SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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GEOPHYSICAL 2D SELF-POTENTIALS AND EARTH RESISTIVITY SURVEY OVER SLOPE STABILITY STUDY

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled **"Geophysical 2D Self-Potential and Earth Resistivity Survey over Slope Stability Study".** I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this for any other examining body or university.

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TABLE OF CONTENTS

Contents **Page**

LIST OF TABLES

LIST OF FIGURES

KAEDAH GEOFIZIK POTENSI KENDIRI DAN KEBERINTANGAN UNTUK KAJIAN KESTABILAN CERUN

ABSTRAK

Dalam projek ini, kaedah geofizik iaitu keberintangan dan potensi kendiri telah digabungkan untuk membuat kajian kestabilan cerun di Kampung Sungai Buaya, Nibong Tebal, Penang. Secara umumnya, struktur geologi bandar ini terdiri daripada deposit terluluhhawa kuarteneri yang merujuk kepada lempung, pasir dan batu kerikil di bawah batuan dasar granite. Kawasan kajian ialah tanah rendah dan terdiri daripada deposit alluvium. Cerun itu ialah cerun semulajadi dan jenis tanahnya ialah berpasir dan lempung berpasir. Darjah kecerunan ialah 30^0 menghala ke barat dan terletak di kawasan tanam-tanaman. Kestabilan cerun dipengaruhi oleh banyak faktor. Survei potensi kendiri dan keberintangan diaplikasikan untuk mengkaji pengaruh ciri-ciri tanah terhadap kestabilan cerun. Survei dijalankan sewaktu musim panas dan musim hujan untuk memerhati ketepuan air dalam cerun. Keputusan potensi kendiri menunjukkan air bawah tanah bergerak menuruni cerun. Selepas hujan, ketepuan air meningkat dan cerun menjadi lemah. Bahan berdekatan permukaan iaitu lempung berpasir mempunyai nilai resistiviti rendah menunjukkan kehadiran air. Nilai keberintangan sederhana tinggi merujuk kepada jenis tannah berpasir. Campuran pasir dan lempung meningkatkan kekuatan bahan dalam cerun terutamanya dalam keadaan lembap kerana wujud daya permukaan air dan daya geseran antara satu sama lain. Tanaman di sekeliling membantu menetapkan cerun dengan pengukuhan oleh akar dan penyerapan lebihan air. Kesimpulan dibuat iaitu cerun yang dikaji mempunyai kestabilan yang tinggi.

GEOPHYSICAL 2D SELF-POTENTIAL AND EARTH RESISTIVITY SURVEY OVER SLOPE STABILITY STUDY

ABSTRACT

In this project, geophysical methods of self-potential and electrical resistivity survey are joined to study slope stability at Kampung Sungai Buaya, Nibong Tebal, Penang. Generally, the geological structure of this town consists of quaternary unconsolidated deposit which refers to loose materials, ranging from clay, sand to gravel underlain by granitic bedrock. The study site is a natural ground slope and the soil type within the slope is brownish sandy to sandy clay. The slope angle was 30^0 in the direction towards west and located in a vegetated area. Slope stability is affected by many factors namely the slope angle, rainfall distribution and groundwater, type of material within slope and vegetation. SP and resistivity surveys are applied to investigate the influence of soil properties on slope stability. The surveys are conducted on hot weather and rainy season to observe the water saturation in soil slope. SP results show that water movement down the slope. After rainfall, water saturation increases which leads to weakening of the slope. Near surface materials which are sandy clay soils have low resistivity values indicating the high moisture content. Moderately high resistivity values obtained refer to sandy type of soils. Mixture of sand and clay increases the strength of soil slope materials especially in moist condition due to water surface tension and frictional contact to each other. Vegetation around the study area helps to keep slope in place by roots reinforcement and absorption of excessive water. Thus, it is concluded that the studied soil slope has high stability.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Geophysical methods are used to determine the physical properties of sub-surface materials from surface measurements. Each geophysical technique measures a distinct variable depending on the physical properties. For examples, magnetic survey is carried out based on the magnetic susceptibility of the target, gravity survey measures the magnitude of gravitational field or density, and seismic survey relies on the properties of P-wave and S-wave velocity. Applications of geophysical methods include hydrocarbon exploration, mineral exploration, engineering site investigation, hydrogeological investigation, detection of cavities and mapping of leachate and contaminant plumes. The variation of physical properties influences the implementation of geophysical methods for a particular situation.

These techniques are non-destructive and do not cause disturbance of sub-surface materials. Other than that, they are rapid and cost-effective in covering a large study area. Two dimensional (2-D) methods measure geophysical properties along a surface survey line which will produce cross-section through subsurface. 3-D techniques determine those properties over an area. In this project, electrical methods which include 2-D self-potential survey and earth resistivity survey are chosen for the purpose of slope stability study. The study area is a slope of a palm plantation in Kampung Sungai Buaya, Nibong Tebal, Pulau Pinang.

1.2 Problem Statement

Unstable slope is caused by to various factors such as high water content due to significant rainfall dispersal, weak soil or rock mass, geological discontinuities and also unstable angle. These factors contribute to the increasing of shear stress which is the force that pushes the slope and decreasing shear strength that holds the slope in place. Then, it will lead to soil dislocation or mass movement that may trigger slope failure, especially near surface. Slope failure involves soil movement or sliding down the slope and also debris flow which brings along vegetation with soil dislocation. Disaster such as landslides and debris flows can cause property damage and loss of life. In order to minimise the failure, physical properties of the subsurface materials are fundamental because they are one of the aspects that contribute to slope failures. Geophysical methods are applied to investigate subsurface structure and moisture content for the slope stability study.

