SLOPE STABILITY AT KM 50.0, TELUK BAHANG, PULAU PINANG USING RESISTIVITY METHOD

By

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ABSTRAK

Kejadian tanah runtuh dan fenomena yang berkaitan dengan ketidakstabilan cerun telah memberi kesan kepada banyak kawasan di seluruh dunia termasuk Malaysia. Bertahun-tahun lamanya, kejadian tanah runtuh telah menjadi suatu perkara biasa di Malaysia. Bilangan kematian yang tinggi dan kehilangan ekonomi telah dilaporkan, kesan daripada kejadian bencana alam ini. Kajian ini memberi tumpuan kepada taburan keberintangan elektrik di cerun yang terletak di Km 50.0, Teluk Bahang, Pulau Pinang. Umumnya, kawasan kajian terletak di atas kawasan tanah baki kepada tanah granit terluluhawa tinggi, berpunca daripada proses luluhawa berkeamatan tinggi oleh "Feringghi Granite". Kaedah "2-D Resistivity Imaging" telah digunakan untuk menghasilkan imej taburan keberintangan elektrik di kawasan kajian. Kaedah ini mampu mengenalpasti kehadiran air dan juga mengesan banyak ciri-ciri geologi bawah tanah. Tiga garis tinjauan telah dibuat bersudut tegak dengan bahagian cerun yang telah dipotong untuk tujuan pengambilan data. Keputusan kajian menunjukkan bahawa kehadiran batu bongkah, zon-zon lemah, zon-zon retak dan rekahan telah dikesan di kawasan kajian. Selain itu, satu kawasan jangkaan tanah runtuh telah dikenalpasti di salah satu garis tinjauan berdasarkan ciri-ciri keberintangan yang ditunjukkan. Ini telah menandakan bahawa kaedah "2-D Resistivity Imaging" merupakan suatu kaedah yang efektif dalam menjalankan penyiasatan terhadap kestabilan cerun.

ABSTRACT

Landslides and related slope instability phenomena affects many parts of the world including Malaysia. For many years, landslide is a common occurrence in Malaysia. As a result of this disastrous phenomenon, large number of death and economic losses were reported. This study focuses on the electrical resistivity distribution on a cut slope located at Km 50.0, Teluk Bahang, Pulau Pinang. Generally, the study area is overlyaid by thick profile of highly weathered to residual soil of granitic, resulting from intense in-situ weathering of Feringghi Granite. A 2-D Resistivity Imaging is used in mapping the electrical resistivity distribution at the study area. Electrical resistivity imaging can help in identifying the presence of water and other geological features underneath the ground. Three survey lines were established perpendicular to the cut slope (berm) for data acquisition purposes. Result shows that the presence of core boulders, weak zones, fractured zones and cracks detected on the study area. Besides this, a landslide is predicted to happen in one of the survey lines based on its resistivity features. This implies that the 2-D Resistivity Imaging method is an effective technique for slope stability investigation.

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SYMBOL	EXPLANATION
V	VOLTAGE
I	CURRENT
R	RESISTANCE
Ω	Ohm, THE UNIT OF MEASURE FOR ELECTRICAL RESISTANCE
ρ	ELECTRICAL RESISTIVITY FOR SATURATED SOIL
ρ_w	ELECTRICAL RESISTIVITY FOR PORE FLUID

LIST OF ABBREVIATION

ABBREVIATION	EXPLANATION
MSMA	MANUAL SALIRAN MESRA ALAM MALAYISA
MINT	MALAYSIAN INSTITUTE FOR NUCLEAR TECHNOLOGY RESEARCH
CPT	CONE PENETRATION TEST

CHAPTER 1
INTRODUCTION

1.1 AN OVERVIEW

Malaysia comprises two major land masses facing each other across the South China Sea: Peninsular Malaysia and the Bornean states of Sabah and Sarawak. It occupies a total area of 330,000 sq. km. Malaysia is warm and humid throughout the year, as characterized by the equatorial climate. It has an average annual rainfall of more than 2500 mm (MSMA, 2000). Due to heavy rainfall through out the year, many hill slopes are exposed to slope failures. Besides this, many hill slopes in Malaysia are particularly vulnerable to landslide and erosion due to their steep slope.

