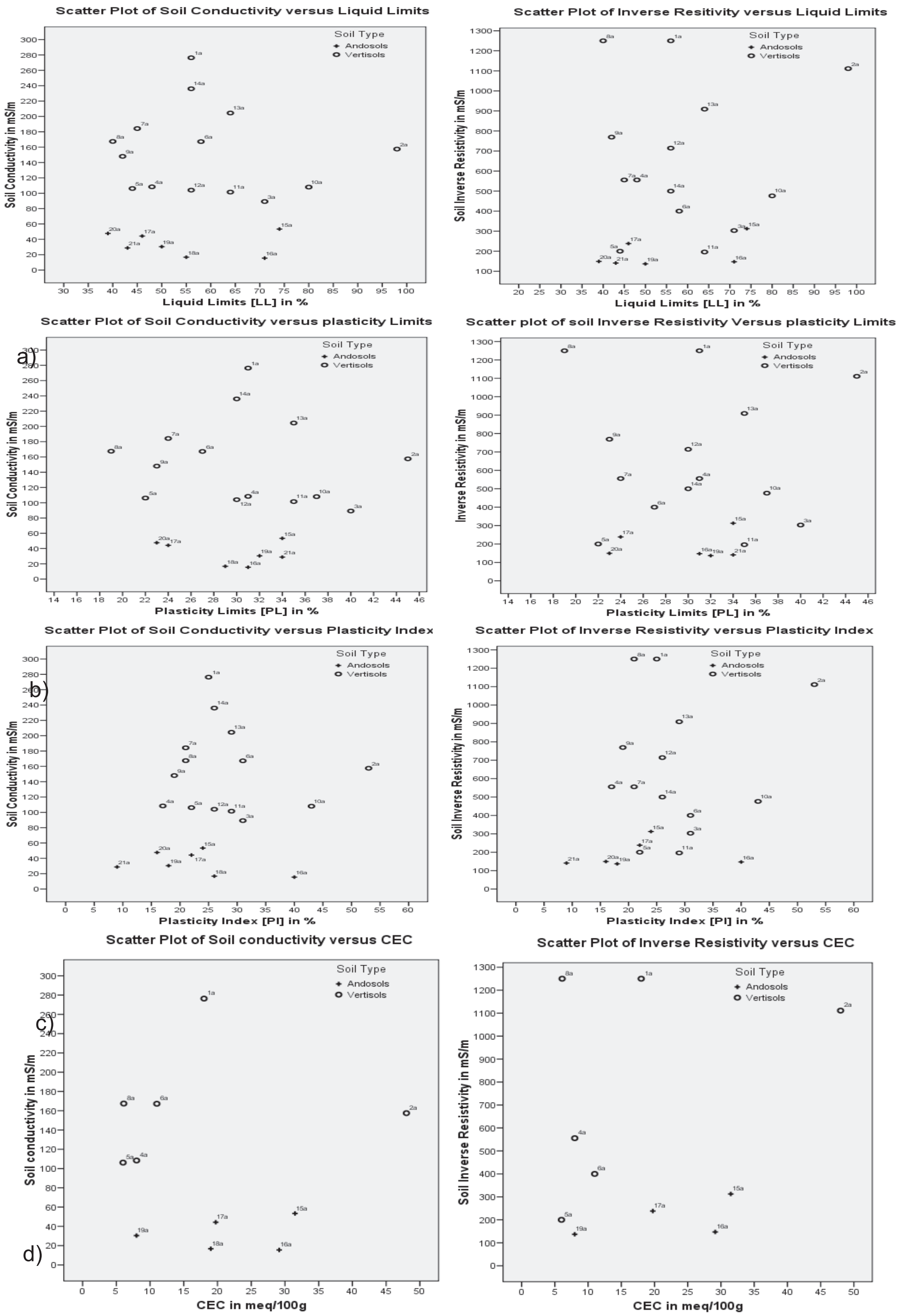


Figure 6-6: *Scatter plots of soil engineering parameters against geophysical survey results (soil conductivity and resistivity) a) with LL b) with PL c) with PI d) with CEC*

The bulk electrical properties that measured in-situ are influenced by many physical and chemical properties of soils and others factor that affecting electrical geophysical survey. Some of these factors are porosity; moisture content, clay fraction, soil grain size, concentration of dissolved electrolytes, temperature and phase state of the pore water, and amount and composition of colloids[23, 24] [42] .

Another comparison of soils properties and the Geophysical measurement (EM and ER data) are shown in figure 6-7. The soils of the study area mainly fall into two types, Andosols and Vertisols, further the soil Casagrande classification are categorized in to four, Intermediate plasticity (#1) , High plasticity (#2), Very high plasticity (#3) and Extremely high plasticity (#4).

An attempt made to see the relation between Casagrande Plasticity classification and in-situ geophysical measurement. The Casagrande soil classification does not show any relation with bulk conductivity and resistivity values. But, the geophysical data results show a good correlation between bulk soil conductivity or resistivity data and the soil types. The bulk conductivity is clearly distinguishing the soil type of Andosols and Vertisols. Andosols soil type has the bulk conductivity values between 10 mS/m and 60 mS/m whereas the Vertisols soil type is represented values between 82 mS/m and 276 mS/m. This also similarly explained by bulk resistivity data that distinguishes the two soil types with the exception of a few outliers. Andosols soil type is represented by bulk resistivity values between 6 ohm-m and 12.6 ohm-m whereas Vertisols soil type is represented by resistivity value between 1 ohm-m and 3.5 ohm-m.

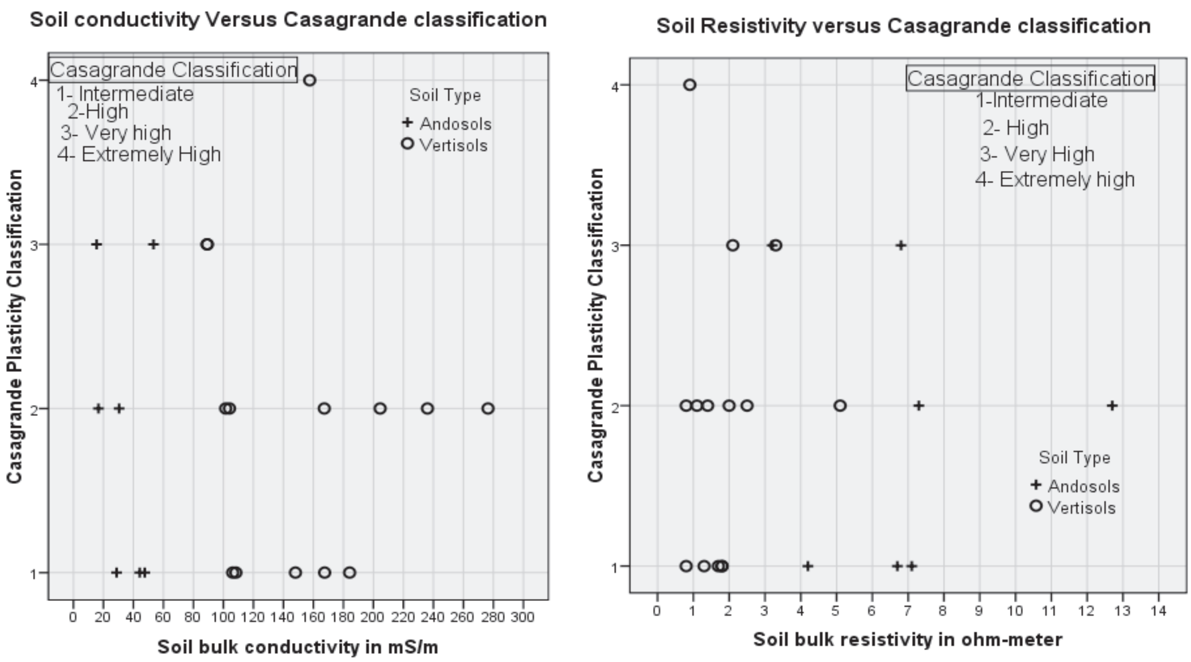


Figure 6-7: *Chart of geophysical Measurement (EM & ER data) vs. Casagrande Plasticity.*

Table 6-5 : *Table showing correlation coefficient of geophysical parameters and soil plasticity and mineralogy class*

Correlations

		Resistivity	Conductivity	Plasticity class	Mineralogy class
Resistivity	Pearson Correlation	1.000	-.796**	-.020	-.226
	Sig. (2-tailed)		.000	.931	.325
	N	22	22	21	21
Conductivity	Pearson Correlation	-.796**	1.000	-.035	-.044
	Sig. (2-tailed)	.000		.881	.849
	N	22	22	21	21
Plasticity class	Pearson Correlation	-.020	-.035	1.000	.742**
	Sig. (2-tailed)	.931	.881		.000
	N	21	21	21	21
Mineralogy class	Pearson Correlation	-.226	-.044	.742**	1.000
	Sig. (2-tailed)	.325	.849	.000	
	N	21	21	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

Table 6-5 indicates the correlation coefficients between bulk conductivity with soil plasticity and mineralogy class as well as the bulk resistivity with soil plasticity and mineralogy class. The result show the geophysical result of bulk conductivity and resistivity has weak relation with the soil plasticity and mineralogy class. It means the geophysical measurement could not be characterized as it is explained in Casagrande plasticity chart characterization , low, high , very high and extremely high plasticity in addition it could not be related with the soil mineralogy class of Halloysite, Mixture and Smectite. The table is also showing no statistical significant relation between them since the 2-tailed significance that p-value is much higher than p=0.05.

7. STATISTICAL MODEL

In previous section, Correlation tables have been made to measure the direction and the strength of the linear relationship between engineering parameters and geophysical measurements. Here a statistical model of linear regression was used to summarize the relationship between them, in specific setting when geophysical measurements (Conductivity and Resistivity) help to explain or predict the soil engineering parameters. Linear Regression estimates the coefficients of the linear equation, involving one or more independent variables that best predict the value of the dependent variable. Linear regression was used to model the value of Soil Conductivity or Resistivity based on its linear relationship to engineering parameters (LL, PL, PI, CEC and moisture content).

The linear regression model assumes that there is a linear, or "straight line," relationship between the Soil Conductivity or Resistivity variable and soil engineering parameters (LL, PL, PI, CEC and moisture content). This relationship is described general formula in the following, it works for both linear and multiple regression model.

$$y_i = b_0 + b_1 X_1 + ... + b_p X_p + e_i \qquad \text{Eq. (7-1)}$$

Where:

y_i is the value of the ith case of the outcome variable

p is the number of predictors

b_j is the value of the jth coefficient, j=0,...,p

x_{ij} is the value of the ith case of the jth predictors

e_i is the error in the observed value for the ith case (the difference between the predicted and the observed value of y for the ith case)

Note that: b_0 is the intercept, the model-predicted value of the dependent variable when the value of every predictor is equal to 0. The detail description of the linear regression model is found most statistical books [51, 55, 56].

For the purpose of testing hypotheses about the values of model parameters, the linear regression model also assumes the following:

• The error term has a normal distribution with a mean of 0.
• The variance of the error term is constant across cases and independent of the variables in the model.