Seismic methods are often the most suitable because the measurements depend on the mechanical properties that are also useful in the mechanical calculation of slope stability assessment. The chosen methods are self-potential or spontaneous potential and electrical resistivity survey. Electrical resistivity technique is used to find groundwater condition and to locate sub-surface cavities. Resistivity imaging can determine the structure of subsurface materials. Self-potential (SP) survey is the simplest and oldest technique to detect the presence of massive ore bodies. In recent years, SP method has been extended to groundwater and geothermal investigations. SP and electrical resistivity techniques are complementary for slope stability study.

1.3 Objectives

The objectives of this project are listed below :

- To study the slope stability in Kampung Sungai Buaya area using self-potential and electrical resistivity geophysical surveys.
- To investigate the influence of the soil properties (water content and soil type) on slope stability.

1.4 Geophysical Surveys Over Slope Stability Study

Slope stability is the potential of an inclined surface to resist failure by the movement of rock or soil mass down the slope. Sliding or collapsing of slopes is mainly driven by the gravitational force which resolved into the components of shear stress and shear strength. Slope can experience failures due to erosion, rainfall, earthquake, geological factors and topography change. Slope failures are popularly known as landslides or mass wasting. Types of slope failures are circular failure, planar failure surfaces, wedge failures, and toppling failures.

There are various controlling factors of slope stability such as soil or rock strength, type of soil and its stratification, discontinuities and plane of weakness, groundwater and seepage through the slope and also slope geometry. Moisture content has a great influence on slope stability. Water pressure acting in the pore spaces or fractures will affect the strength of slope materials.

For examples, strength of the soils will reduce when large amount of water present and saturate the pore spaces. This is because excessive water pushes the grains apart and eliminates the frictional contact that keeps them together, especially when pressure acts on the water. Whereas, dry soils which have air filling the pore spaces are held together by the friction between grains with minimal cohesion. Adequate level of water can improve the soil strength because the surface tension of thin water films holds the grains in place.

It is a pre-requisite to know the physical properties of the soil or rock mass of slope to analyse the slope stability. Direct observation of sub-surface materials through boreholes is always preferred but it is way too costly. Slope can experience failures due to various factors. In order to minimise the failure, physical properties of the subsurface materials are fundamental and geophysical methods can be applied for the slope stability study.

Geophysical techniques have been used for slope investigation increasingly. They are based on the field acquisition of physical measurements from which physical parameters can be deduced, generally through inversion or imagery process. Strength of the slope depends on the role of water and also subsurface structure such as cavities and unconsolidated soils. The information of these factors can be obtained using geophysical surveys. For this research over slope stability study, electrical surveying is chosen which include resistivity method and self-potential method.

1.4.1 Resistivity Survey

Electrical resistivity survey is a geophysical method for imaging internal structure from resistivity (inverse of conductivity) measurement. This survey determines apparent resistance of ground to direct current flow. A display of tomographic inversion or resistivity imaging is one of the geophysical techniques employed to map subsurface structure which then can be used to investigate slope stability.

The measurements are made by penetrating steel electrodes in soil to allow direct current to pass through. The current and potential electrodes are moved along a profile with the spacing according to electrode arrays. Common electrode arrays are Wenner Alpha, Wenner Schlumberger and dipole-dipole. Each has its own advantages and disadvantages and some can be complementary with each other. Electrode configurations used for this resistivity survey are Wenner Alpha and dipole-dipole.

1.4.2 Self-Potential Survey

Self-potential method measures spontaneous or naturally occurring electrical potential differences between two points on the ground along the profile lines, commonly in units of millivolts (mV). The self-potentials develop based on processes such as electrochemical and streaming potentials that are influenced by groundwater as controlling factor. Topography and heavy rainfalls can affect self-potentials. On regular ground, the anomalies are typically in the range of a few millivolts. When measuring over a mineralized area, SP anomaly shows negative voltages of several hundred millivolts and down to a volt. SP method is passive because no electric current is required during the procedure.

The materials and equipment needed for SP surveying is very simple. It consists of two non-polarising porous pot electrodes in contact with ground and connected to a voltmeter. Normally, SP method is combined with resistivity survey and the data interpretation is done qualitatively. The main application of SP survey is in mineral exploration because it can locate massive ore bodies. Self-potential is also used to detect porous zones in a borehole where oil can exist.

However, this technique is used less today because other geophysical methods are taking over and most ore bodies that are close enough to the surface to be detected by SP have already been discovered. It is difficult to use SP for finding deeper ore bodies.

1.5 Survey Location and Geology

Geophysical survey is carried out at Kampung Sungai Buaya, Nibong Tebal which is situated at approximately 100° 32' 44" E and 5° 09' 58" N. Nibong Tebal district is located in Penang mainland, the northern region of Peninsular Malaysia and it is bounded by Kedah and Perak state. Generally, the geological structure of this town consists of quaternary unconsolidated deposit which refers to loose materials, ranging from clay to sand to gravel over granitic bedrock. According to geological map of Peninsular Malaysia (**Appendix A**), area of Nibong Tebal comprise unconsolidated deposit of sand, clay and silt.

