Correlation of Field and Laboratory Electrical Resistivity with Strength Properties of Soil

By

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Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Civil Engineering)

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Universiti Teknologi PETRONAS

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
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September 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this final year project, that the original work is my own except as specified in the references and acknowledgements, and that original work contained herein have not been undertaken or done by unspecified sources or persons.

(CHARLES PITIA SANTO TONGUN)

ABSTRACT

This Final Year Project involves the correlation of field and laboratory electrical resistivity with strength properties of soil. In general, this report embraces the use of electrical resistivity (ER) and geotechnical laboratory soil testing methods to obtain soil resistivity and soil strength properties.

The objective of this study is to find correlation between field and laboratory electrical resistivity with strength properties of soil such as cohesion, Internal Angle of Friction, moisture content, unit weight, and plasticity index.

Field electrical resistivity was conducted at a particular location at University Teknologi PETRONAS (UTP) in the vicinity Block 13. From the same location two boreholes were drilled and soil samples were extracted using Percussion Gouges Gasoline Driven Hammer. Laboratory electrical resistivity and geotechnical laboratory tests were further carried out on the soil samples.

The results obtained were compared and correlated with soil strength properties obtained from the two boreholes. Results from both the boreholes and electrical resistivity survey located at the boreholes locations indicated that there were consistent in the correlation between the resistivity and soil strength properties. The results indicated that there are some correlation between moisture content, internal angle of friction, and plasticity index with electrical resistivity (Field and laboratory). However, it shows lack of correlation between unit weight and cohesion with electrical resistivity.

This final year project report covers background study, literature review, methodology & tools, results & correlations, and conclusion & recommendations on the title of this study.

ACKNOWLEDGEMENTS

First and foremost, the author would like to thank and praise Almighty God for having kept him safe and for His unyielding support throughout my life and during my project undertaking.

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LIST OF ABBREVIATIONS

ER	Electrical Resistivity
FOS	Factor of Safety
PI	Plasticity Index
UTP	Universiti Teknologi PETRONAS
SPT	Standard Penetration Test
CPT	Cone Penetration Test
BH	Borehole
FYP	Final Year Project
LAB	Laboratory
LCD	Liquid Crystal Display

CHAPTER 1

INTRODUCTION

1.1. Background Study

Soil investigation studies are mainly conducted to find the mechanical and physical properties of the soil for civil engineering constructions whereas, its properties of the electrical resistivity are not well addressed. Soil electrical properties are the parameters of natural and artificially created electrical fields in soils and influenced by distribution of mobile electrical charges.

The Electrical Resistivity (ER) method is one of the oldest geophysical methods used in prospecting or oil exploration that was documented in the 1830s through experiments conducted by Robert W. Fox, an English Geologist, and Natural Philosopher. This method became active in the 1920s when Schlumberger, located in France, and Wenner, located in United States, began applying current into the ground, and measuring the potential difference for mineralogical prospecting mainly by the Schlumberger Company in France.

Electrical Resistivity is a method in which an electrical current is injected into the ground through steel electrodes. The basic method requires at least 4 steel electrodes be driven into the ground. The injection of electrical current is then applied in an attempt to measure the electrical properties of the subsurface.

The most commonly used method of measuring soil resistivity is the four-electrode method. A current is passed through two outer electrodes, and a drop in potential through the soil due to the passage of the current is measured with a second pair of the inner electrodes. A specialized instrument is used to supply the current and measure the potential drop. To reduce the influence of any stray currents in the area, the instrument supplies alternating current. The arrangement of electrodes is shown in the figure below.

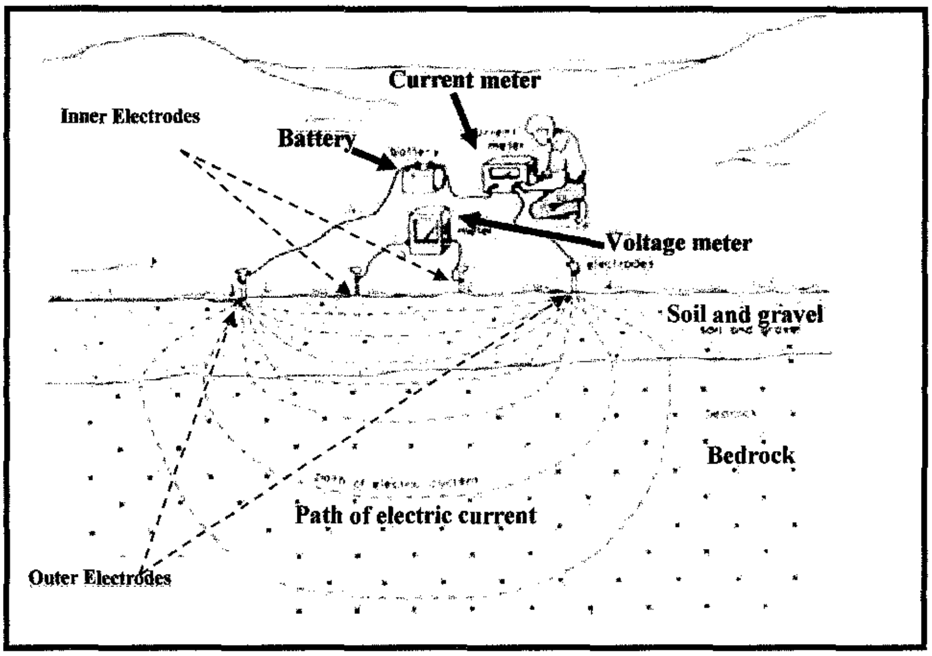


Figure 1.1: Wenner Method Arrangement of Electrodes and Test Set-Up

Since then, electrical resistivity methods have been used in various fields such as engineering, environmental studies, archaeology etc. However, in civil and environmental engineering, it has been used to determine things such as potable groundwater supplies, trace underground contamination as it migrates through the saturated zone, soil resistivity for purposes of designing electrical substations, estimating pipeline corrosion, and determine water content in soil. Electrical resistivity also is used to detect shallow structures and subtle changes in soil apparent resistivity.

Resistance is calculated by the resistivity meter, and displayed on the LCD display. The parameter that is actually contoured and from which an interpretation is derived is called apparent resistivity. This is because Resistance values, besides being influenced by a soil's mineralogy, porosity, and water saturation, is also influenced by the electrode geometry used. By converting Resistance values to apparent resistivity values, the influence of the array configuration is removed from the data.

In addition to that, previous Final Year Project in University Teknologi PETRONAS has used electrical resistivity to determine soil strength parameters of remoulded clayey soil.

1.2. Problem Statement

Geotechnical engineering practices depend to a large extent on the conventional geotechnical methods (i.e. bole sampling, SPT, CPT, and lab tests) to determine soil strength parameters (e.g. shear strength, cohesion, internal angle of friction, etc.) for the purpose of obtaining the subsurface soil strata and design of geotechnical structures.

However, the conventional geotechnical methods are time consuming and costly. In addition to that, these methods lack efficiency and practicality in quick assessment of soil parameters for the purpose of computing factor of safety (FOS). FOS aids in risk identification, hazard quantification and mitigation of negative events in hillside development.

This has challenged researchers and engineers to seek for alternative method in order to address the shortcomings of the conventional geotechnical methods.

The alternative method is electrical resistivity which measures the electrical properties of soil such as apparent electrical resistivity and conductivity. If this method is developed well, it will eliminate the shortcomings of the conventional geotechnical methods.

Some investigation works have been conducted in these regard and the method has shown some significant findings in assessing soil strength properties.

1.3. Objective of the Study

The objective of carrying out this project study is to find the correlation between field and laboratory electrical resistivity with strength properties of soil in the vicinity of block thirteen (13) at Universiti Teknologi PETRONAS (UTP).

1.4. Scope of the Study

This project involves the use of electrical resistivity and geotechnical laboratory soil testing methods to determine soil resistivity and some soil strength properties respectively. The nature of this project requires understanding of electrical resistivity method and its application into soil from relevant sources, books and journals. The final goal is to find correlation between soil electrical resistivity and strength properties of soil obtained from these two methods.

The scope of the project covers the following:

- ❖ Search and review of literatures on the topic/title of this study
- ❖ Soil extraction and sampling for the study
- ❖ Field electrical resistivity and laboratory testing on the soil the samples
- ❖ Analysis and correlation of the test results obtained from the field and laboratory.
- ❖ Findings and recommendation from the study for further research in this particular area.
- ❖ Submission of final report that documents the entire study.

CHAPTER 2

LITERATURE

2.1. Literature Review

Great deals of researches have been conducted on the use of electrical resistivity method in soil and its relation with other soil properties. The previous researches on soil properties have indicated some correlation of some of the properties such as water content and hydraulic conductivity.

A number of people have carried out research on the application of electrical resistivity to find out the relationship between soil resistivity and soil properties. The researches are discussed below:

Zeyad et al. (1996) carried out research on electrical resistivity of compacted clay. Electrical resistivity is found to be sensitive to temperature, compaction effort, initial saturation and moulding water content. A correlation of water content and Atterberg limits (liquid limit and plastic index) with electrical resistivity was found to have inversely proportional relationship.

The relationships between electrical resistivity and liquid limit (LL) and plasticity index (PI) are shown in Fig. 2.1; LL and PI (a, b & soil C). It is generally found out that, soils with higher LL or PI have lower electrical resistivity. An exception to this trend is soil C, which is highly plastic (PI = 35). The reason for this discrepancy according Zeyad et al. appears to be the higher percentage of coarse-size particles in soil. This soil contains 9% gravel and has a coarse fraction of 47%. When the coarse fraction was removed from soil C, it was found to be consistent with the electrical resistivity of the other soils having similar LL or PI. The trend of decreasing electrical resistivity with increasing LL and PI is consistent with the mineralogy of the soils. Those soils having a clay fraction containing a greater quantity of smectite have higher LL or PI and lower electrical resistivity. These soils are more active and therefore should exhibit greater surface conductance. Consequently, their electrical resistivity should be lower. Resistivity and moulding water content is also found to be increasing with decreasing moulding water content as shown in the fig 2.1. Moulding content (soil a, b, & c)