• The value of the error term for a given case is independent of the values of the variables in the model and of the values of the error term for other cases.

Standardized Residual Plots and normal probability plots were made to compare the distribution of standardized residuals to a normal distribution. Summary statistics were displayed for standardized predicted values and standardized residuals (*ZPRED and *ZRESID).

7.1. Regression

The Electrical conductivity data were converted to soil properties based on linear regression [57]. Here Soil moisture content was considered to see its variation influence the conductivity of soil and the estimate parameters from Univariate regression model. Figure 7-1 depicts the linear relationship between soil conductivity and moisture content which shown the fit line of the model that described by the equation Y = 0.092 * X + 12.74, the predicted value of soil moisture content (Y) for a given value of soil conductivity (X).

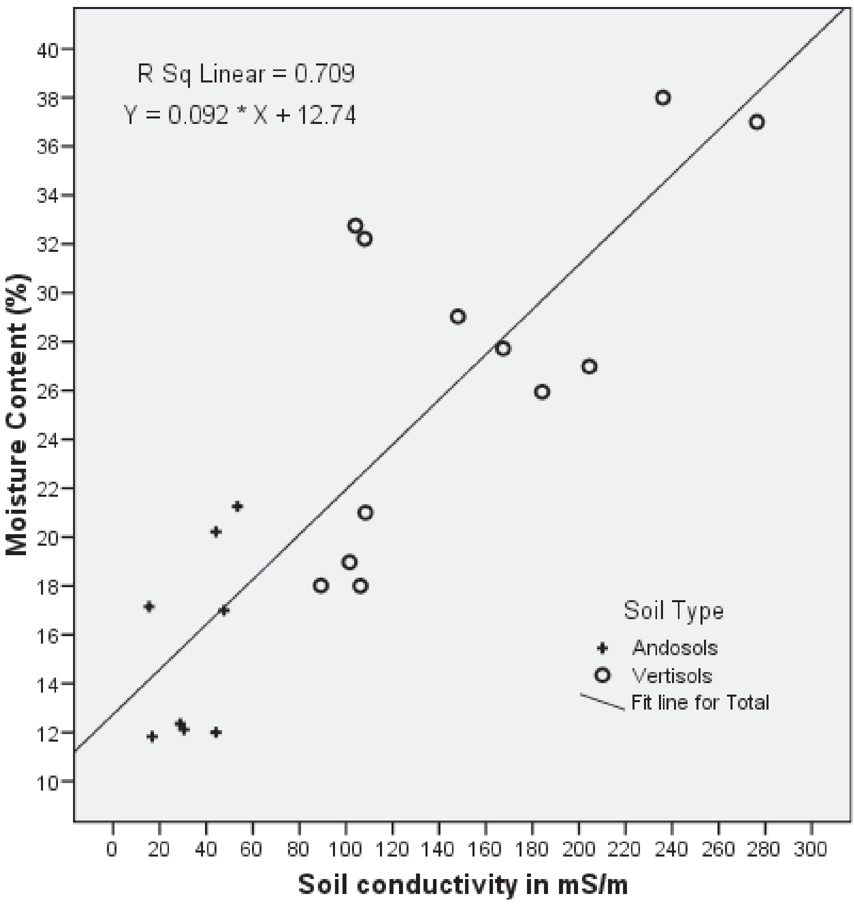


Figure 7-1: *Linear regression graph of Soil conductivity versus moisture content*

The model would estimate the standard error, which measures the variation of soil conductivity from the fit regression model line i.e. 4.6. The correlation coefficient (R=0.842) is indicated the moisture content and conductivity of soil are highly correlated and the R square (R^2 =0.709) is also indicated about 70 percent of the moisture content is explained by the variable soil conductivity.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.842a	.709	.693	4.601

a. Predictors: (Constant), bulk conductivity

The statistical test includes the ANOVA table and t-test results, The ANOVA F statistic is 43.79, with a P-value of approximately zero. Therefore, the conclusion drew from F-statistic result, the moisture content could be estimated from soil conductivity and they have high statistical significant relation. The regression coefficient for soil conductivity is statistically significant for 95 % confidence interval for p= is approximately zero i.e, < 0.005, to estimate the soil moisture content.

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	926.841	1	926.841	43.789	.000a
	Residual	380.989	18	21.166		
	Total	1307.830	19			

a. Predictors: (Constant), Bulk Conductivity

b. Dependent Variable: Moisture Content (%)

In addition, examination of the t-statistics (t= 6.61) and the associated P-values, (approximately zero, P = 000) for regression the coefficient reveals that is statistically significant to estimate moisture content from soil conductivity.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	12.710	1.796		7.078	.000
	Conductivity	.092	.014	.842	6.617	.000

a. Dependent Variable: Moisture Content (%)

Soil moisture content can also be estimating from in-situ Soil resistivity measurements; it would be shown in graphical in figure 7-2 as well as statistical result expressed in table below. The linear regression model is described in equation Y = -2.83 * X + 33.34, the negative slope shows the soil moisture has inverse relationship with the soil resistivity. The correlation coefficient (R=0.854 is indicated the moisture content and Resistivity of soil are highly correlated and the R square (R^2 =0.729) is also indicated about 73 percent of the moisture content is explained by the soil Resistivity values.

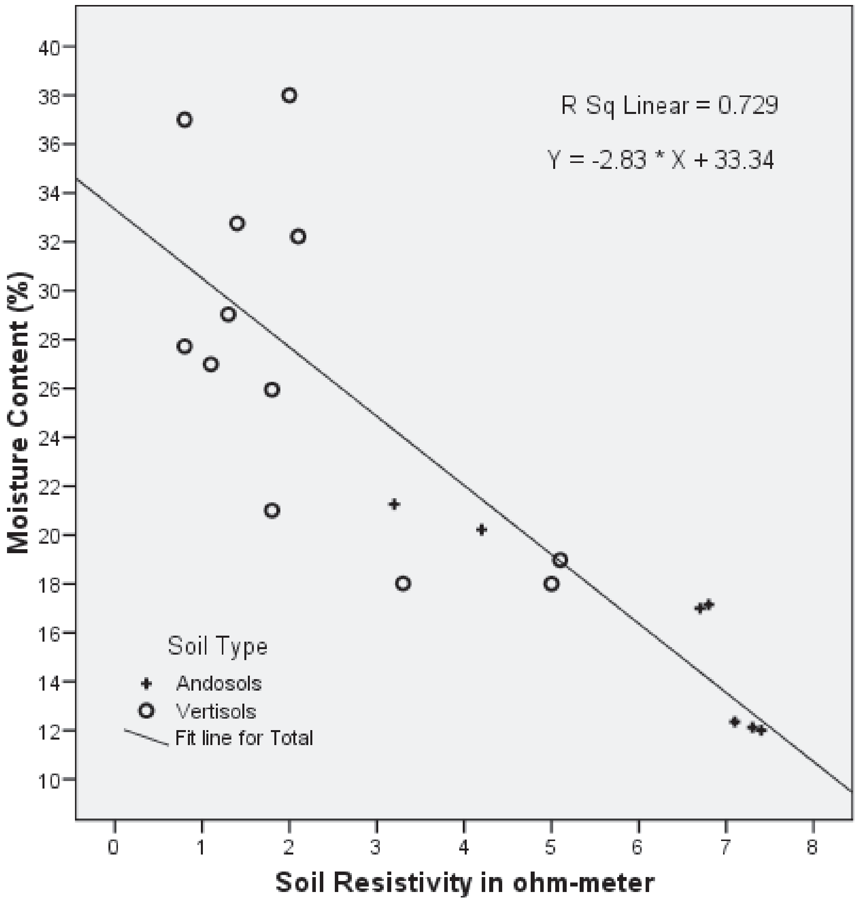


Figure 7-2: Linear Regression Graph of soil Resistivity versus moisture content

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.854a	.729	.713	4.350

a. Predictors: (Constant), Soil Resistivity

b. Dependent Variable: Moisture Content (%)

The ANOVA F statistic is 45.812, with a P-value of approximately zero. Therefore, the conclusion drew from F-statistic result, the moisture content can be estimated from soil Resistivity and they have high statistical significant relation. The regression coefficient for soil Resistivity is statistically significant for 95 % confidence interval for p= is approximately zero, to estimate the soil moisture content.

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	866.750	1	866.750	45.812	.000a
	Residual	321.632	17	18.920		
	Total	1188.382	18			

a. Predictors: (Constant), Soil Resistivity

b. Dependent Variable: Moisture Content (%)

In addition, examination of the t-statistics (t= -6.768) and the associated P-values is approximately zero, (P = 000) for regression the coefficient reveals that is statistically significant to estimate moisture content from soil Resistivity.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	33.339	1.820		18.320	.000
	Soil Resistivity	-2.828	.418	-.854	-6.768	.000

a. Dependent Variable: Moisture Content (%)

The correlation coefficient and the R square value of the linear model show very weak relation between the geophysical measurement and engineering parameters. Table 7.1 depicts the coefficient of correlation and R square of Liquid Limits [LL], Plastic Limits [PL], Plastic Index [PI] and Cation Exchange Capacity [CEC] that are very low. As the result of the statistical analysis and model shows the engineering parameters could not be estimated from the in-situ geophysical measurements of conductivity or resistivity.

Table 7-1: *Correlation coefficient and R- square of soil engineering parameters against geophysical measurements.*

Soil Engineering Parameters	Soil conductivity	
	R	R Square
LL	0.046	0.0021
PL	-0.032	0.001
PI	0.158	0.025
CEC	-0.072	0.0052

Soil Engineering Parameters	Soil Resistivity	
	R	R Square
LL	-0.217	0.047
PL	-0.048	0.0023
PI	-0.299	0.089
CEC	-0.142	0.020

7.2. Multiple Linear Regression Model

Here an attempt was made by combining all engineering parameters and geophysical measurements to construct the multiple linear regression models. The same notation and equation that described in equation 7.1 that used in the simple linear regression model. In this case, several explanatory variables such as LL, PL, PI, CEC, Moisture content used to see the response for soil conductivity and resistivity. This statistical analysis helps to examine the relationships between all pairs of variables. The model would give the Pearson correlation coefficients, the residual and P-values for the ANOVA and t-test. The model was run excluded the CEC parameters since the number of data is not equal to the rest of the soil engineering parameters which is only 11 but the rest are 22.It would help us to have better understanding of the data even though the correlation of explanatory variables do not achieve statistical significant [55]. This does not imply that it will not be a useful predicator in a multiple regression.

The model result (model Summary) reveals the correlation coefficient (0.873) and R square (0.762) that is high enough but the standard error (42.77) is not reasonable value to explain the relation between engineering parameters and conductivity.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.870a	.757	.687	42.75517

a. Predictors: (Constant), Moisture Content (%), PL, PI, LL

The ANOVA table below describes the estimated parameters. According to the distribution, the chance of obtaining an F-statistics is 10.893 and p-value approximately zero indicates that at least one of engineering parameters has high relation with the conductivity. Although the p-value is very small, the model does not explain very much the variation of conductivity.