The rocks beneath the ground are impacted by weathering because of the hot and humid tropical climate in the Malay Peninsula where almost everywhere the granite mass is covered by soil and alluvium. **Figure 1.1** shows a typical weathering profile over porphyritic biotite granite. The weathering profiles are characterized by lateral and vertical variations that allow recognition of several morphological zones and horizons that can be correlated with Rock Mass Weathering Grades (Raj, 1983, 1985). The weathered materials can be separated into an upper, sandy clay IA horizon (<1 m thick), an intermediate, sandy clay IB horizon (<2 m thick) and a lower, stiff to very stiff, gravelly sandy clay, IC horizon (up to 10 m thick).

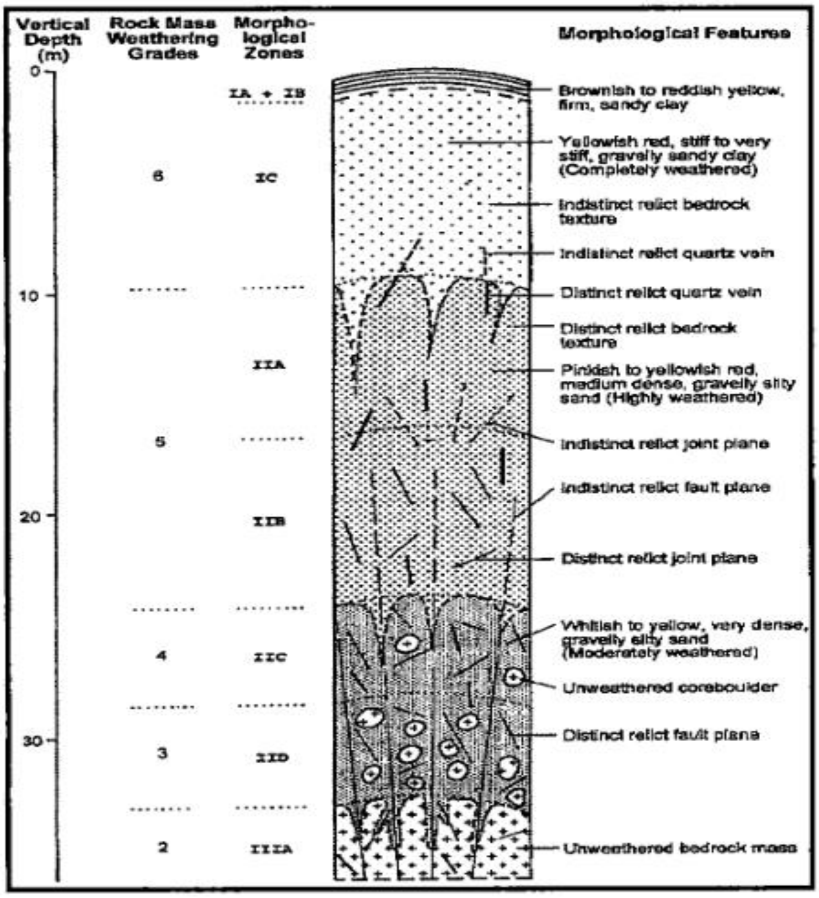

Figure 1.1 Weathering profile over porphyritic biotite granite

The study site chosen is a lowland area, with estimated terrain elevation above sea level of 25 metres, and made up of alluvial deposits. It is a natural ground slope and the soil type within the slope is brownish sandy clay. The location is in a palm plantation area and the surroundings are covered mostly with plantations, estates as well as forest (**Figure 1.3)**. Residential areas are scattered around the region and the nearest water source is Sungai Kechil. The area of investigation is about 700m^2. It has a slope angle of 30^o (**Figure 1.2**). There are three survey lines conducted to study the slope stability of that site.

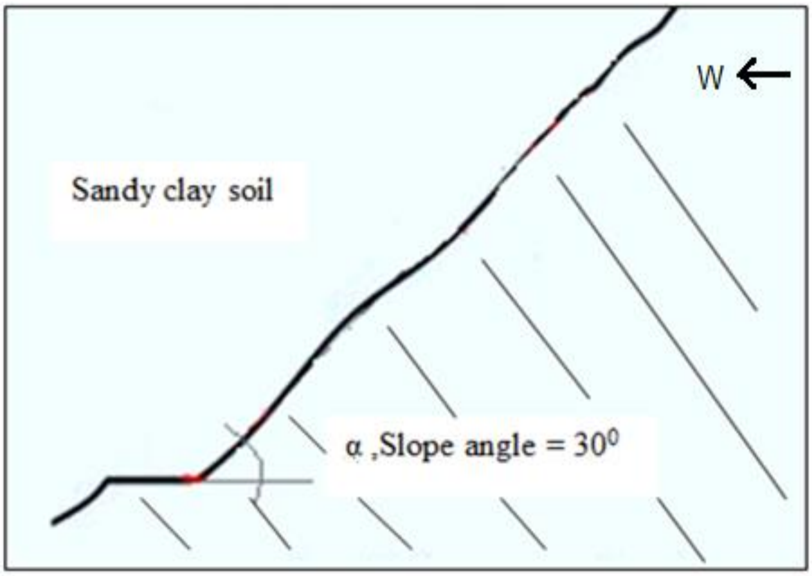

Figure 1.2 Slope of investigation

Figure 1.3 Study area

Rainfall distribution in Malaysia varies according to seasons. For North Peninsula, average of 2000-2300 mm rainfall is distributed annually. High amount of rainfall received by north area occurs in April – May while minimum dispersal occurs in January – February (Malaysian Meteorological Department, 2017).