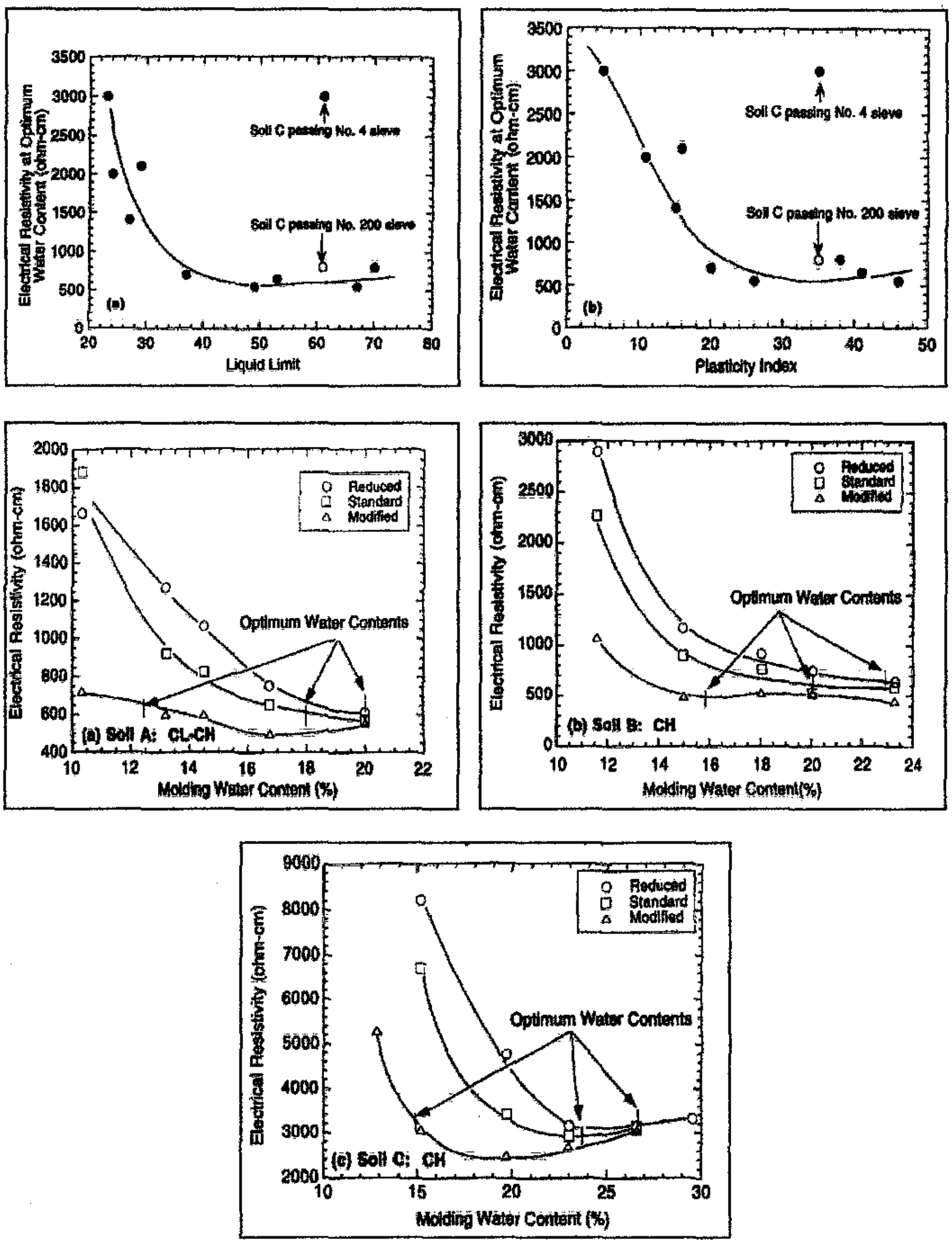


Figure 2.1: Zeyad et al.: Moulding water content and Atterberg limits of Electrical Resistivity of Compacted Clay.

An attempt was made by Larisa P. et al (2001) on case study application of geophysical method to evaluate hydrology and soil properties in urban areas. No clear relation between electrical resistivity and soil properties was observed.

The relationship between electrical resistivity and hydraulic conductivity has been studied (Worthington 1977; Huntley 1986; Heigold et al. 1979; Kelly 1977; Mazac et al. 1985), but contradictory results have been reported. Direct correlations between electrical resistivity and hydraulic conductivity (i.e., hydraulic conductivity increases as electrical resistivity increases) have been reported for some soils, whereas inverse relationships (i.e., hydraulic conductivity decreases as electrical resistivity increases) have been reported for others.

Mazac et al. (1990) conclude that the relationship between hydraulic conductivity and electrical resistivity has inverse relation for soils of a particular type. For example, saturated dense clean sands have lower porosity, lower hydraulic conductivity, and greater electrical resistivity than loose clean sands [e.g., see Arulanandan and Muraleetharan (1988)]. Conversely, when a comparison is made between the electrical resistivity and hydraulic conductivity of different types of soils (e.g., clay, sand, silt), the relationship between electrical resistivity and hydraulic conductivity is direct, with coarse grained soils generally having the highest electrical resistivity and highest hydraulic conductivity. The direct relationship between .electrical resistivity and hydraulic conductivity for soils of different type is primarily due to changes in surface conductance; that is, surface conductance decreases as soils become increasingly coarse grained.

For compacted clays, Sadek (1993) reports that the relationship between electrical resistivity and hydraulic conductivity is not unique since the same electrical resistivity can be attained for specimens having different structure and hydraulic conductivity.

Kalinski and Kelly (1994) found that a distinct relationship between electrical resistivity and volumetric water content exists and suggest that this relationship may prove useful in assessing the hydraulic conductivity of compacted soil liners.

Harshad et al. did research on comparison of electrical resistivity by geophysical method and neutron probe logging for soil moisture monitoring in a forested watershed. Electrical Resistivity is found to be inversely proportional to water content but the volumetric moisture content was not satisfactory.

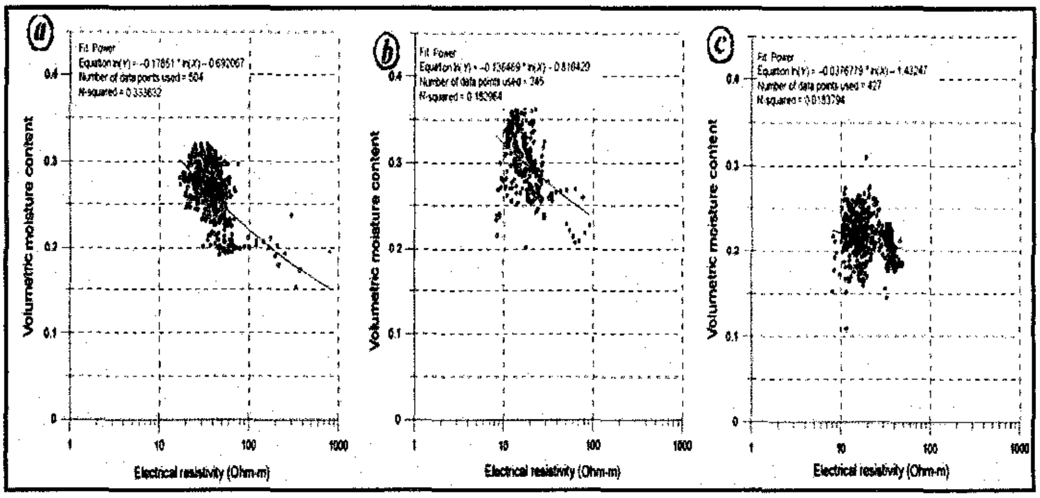


Figure 2.2: Harshad et al comparison of resistivity by geophysical method.

Ozcep et al conducted research on correlation between electrical resistivity and soil-water content. The relation between electrical resistivity and water content is found to be given by $W= 49.21e^{-0.017R}$

Electrical resistivity method is also used to determine relationship between Water Tension and Electrical resistivity in soils, electrical resistivity measurement for evaluation compacted soil liner, monitoring forest soil properties with electrical resistivity.

Base on the literatures and previous researches, no attempts have been made to specifically correlate electrical resistivity with strength properties of soil except the research conducted on the correlation of electrical resistivity with some soil properties for predicting safety factor of slopes using simple multimeter (2010) by Baharoum and Zahir. Correlation or similarities between the electrical resistivity and some soil parameters (i.e. moisture content, friction angle, bulk density, and SPT) was observed in this research. Fig 2.3: indicates that the SPT increases with increasing resistivity while moisture content increases with decreasing resistivity.

Bulk density also increases with increasing resistivity. Baharoum et al suspects that the higher bulk density is contributed by the increase in sandy size particles and reduction of water content in the soil which probably explains the higher resistivity value. The frictional angle (φ) increases with increasing resistivity from borehole 1. This is again probably due to the fact that the increase in frictional angle is an indication that samples taken at a deeper strata contains more sandy material and possibly mixed with gravels which reflects in the higher resistivity value, but the researcher(s) suggested more field tests in order to achieve more precise correlations that would enable physical strength parameters replacement with electrical parameters. The graphs below show the relationship between electrical resistivity and soil strength properties obtained from the research.

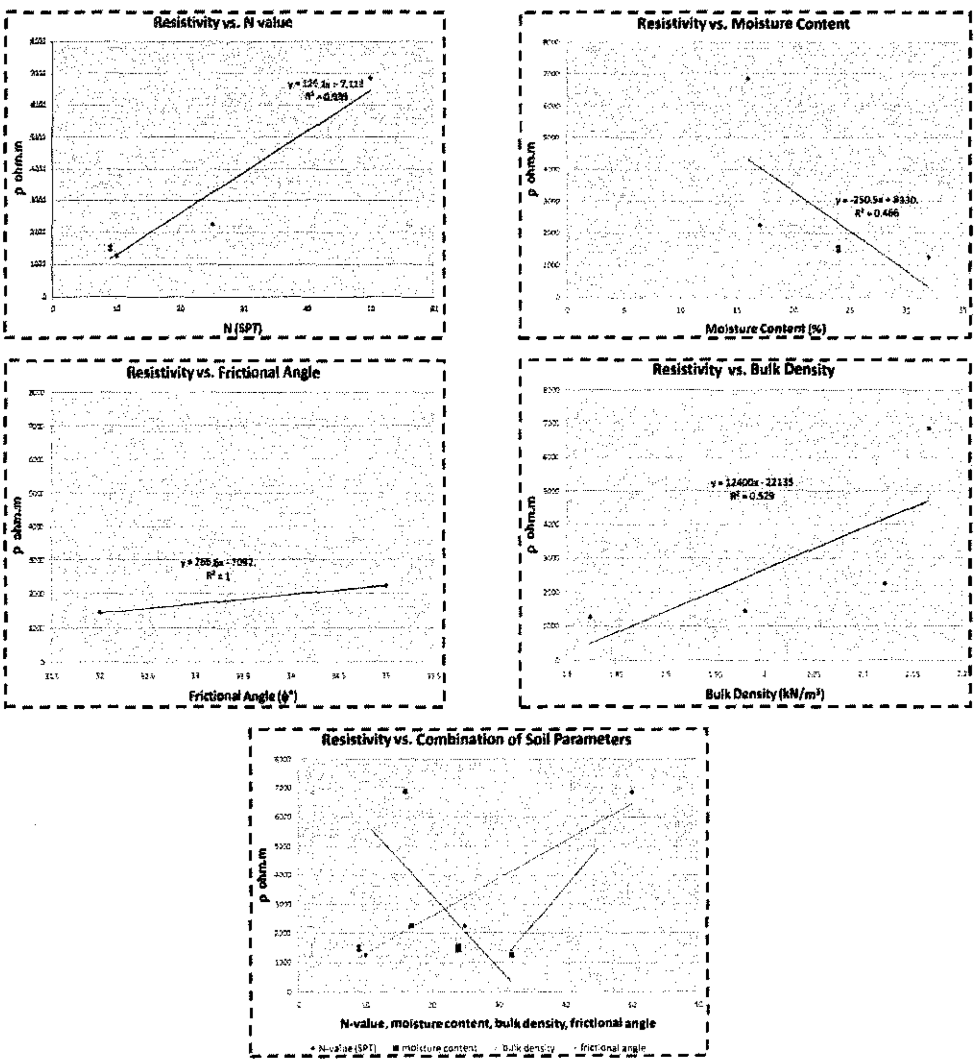


Figure 2.3: Baharoum & Zahir; Correlation Graphical Results.