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	79646.677	4	19911.669	10.893	.000a
	Residual	25592.062	14	1828.004		
	Total	105238.739	18			

a. Predictors: (Constant), Moisture Content(%), PL, PI, LL

b. Dependent Variable: Bulk Conductivity

The significance tests for the individual engineering parameters regression coefficients seem contradict the impression obtained by examining the correlation in t-test result table below. The statistical t-value and p-value of each soil engineering parameters do not show statistically significance to explain the relation. The p- values for LL, PL, and PI are 0.298, 0.3, and 0.788 that is much greater than α=0.05 so LL, PL and PI are not statistically significance to predict the conductivity. The soil moisture content is statistically significance that p-value is approximately zero. It is also proved the high correlation and significance test in Univariate linear regression test in section 7.1.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-60.913	62.254		-.978	.344
	LL	-3.035	2.808	-.498	-1.081	.298
	PL	4.087	3.794	.307	1.077	.300
	PI	.837	3.055	.088	.274	.788
	Moisture Content	8.463	1.325	.901	6.388	.000

a. Dependent Variable: Bulk Conductivity

The model was run again considering soil engineering parameters against resistivity, to be evaluated the possibility of estimating resistivity from several explanatory soil engineering parameters. Multiple linear regression model result (see table 7.2) showed engineering parameters (LL, PL, and PI) are very weak to predict the resistivity, the p-values indicates they are not statically significant. Except the soil moisture content is well estimated from resistivity values and the p-value is also proved it is statically significance.

Table 7-2: *the multiple linear regression model soil engineering parameters against resistivity*

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.845a	.713	.625	1.4354

a. Predictors: (Constant), Moisture Content(%), PL, PI, LL

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	66.677	4	16.669	8.091	.002a
	Residual	26.783	13	2.060		
	Total	93.460	17			

a. Predictors: (Constant), Moisture Content (%), PL, PI, LL

b. Dependent Variable: Bulk Resistivity

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	9.038	2.158		4.188	.001
	LL	-.055	.094	-.302	-.581	.571
	PL	.050	.127	.127	.396	.699
	PI	.085	.104	.297	.818	.428
	Moisture Content (%)	-.260	.048	-.876	-5.396	.000

a. Dependent Variable: Bulk resistivity

The analysis of the multiple linear regressions could not help us to draw conclusion that the pair of explanatory variables LL, PL and PI contribute nothing for the prediction in the model. It is likely due to the influence of many physical and chemical soil properties and soil forming factors, the limited number of data set as well as a few variability of soil types present to be considered. Further more, Geophysical survey was conducted at different time and about 25 m radius of the place where soil samples grab for laboratory test of engineering parameters, it might also have a contribution the weak relation. In short, the model result shows the moisture content can be predicted from soil geophysical measurement of conductivity or resistivity but the rest engineering parameters (LL, PL and PI) could not be estimated from the geophysical measurement as the Univariate and Multiple linear regression models.

8. DISCUSSION, CONCLUSIONS AND RECOMENDATION

8.1. DISCUSSION

As described the analysis and result of geophysical result against the soil physical and chemical properties in previous chapters, the electrical properties of different soil samples of 22 data points were discussed and found some relation which indicated the properties that affects the in-situ geophysical measurement. In this paper more focus given the capability of differentiating electrical properties of expansive soils. Expansive soils contain clay minerals such as smectite clays that notably characterize of the presence of Cation exchange elements (CEC) and affinity to adsorb water. These characteristics of expansive soils have an influence on the electrical properties of soils [17, 20, 46] .The geophysical survey result as shown in figure 5-2 and figure 5-3 revealed the conductivity of the expansive soils are relatively high value respect to their soil type and the resistivity of expansive soil inverse of conductivity, it shows relatively low value respect to their soil type. See table A-1 and B-1 in apex , from soil samples data points / transects 2a, 10a and 15a are expansive soils that contain clay mineral of smectite and characterized by high conductivity and low resistivity relatively respect to their soil type.

Figure 6-4 depicts the measured in-situ EM and ER are inversely proportional and shows a high correlation coefficient of -.796, see table 6.4. Both methods indicated that the moisture content has influence the in-situ electrical measurement of soil properties, it was shown in figure 7-1 and figure 7-2 soil conductivity has strong positive correlation with soil moisture of R-square coefficient of 0.709 and soil resistivity has also indicated strong negative correlation with soil moisture of R-square coefficient 0.729.This proved in many research paper the water content in soil has an influence the electrical properties of soil. However the moisture content of soil is temporally varies [26, 33].

The two type of soil Vertisols and Andosols has distinguished the conductivity and resistivity values clearly as shown in figure 5-2 and figure 5-3. The Vertisols soil type is mostly characterized by expansive soil; it is a residual soil of formed from weathering of basic parent rock of basalt[17] and the Andosols is derived from young volcanic ash[48]. The Vertisols soil has characterized by high conductivity between 89 mS/m and 276 mS/m whereas the Andosols has characterized by low conductivity between 15 mS/m and 54 mS/m. In addition the resistivity values obtained from the survey is also indicated Vertisols has relatively low values and Andosols has relatively high values.

An attempt has been made to answer the question that noted in section 1.6, in chapter 6 and 7 have shown the analysis and the result of geophysical measurements against engineering parameters. The correlation coefficients have obtained between geophysical measurement (in-situ soil conductivity and resistivity) and engineering parameters (LL, PL, PI and CEC) shown weak .Table 7-1 indicated the weak correlation coefficient between them, this may be due to the geophysical measurement characterized the bulk (volumetric) electrical properties of soil but the engineering parameters determined in laboratory characterized the intrinsic property of a small gram of soil. In addition in-situ geophysical measurement is influenced by many others physical and chemical properties of soil. As described in data acquisition section 3.2, the geophysical measurements were conducted in a radius of 25 meter and about a year before the soil sampling was grabbed for laboratory determination of engineering parameters that also contributed to the observed weak relation since the soil forming factors may affect the physical and chemical properties of soils. Figure 6-7 indicated the soil conductivity and resistivity against the representation of Casagrande plasticity class. The result in table 6-5 reveals weak correlation between geophysical measurements and major mineralogy class of the soil samples; Halloysite, Mixtures and Smectite and the coefficient between geophysical measurement and Casagrande plasticity class is also weak. The poor relation might be due to the above mentioned reasons.

The weak relation was unexpected between the geophysical measurements and Cation exchange capacity (CEC) since the presence of CEC in clay soils have influence the measured electrical properties of soils. The result found that shows poor correlation may not expressed the reality due to the number of soil samples considered particularly for CEC is very small that is only 11 soil samples and the above noted reasons also contributed much to this result because the chemical properties of soil is much affected greatly by temporal change , temperature and other factors.

Figure B-1 and Figure B-2 in apex show the soil conductivity map of each transects, the map depicts the spatial and the vertical variation of soil conductivity in addition the overall change of the soil conductivity among each transects. This would provide information to the geo-engineer about the conductivity variation laterally and in depth to characterize soil respect to their soil type to determine the boring location for further laboratory analysis. This would help to a better understanding about the expansive soils and to proper planning, design engineering works and which measure should be taken to minimize the damage caused by the swelling and shrinkage property of clay soils.

8.2. CONCLUSION

Geophysical methods such as electrical resistivity and electromagnetic methods have been commonly used by Geophysicists and Geo-engineers to successfully map soil in unconsolidated sediments. The geophysical data results have shown that soil samples typically have lower electrical resistivity between 1 ohm-meter and 12.5 ohm-meter (see table B-2 in apex). However, soil samples also exhibit a wide range in electrical conductivity between 15 mS/m and 276 mS/m. In particular, swelling clays have a higher capacity for ion exchange, which results in much lower measured resistivity than non-swelling clays. Swelling soil sample of transects 2a and 10a are characterized relatively with high conductivity and low resistivity among from their Vertisols soil type, they are smectite group of high swelling potential. Soil sample of Transect 15a is also group of smectite that characterized relatively high conductivity and low resistivity comparing among their group of Andosols soil.

Interpretation of EM data and ER data qualitatively have distinguished stratified soil thickness layer at different depth. Both geophysical methods have shown a distinctive boundary of resistivity and conductivity values for two types of soil. Andosols soil type has characterized with relatively very low bulk conductivity and very high resistivity range compare to that of Vertisols soil type.

The response of conductivity has been used to accurately predict the depth of topsoil layer that has been applied to relate engineering parameters that determines soil samples of the first top soil layer exactly at 1m depth. However the response of resistivity has not been predicted the topsoil layer as exactly as the depth of our interest, it could estimate the first bulk resistivity of topsoil layer varies from 0.8 to 2.3 meter. The geophysical survey result has provided more detailed information about the spatial electrical characteristics of the study area. As stated earlier, the results from geophysical measurements indicated that mapping for the lateral extent of clay is a readily available and interpretable result obtained directly from the bulk conductivity measurements.

From the processing and interpretation of all the EM data, a prediction was made that the broad areas of high bulk conductivity are attributable to high soil moisture content particularly swelling soil potential content of soil type of Vertisols and low bulk conductivity are corresponding to relatively low soil moisture content for Andosols soil type in 1m topsoil depth. High correlation coefficient and R-square (R=0.842, R^2 =0.709) between soil bulk conductivity and moisture content. It is also observed high correlation coefficient and R-square(R= -0.854, R^2 =0.729) between bulk resistivity and soil moisture content. It should be noted however, that apparent conductivity values may be affected by increased salinity content in the interstitial water, changes in water content, or the presence of metallic debris buried under beneath the surface. These fields had different electrical conductivity measurements, but these differences were due to soil water content and not much due to soil properties particularly engineering parameters. A good correlation between soil conductivity and moisture content was expected since the result indicted that the electrical conductivity variation is most influenced by the amount of water in the soil during measurements.

Interpretation of these results suggest that the primary correlation between soil conductivity and the soil properties typically measured for geotechnical analysis of a soil are not related to the LL, PL, PI and CEC of the soil it has a weak correlation coefficients of R-square (R^2=0.0021, 0.001, 0.025 and 0.0052 respectively with bulk conductivity and also R^2=0.047, 0.0023, 0.089 and 0.02 respectively with bulk resistivity, see table 7-1). However, the correlation between soil conductivity and soil CEC (from the lab samples) has been found poor was unexpected since In clay soil, the electrical charges located at the surface of the clay particles lead to greater electrical conductivity because of the magnitude of the specific surface area and mobile electrical charges[58]. In addition, this is most likely due to the limited and less variable number of swelling soil presence in analysed soil samples that do not sufficient to compare the relation and draw a conclusion. A weak correlation is shown between soil electrical survey result and LL, PL, PI and CEC this is due to electrical measurement data is measuring a larger volume of material than the soil boring grab sample. It means the electrical geophysical survey results (EM & ER) are sensitive to bulk property changes, which directly or indirectly affect many different soil properties such as humus content, soil mineral composition, amount of soluble salts, water content, temperature, CEC, particle size distribution, arrangement of voids (porosity, pore size distribution) and etc. Hence the electrical measurement has shown weak correlation coefficient with engineering parameters of LL, PL, PI and CEC. Table 7-1 presents a summary of the correlation of coefficients comparing Atterberg Limits of soils with electrical properties. As shown in the table, none of the attributes correlate strongly.