When the project was held from February to May, rainy season started in the end of March. North area received average amount of rainfall because March is the ending month of Northeast Monsoon. Then, there is a period between Northeast Monsoon (early November to March) and Southwest Monsoon (late May to September) called inter-monsoon season. During this transition, winds are light and variable. Morning skies are usually clear and thunderstorm developed in the afternoon and early evening. Rains from thunderstorms contribute to the increase of rainfall distribution.

1.6 Scope of Work

After the approval of research proposal, the project was being held for about 14 weeks, starting from February until May. The work outline and tasks had been carried out to achieve the above objectives. Firstly, basic knowledge is vital before proceeding to research work and it can be obtained from literature readings. Literature review is the assessment of available scholarly paper of the chosen research subject. It discusses and analyses the information gathered from published resources of that particular topic in a summary. This helps me to understand the concepts and theory related to my research of geophysical methods over slope stability study. Literature review serves as support and foundation of substantive findings as well as gives an overview to make this research possible.

Next task is to select the study area. To investigate slope stability, a slope or an inclined surface must be chosen whether it is natural or man-made. Nibong Tebal district is considered as low-land area and there are not many hilly surfaces. However, in Kampung Sungai Buaya which is close to Bukit Panchor State Park, a slope in a palm plantation exists. This site consists of forest mostly and also scattering housing areas.

Since the slope condition is dangerous like some parts are too steep and covered with thick bushes, only a small specified area can be taken as study site. This project is significant to assess and monitor slope stability around the area so that when slope failure is going to happen, the residents can be alerted about it. After selection of worksite, information of that selected study site such as the slope angle, area, map and geology are gathered.

After getting adequate site information, investigation of the study area was carried out using proposed research methodology. For slope stability investigation, the methods used are geophysical techniques which include self-potential survey and electrical resistivity survey. Data acquisition is done during this stage considering all parameters that will affect the results. Self-potential survey involves data of potential differences between two points on the ground while electrical resistivity measures the resistivity along survey lines which is influenced by electrode array configuration.

The application of software such as Surfer 8, ImagerPro 2006 and RES2DINV helps to process the data so that the results are able to be assessed and interpreted. The results obtained are analysed and presented in a way that ensure the objectives of this research are satisfied. After all tasks are done, research conclusion has to be stated clearly by restating the argument and summarizing the main points of thesis to emphasize what this project is all about. Then, recommendations are suggested to improve the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Slope Stability

Slope stability is the potential of an inclined surface to resist failure by the movement of rock or soil mass down the slope. Slope can experience failures due to erosion, rainfall, earthquake, geological factors and topography change. Slope failures are popularly known as landslides or mass wasting. Slope stability is ultimately determined by two factors: the angle of the slope and the strength of the materials on it (Steven Earle, 2015).

Slope failure can be caused by a number of factors. Some of these factors are slope angle, and vegetation can be known easily, but the others factors that need techniques to know them are the loose or poorly consolidated material within slope, the rocks dipping in the same direction as the slope, and the amount of water in rock or soil (James S. Monroe 2005).

The main force responsible for mass movement is gravity. Gravity is the force that acts on the Earth's surface, in a direction toward the centre of the Earth. On a flat surface the force of gravity acts downward. So long as the material remains on the flat surface it will not move under the force of gravity except if the material becomes weak, the unsupported mass will move downward (Stephen A. N., 2013).

Gravitational force can be resolved into two components relative to the slope: one pushing the block down the slope (the shear force), and the other helps to hold the block in place on the slope (the shear strength). Shear force parallel to the slope pulls the object in the down-slope direction while shear strength which includes frictional resistance and cohesion among the particles that make up the object are forces resisting movement down the slope. Shear strength must be greater than shear force so that the mass will not move. Steeper slope angle increases shear force so it is considerably greater than the shear strength, and the block will very likely move.

The strength of the materials on slopes can vary widely. Solid rocks tend to be strong, but there is a very wide range of rock strength. If we consider just the strength of the rocks, and ignore issues like fracturing and layering, then most crystalline rocks like granite are very strong, while some metamorphic rocks are moderately strong. Sedimentary rocks have variable strength. Dolostone and some limestone are strong, most sandstone and conglomerate are moderately strong, and some sandstone and all mudstones are quite weak.

Fractures, metamorphic foliation, or bedding can significantly reduce the strength of a body of rock, and in the context of mass wasting, this is most critical if the planes of weakness are parallel to the slope and least critical if they are perpendicular to the slope.

Unconsolidated sediments are generally weaker than sedimentary rocks because they are not cemented and, in most cases, have not been significantly compressed by overlying materials. This binding property of sediment is sometimes referred to as cohesion. Sand and silt tend to be particularly weak, clay is generally a little stronger, and sand mixed with clay can be stronger still (Steven Earle, 2015).

Apart from the type of material on a slope, the amount of water that the material contains is the most important factor controlling its strength. This is especially true for unconsolidated materials.

Addition of water from rainfall adds weight to the slope. Water can seep into the soil or rock and replace the air in the pore space or fractures. Since water is heavier than air, this increases the weight of the soil. The stress increases and this can lead to slope instability.