Landslide is not a common phenomenon in Malaysia. The catastrophic consequences of landslides can cause devastation for people and the environment. The most dramatic was the collapse of Block 1 of Highland Towers which occurred on Dec 11, 1993. The whole nation went into a state of a shock. The tragedy claimed 48 lives. A devastating landslide occurred in Cameron Highland, Pahang due to an exceptional heavy rainfall on January 2000, resulted in 6 fatalities and a major damage of houses, farms and transportation problems. The main road had been closed for few days before a temporary road was constructed to support 15 000 local citizen. It was estimated that the locals had suffered a financial loss of RM 70, 000 (www.malaysiasite.nl). A rockfall incident at Bukit Lanjan on 24th November 2003 resulted in six months of road closure for road clearing and remedial works. The repair and clearance costs at the Bukit Lanjan stretch was between RM20 million and RM25 million, while the loss of revenue was about RM80, 000 daily or RM2 million to RM3 million per month (www.theedgedaily.com).

1.2 LANDSLIDES

Landslides are the downward and outward movement of a slopes composed of natural rock, soils artificial fills, or combinations there of (http://pubs.usgs.gov). Common names for landslide types include slump, rockslide, debris slide, lateral spreading, debris avalanche, earth flow, and soil creep. Landslides move by falling, sliding, and flowing along surfaces marked by differences in soil or rock characteristics. A landslide is the result of a decrease in resisting forces that hold the earth mass in place and/or an increase in the driving forces that facilitate its movement. The rates of movement for landslides vary from tens of feet per second to fractions of inches per year. Landslides can occur as reactivated old slides or as new slides in areas not previously experiencing them. Areas of past or active landsliding can be recognized by their topographic and physical appearance. Areas susceptible to landslides but not previously active can frequently be identified by the similarity of geologic materials and conditions to areas of known landslide activity. Landslides can cause great number of lives and property losses.

1.2.1 TYPES OF LANDSLIDES

The various types of landslides can be differentiated by the kinds of material involved and the mode of movement (www.oceansidecleanwaterprogram.org). A classification system based on these parameters is shown in the Table 1.1:

Table 1.1: Types of Landslides. Abbreviated version of Varnes classification of slopes movement (Varnes, 1978).

<table>
<tr><th colspan="2" rowspan="3">TYPE OF MOVEMENT</th><th colspan="3">TYPE OF MATERIAL</th></tr>
<tr><th rowspan="2">BEDROCK</th><th colspan="2">ENGINEERING SOILS</th></tr>
<tr><th>PREDOMINANTLY COARSE</th><th>PREDOMINANTLY FINE</th></tr>
<tr><td colspan="2">FALLS</td><td>ROCK FALL</td><td>DEBRIS FALL</td><td>EARTH FALL</td></tr>
<tr><td colspan="2">TOPPLES</td><td>ROCK TOPPLE</td><td>DEBRIS TOPPLE</td><td>EARTH TOPPLE</td></tr>
<tr><td rowspan="2">SLIDES</td><td>ROTATIONAL</td><td rowspan="2">ROCK SLIDE</td><td rowspan="2">DEBRIS SLIDE</td><td rowspan="2">EARTH SLIDE</td></tr>
<tr><td>TRANSLATIONAL</td></tr>
<tr><td colspan="2">LATERAL SPREADS</td><td>ROCK SPREAD</td><td>DEBRIS SPREAD</td><td>EARTH SPREAD</td></tr>
<tr><td colspan="2">FLOWS</td><td>ROCK FLOW (DEEP CREEP)</td><td>DEBRIS FLOW (SOIL CREEP)</td><td>EARTH FLOW (SOIL CREEP)</td></tr>
<tr><td colspan="2">COMPLEX</td><td colspan="3">COMBINATION OF TWO OR MORE PRINCIPAL TYPES OF MOVEMENT</td></tr>
</table>

1.2.1.1 SLIDES: The two major types of slides are rotational slides and translational slides. Rotational slide: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (Figure 1.1A). Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (Figure 1.1B). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move down slope as a relatively coherent mass (Figure 1.1C).