ADVANTAGES OF ELECTRICAL GEOPHYSICAL SURVEY

However, a strong correlation between soil conductivity and the engineering soil parameters were not established, Electrical geophysical surveys (EM & ER) provide advantages over the traditional soil sampling alone (e.g. augering and excavation).

- EM method is quick and non-invasive means of measuring soil conductivity that able to survey large and continuous length of study area efficiently and effective cost.
- Soil EC is one of the simplest, least expensive soil measurements available for Hydrology, Agriculture and engineering purposes. In addition, Soil EC measurement can provide more measurements in a shorter amount of time than traditional grid soil sampling techniques.
- Currently, the available EM inversion modelling software, like McNeill and Tikhonov Inversion are good to easily capable of Processing EM data and obtained estimated conductivity of soil at different layer depth as required from inversion result.
- Electrical resistivity prospecting is a very attractive method for soil characterisation.
- Electrical resistivity permits the delineation of the two soil types that is 0.8-3.3 ohm-meter for Vertisols and 3.2 - 12.5 ohm-meter for Andosols and EM also permits the delineation of the two soil types that is 8-45 mS/m for Andosols and 89-276 mS/m for Vertisols (see figure 5-2 and figure 5-3) [59].
- Electrical prospecting can be applied within a large range of scales by adjusting the inter-electrode spacing. From the macroscopic to field scale, the measurements can be done without limitation and provide useful information. In this way, there is greater flexibility in the volume of soil that may be investigated.
- The sensitivity of the electrical resistivity measurement is spread over a wide range depending on the soil physical properties.
- From the geophysical survey result EM and ER surveys could provide an efficient means to map the spatial distribution (laterally and vertically) of soil conductivity.

Therefore, EM and ER are sensitive to bulk changes and but can be used to guide soil-boring locations to reduce overall cost because Electrical geophysical method can provide information of large area about the lateral and vertical conductivity and resistivity variation of the soil and offers complete data coverage between planned soil boring locations.

8.3. RECOMMENDATION

The results that have been obtained, sofars have not created confidence to say the geophysical techniques that are not capable of estimating engineering parameters. This is due to the geophysical measurement have not been done exactly at point where soil samples taken for laboratory test of soil engineering parameters. The author suggested the following noted points below to be considered and the approach also reviewed to come up to the final conclusion.

- The number of Soil Samples collected and analyzed should be large enough and the variability of soil types should be many enough to compare and to study in depth.

- The soil sampling and geophysical measurement had better to carry out at the same time in different seasons to see the temporal variation of electrical properties of soil and then relate with Atterberg limits and other soil properties.

- In addition to soil engineering parameters those considered in this study, the amount of clay content (often consists of essentially clay minerals) and the particle size or fraction of gravel, sand, silt, and clay if known, it would be better to associate with the electrical properties and to analyze in wide comparing with others soil properties. Since these soil properties are influencing much directly and indirectly the in-situ geophysical electrical properties.

- It is well known that the geophysical measurement provide the volumetric weight property of soil so that it would be recommended to include the laboratory measurement of resistivity and conductivity of soil samples to see the relation under certain controlled conditions.

- The approach to get answer for this research question might be needed some systematic techniques to be adopted. After conducting geophysical survey along the transect line, It would be better soil sampling proceeded at different depth such a way that from top surface to a certain depth (let be 3m) by digging pit dimension grid (let be 2*3 m) to see the variation of soil and to log the soil characteristics at different layer depth and then again conduct geophysical survey at different depth at the same day of soil sampling.

- In any attempt to correlate soil electrical properties with annual moisture content, attention should be given to seasonal fluctuations. The seasonal distribution pattern assumes the status of an additional independent variable or soil forming factors.

- It is important that taking a deep soil sample or compaction measurement at a few points in each field. Soil physical characteristics and moisture measurements will aid in interpreting what is causing soil electrical property variations. The sampling should be done at the same time as soil EC & ER data are collected.

References

1. *Rhoades, J.D., S.M. Lesch, P.J. Shouse and W.J. Alves New Calibrations for determining soil electrical conductivity-depth relations from electromagnetic measurements Soil Sci Soc Am J, 1989.* ***53****: p. 74-79.*
2. *J. Glenn Davis, N.R.K., Kenneth A. Sudduth and Scott T. Drummond, Using Electromagnetic Induction to Characterize Soils.*
3. *Kachanoski, R.G., Gregorich,E.G., and Van-Wesenbeeck, I.J., Estimating spatial variations of soil water content using non contacting electromgnetic inductive methods. Can.j.Soil Sci., 1988.* ***68****: p. 715-722.*
4. *Kachanoski, R.G., De Jong, E., and Van-Wesenbeeck, I.J., Field scale patterns of soilwater content storage from non-contacting measurements of bulk conductivity. Can.j.Soil Sci., 1990.* ***70****: p. 537-541.*
5. *Banton, O., Seguin, M. K., and Cimon, M. A., Mapping field scale physical properties of soil with electrical resistivity. Soil Sci. Soc. of Am. J., 1997.* ***161****: p. 1010-1017.*
6. *Jaynes, d.b., Novak, J. M., Moorman, T.B.,and Cambardella, C. A., Estimating herbicide partition coefficients from electromagnetic induction measurements. J. Environ Qual., 1990.* ***24****: p. 36-41.*
7. *Williams, B.G., and Hoey, D., The use of electrical induction to detect the spatial variability of the salt and clay contents of soils Australian Journal of Soil Research, 1987.* ***25****: p. 21-27.*
8. *Kiberu, J., Induced polarization and resistivity measurements on a suite of near surface soil sampless and their empirical relationship to selected measured engineering parameters. 2002, ITC: Enschede. p. 118.*
9. *Keller, G.V. and F.C. Frischknecht, Electrical methods in geophysical prospecting. (International series in electromagnetic waves ; 10). 1966, Oxford etc.: Pergamon Press. 523.*
10. *Fekerte, A.Y., Spectroscopy to derive engineering parameters of expansive soils. 2006, ITC: Enschede. p. 104.*
11. *Kariuki, P.C., Spectroscopy and swelling soils: an integrated approach. 2003, PhD thesis: Enschede, The Netherlands, ITC.*
12. *van der Meer, F., Can we map swelling clays with remote sensing? International Journal of Applied Earth Observation and Geoinformation, 1999.* ***1****(1): p. 27-35.*
13. *J. Glenn Davis, N.R.K., Kenneth A. Sudduth and Scott T. Drummond, Using Electromagnetic Induction to Characterize Soils. 1997.* ***N0. 4****.*
14. *Vinegar, H.J., Induced polarization of shaly sands. Geophysics, 1984.* ***49(8)****: p. 1267-1287.*
15. *Alain Pascal, F.s., Spatio - temporal groundwater recharge assessment : a data - integration and modelling approach. 2008, ITC: Enschede. p. 57.*
16. *O'Flaherty, C.A., Highway Engineering. 2 nd Edition ed. Vol. Vol 2. 1974, London: edward Arnold Ltd.*
17. *Chen, F.H., Foundation on expansive soils. Elsevier, 1998.*
18. *Schuffelen, A.C., The cation exchange system of the soil. 1972(In Potassium Soil. Berne): p. 75-88.*
19. *Kariuki, P.C., T. Woldai, and F.D. van der Meer, Effectiveness of spectroscopy in identification of swelling indicator clay minerals. International journal of remote sensing, 2004.* ***25****(2).*

20. *Pozdnyakov, L.A., Electrical properties of soils. 1999: p. 175.*
21. *Day, R.W., Soil Testing Manual:Procedure, Classification Data , and sampling Practices. 2001.*
22. *Verhoef, P.N.W., The Methylene Blue Adsorption Test Applied to Geo-materials. Delft ,Delf University of Technology, 1992.*
23. *Reynolds, J.M., introduction to applied and environmental geophysics. 1997, Chichester etc.: Wiley & Sons. 796.*
24. *Parasnis, D.S., Principles of applied geophysics. Third edition ed. 1979, London etc. ; New York etc.: Chapman & Hall ; Wiley & Sons. 275.*
25. *McNeill, J.D., Electromagnetic terrain conductivity measurement at low induction number. Geonics, 1980.* ***TN-6****(Ontario-Canada).*
26. *Telford, W.M., L.P. Geldart, and R.E. Sheriff, Applied geophysics. Second edition ed. 1990, Cambridge: Cambridge University Press. 770.*
27. *Borchers, B., T. Uram, and J. M. H. Hendrickx Tikhonov regularization of electrical conductivity depth profiles in field soils Soil Sci Soc Am J, 1997.* ***61****: p. 1004-1009.*
28. *Sudduth et al., Electromagnetic induction as a soil productivity index. Agronomy journal 95:472-482, 1997.*
29. *Lesch, S.M., et. al, spatial prediction of soil salinity using electromagnetic induction techniques: Statistical prediction models. Water resource Res. 31:373-386, 1995a.*
30. *Lesch, S.M., et. al, Spatial Prediction of soil salinity using electromagnetic induction techniques: An efficient spatial algorith suitable for multiple linear regression model indentification and estimation. Water resource. Res. 31:387-398, 1995b.*
31. *Doolittle, J.A., et.al., Estimating depths to claypans using electromagnetic induction methods Soil Water Conserv. 49(6):572–575. , 1994.*
32. *Kitchen, N.R., et.al. , Soil electrical conductivity as a crop productivity measure for claypan soils. J. Prod. Agric. 12:607–617. , 1999.*
33. *Drummond, K.A.S.a.S.T., Soil electrical conductivity as a crop productivity measure for claypan soils. J. Prod. Agric. 12:607–617, 1999.*
34. *Israil and Pachauri, Geophysical characterization of a landslide site in the Himalayan foothill region. Journal of Asian Earth Sciences 22 (2003), , 2003: p. 253-263.*
35. *Cosenza et al., Correlations between geotechnical and electrical data: a case study at Garchy in France. Journal of Applied Geophysics 60 (2006), , 2006: p. 165–178*
36. *Samouëlian et al., Electrical resistivity survey in soil science. a review, Soil & Tillage Research 83 (2005), , 2005: p. 173-193.*
37. *Walker, C.a., Depth Profiles of Electrical Conductivity from Linear Combinations of Electromagnetic Induction Measurements. Soil Sci Soc Am J 56:1015-1022 1992.*
38. *Borchers, B.e.a., Tikhonov regularization of electrical conductivity depth profiles in field soils. Soil Science Society of America Journal 66:673-685, 1997.*
39. *Rhoades, J.D.e.a., Determining soil elaectrical conductivity-Depth relations using an inductive electromagnetic soil conductivity meter. Soil Sci Soc Am J 45:255-260, 1981.*
40. *Hendrickx, J.M.H., et.al., Inversion of soil conductivity profiles from electromagnetic induction measurements: theory and experimental verification. Soil Science Society of America Journal 66:673-685., 2002.*
41. *Vervoort, R.W.a.A., Y.L., palaeochannels in Northern New South Wales: Inversion of electromagnetic induction data to infer hydrologically relevant stratigraphy. Australian Journal of Soil Research, 2006.* ***44 (1)****: p. 35-45.*