Water has the ability to change the angle of repose (the stable angle for the slope). Dry unconsolidated grains will form a pile with a slope angle determined by the angle of repose. The angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable, and is controlled by the frictional contact between the grains. In general, for dry materials the angle of repose increases with increasing grain size, but usually lies between about 30 and 45 ^{o}. Slightly wet or moist unconsolidated materials exhibit a very high angle of repose because surface tension between the water and the solid grains tends to hold the grains in place. When the material becomes saturated with water, the angle of repose is reduced to very small values and the material tends to flow like a fluid. This is because the water gets between the grains and eliminates grain to grain frictional contact.

Liquefaction occurs when loose sediment becomes oversaturated with water. Water completely surrounds all the grains and eliminates all grain to grain contact. Sediment flows like a fluid. It can occur when water is added as a result of heavy rainfall. It can also occur gradually by slow infiltration of water into loose sediments and soils.

Another aspect of water that affects slope stability is fluid pressure. As soil and rock get buried deeper in the earth, the grains can rearrange themselves to form a more compact structure, but the pore water is constrained to occupy the same space. This can increase the fluid pressure to a point where the water ends up supporting the weight of the overlying rock mass. When this occurs, friction is reduced, and thus the shear strength holding the material on the slope is also reduced, resulting in slope failure.

Groundwater exists nearly everywhere beneath the earth surface. It is water that fills the pore spaces between grains in rock or soil or fills fractures in the rock. The water table is the surface that separates the saturated zone below, wherein all pore space is filled with water from the unsaturated zone above. Changes in the level of the water table occur due changes in rainfall. The water table tends to rise during wet seasons when more water seeps into the system, and decreases during dry seasons when less water infiltrates. Such changes in the level of the water table can have effects on the factors discussed above (Stephen A. N., 2013).

2.2 Geophysical Survey

Direct observation of the internal structure and testing of properties of soil or rock mass is always preferred, but this requires boreholes or trenches that are often impossible or too costly to be made. Hence, geophysical methods may be used for the purpose of slope stability analyses (Robert Hack, 2001). Geophysical surveys respond to the physical properties of subsurface materials. It can be classified into two types :

a) Passive : Methods that detect variations within the natural field associated with the Earth such as gravitational and magnetic field.

b) Active : Such as those used in exploration seismology, in which artificially generated signals are transmitted into the ground, which then modifies those signal in ways that are characteristic of materials through which they travel.

Each geophysical technique measures a specific parameter, which depends on one or more physical properties of the Earth. Because not all physical properties will vary in a particular situation, certain techniques are not suitable for all problems. Examples of geophysical surveying with its respective physical properties to be measured are shown below :

- Gravity survey method depends on density and magnitude of Earth's gravitational field.
- Magnetic survey measurement depends on magnetic susceptibility of subsurface materials.
- Electrical resistivity or induced polarisation survey technique measures electrical conductivity or electrical capacitance.
- Seismic refraction survey depends on P wave and S wave velocity.

Data of geophysical surveying method is usually processed in some way after acquisition. One of the advantages of this technique is that it is non-destructive and causes no disturbance to subsurface materials. Geophysical surveying is rapid and cost-effective in covering a large area and also can infer properties of subsurface from surface measurements (John M. R., 1997).

The main application of geophysical methods are hydrocarbon exploration, regional geological studies, mineral deposit exploration, engineering site investigation, detection of subsurface cavities, mapping of leachate and contaminant plumes and location of buried metallic objects (Reynolds, 2000).

2.3 Resistivity Method

2.3.1 Concept

The 2D electrical resistivity method is one of geophysical methods employed to map subsurface structure which can be used to monitor slope failure. It measures apparent resistivity of the ground to direct current flow. The 2D electrical resistivity method gives an impression of internal structures (De Vita et al., 2006) which is an active prospective method used for obtaining a high resolution image of subsurface patterns.

Ohm's Law describes electric current flow through a resistive material. The basic concept of the law relates electric current (I) flowing through a resistor to voltage (V) applied across the resistor. The inverse quantity of electrical conductance is electrical resistance (R). For a uniform wire or cube, resistance is proportional to the length and inversely proportional to cross-section area. The constant of proportionality is called resistivity (ρ), measured in ohm-m. Resistivity is the fundamental physical property of the metal in the wire.

Resistivity method is largely applied for the investigation of areas having complex geology (Perrone et al., 2004). It is a good indirect predictor of water content and is an interesting tool to estimate the depth of bedrock covered by superficial clay deposits or to determine the thickness of the latter (Cosenza et al., 2006). In addition it can be used in areas that are noisy or have low resistivity where seismic and GPR surveys cannot be used. Examples of its use include detection of cavities in limestone areas, bounders, pipes, groundwater contamination and archaeological surveys (Loke Meng Heng and Zuhar Zahir Tuan Harith, 2003).

2.3.2 Electrical Properties of Earth Materials

Electric current flows in earth materials at shallow depths through two main methods. They are electronic conduction and electrolytic conduction. In electronic conduction, the current flow is via free electrons, such as in metals. In electrolytic conduction, the current flow is via the movement of ions in groundwater. In environmental and engineering surveys, electrolytic conduction is probably the more common mechanism. Electronic conduction is important when conductive minerals are present, such metal sulfides and graphite in mineral surveys. The resistivity of the subsurface depends upon:

- The presence of certain metallic ores.
- The temperature of the subsurface (Geothermal energy).
- The presence of archeological features such as graves, fire pits, and post holes.
- Amount of groundwater present (including amount of dissolved salts, presence of contaminants and porosity and permeability percentage).