1.2.1.2 **FALLS**: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders that become detached from steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water. (Figure 1.1D)

1.2.1.3 **TOPPLES**: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks. (Figure 1.1E)

1.2.1.4 **FLOWS**: There are five basic categories of flows that differ from one another.

a) Debris flow: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as slurry that flows downslope (Figure 1.1F)

b) Debris avalanche. This is a variety of very rapid to extreme debris flow (Figure 1.1G)

c) Earthflow. Earthflows have a characteristic "hourglasss" shape (Figure 1.1H). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongated and usually occurs in fine grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, the dry flow of the granular material is also possible.

d) Mudflow: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles.

e) Creep: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (Figure 1.1I)

1.2.1.5 LATERAL SPREADS: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (Figure 1.1J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

1.2.1.6 COMPLEX MOVEMENT: A combination of two or more of the principal types of flows is referred to as a complex movement.

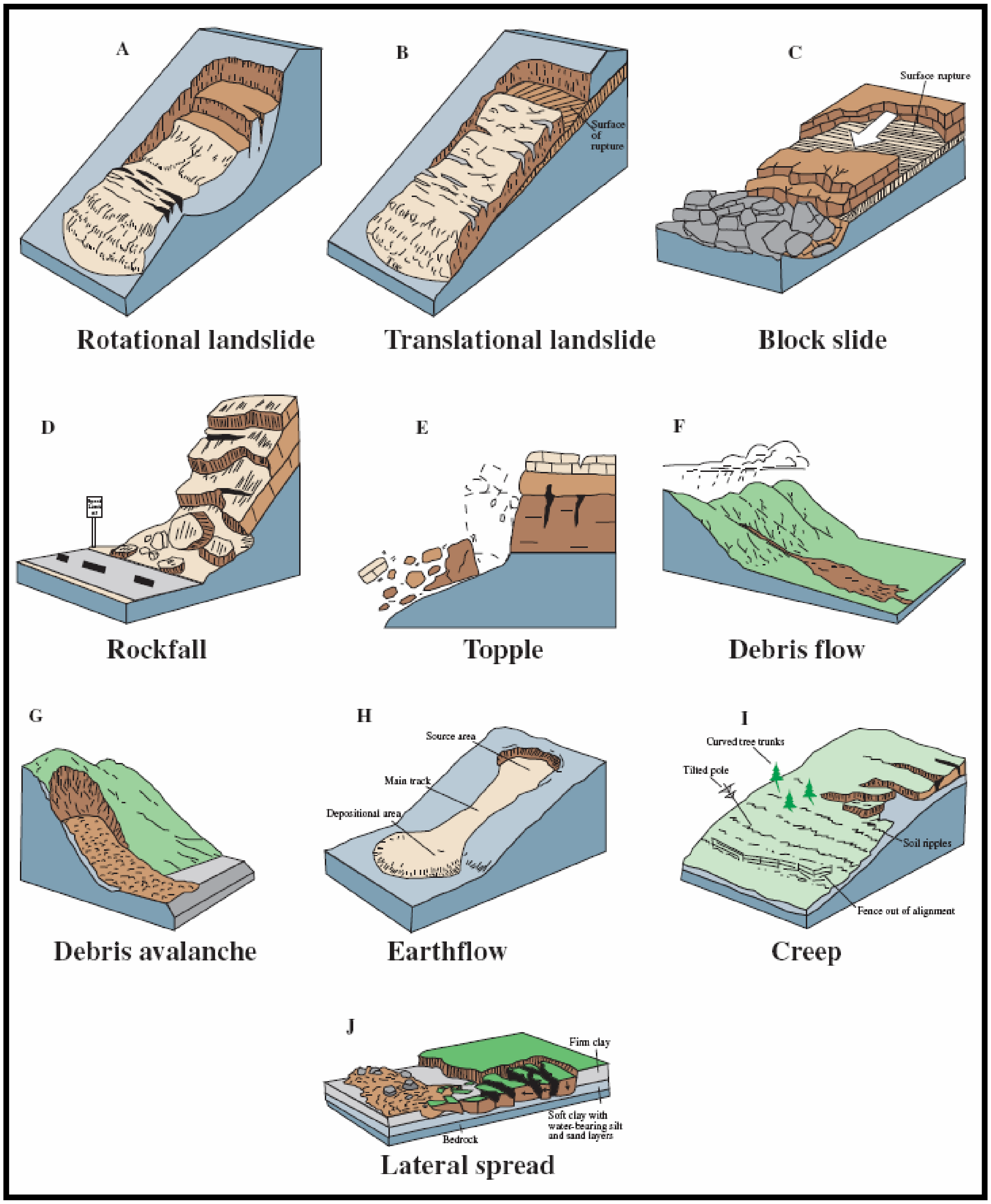

Figure 1.1: Types of Landslides diagram

(Source taken from: www.oceansidecleanwaterprogram.org **)**

1.2.2 LANDSLIDE CAUSES

There are multiple types of causes of landslides (http://pubs.usgs.gov). They can be divided into three different categories:

1.2.2.1 Geological causes - Weak or sensitive materials, weathered materials, sheared, jointed, or fissured materials, adversely oriented discontinuity, and contrast in permeability and or stiffness of materials.

1.2.2.2 Morphological causes - Tectonic or volcanic uplift, glacial rebound, fluvial, wave, or glacial erosion of slope toe or lateral margins, subterranean erosion, deposition loading slope or its crest, and vegetation removal (by fire, drought)

1.2.2.3 Human causes - Excavation of slope or its toe, loading of slope or its crest, drawdown (of reservoirs), mining, artificial vibration, and water leakage from utilities.

However, the three that cause most of the damaging landslides around the world (http://pubs.usgs.gov), are as follows:

1.2.2.4 Landslides and Water

Slope saturation by water is a primary cause of landslides. This effect can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and water-level changes along coastlines, earth dams, and the banks of lakes, reservoirs, canals, and rivers. Landsliding and flooding are closely allied because both are related to precipitation, runoff, and the saturation of ground by water. In addition, debris flows and mudflows usually occur in small, steep stream channels and often are mistaken for floods; in fact, these two events often occur simultaneously in the same area. Landslides can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back up. This causes backwater flooding and, if the dam fails, subsequent downstream flooding. Also, solid landslide debris can "bulk" or add volume and density to otherwise normal stream flow or cause channel blockages and diversions creating flood conditions or localized erosion. Landslides can also cause overtopping of reservoirs and/or reduced capacity of reservoirs to store water.

1.2.2.5 Landslides and Seismic Activity

Many mountainous areas that are vulnerable to landslides have also experienced at least moderate rates of earthquake occurrence. The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or shaking-caused dilation of soil materials, which allows rapid infiltration of water.

1.2.2.6 Landslides and Volcanic Activity

Landslides due to volcanic activity are some of the most devastating types. Volcanic lava may melt snow at a rapid rate, causing a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris flows (also known as lahars) reach great distances, once they leave the flanks of the volcano, and can damage structures in flat areas surrounding the volcanoes.