42. *Chabrillat, S., et al., Use of hyperspectral images in the identification and mapping of expansive clay soils and the role of spatial resolution. Remote Sensing of Environment, 2002.* ***82****(2-3): p. 431-445.*
43. *Mengesha, M.T., Geological Map of Ethiopia. 1996.*
44. *AAU, Soils of the Bole area, Engineering characteristics of soils of Addis Ababa, Addis Ababa. 2004.*
45. *Berhanu, D., The Vertisols of Ethiopia. Their properties, Classification, Management, World soil Resources Reports, 1983(FAO): p. p. 31-54.*
46. *Singh, A., Soil Engineering in Theory and Practice. 1967.*
47. *Morin, W.J., and Parry, W.T, Geotechnical properties of Ethiopian Volcanic Soils. Geotechnique, 1971.* ***Vol. 21, No. 3****.*
48. *Allbrook, R.F., The effect of allophane on soil properties. Applied Clay Science, 1985.* ***1****(1-2): p. 65-69.*
49. *Hendrickx, e.a., Inversion of soil conductivity profiles from electromagnetic induction measurements. Soil Science Society of America Journal 66:673-685, 2002.*
50. *EM31-D operating Manuals : set - up and operating procedure for the EM31-D terrain conductivity meter. COPY. 1984, Mississauga: Geonics Limited. 65.*
51. *Till, R., Statistical methods for the earth scientist : an introduction. 1974, London etc.: MacMillan. 154.*
52. *Vander Velpen, B.P.A., RESIST: a computer processing package for DC resistivity interpretation for the IBM PC and compatibles. 1988, ITC: Delft. p. 300.*
53. *de Groot hedlin, C., and Constable, S.,, Occam's inversion to generate smooth , two dimensional models from magnetotelluric data. Geophysics, 55, 1613-1624, 1990.*
54. *Perloff, W.H., and Baron, W., Soil mechanics Principles and Applications. 1976.*
55. *Moore, D.S., Introduction to the practice of statistics. Fifth edition ed. 2006, New York: Freeman. 800.*
56. *Marsal, D., Statistics for geoscientists. 1987, Oxford etc.: Pergamon Press. 176.*
57. *Odeh I, M.A., chittleborough DJ,, Further results on prediction of soil properties from terrain attributes:heterotropic cokriging and regression kriging. Geoderma 67, 1995: p. 215-226.*
58. *M. Fukue, T.M., H. Horibe and N. Taya,, The micro-structure of clay given by resistivity measurements Eng. Geol.* ***54*** *(1999), p. 43–53*

59. *Samouëlian, A., et al., Electrical resistivity survey in soil science: a review. Soil and Tillage Research, 2005.* ***83****(2): p. 173-193.*

Appendices

Appendix A: Summary of the laboratory results of four engineering parameters (Provided Data set)

Table A-1 Soil engineering parameters that provided by Fekerte Yitagesu

No./ID	Transect	X	Y	LL	PL	PI	CEC	Plasticity	Mineralogy
AK01	1a	479769.28	977880.63	56	31	25	18	high	Halloysite
Ak02	2a	480263.66	977955.56	98	45	53	48	Extremely high	Smectite
DK01	3a	489896.03	973746.19	71	40	31	.	very high	mixture
DK02	4a	490216.78	973362.63	48	31	17	8	Intermediate	Halloysite
DK03	5a	490546.88	972987.50	44	22	22	6	Intermediate	Halloysite
DK04	6a	490947.69	972690.75	58	27	31	11	high	mixture
DK05	7a	491409.47	972502.44	45	24	21	.	Inter	Halloysite
GD01	8a	497968.50	972945.50	40	19	21	6	Inter	Halloysite
GD02	9a	498447.91	972805.63	42	23	19	.	Inter	Halloysite
GD03	10a	499948.66	971540.00	80	37	43	.	Very high	Smectite
GD04	11a	500167.50	971091.06	64	35	29	.	high	Halloysite
GD05	12a	500351.13	970626.00	56	30	26	.	high	Halloysite
GD06	13a	500534.75	970160.94	64	35	29	.	high	Halloysite
GD07	14a	500693.81	969687.31	56	30	26	.	high	Halloysite
Naz01	15a	522236.13	946080.88	74	34	24	31	Very high	Smectite
Naz02	16a	522512.22	945665.63	71	31	40	29	Very high	Halloysite
Naz03	17a	522848.63	944724.63	46	24	22	20	Intermediate	Halloysite
Naz04	18a	523008.91	944251.00	55	29	26	19	high	Halloysite
Naz05	19a	523169.19	943777.38	50	32	18	8	high	Halloysite
Naz06	20a	523329.47	943303.75	39	23	16	.	Intermediate	Halloysite
Naz07	21a	523522.53	942843.13	43	34	9	.	Intermediate	Halloysite
Naz08	22a	523789.06	942420.81	.	.	.	.	NP	quartz
22	22	22	22	21	21	21	11	22	22

Table A-2 Soil sample weight of wet and dry and determined its moisture content

Area ID	Transect	Container No	Container Wt. (gm)	Cont. Wt + Wt. of wet Soil(gm)	Dry Soil Wt. + Container (gm)	Wt. Dry soil (gm)	wt. of water (gm)	moisture content (%)
AK01	1a	AQ	39.5	175.4	138.6	99.1	36.8	37.13
		MA	38.9	162.9	127.4	88.5	35.5	40.11
DK01	3a	M-4	39.9	196.1	172.4	132.5	23.7	17.89
		MP	38.7	194.4	170.5	131.8	23.9	18.13
DK02	4a	AC	38.6	185.3	158.7	120.1	26.6	22.15
		MA	38.9	192.2	166.8	127.9	25.4	19.86
DK03	5a	BL	38.5	195.2	170.9	132.4	24.3	18.35
		MF(red)	38.4	183.2	160.4	122	22.8	18.69
DK05	7a	C-2	38.7	193.5	161.4	122.7	32.1	26.16
		MJ	39.6	188.6	158.1	118.5	30.5	25.74
GD01	8a	MX	38.3	180.4	149.4	111.1	31	27.90
		ML	38.8	173.1	144.1	105.3	29	27.54
GD02	9a	RB	38.9	176.1	146.3	107.4	29.8	27.75
		MC	38.3	173.7	142.2	103.9	31.5	30.32
GD03	10a	PE	38.3	179.3	145.2	106.9	34.1	31.90
		A-3	38.9	172.5	139.7	100.8	32.8	32.54
		PQ	39	172	142.3	103.3	29.7	28.75
		MC	38.9	171.8	142.2	103.3	29.6	28.65
GD04	11a	AB	38.9	185.2	161.8	122.9	23.4	19.04
		RA	38.5	179.4	157	118.5	22.4	18.90
GD05	12a	M-6	40	165.6	134.3	94.3	31.3	33.19
		MO	39.8	161.8	132	92.2	29.8	32.32
GD06	13a	RC	38.3	185.1	153.9	115.6	31.2	26.99
		MW	40.2	150.3	126.9	86.7	23.4	26.99
GD07	14a	A-2	38.8	171.4	134.5	95.7	36.9	38.56
		C-1	38.4	165.4	128.1	89.7	37.3	41.58
Naz01	15a	ME	38.9	197	169.4	130.5	27.6	21.15
		MH	39	182.2	157	118	25.2	21.36
Naz02	16a	PH	39.1	188.3	167.1	128	21.2	16.56
		S-4	39	181.7	160.2	121.2	21.5	17.74
Naz03	17a	MU	39	182.2	158.4	119.4	23.8	19.93
		MZ	40	181.7	157.6	117.6	24.1	20.49
Naz04	18a	PG	38.9	175.8	161.1	122.2	14.7	12.03
		PR	39.8	161.8	149.1	109.3	12.7	11.62
Naz05	19a	MD	38.4	185.5	169.7	131.3	15.8	12.03
		MF(brown)	39.5	182.9	167.3	127.8	15.6	12.21
Naz06	20a	MD	40.5	209.2	184.5	144	24.7	17.15
		MB	38.5	207.1	182.6	144.1	24.5	17.00
Naz07	21a	PD	39	181	165.4	126.4	15.6	12.34
		PM	38.4	178.4	163	124.6	15.4	12.36
Naz08	22a	M-8	39.1	186.7	171	131.9	15.7	11.90
		S-3	39.5	180.7	166.1	126.6	14.6	11.53

Table A-3, Soil samples description

Transect	Area _code	Soil Type	Description
1a	AK01	Vertisols	Reddish silty Clay mixed with scoria gravel
2a	AK02	Vertisols	Dark brown silty Clay
3a	DK01	Vertisols	Dark silty Clay
4a	DK02	Vertisols	Pinkish white weathered rhyolite gravel mixed with pinkish white silty Clay
5a	DK03	Vertisols	Pinkish gray weathered rhyolite gravel pinkish gray silty Clay
6a	DK04	Vertisols	Light brown silty Clay with few weathered gravels
7a	DK05	Vertisols	Brown gravely sandy silty Clay
8a	GD01	Vertisols	Light brown sandy silty Clay
9a	Gd02	Vertisols	Light brown sandy silty Clay
10a	GD03	Vertisols	Dark silty Clay
11a	GD04	Vertisols	Light brown sandy silty Clay
12a	GD05	Vertisols	Dark gray silty Clay
13a	GD06	Vertisols	Dark gray silty Clay
14a	GD07	Vertisols	Dark gray silty Clay
15a	Naz01	Andosols	Dark brown silty Clay
16a	Naz02	Andosols	Dark brown silty Clay
17a	Naz03	Andosols	Brown to light brown silty Clay mixed with ignimbrite gravel
18a	Naz04	Andosols	Dark brown silty Clay
19a	Naz05	Andosols	Ignimbrite gravel mixed with light gray silty clay
20a	Naz06	Andosols	Brown to light brown silty Clay
21a	Naz07	Andosols	Light brown sandy silty Clay
22a	Naz08	Andosols	Light gray to Smokey colour weathered and decomposed Ignimbrite

Appendix B: Geophysical Data obtained from inversion model (Table, and Graphs and Maps)

Table B-1 Soil conductivity and resistivity values obtained from geophysical survey result