The resistivity of common rocks, soil materials and chemicals (Keller and Frischknecht 1966, Daniels and Alberty 1966, Telford et al. 1990) is shown in **Figure 2.1**. Igneous and metamorphic rocks typically have high resistivity values. The resistivity of these rocks is greatly dependent on the degree of fracturing, and the percentage of the fractures filled with ground water. Thus a given rock type can have a large range of resistivity, from about 1000 to 10 million **Ω**·m, depending on whether it is wet or dry. This characteristic is useful in the detection of fracture zones and other weathering features, such as in engineering and groundwater surveys.

Sedimentary rocks, which are usually more porous and have higher water content, normally have lower resistivity values compared to igneous and metamorphic rocks. The resistivity values range from 10 to about 10000 Ω·m, with most values below 1000Ω·m. The resistivity values are largely dependent on the porosity of the rocks, and the salinity of the contained water.

Unconsolidated sediments generally have even lower resistivity values than sedimentary rocks, with values ranging from about 10 to less than 1000 Ω·m. The resistivity value is dependent on the porosity (assuming all the pores are saturated) as well as the clay content. Clayey soil normally has a lower resistivity value than sandy soil. However, note the overlap in the resistivity values of the different classes of rocks and soils. This is because the resistivity of a particular rock or soil sample depends on a number of factors such as the porosity, the degree of water saturation and the concentration of dissolved salts.

The resistivity of groundwater varies from 10 to 100 Ω·m. depending on the concentration of dissolved salts. Note the low resistivity (about 0.2 Ω·m) of seawater due to the relatively high salt content. This makes the resistivity method an ideal technique for mapping the saline and fresh water interface in coastal areas. One simple equation that gives the relationship between the resistivity of a porous rock and the fluid saturation factor is Archie’s Law. It is applicable for certain types of rocks and sediments, particularly those that have a low clay content. The electrical conduction is assumed to be through the fluids filling the pores of the rock. Archie's Law is given by

$$\rho = a\rho_w \varphi^{-m}$$

where ρ is the rock resistivity, ρw is fluid resistivity, φ is the fraction of the rock filled with the fluid, while *a* and *m* are two empirical parameters (Keller and Frischknecht

1966). For most rocks, *a* is about 1 while *m* is about 2. For sediments with significant clay content, other more complex equations have been proposed (Olivar et al.1990).

The resistivity of several types of ores is also shown. Metallic sulfides (such as pyrrhotite, galena and pyrite) have typically low resistivity values of less than 1 Ω·m. Note that the resistivity value of a particular ore body can differ greatly from the resistivity of the individual crystals. Other factors, such as the nature of the ore body (massive or disseminated) have a significant effect. Note that graphitic slate has a low resistivity value, similar to the metallic sulfides, which can give rise to problems in mineral surveys. Most oxides, such as hematite, do not have a significantly low resistivity value. One of exceptions is magnetite.

The resistivity values of several industrial contaminants are also given in **Figure 2.1**. Metals, such as iron, have extremely low resistivity values. Chemicals that are strong electrolytes, such as potassium chloride and sodium chloride, can greatly reduce the resistivity of ground water to less than 1 Ω·m even at fairly low concentrations. The effect of weak electrolytes, such as acetic acid, is comparatively smaller. Hydrocarbons, such as xylene (6.998x1016 Ω·m), typically have very high resistivity values. However, in practice the percentage of hydrocarbons in a rock or soil is usually quite small, and might not have a significant effect of the bulk resistivity. As an example, oil sands in **Figure 2.1** have the same range of resistivity values as alluvium.