Moreover, Daoussa S. (2010) conducted FYP on correlation of electrical resistivity with properties of clayey soil such as cohesion (c), internal frictional angle (Ø) and unit weight (γ) at Universiti Teknologi PETRONAS. A significant relationship between physical and strength properties of soil that obtained from direct shear box test and electrical resistivity was found. A distinct relationship between electrical resistivity and moisture content existed. Electrical resistivity was found to be increasing when the soil was compacted at less moisture content whereas, the electrical resistivity decreases when the soil was compacted at high moisture content. The influence of compactive effort on electrical resistivity is more significant with degree of compaction, the electrical resistivity decreases when numbers of blows are increased (high degree of compaction decreases soil resistivity). From the electrical resistivity, the friction angle and cohesion were found to be increasing when resistivity increases and vice versa.

However, in his FYP thesis he suggested that further tests need to be conducted to confine result in order to remove inconsistent data and result. Also more work need to be carried out to correlate parameters of all types of soils with electrical resistivity. The graphs below show the relationship between electrical resistivity and the clayey soil properties.

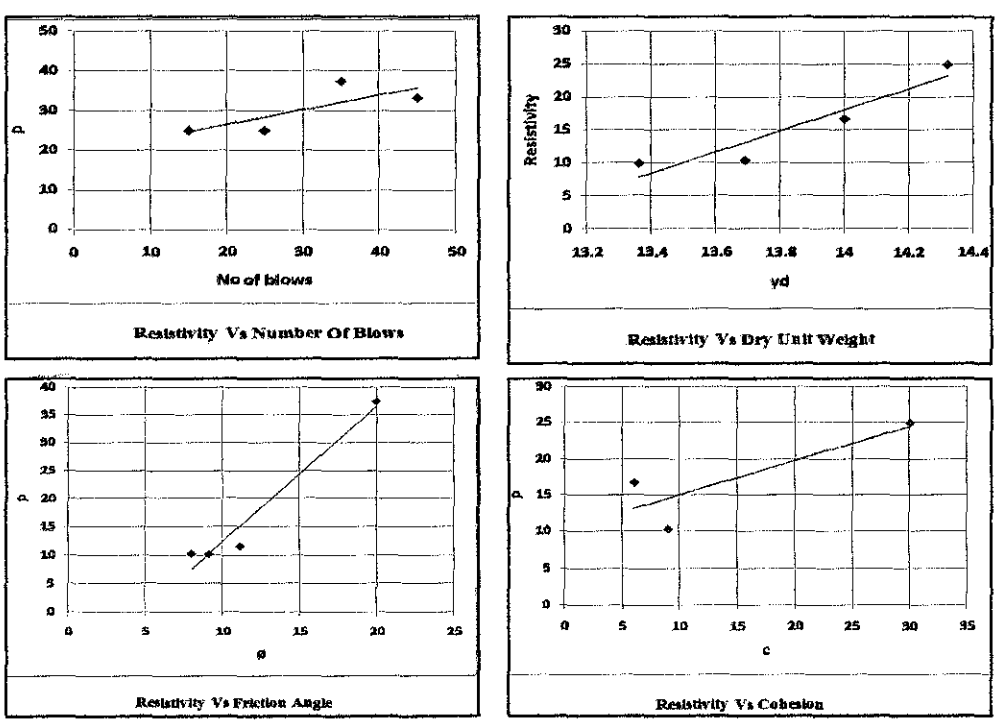


Figure 2.4: Daoussa (FYP) Correlation Graphs.

Principle of Electrical Resistivity

Soil resistivity contents are widely varying depending on the type of terrain (Adopted from a PhD thesis by Gilbert Gary, 2011).

- Type of earth (e.g., clay, loam, sandstone, granite)
- Stratification of layers of different types of soil (e.g., loam backfill on a clay base).
- Moisture content: resistivity may fall rapidly as the moisture content is increased, but after a value of about 20%, the rate of change in resistivity is much less.
- Temperature: above and below the freezing point, the effect of temperature on earth resistivity changes the resistivity significantly.
- Chemical composition and concentration of dissolved salts.

Table 2.1: Resistivity values for several types of soils

Type of Soil	Typical Resistivity Ωm	Usual Limit Ωm
Clay	40	8 to 70
Clay & Sand Mixtures	100	4 to 300
Shale, slates, sandstone and etc	120	10 to 100
Mud	150	5 to 250
Sand	2000	200 to 3000
Moraine gravel	3000	40 to 10000
Ridge gravel	15000	3000 to 30000
Solid granite	25000	10000 to 50000

Adopted from Earthing Fundamentals: *(Courtesy Lightning & Surge Technologies)*

Wenner Four-Pin Method

The most commonly used method of measuring soil resistivity is the four-pin method. According to Zhu et al. (2007), in the Wenner configuration method, there are four-electrode soil conductivity/resistivity measurements. The application of the Wenner configuration method requires an electrical current to be injected into the ground by surface electrodes to detect the soil resistivity. A combination electric current source and resistance meter, four metal electrodes (made of stainless steel), connecting wires, a measuring tape, and a thermometer are all that is needed for the Wenner configuration method. The schematic diagrams below show the basic principle of soil resistivity measurements for typical basic equipment and the basic concept of electrical earth resistivity measurements when the soil is in homogeneous nature and the equipotential surfaces are hemispherical in shape. Two short metallic stakes (electrodes, C1 and C2) are driven about 0.20 m to 0.30 m into the earth to apply the electrical current into the ground; two additional electrodes (P1 and P2) are used to measure the earth voltage (or electrical potential) generated by the electrical current. Therefore, the subsurface ground resistivity can be calculated by knowing the electrode interval, geometry of the electrode positions, applied current, and the measured voltage. The soil resistivity (SR) or conductivity (ECa) at any depth can be calculated from SR or ECa values obtained successively by increasing the inter-electrode intervals. This is based on the assumptions that the depth to which the conductivity measured is equal to the inter-electrode interval. Fig. 1 illustrates how expanding the inter-electrode intervals helps to increase the depth (and volume) of measurement. Effective depth of measurement of soil ECa or SR might be equal to the inter-electrode interval.

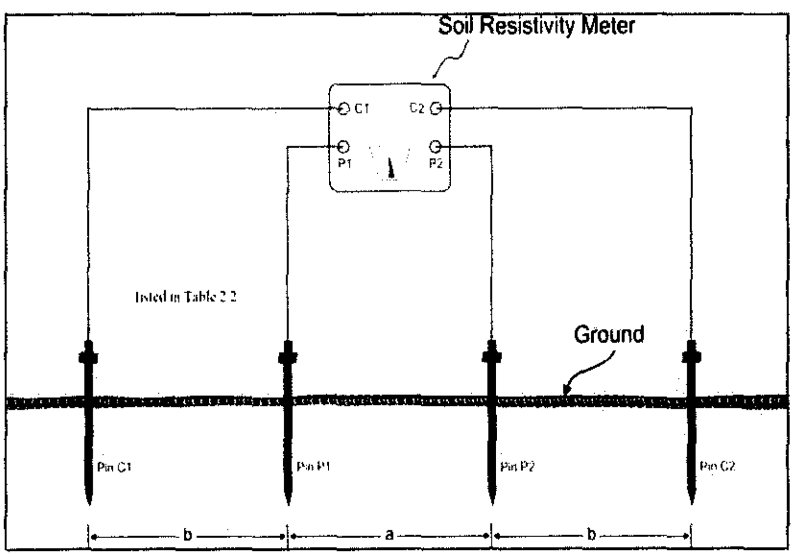


Figure 2.5: Wenner Four Pin Soil Resistivity Test Set-Up

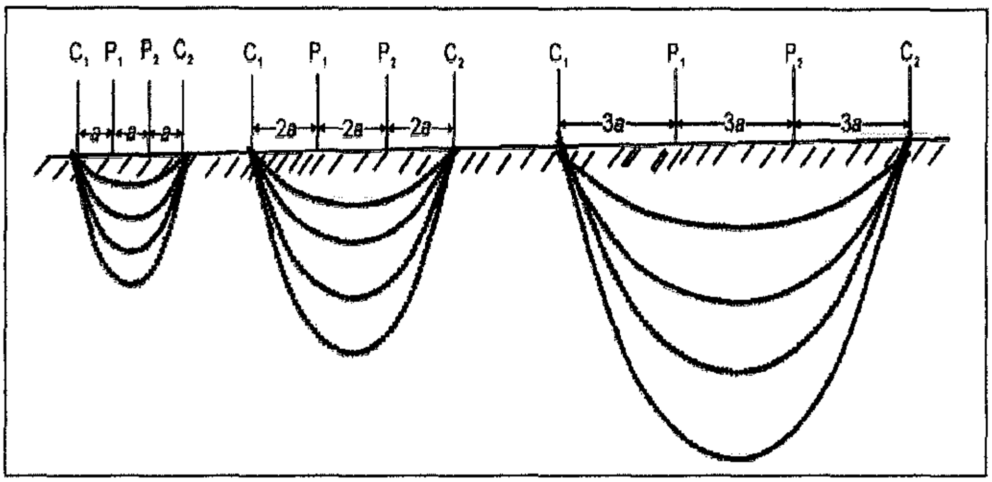


Figure 2.6: Inter-Electrode and Depth Spacing

Wenner Array

The Wenner array Fig. 2.7 is the least efficient from an operational perspective. It requires the longest cable layout, largest electrode spreads and for large spacing one person per electrode is necessary to complete the survey in a reasonable time. Also, because all four electrodes are moved apart after each reading, the Wenner Array is most susceptible to lateral variation effects.

However the Wenner array is the most effective in terms of the ratio of received voltage per unit of transmitted current. Where unfavourable conditions such as very dry or frozen soil exist, considerable time may be spent trying to improve the contact resistance between the electrode and the soil.