Transect	R_1	depth	R_2	Res. RMSE	σ_{1av}	σ_{2av}	σ_{3av}	σ_{4av}	σ_{5av}	σ_{6av}	$\sigma_{1\_4/10}$	σ_{1_pt8}	Cond. RMSE
1a	.8	1.3	.1	9.8	276	193	124	79	53	37	283	276	17.79
2a	.9	.9	.2	2.0	158	142	99	65	44	31	160	157	12.49
3a	3.3	1.2	.4	2.3	89	49	29	17	11	8	93	81	10.48
4a	1.8	1.4	.4	1.0	108	77	49	31	21	14	105	105	9.63
5a	5.0	2.1	.3	3.6	106	55	31	19	12	8	104	98	11.81
6a	2.5	.8	.3	2.6	167	106	65	40	26	18	168	163	14.70
7a	1.8	.9	.2	3.2	184	122	77	48	32	22	170	149	12.80
8a	.8	2.2	.2	2.0	167	110	69	43	29	20	169	140	12.38
9a	1.3	1.2	.4	2.0	148	78	48	32	22	16	159	164	15.95
10a	2.1	1.4	.2	2.2	108	86	60	38	25	18	90	82	8.97
11a	5.1	1.2	1.0	2.2	102	45	23	13	8	5	119	127	14.07
12a	1.4	1.3	.4	1.9	104	90	62	41	27	19	106	110	7.74
13a	1.1	1.7	.1	1.9	204	132	82	51	34	23	210	226	16.22
14a	2.0	.9	.2	2.8	236	163	104	66	44	31	238	238	15.62
15a	3.2	1.3	.6	2.2	53	44	30	20	13	9	49	49	4.46
16a	6.8	1.9	2.0	1.5	15	17	13	9	6	4	18	14	2.84
17a	4.2	.8	.9	1.9	44	45	32	21	14	10	35	26	5.51
18a	.	2.3	1.4	5.9	17	8	5	3	2	1	18	21	2.10
19a	7.3	1.6	1.1	2.4	30	16	9	5	3	2	29	30	3.96
20a	6.7	1.0	.8	4.8	48	25	14	9	6	4	49	50	5.62
21a	7.1	1.3	1.1	3.6	29	30	21	13	8	5	33	37	3.20
22a	7.4	1.0	1.0	5.2	44	37	25	16	11	8	45	49	3.85
22	21	22	22	22	22	22	22	22	22	22	22	22	22

Remark: R_1 and R_2 Resistivity of the first layer at depth listed in the table and the second layer respectively

σ_{1av}- σ_{6av} is the average conductivity of soil from the first to sixth layer in 1m thickness and

$\sigma_{1\_4/10}$ is the average conductivity of the first 1m depth from data points 4 to 10 and

σ_{1_pt8} is the conductivity of the first 1m depth at data point 8 where the soil sample taken

Res. RMSE & Cond. RMSE are resistivity and conductivity root mean square error respectively

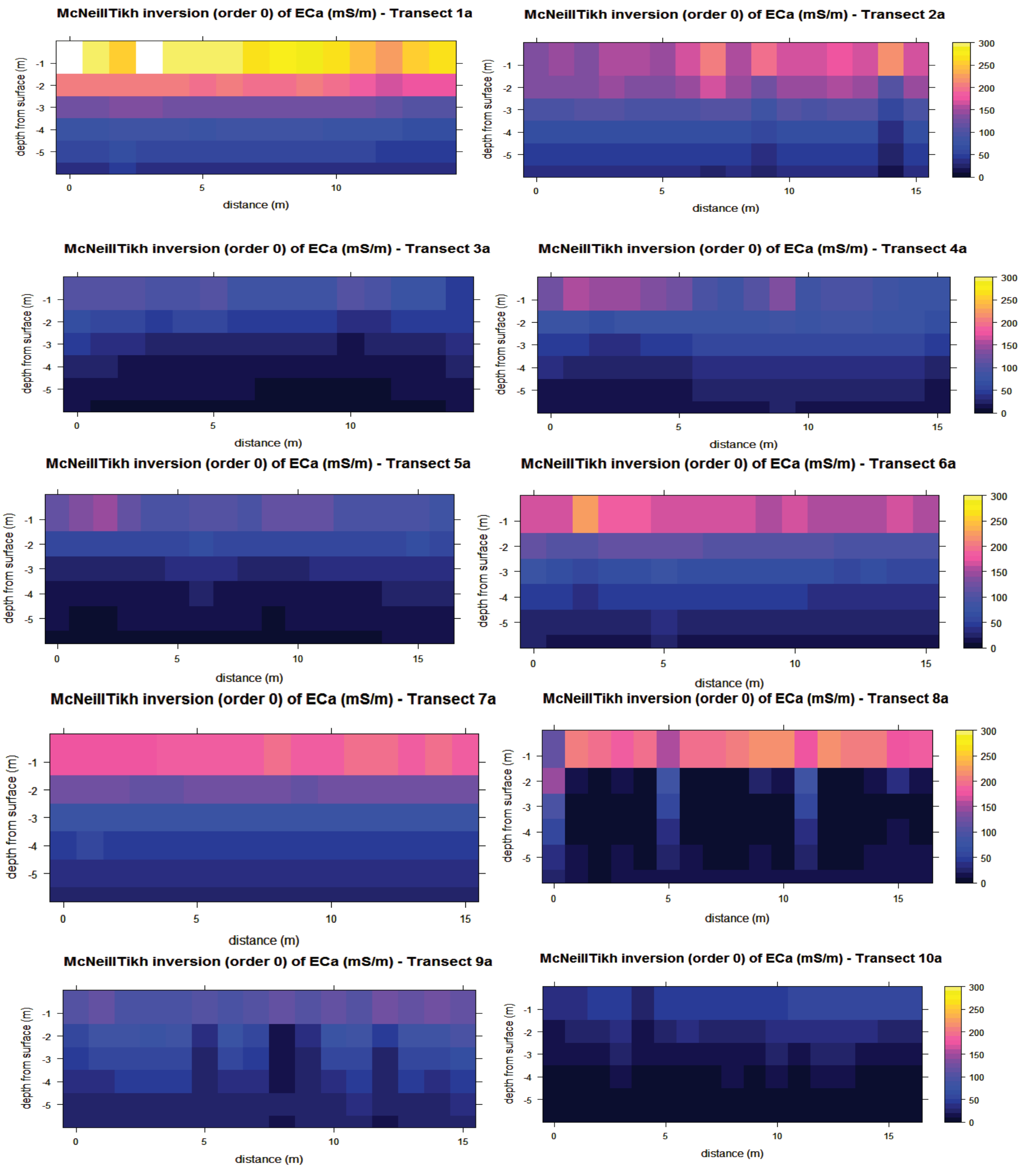


Figure B-1 Conductivity map that obtained from McNeill Tikhonov inversion of the Transects 1a-14a

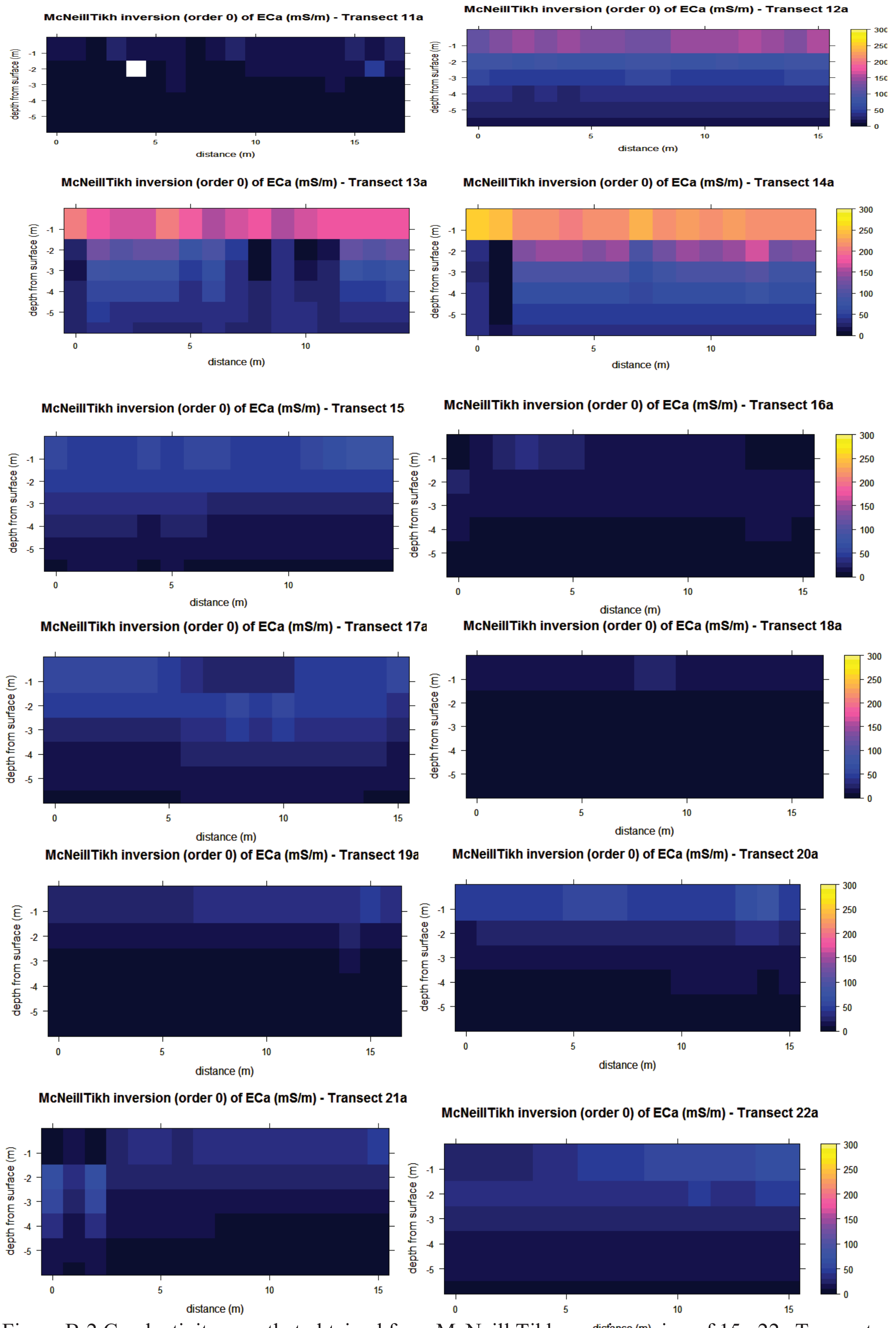


Figure B-2 Conductivity map that obtained from McNeill Tikhonov inversion of 15a-22a Transects