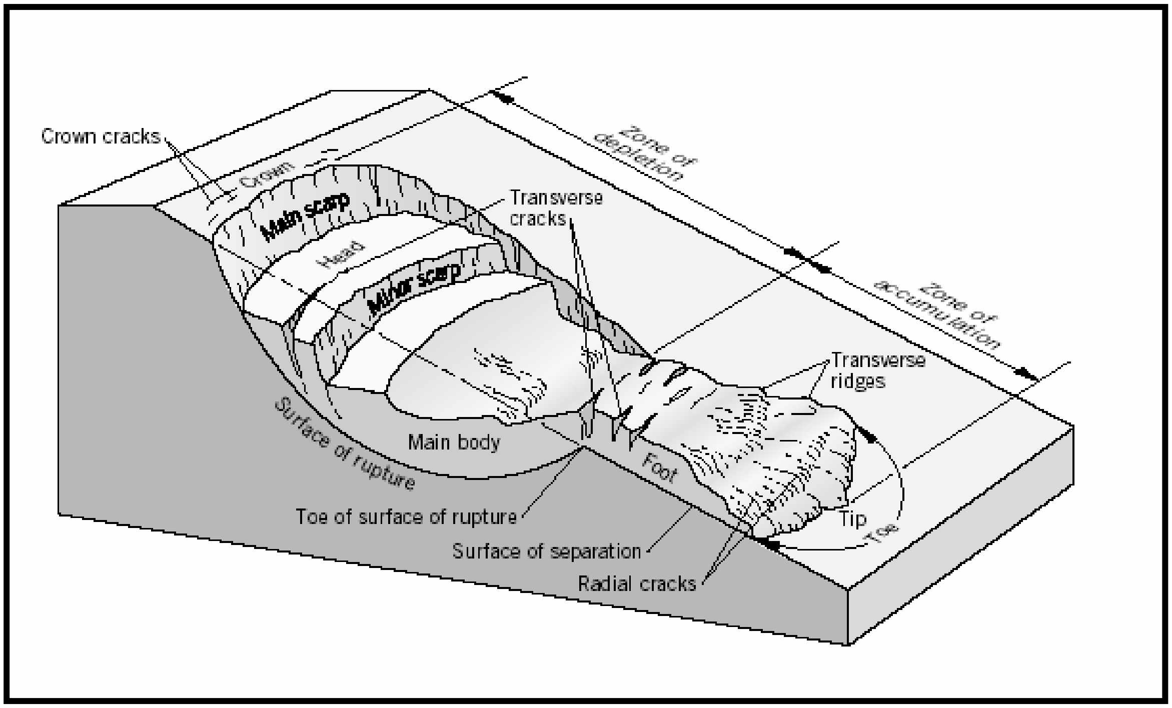

Figure 1.2: Terminology for describing landslide features (modified from Varnes, 1978)

Following numerous landslide occurrence in Malaysia, there is a great concern that the slopes area are extremely sensitive to disturbance of any sort. Based on the landslide cases, rainfall is considered to be the most important factor in triggering slope failure.

During rainfall, water infiltrates into the ground and increases the pore water pressure, weakening the soil and facilitating landslide. Therefore, it is important to know the exact location where water infiltrates the most. This indicates the weak spot on slopes. One of the ways to identify the weak spot is by using the Resistivity method.

1.3. ELECTRICAL RESISTIVITY METHOD

1.3.1 THEORY

Various materials differ in their ability to conduct electricity. In some materials at least one of the electrons in each atom is loosely held and it requires only slight external influence to move or conduct some of the electrons from atom to atom through the material. In other materials there are very few free electrons and they conduct electricity poorly. This type of electrical conduction is called electronic conduction. Metals are excellent electronic conductors while rocks are poor to very poor electronic conductors. Another form of electrical conduction is electrolytic conduction, where the current is carried by ions, such as in mineralized ground water, resulting in actual movement of matter. In electrical resistivity investigations both types of electric conductivity are involved; electronic conductivity through the soil particles and rock and electrolytic conducting in the ground water. The more mineralized (higher ion concentration) the ground water is, the higher its conductivity is.

1.3.1.1 Ohm's Law

In a given metallic circuit at a constant temperature a definite ratio exists between the current and the potential difference. This ratio is the resistance of the circuit. The equations for Ohm's Law are:

$$V = IR$$

$$I = V/R$$

$$R = V/I$$

where V is voltage or potential in volts, I is current in amperes, and R is resistance in Ohms.

1.3.2 RESISTIVITY

In electrical resistivity investigations, it is assumed that the earth acts as a linear conductor and Ohm's Law applies. Whenever an electric current flows, an interchange of energy takes place. If the moving particles which constitute the current have work done on them by an external force, they gain energy; if they do work on something else, they lose energy. The gain or loss in energy when one coulomb of electricity (one coulomb per second equals to one ampere) is moved from one point to another in an electric circuit is called the difference in potential and is measured in volts. The flow of electricity can be considered as analogous to the flow of water in an aquifer and Ohm’s Law and Darcy's Law as similar.

Electrical imaging is a survey technique which makes use of the electrical properties of ground material. There must always be at least two current electrodes in contact with the earth: one as a source and the other as a sink. The total potential at any point can be computed by algebraic addition of the separate potentials due to each of the sources considered as though each were acting alone. Since a sink is no more than a negative source, the potential at a point may be computed for any combination of sinks and sources.

If current is applied to the earth through two current electrodes, C1 and C2, spherical equipotential surfaces develop (Refer figure 1.3). Since the air is considered to have infinite resistivity the figure only shows the lower half of the sphere of equipotential surfaces that are developed in the earth. Perpendicular to these equipotential surfaces is current flow lines generated between the two electrodes.

Figure 1.3 is similar to a ground-water flow net. The equipotential lines represent contours of equal head in ground water and equal potential (volts) in electricity. The flow lines represent amount of water flow in ground water and amount of current flow (amperes) in electricity.