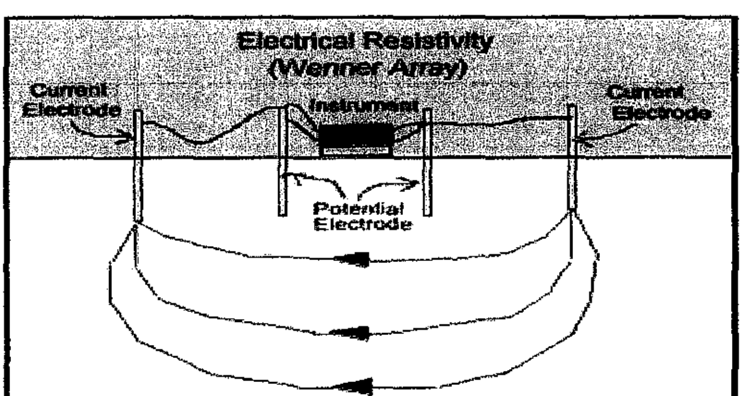


Figure 2.7: Wenner Array

Driven Rod Method

The driven rod method (or Three Pin or Fall-of-Potential Method) is normally suitable for use in circumstances such as transmission line earthen structure, or areas of difficult terrain, because of its shallow penetration that can be achieved in practical situations, the much localized measurement area, and the inaccuracies encountered in two layer soil conditions.

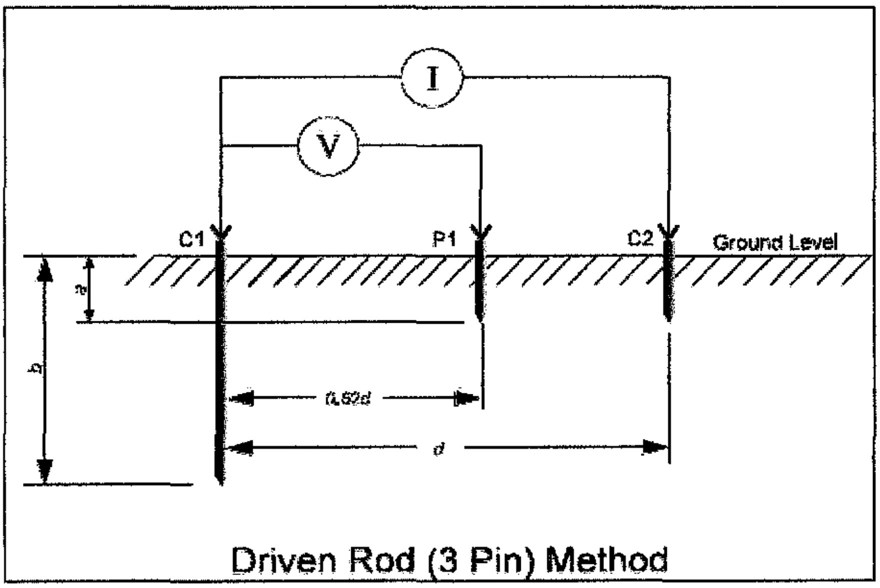


Figure 2.8: Driven Rod Method

Schlumberger Array

Economy of manpower is gained with the Schlumberger array since the outer electrodes are moved four or five times for each move of the inner electrodes. The reduction in the number of electrode moves also reduces the effect of lateral variation on test results.

Considerable time saving can be achieved by using the reciprocity theorem with the Schlumberger array when contact resistance is a problem. Since contact resistance normally affects the current electrodes more than the potential electrodes, the inner fixed pair may be used as the current electrodes, a configuration called the 'Inverse Schlumberger Array'. Use of the inverse Schlumberger array increases personal safety when a large current is injected. Heavier current cables may be needed if the current is of large magnitude. The inverse Schlumberger reduces the heavier cable lengths and time spent moving electrodes. The minimum spacing accessible is in the order of 10 m (for a 0.5m inner spacing), thereby, necessitating the use of the Wenner configuration for smaller spacing.

Lower voltage readings are obtained when using Schlumberger arrays. This may be a critical problem where the depth required to be tested is beyond the capability of the test equipment or the voltage readings are too small to be considered.

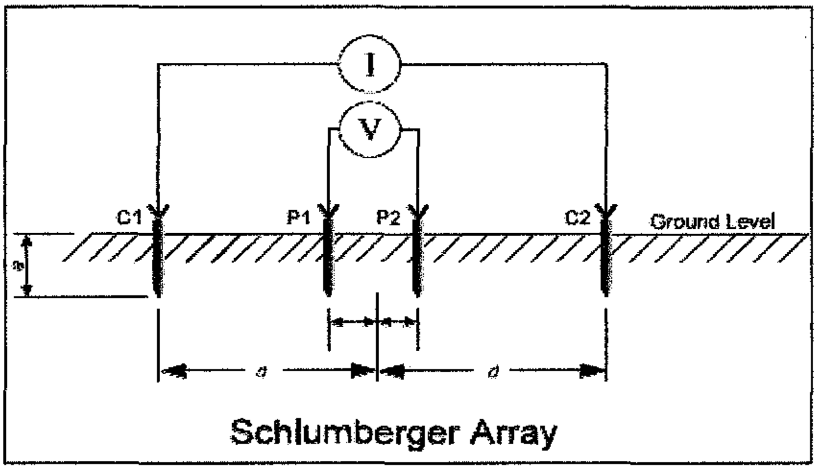


Figure 2.9: Schlumberger Array

Factors Affecting the Electrical Resistivity of Soil

The Factors affecting soil resistivity besides the soil water content include soil salinity, temperature, and texture (Zhu et al., 2007).

According to Syed et al., (2010); for most common minerals forming soils and rocks, the resistivity is high in a dry condition and therefore in general, the resistivity of soils and rocks depends on the amount and type of water in the pore spaces and fractures. The amount of water in a material depends on the porosity of the soil. However, the basic mechanism affecting conductivity in moist soils and water bearing rocks occurs as a result of the movement of ions and the ability to transmit ions is governed by the electrical resistivity which is a basic property of all materials. Besides being dependant to the amount and type of water and porosity, electrical resistivity also depend on other properties such as type of material, particle shape and orientation, mineralogy, amount of clay content and electrical resistivity of the pore fluid. The presences of clay minerals strongly affect the resistivity of sediments and weathered rock. This is due to the fact that clay minerals are electrically conductive particles having the ability to absorb and release ions and water molecules on its surface through an ion exchange process. Therefore, it is in clean sands and gravels, electrical conduction occurs primarily in the pores while in clayed soils and clay-bearing rocks electrical conduction occurs in the pores and on the surfaces of electrically charged particles. The bulk electrical resistivity of the soil can also be affected significantly by addition of surface conductance in clays. Other factors which indirectly affect the electrical resistivity are frequency of the current, geometry, spacing and type of electrodes used. Temperature can also affect the electrical resistivity of soil in the sense that rising temperature improved the mobility of the ions and this decreases the electrical resistivity of soil. The statements above demonstrate the intricacies in correlating resistivity with the different factors related to the soil, rocks and pore fluid.

The table 2.2 and figure 2.10 below show an example of resistivity correlation variation with some types of materials.

Table 2.2: Resistivity Correlation

Resistivity (Ohm-ft)	**Types Of Materials**
5-10	Wet to moist clay soils
10-50	Wet to moist silty clay and silty soils
50-500	Moist to dry silty and sandy soils
500-1000	Bedrock with moist-soil-filled cracks
1000	Sand and gravel with silt
1000-8000	Slightly fractured bedrock with dry-soil-filled cracks; sand and gravel with layers of silt
8000 (plus)	Massive bedded and hard bedrock; coarse, dry sand and gravel deposits

Adopted From Soils And Foundations 7^{th}ed By Liu C & Evett J:

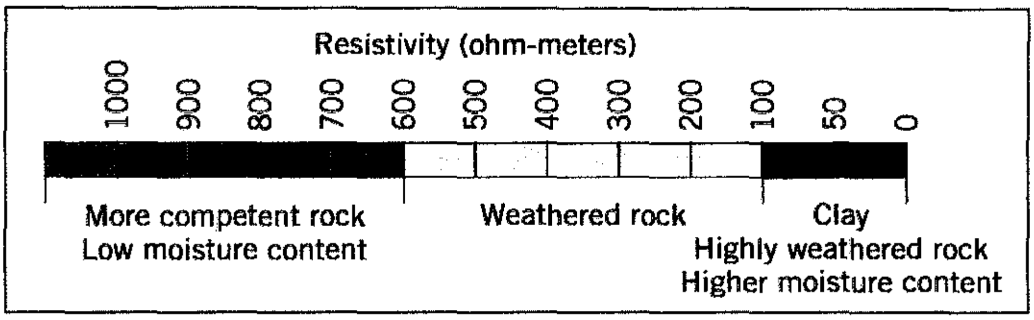


Figure 2.10: Soil Profile from Electrical Resistivity Tests. ***(Courtesy Muni Budhu)***

The four electrode probe concept is utilized throughout research because all electrical resistivity methods applied in geophysics and soil science are based on the standard four-electrode principle.

The electrical resistivity of soil varies between different geological materials, soil types and is dependent on many factors:

- Moisture and chemical content of the soil
- Size and type of electrode used
- Depth to which the electrode is buried
- Stratification and layers of different types of soil

CHAPTER 3

METHODOLOGY AND TOOLS

3.1. Research Methodology

This section will describe the research method and tools adopted in this study. The figure below shows the experimental methodology.

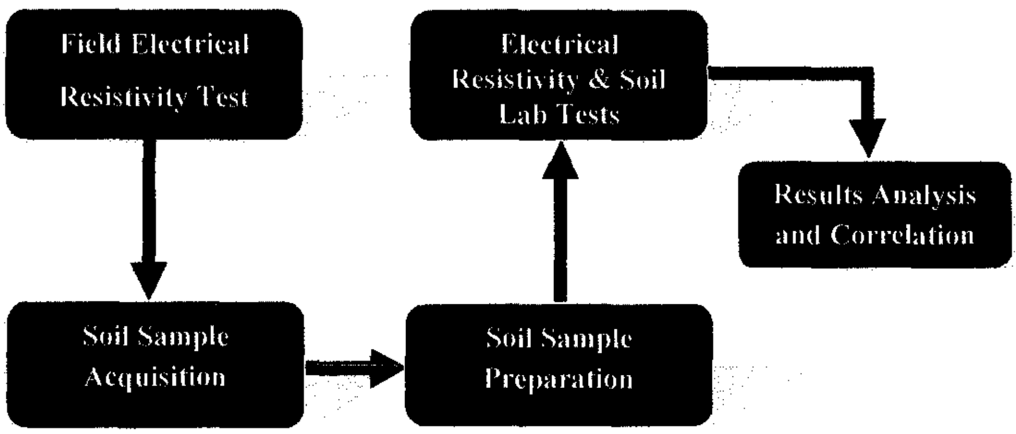


Figure 3.1: Experimental Methodology

3.1.1. Soil Samples Acquisition

The Soil Samples were obtained from at location in vicinity of Block 13 and 14 at Universiti Teknologi PETRONAS using the Percussion Gouges Gasoline Driven Hammer.

Percussion gouges is used to obtain reasonably undisturbed samples up to depth of about 3 metres. A total of three samples one meter in length each were obtained from each borehole. The figure below shows the percussion gouges tool and the location of the where the samples were extracted.