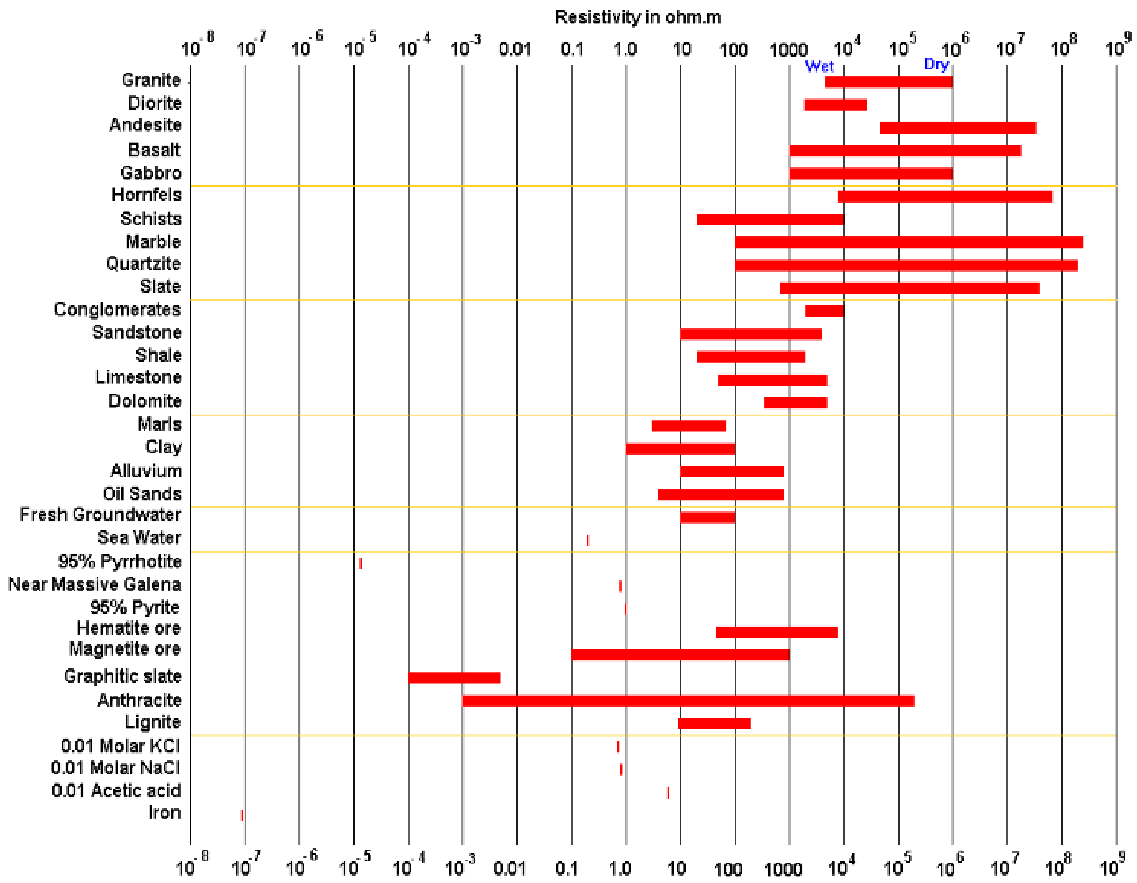

Figure 2.1 Resistivity values of rocks, soils and minerals.

Gilkeson and Wright (1983) have found that the porous geological formations saturated with groundwater of high ionic strength are characterized by very low resistivity. However, low resistivity values need not always a water bearing zone. The horizontal discontinuities also show low resistivity values. It is possible that such anomaly can be mistaken for water bearing zone either a gravel or weathered fractured granite (Singhal and Gupta, 1999). Apparent resistivity maps and profiles are commonly used to delineate potential groundwater source (Zohdy et. Al., 1974 ; Todd, 1980)

Of all geophysical properties of rocks, electrical resistivity is by far the most variable. Values ranging as much as 10 orders of magnitude may be encountered. Even individual rock types can vary by several orders of magnitude.

The minerals that form matrix of a rock are generally poor conductors than groundwater, but conductivity of sediment increases with the amount of groundwater it contains. The conductivity of groundwater is quite variable because it depends on the concentration and type of dissolved mineral and salts (Lowrie, 1997).

In general, resistivity ranges can give lithological information of an area shown in **Table 2.1.**

Table 2.1 Correlation of resistivity range and lithology.

Resistivity range (ohm-m)	**Lithological correlation**
< 50	Soil / Highly weathered zone
50-100	Weathered / Fractured zone
100-200	Fractured zone
>200	Massive rock

2.3.3 Electrode Arrays

Various electrode arrays are possible in resistivity surveys. The maximum sensitivity of all arrays is obtained near the measuring electrodes. Different arrays give different depth of investigation for sub-surface model. The choice of the array for a field survey depends on the type of feature to be surveyed (e.g., the sensitivity of the array to vertical and horizontal changes in the subsurface resistivity and the depth of investigation), the sensitivity of the resistivity meter, the background noise level, and the signal strength (Robert Hack, 2000). Below are common electrode arrays used in resistivity survey :

1) Wenner array

The Wenner array is relatively sensitive to vertical changes in the subsurface resistivity below the center of the array and less sensitive to horizontal changes in the subsurface resistivity. The Wenner array is best used for horizontal structures, but is relatively poor in detecting narrow vertical structures. The Wenner array has large signal strength.

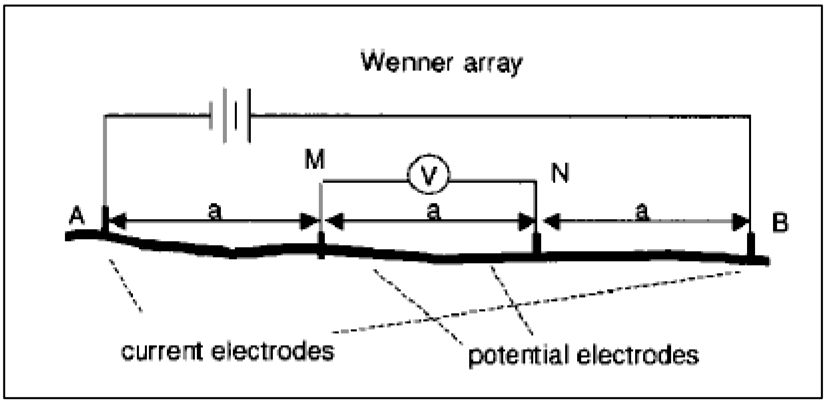

Figure 2.2 Wenner Electrode Array

2) Dipole-dipole array

The array is suitable for vertical structures, vertical discontinuities and cavities, but less for identifying horizontal structures. The array is most sensitive to resistivity changes between the electrodes in each dipole pair. The depth of investigation is smaller than for the Wenner array. The signal strength becomes small for large values of the '*n*' (**Figure 2.3**). The equipment should therefore be of good quality and the resistivity meter should have a high sensitivity. A good contact between the electrodes and the ground should be maintained.