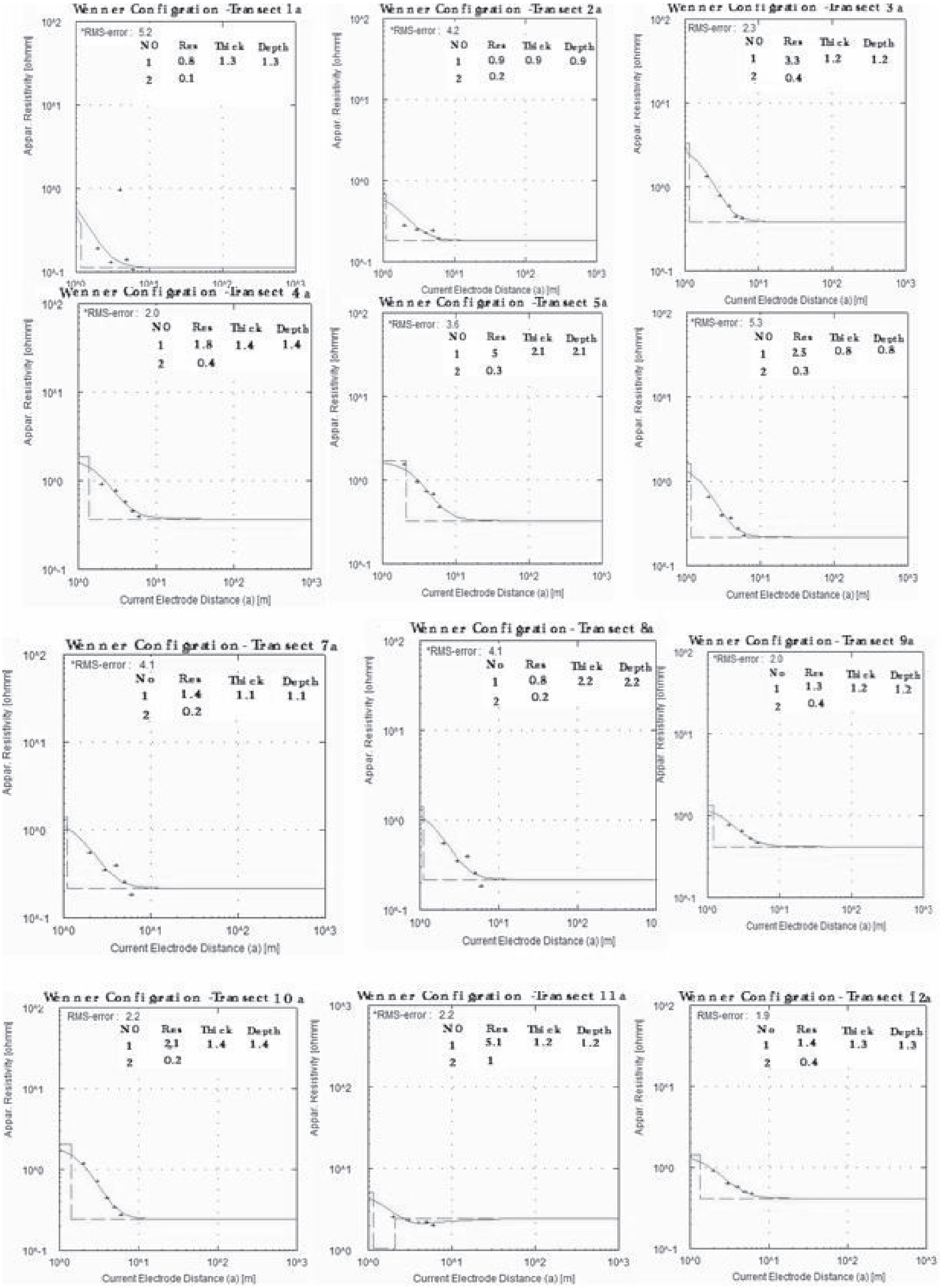


Figure B-3, Resistivity Graphs of the first twelve transects obtained after run RES model

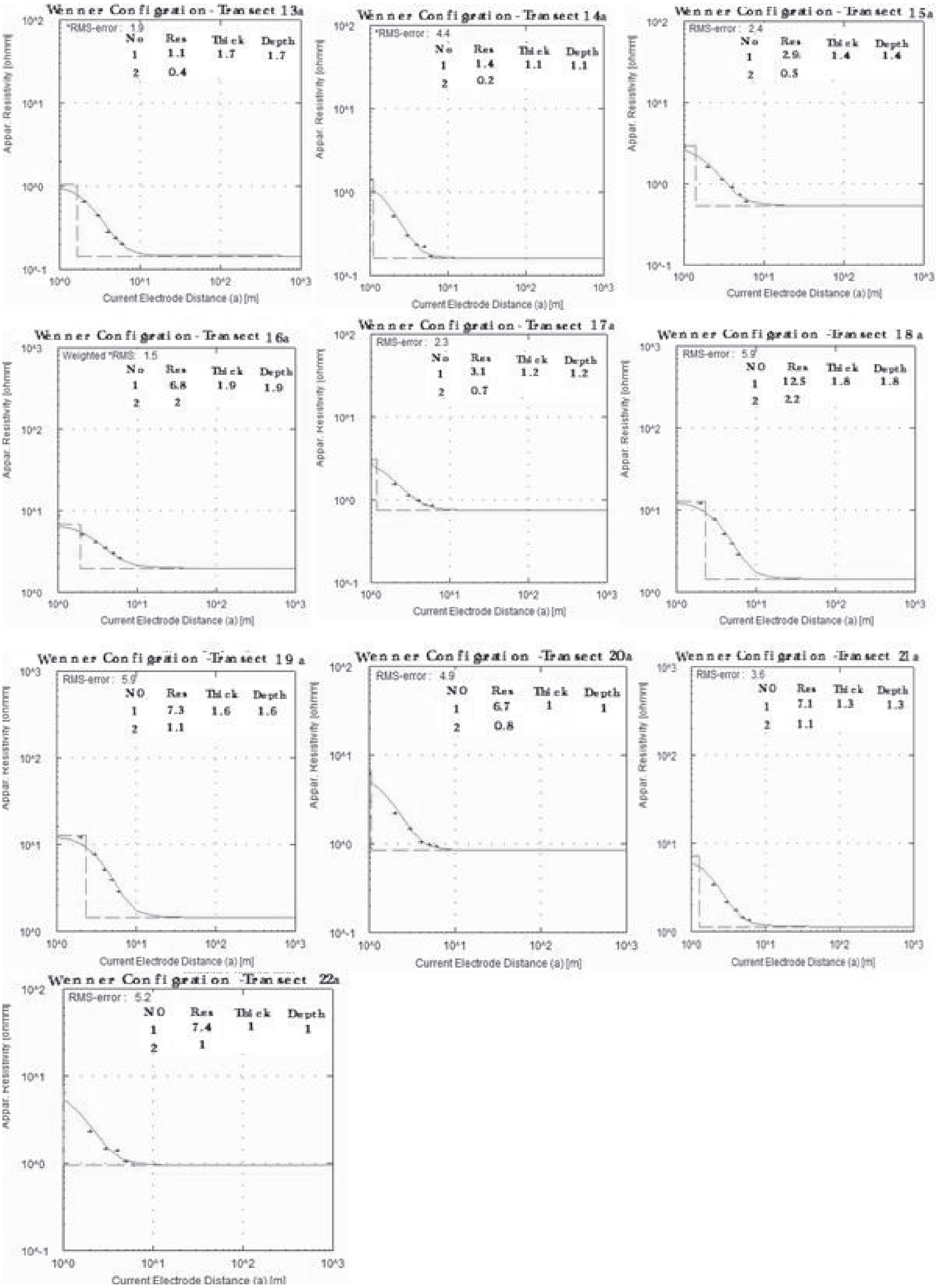


Figure B-4, Resistivity Graphs of transects 13a -22a obtained after run RES model