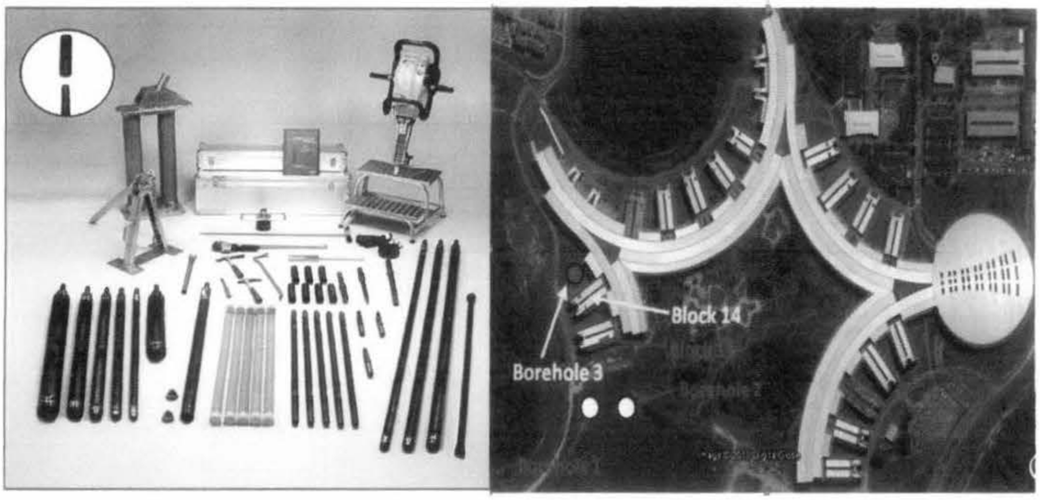


Figure 3.2: Percussion Gouges and Sample Location

3.1.2. Soil Sample Preparation

The samples were wrapped in a plastic nylon after they were obtained from the site by the percussion gouges tool. The samples were brought to laboratory and the one meter samples were further divided in to six segment. The segments were kept in a nylon bags to avoid moisture content losses through evaporation before the experiments are conducted. The segments were taken at the point where the resistivity in the field was measured and then tested for strength/physical soil properties such as moisture content, direct shear test, lab resistivity, unit weight, and plasticity index. The figure below illustrates the segments points.

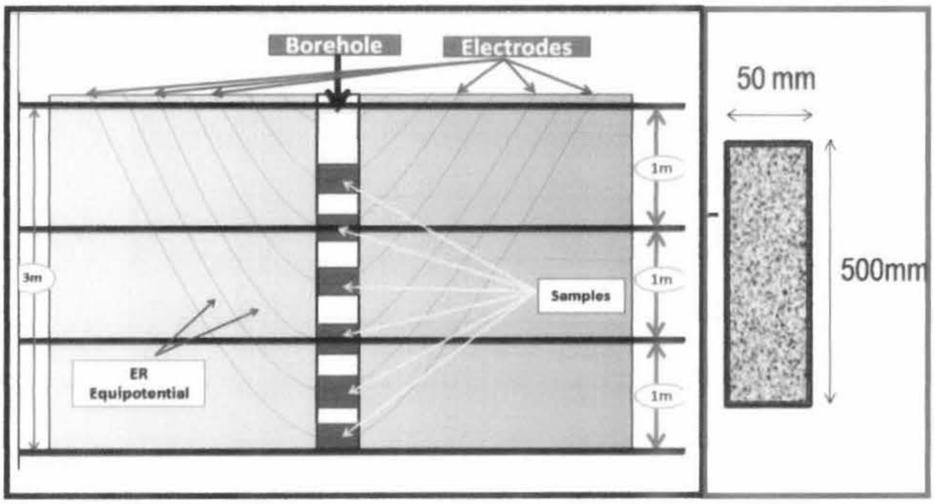


Figure 3.3: Segments Locations/Points

3.1.3. Field Electrical Resistivity Test

The field electrical resistivity (ER) test is conducted using the four equally spaced electrodes known as the Wenner method. The four electrodes are placed in a straight spaced distance D apart as illustrated in the figure 3.4 below. An electrical current is supplied (by a battery or small generator) through the outer electrodes; its value is measured by an ammeter. The voltage drop in the soil material within the zone created by the electrodes' electric field is measured between the two inner electrodes by a simple multi-meter. A measured resistance is calculated by dividing the measured voltage by the measured current. This resistance is then multiplied by a geometric factor that includes the spacing between each electrode to determine the apparent resistivity. The soil material's electrical resistivity is computed by using the following equation:

$$\rho = 2\pi D\,(V/I) = 2\pi DR \qquad (1)$$

Where,
ρ = Resistivity of the Soil Material, Ohm-ft or Ohm-m
D = Electrode Spacing, ft or m
V = Voltage Drop between the Inner Electrodes, Volts
I = Current Supplied through the Outer Electrodes, Amperes
R = Resistance, Ohms

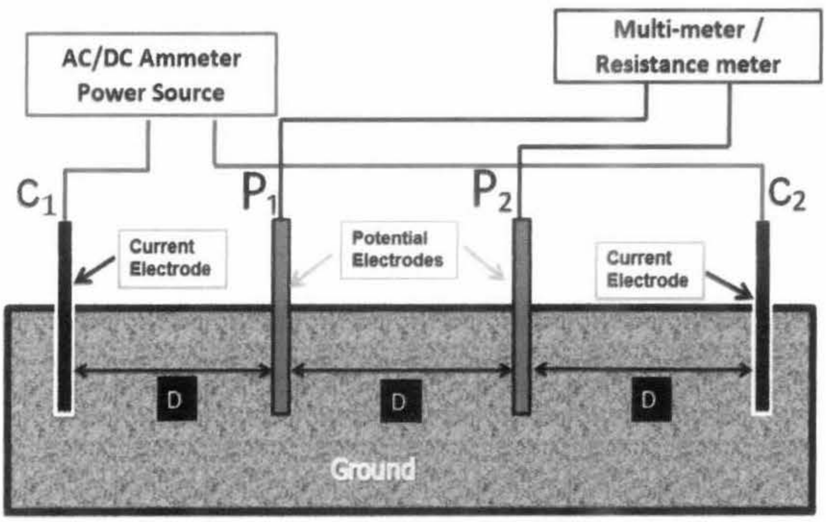


Figure 3.4: Wenner four electrode arrangement

3.1.4. Soil Lab Tests

The laboratory tests or experiments include the following:

3.1.4.1. Laboratory Electrical Resistivity

The laboratory electrical resistivity is conducted using the two electrode aluminium disc method. The segment of the soil sample is placed between the two electrodes. A constant voltage is supplied and the current is measured using multi-meter. The soil resistivity is computed using the following equation/relation:

$$\rho = (A/L)\,(V/I) = (A/L)\,R \qquad (2)$$

Where,
ρ = Resistivity of the soil material, Ohm-cm/Ohm-m
A= Area, $mm^2/cm^2/m^2$ (soil sample)
L = Length, mm/cm/m (soil sample)
V = Voltage supplied, Volt
I = Current measured, amperes/mili-amperes
R = Resistance, Ohms

The figure below illustrates the Laboratory Electrical Resistivity Equipments.

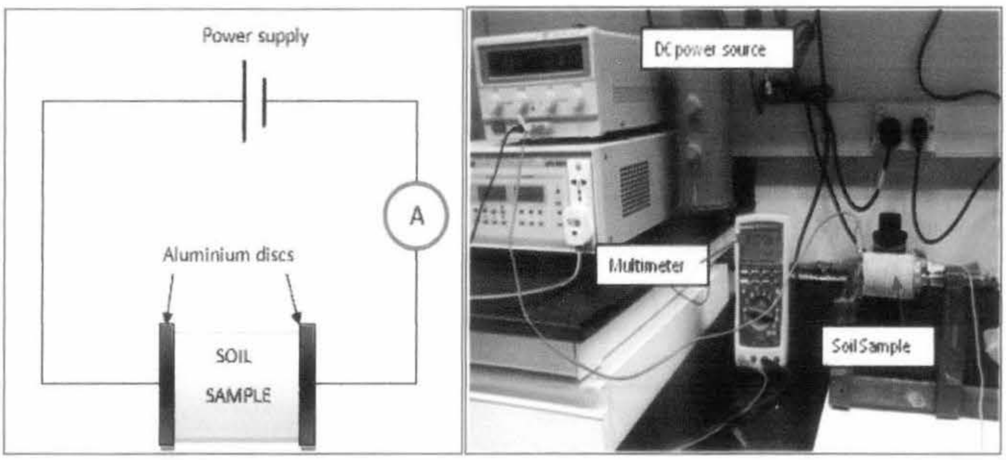


Figure 3.5: The Laboratory Electrical Resistivity Configuration

3.1.4.2. Direct Shear Test

The Direct Shear Test is used for determination of the consolidated drained (or un-drained) shear strength of soils. The test is carried out on three samples of undisturbed soil. The soil sample is placed in a cubic shear box composed of an upper and lower box. The limit between the two parts of the box is approximately at the mid height of the sample. The sample is subjected to a controlled normal stress and the upper part of the sample is pulled laterally at a controlled strain rate or until the sample fails. The applied lateral load and the induced strain are recorded at given intervals. These measurements are then used to plot the stress-strain curve of the sample during the loading for the given normal stress. Different tests results for the same soil are presented in a graph with peak stress on horizontal axis and normal stress on the vertical axis. A linear curve fitting is often made on the test result points. The intercept of this line with the vertical axis gives the cohesion value and its slope gives the peak friction angle value.

The figure below shows the shear & normal stresses plot and direct shear box equipment.