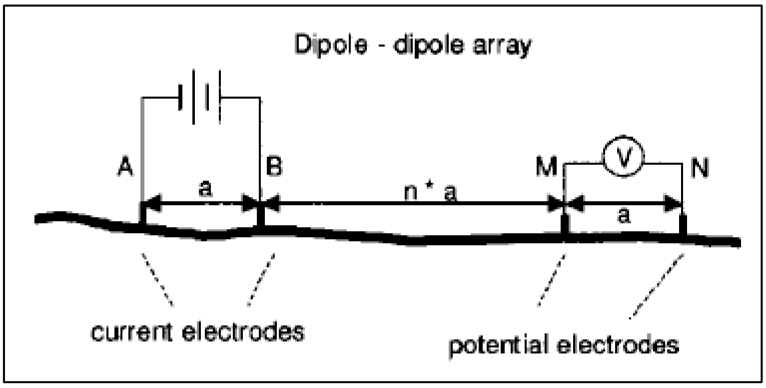

Figure 2.3 Dipole-Dipole Electrode Array

3) Wenner Schlumberger array

This array is moderately sensitive to both horizontal and vertical structures. The median depth of investigation for this array is larger than that for the Wenner array for the same distance between the outer electrodes. The signal strength for this array is smaller than that for the Wenner array, but it is higher than for the dipole-dipole array.

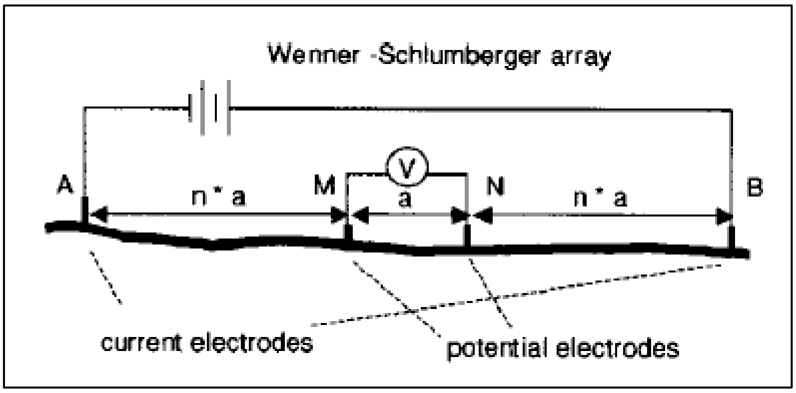

Figure 2.4 Wenner Schlumberger Electrode Array

4) Pole-dipole array

The pole-dipole array is asymmetrical and results in asymmetrical apparent resistivity anomalies in the pseudo section for surveys over symmetrical structures. This effect can be removed by repeating the measurements with the electrodes reversed. The *A* electrode must be placed sufficiently far from the survey line. The error caused by neglecting the effect of the *A* electrode in the calculations is less than 5% if the distance to the *A* electrode is more than 5 times the *N–B* distance. The pole-dipole array has a higher signal strength compared with the dipole-dipole array. The array is not as sensitive to noise as the pole-pole array because the distance between the potential electrodes is not as large. The signal strength is lower compared with the Wenner and Wenner-Schlumberger arrays but higher than the dipole-dipole array.

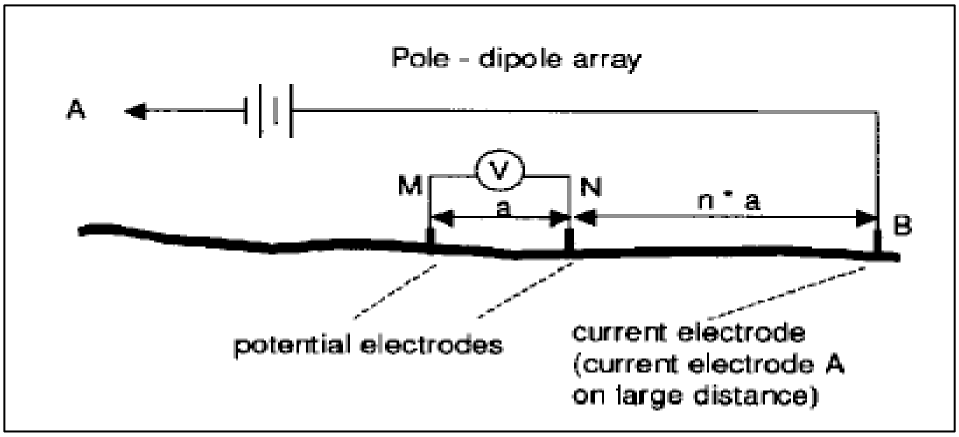

Figure 2.5 Pole-Dipole Electrode Array

2.3.4 Limitations in Resistivity Survey

Electrical resistivity is a geophysical method in which an electrical current is injected into the ground through steel electrodes in an attempt to measure the electrical properties of the subsurface. Most soils and non-ore bearing rocks are electrically resistive, (i.e., insulators). Soil moisture and ground water are often electrically conductive due to contained dissolved minerals. Therefore the resistivity measured in the ground is predominantly controlled by the amount of moisture and water within the soil and rock (a function of the porosity and permeability), and the concentration of dissolved solids (salts) in that water.