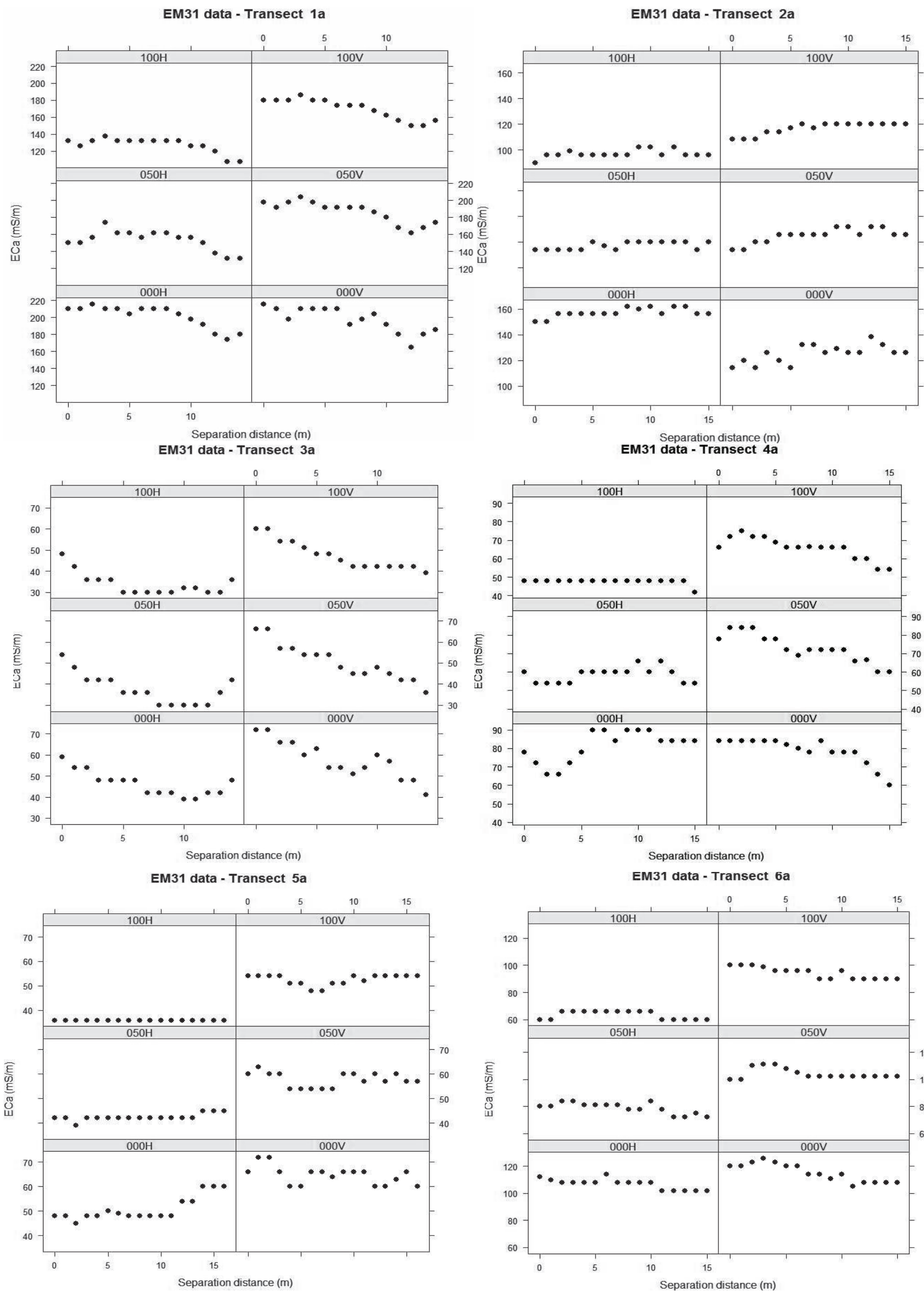


Figure B-5, EM-31 Data Profile Plots of transects 1a -6a

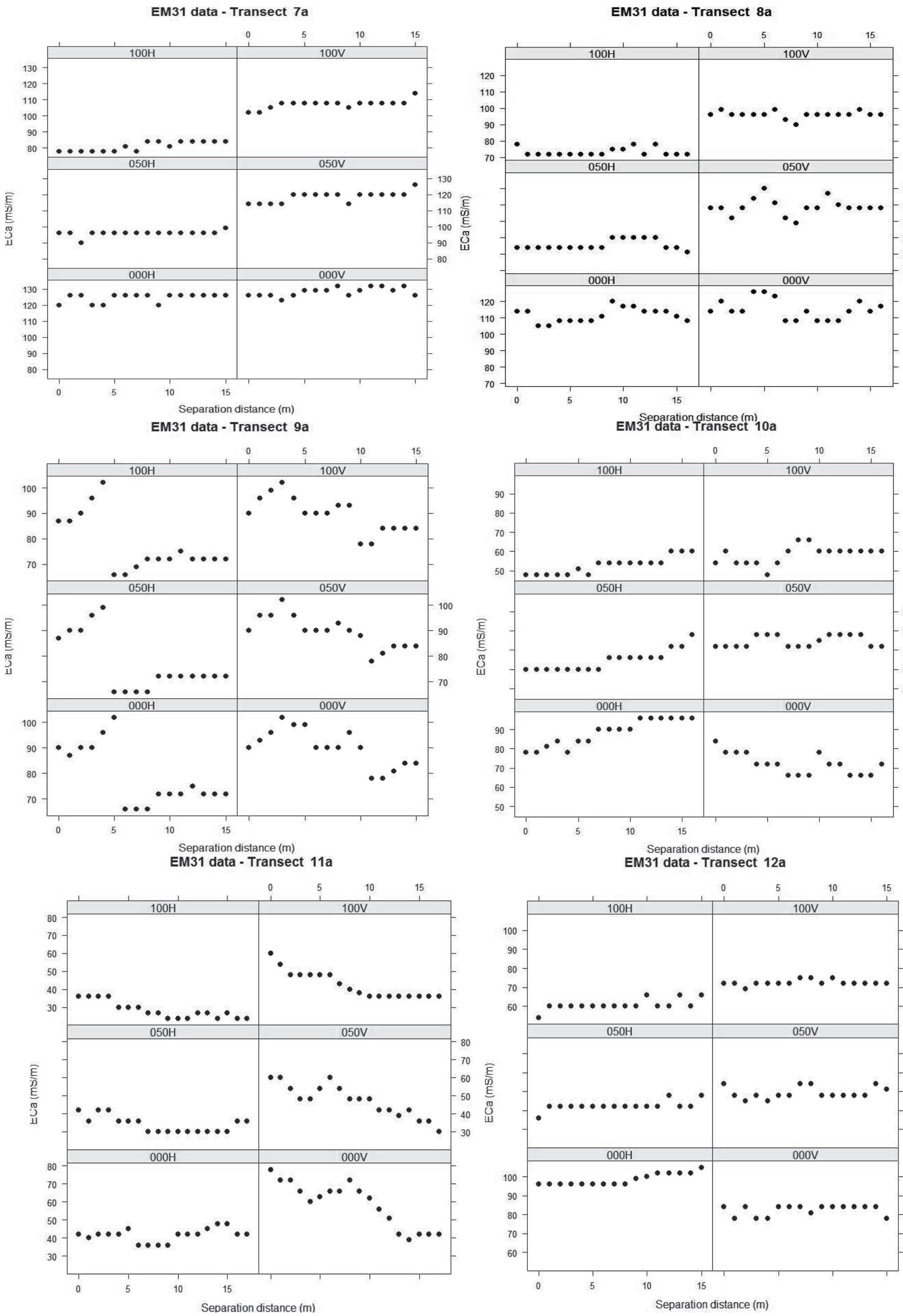


Figure B-6, EM-31 Data Profile Plots of transects 7a -12a

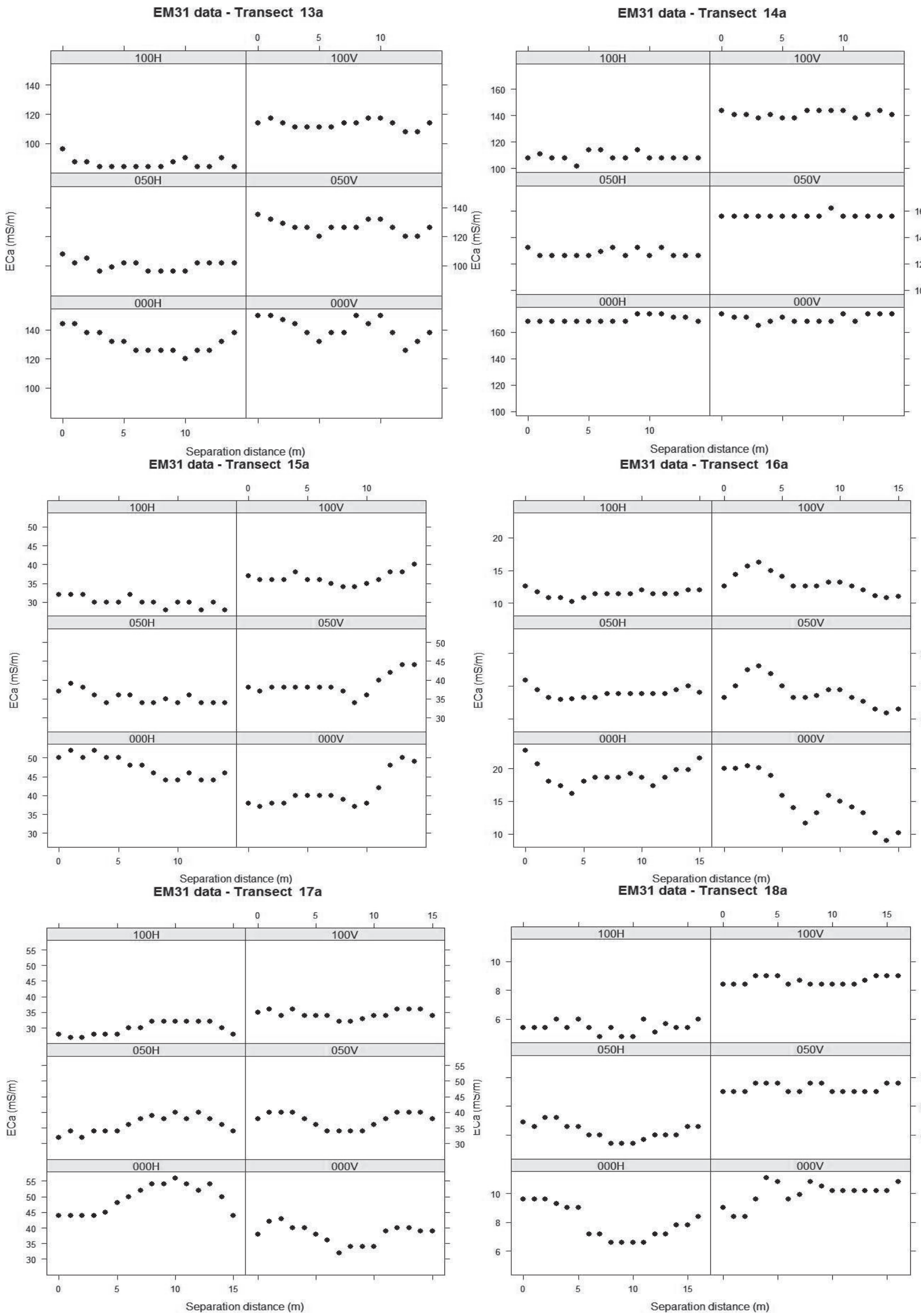


Figure B-7, EM-31 Data Profile Plots of transects 13a -18a

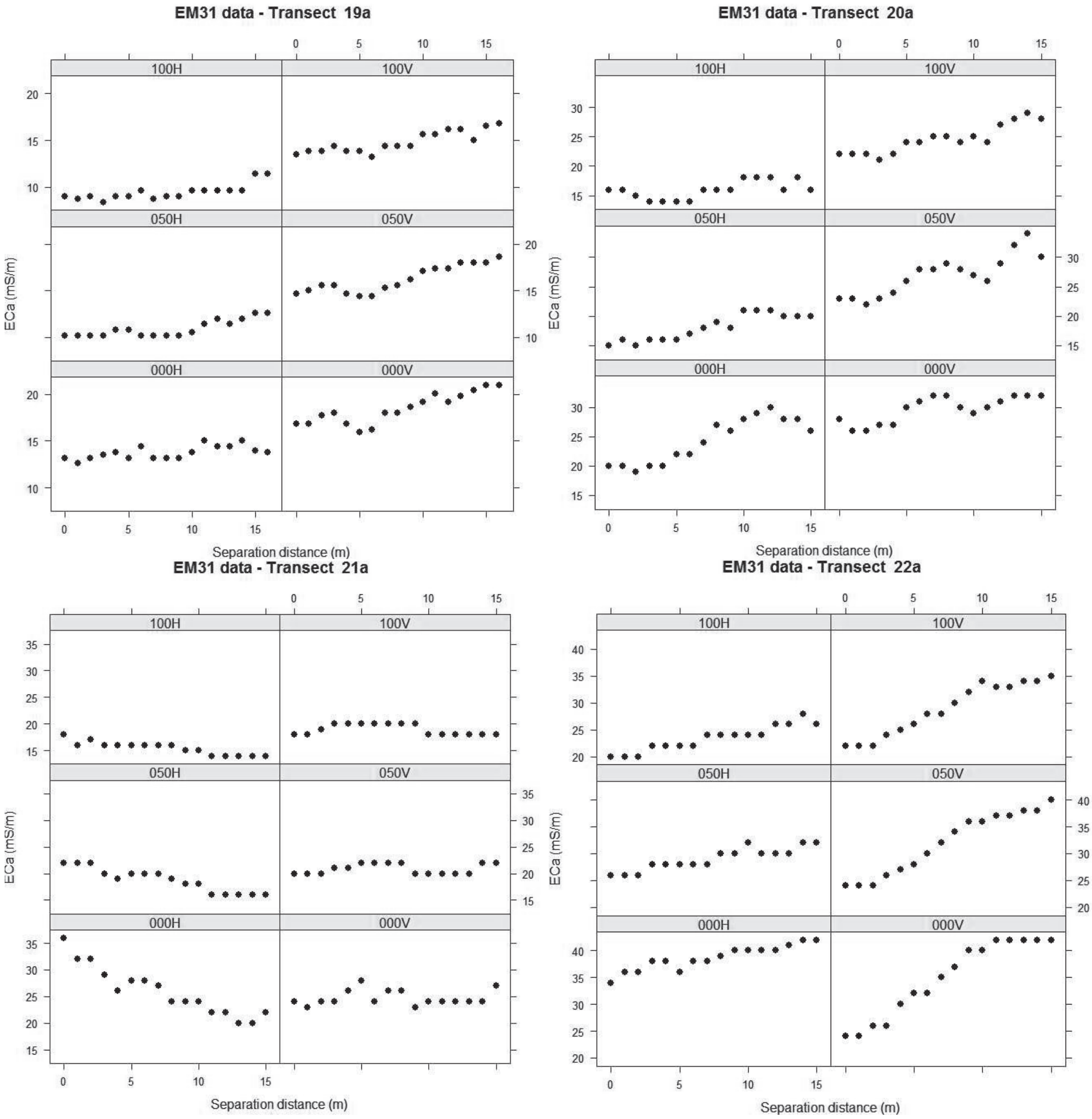


Figure B-8, EM-31 Data Profile Plots of transects 19a -22a