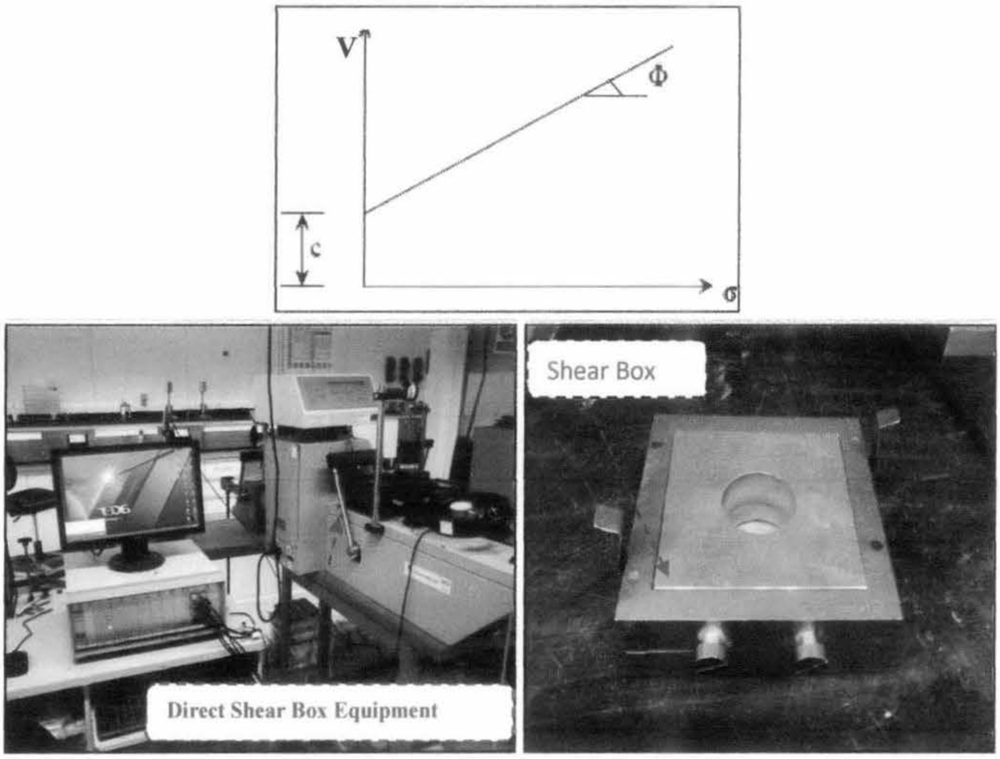


Figure 3.6: Shear & Normal stress Plot and Direct Shear Box Equipment

3.1.4.3. Moisture Content

The moisture content of soil is an indicator of amount of water present in soil. Moisture content is the ratio of the mass of water in a sample to the mass of solids in the sample, expressed as a percentage as in the following expression:

$$w\ (\%) = (M_W/M_S) \times 100 \qquad (3)$$

Where,
w = moisture content of soil (%)
M_w = mass of water in soil sample (i.e. initial mass of moist soil minus mass of oven dried soil
M_s = mass of soil solids in sample (i.e. the soil "oven dried mass")

3.1.4.4. Unit Weight

Bulk Unit Weight (ρ_t) is the weight density, that is, the weight of a soil per unit volume. It computed using the following relation:

$$\rho_t = W_t/V \qquad (4)$$

Where,
ρ_t = wet density (g/cm^3 or kg/m^3)
W_t = weight of the wet soil (g or kg)
V = volume of the wet soil (cm^3 or m^3)

3.1.4.5. Plasticity Index

The plasticity index is the difference between the liquid and the plastic limits. The plasticity index is computed based on the following relations:

$$PI = LL - PL \qquad (5)$$

Where,
PI = Plasticity Index (%)
LL = Liquid Limit (%)
PL = Plastic Limit (%)

3.1.5. Results analysis and correlation

Simple regression analysis was adopted in the analysis and correlation of results in this project study. The data were analysed using the method of least squares regression. Resistivity values were correlated with the corresponding moisture content, unit weight, cohesion, angle of friction and plasticity index values. Linear, logarithmic, exponential and power curve fitting approximations were tried and the best approximation equation with highest correlation coefficient was determined for each regression.

3.2. Tools

Table 3.1: List of Tools and their Purpose/Usage

Tools	Purpose/Usage
✚ Electrical Resistivity Survey ◆ Handheld Multi-meter ◆ D.C. power source ◆ Insulated wires ◆ Measuring tapes ◆ Stainless steel electrodes	✓ Field Electrical Resistivity
✚ Percussion Drilling Set Cobra-TT	✓ Acquisition of undisturbed soil samples
✚ Direct Shear Box	✓ Determination Of Shear Strength (Internal Angle of Friction And Cohesion)
✚ Dry Oven	✓ Drying soil samples
✚ Cone Penetrometer	✓ Liquid limit
✚ Cylindrical PVC Cell	✓ Lab electrical resistivity
✚ Balance	✓ weighing
✚ Spatula	✓ Scooping samples

CHAPTER 4

RESULTS AND CORRELATIONS

Three field electrical resistivity tests had been conducted and three sets of samples had been extracted from two boreholes at the locations where the field electrical resistivity were conducted. The three sets of the samples had undergone the Lab Electrical Resistivity and Soil Strength Properties (Direct Shear, Moistures Content, Plasticity Index, and Unit Weight) tests.

4.1. Electrical Resistivity and laboratory Results

Results from the field electrical resistivity tests conducted at the location of borehole 1, 2 and 3 (BH1, 2 & 3) are presented in Table 4.1, 4.2 and 4.3.

Table 4.1: Field Resistivity Results at Location BH 1

Field Electrical Resistivity Data				
Spacing (m)	Current (amperes)	Voltage (volts)	Resistance (ohm)	Resistivity (ohm.m)
0.5	0.02	18.77	938.50	2948.30
1	0.02	3.26	162.92	1023.60
1.5	0.02	1.30	65.19	614.35
2	0.02	0.58	28.86	362.61
2.5	0.02	0.52	26.10	409.96
3	0.02	0.36	18.15	342.10

Table 4.2: Field Resistivity Results at Location BH 2

Field Electrical Resistivity Data				
Spacing (m)	Current (amperes)	Voltage (volts)	Resistance (ohm)	Resistivity (ohm.m)
0.50	0.02	1.52	76.00	238.75
1.00	0.02	0.65	32.50	204.20
1.50	0.02	0.17	8.65	81.52
2.00	0.02	0.08	4.00	50.26
2.50	0.02	0.02	1.15	18.06
3.00	0.02	0.05	2.50	47.12

Table 4.3: Field Resistivity Results at Location BH 3

Field Electrical Resistivity Data				
Spacing (m)	Current (amperes)	Voltage (volts)	Resistance (ohm)	Resistivity (ohm.m)
0.5	0.02	0.54	26.89	84.44
1	0.02	0.35	17.41	109.37
1.5	0.02	0.28	14.14	133.31
2	0.02	0.23	11.58	145.47
2.5	0.02	0.19	9.53	149.77

From the results shown in Tables 4.1 and 4.2, it is clear that resistivity of the soil decreases with depth instead of increasing as stated in the research conducted by B. S. O. Syed & Z. T. H. Zuhar, 2010. [Correlation of electrical resistivity with some soil properties in predicating factor of safety in slopes using simple multimeter," *presented at the Conference on Sustainable Building and Infrastructure,* 15th-17th June, Kaula lumpur, Malaysia.]

Borehole (BH) 1 results shows the value of resistivity from the surface to the depth of 3 meter ranges from 2948.30 to 342.10 ohm.m and borehole 2 ranges between 238.75 to 47.12 ohm.m. The decreasing resistivity is due to high ground water table which was evident at the borehole location at a depth of about 1.5 meters from the surface.

However, there exists a significant difference between the boreholes results (BH 1 & 2). The author suspected that the BH-1 samples might contain a large fraction of coarse grained soil particles (e.g. sand) which made the resistivity to read high, whereas for the BH-2, the low electrical resistivity could be attributed to existence a large fraction of fine grained soil particles (e.g. clay). This is because clay soil increases the electrical conductivity due to its ability to retain surface charges. Thus, this could be the reason why BH-2 has low resistivity with regard to BH-1.

However, borehole 3 ranges from 84.44 to 47.12 ohm.m. It indicates that resistivity increases with increasing depth and this could be due to high sandy soil content which tends to give high resistivity.

In order to look at the possible correlation of electrical resistivity obtained and the various soil strength parameters, the results of the resistivity are then compared to the values obtained in the laboratory from the borehole samples. The results are presented in Tables 4.4, 4.5 and 4.6 below.

From table 4.4, 4.5 and 4.6 below, there is also significant difference between the laboratory electrical resistivity for the results in table 4.4 and 4.5. The same explanations stated above for the field electrical resistivity could be attributed here too.

However, the laboratory electrical resistivity for BH-1 (table 4.4) is volatile. This volatility could be attributed to different fractions coarse and fine grained soils content of the soil segments used in conducting the laboratory electrical resistivity. This could probably explain why the resistivity is so volatile.

TABLE 4.4: Combined Results from Laboratory and Field Electrical Resistivity BH-1

Sampling Depth (m)	Field Electrical Resistivity (ohm.m)	Lab Electrical Resistivity (ohm.m)	Moisture Content (%)	Wet Unit Weight (KN/m^3)	Cohesion (KPa)	Angle of Internal Friction (φ)	Plasticity Index
0.5	2948.30	1831.98	23.67%	19.99	22.03	29.11	8.94
1	1023.60	2947.40	23.44%	19.17	25.60	16.48	1.41
1.5	614.35	661.23	34.36%	18.18	27.80	6.84	17.23
2	362.61	701.83	42.01%	18.12	21.73	9.48	20.35
2.5	409.96	974.53	32.65%	18.90	25.60	8.08	8.87
3	342.10	1809.17	34.95%	21.87	39.20	10.48	6.04

TABLE 4.5: Combined Results from Laboratory and Field Electrical Resistivity BH-2

Sampling Depth (m)	Field Electrical Resistivity (ohm.m)	Lab Electrical Resistivity (ohm.m)	Moisture Content (%)	Wet Unit Weight (KN/m^3)	Cohesion (KPa)	Angle of Internal Friction (φ)	Plasticity Index
0.5	238.75	410.95	18.79%	20.13	15.92	23.22	9.23
1	204.20	469.76	37.76%	18.39	29.59	31.51	2.35
1.5	81.52	378.65	40.06%	17.38	18.67	23.21	15.35
2	50.26	131.36	52.42%	16.52	21.91	5.36	22.14
2.5	18.06	108.25	45.55%	16.45	11.40	13.01	9.89
3	47.12	108.54	51.79%	17.33	5.16	10.02	8.23

TABLE 4.6: Combined Results from Laboratory and Field Electrical Resistivity BH-3

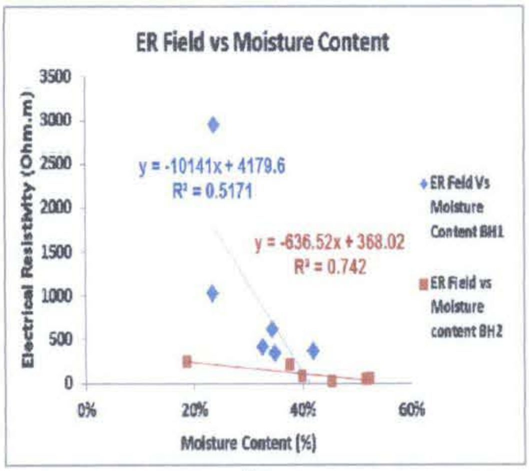
Sampling Depth (m)	Field Electrical Resistivity (ohm.m)	Lab Electrical Resistivity (ohm.m)	Moisture Content (%)	Wet Unit Weight (KN/m^3)	Cohesion (KPa)	Angle of Internal Friction (φ)	Plasticity Index
0.5	84.44	81.35	36.05%	2048.04	1652.98	20.09	16.22
1	109.37	142.43	17.23%	1951.11	1659.25	19.14	16.28
1.5	133.31	193.50	15.23%	1862.34	1438.27	18.27	14.11
2	145.47	168.70	19.25%	1817.51	1399.66	17.83	13.73
2.5	149.77	98.14	28.32%	1796.63	1372.17	17.62	13.46

4.2. Correlations and Discussion

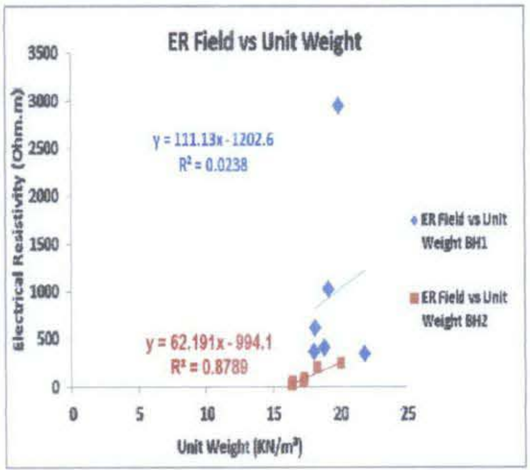
The results from electrical resistivity tests (field and laboratory) and laboratory tests for borehole 1, 2 and 3 were analysed to find the similarities between electricity resistivity and soil strength properties (moisture content, unit weight, cohesion, angle of friction, plasticity index, and unit weight of soil). The correlations between electrical resistivity and strength properties of the soil samples were evaluated using least-squares regression linear, logarithmic, polynomial, exponential, and power curve fitting approximations methods. The approximation equations with correlation coefficient were obtained. However, it should be noted that the curve fitting does not have any relation with the correlations of the resistivity and the of strength properties of the soil.

In order to look at the possible correlation of electrical resistivity obtained and the various soil parameters, the results of the resistivity were then compared to and plotted against values from the borehole results and are shown in figures 4.1 and 4.2 and 4.3 respectively.

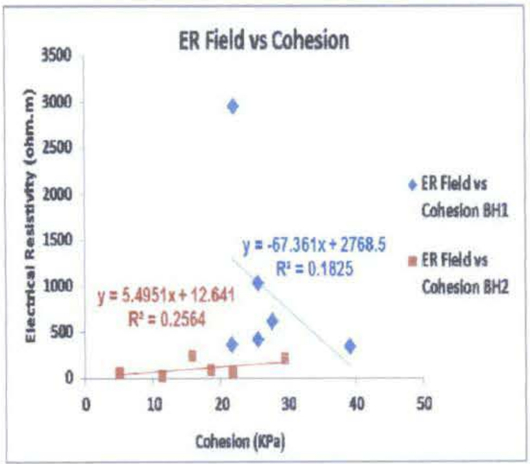
Borehole 1&2 Correlation of Field Electrical Resistivity with some Strength Properties of Soils



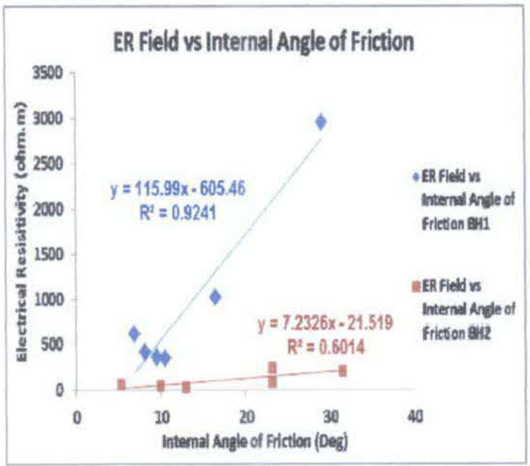
A



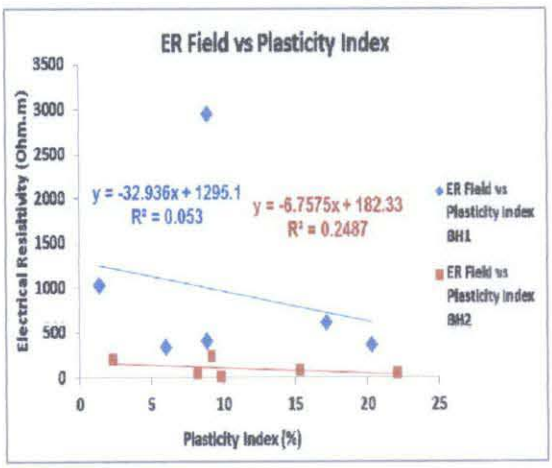
B



C



D



E

Figure 4.1: BH 1 & 2 Field Electrical Resistivity Correlations

Correlations between electrical resistivity values obtained from the field and soil strength properties are shown in Fig.4.1:

Relationship between moisture content and electrical resistivity value demonstrates that resistivity decreases with increasing moisture content and vice versa.

On the other hand, conductivity depends on the amount of moisture content in the tested material in which Figure 4.1: A proves that as moisture content increases, conductivity increases and therefore resistivity decreases (shown in Fig.4.1: A Borehole 1 & 2) as reported in various published research literatures.

Fig.4.1: B indicates that as resistivity increases and decreases, the wet unit weight remains within certain the range for both Borehole 1 & 2. However, it should be noted that resistivity beside moisture content also depends on the porosity of the material/soil and the higher the porosity, the higher is the resistivity.
Higher porosity generally reduces the unit weight and this is not reflected in the results obtained in Figure 4.1 B. The author suspects that the higher resistivity is contributed by the increase in sandy size particles and lower resistivity by increase of water content or the clay fraction in the soil which probably explains the higher and lower resistivity values.

Fig. 4.1: C (Borehole 1 & 2) demonstrates lack of correlation between electrical resistivity and cohesion. As the cohesion increases, the resistivity decreases and increases as well. This could be due to existence of large fraction of coarse grained soil content which tends to give high resistivity and low cohesion.

Or it could also be due to existence of large fraction of fine grained soil content which tends to produce low resistivity and high cohesion. This could perhaps explain why there is lack of correlation between the electrical resistivity and cohesion.

Fig. 4.1: D shows increasing resistivity with increasing frictional angle (φ) from borehole 1 and 2. This probably could be due to the fact that the increasing frictional angle is an indication that samples contains more sandy material which results into the higher resistivity value.

Fig. 4.1 E (borehole 1 & 2) indicates that resistivity increases with decreasing plasticity index. This inverse relation can be attributed to moisture content as we know that plasticity index is quantity or the range of water contents where the soil exhibits plastic properties. Moisture content increases electrical conductivity and hence reduces the resistivity of soil.

The low resistivity could also be attributed to existence of a large of fined grained soil content. This is because fined grained exhibits surface charge and hence it increases electrical conductivity. This might also explain why electrical resistivity decreases as the plasticity index increases.

Borehole 1 & 2 Correlation of Lab Electrical Resistivity with Strength Properties of Soils

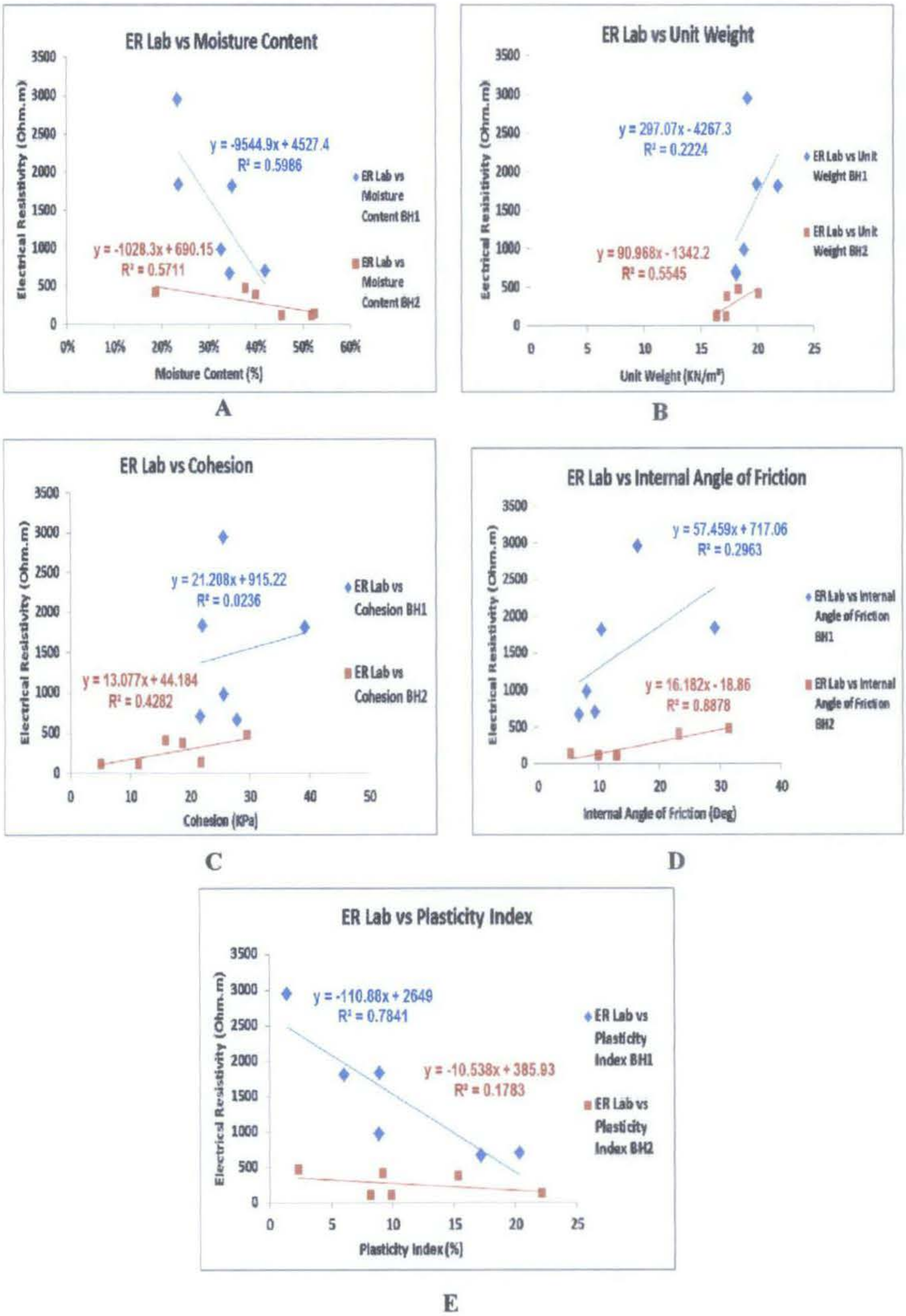


Figure 4.2: BH 1 & 2 Lab Electrical Correlations

Correlations between electrical resistivity values obtained from the laboratory and some soil strength properties are shown in Fig.4.2. It exhibits the same correlation relation of those obtained from the correlation of field electrical resistivity with strength properties of soil.
This same trend to some extend validates the results and correlation obtained from borehole one and two. The same explanation stated above in the field electrical resistivity with strength properties of soil can also be ascribed here.

Relationship between moisture content and lab electrical resistivity value demonstrates that resistivity decreases with increasing moisture content (Fig.4.2: A Borehole 1 & 2).

From another standpoint, conductivity depends on the amount of moisture content in the tested material in which Figure 4.2: A proves that as moisture content increases, conductivity increases and therefore resistivity decreases (shown in Fig.4.2: A Borehole 1 & 2) as reported in various published research literatures.

Fig.4.2: B indicates that as resistivity increases and decreases, the wet unit weight remains within certain the range for both Borehole 1 & 2. However, it should be noted that resistivity beside moisture content also depends on the porosity of the material/soil and the higher the porosity, the higher is the resistivity.
Higher porosity generally reduces the unit weight and this is not reflected in the results obtained in Figure 4.2: B. The author suspects that the higher resistivity is contributed by the increase in sandy size particles and lower resistivity by increase of water content or the clay fraction in the soil which probably explains the higher and lower resistivity values.

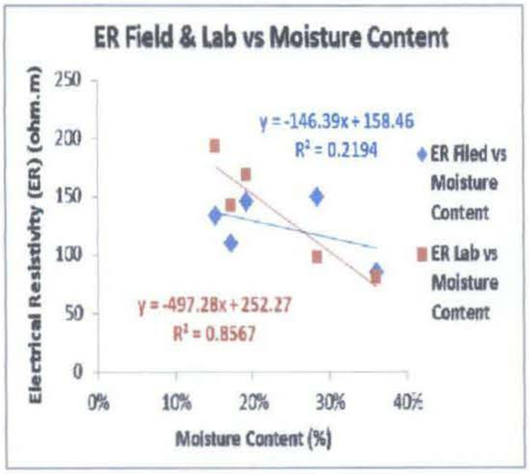
Fig. 4.2: C (Borehole 1 & 2) demonstrates lack of correlation between electrical resistivity and cohesion. As the cohesion increases, the resistivity decreases and increases as well. This could be due to existence of large fraction of coarse grained soil content which tends to give high resistivity and low cohesion.
Or it could also be due to existence of large fraction of fine grained soil content which tends to produce low resistivity and high cohesion. This could perhaps explain why there is lack of correlation between the electrical resistivity and cohesion.

Fig. 4.2: D shows increasing resistivity with increasing frictional angle (φ) from borehole 1 and 2. This probably could be due to the fact that the increasing frictional angle is an indication that samples contains more sandy material which results into the higher resistivity value.

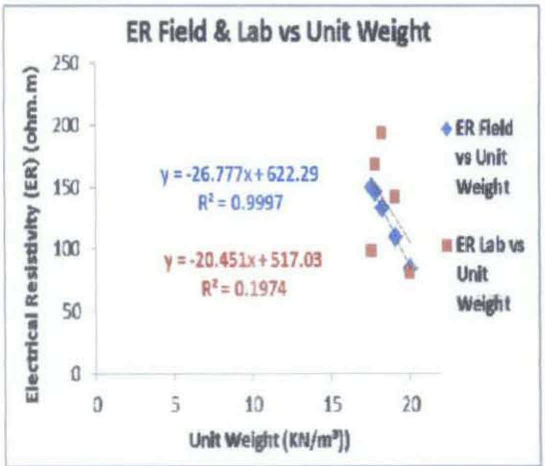
Fig. 4.2: E (borehole 1 & 2) indicates that resistivity increases with decreasing plasticity index. This inverse relation can be attributed to moisture content as we know that plasticity index is quantity or the range of water contents where the soil exhibits plastic properties. Moisture content increases electrical conductivity and hence reduces the resistivity of soil.

The low resistivity could also be attributed to existence of a large of fined grained soil content. This is because fined grained exhibits surface charge and hence it increases electrical conductivity. This might also explain why electrical resistivity decreases as the plasticity index increases.

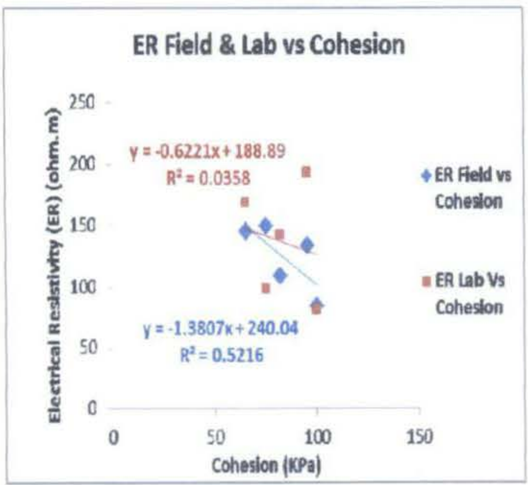
Borehole 3 Correlation of Field and Lab Electrical Resistivity with Strength Properties of Soils



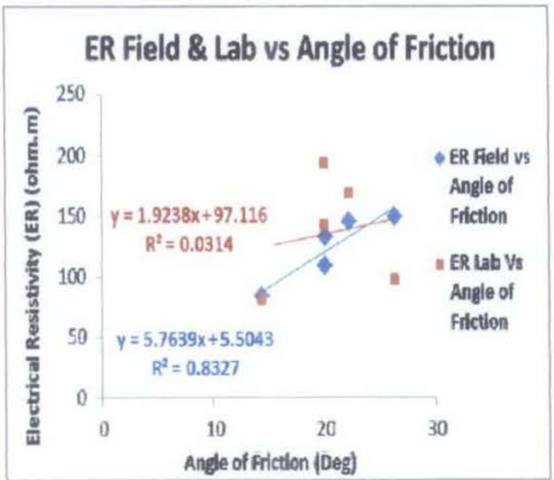
A



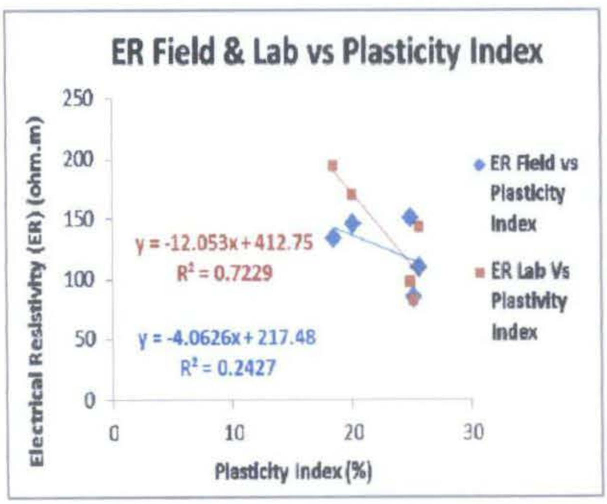
B



C



D



E

Figure 4.3: BH 3 Field & Lab Electrical Correlations

A correlation between electrical resistivity and soil strength properties for borehole 3 is shown in Fig.4.3. It exhibits the same correlation relation of those obtained from borehole 1 and 2.

The same explanation stated above in the borehole 1 and 2 can be also attributed here.

Relationship between moisture content and field & lab electrical resistivity value demonstrates that resistivity decreases with increasing moisture content (Fig.4.3: A Borehole 3).

From another standpoint, conductivity depends on the amount of moisture content in the tested material in which Figure 4.3: A proves that as moisture content increases, conductivity increases and therefore resistivity decreases (shown in Fig.4.3: A Borehole 3) as reported in various published research literatures.

Fig.4.3: B indicates that as resistivity decreases, the wet unit weight increases borehole 3. However, it should be noted that resistivity beside moisture content also depends on the porosity of the material/soil and the higher the porosity, the higher is the resistivity.

Higher porosity generally reduces the unit weight and this is not reflected in the results obtained in Figure 4.3: B. The author suspects that the higher resistivity is contributed by the increase in sandy size particles which may probably explain the higher resistivity values.

Fig. 4.3: C (Borehole 3) demonstrates lack of correlation between electrical resistivity and cohesion. As the cohesion increases, the resistivity decreases and increases as well. This could be due to existence of large fraction of coarse grained soil content which tends to give high resistivity and low cohesion.

Or it could also be due to existence of large fraction of fine grained soil content which tends to produce low resistivity and high cohesion. This could perhaps explain why there is lack of correlation between the electrical resistivity and cohesion.

Fig. 4.3: D shows increasing resistivity with increasing frictional angle (φ) from borehole 3. This probably could be due to the fact that the increasing frictional angle

is an indication that samples contains more sandy material which results into the higher resistivity value.

Fig. 4.3: E (Borehole 3) indicates that resistivity increases with decreasing plasticity index. This inverse relation can be attributed to moisture content as we know that plasticity index is quantity or the range of water contents where the soil exhibits plastic properties. Moisture content increases electrical conductivity and hence reduces the resistivity of soil.

The low resistivity could also be attributed to existence of a large of fined grained soil content. This is because fined grained exhibits surface charge and hence it increases electrical conductivity. This might also explain why electrical resistivity decreases as the plasticity index increases.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The main objective of the study is to correlate electrical resistivity with strength properties of soil. From the results and with these deficient or limited amount of data obtained, it can be concluded that there exists correlation between electrical resistivity and strength properties of soil.

The results indicate that there is correlation between electrical resistivities (field and laboratory) with moisture content, internal angle of friction, and plasticity index. However, there is an indication of lack of correlation between electrical resistivities with unit weight and cohesion. The overall trend is tabulated in the table 5.1 below:

Table 5.1: Overall Correlation Trend

Field & Laboratory Electrical Resistivity	Soil Strength Properties
↑	Moisture content ↓
↔	Unit weight ↔
↔	cohesion ↔
↑	Angle of Friction ↑
↑	Plasticity Index ↓

5.2. Recommendation

The method used in analysis of the data and results obtained in this study were repudiated due to the limited amount of data obtained and also due to opposition of the study to the current practice in field of electrical resistivity.

Therefore, for future study, it is recommended that more field and laboratory tests be conducted to obtain more or massive data in order to validate the method of analysis used in this study and also to achieve better correlations which eventually would enable elimination of discrepancies in the results. In addition to that, field strength tests should be conducted to supplement or confirmed the data obtained through the resistivity test.

It is also recommended that electrical resistivity and laboratory geotechnical test be conducted at different moisture content to enable proper correlation. This is because moisture content has major effect on electrical resistivity.

Finally, laboratory electrical resistivity were volatile and not consistent with the field electrical resistivity, thus, electrical laboratory resistivity should be correlated with the field electrical resistivity find out whether they are closely related or find out why there is volatility in the laboratory electrical resistivity with regards to the field resistivity. It is also recommended that inversion of field electrical resistivity be conducted to enable proper correlation.

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APPENDIX

Appendix 1 Gantt Chart

APPENDIX 1
GANTT CHART

N0	PROJECT ACTIVITIES	SEMESTER ONE WEEKS														SEMESTER TWO WEEKS															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Selection of Project Topic																														
2	Preliminary Research Work																														
3	Submission Of Extended Proposal Defence/Preliminary Report																														
4	Preliminary Proposal Defence																														
5	Project Work Continues																														
6	Submission Of Interim Draft Report																														
7	Submission Of Interim Report																														
8	Field & Laboratory Tests																														
9	Submission of Progress Report																														
10	Pre-EDX																														
11	Submission of Draft Final Report																														
12	Submission Final Report																														
13	Submission of Technical Paper																														
14	Viva																														
15	Submission of Final Hardbound Dissertation Report																														
			Process										**Major Milestone**									**Laboratory and Field Tests**									