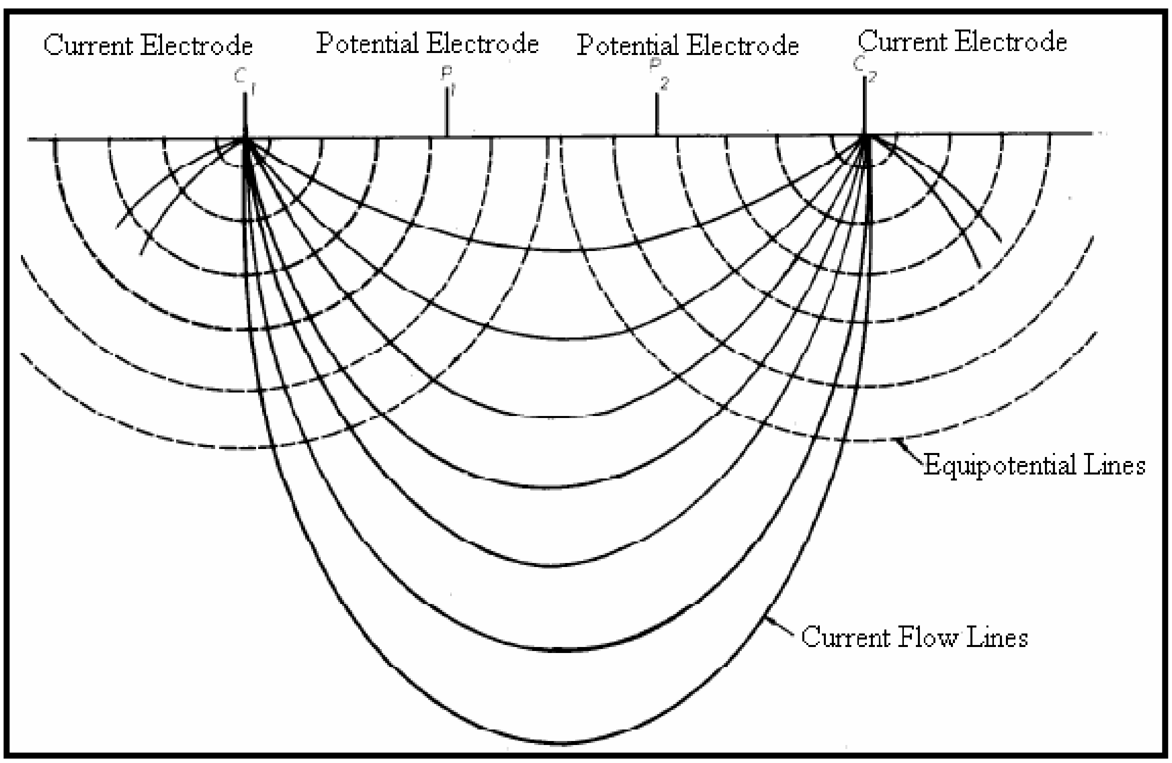

Figure 1.3: Current Flow Lines and Equipotential Lines

(Source taken from: www.info.usda.gov)

The basic procedure in resistivity surveying is to measure the potential drop on the ground surface associated with a known current flow into the earth and then calculate the apparent resistivity. The resistivity applies to a volume of material that depends on the electrode spacing, and as the spacing is increased, the current penetrates deeper into the earth. For a homogeneous material, consider a vertical plane at the midpoint between electrodes. One half the current flows through this plane at a depth equal to one half the electrode spacing and one half flows at a greater depth. When the material is not homogeneous the resistivity calculated is apparent resistivity which depends on the resistivity of the various materials through which the current passes. As the electrode spacing is increased, the current flows through a greater volume of material both horizontally and vertically and the deeper materials will have an effect on the apparent resistivity . Thus, if the deeper material is of higher resistance (lower conductance) the current flow lines will be deflected upward and the current density in the near surface volume element is increased. If the deeper material is of lower resistivity (higher conductance) the current flow lines will be deflected downward and the current density will be decreased. The increase or decrease in current density is measured by the resistivity apparatus. Interpretation of the apparent resistivity changes with change in electrode spacing will indicate changes in and types of material at certain depths. Here are examples of common electrode spacing (electrode array/ configuration) used in the resistivity surveys (Figure 1.4):

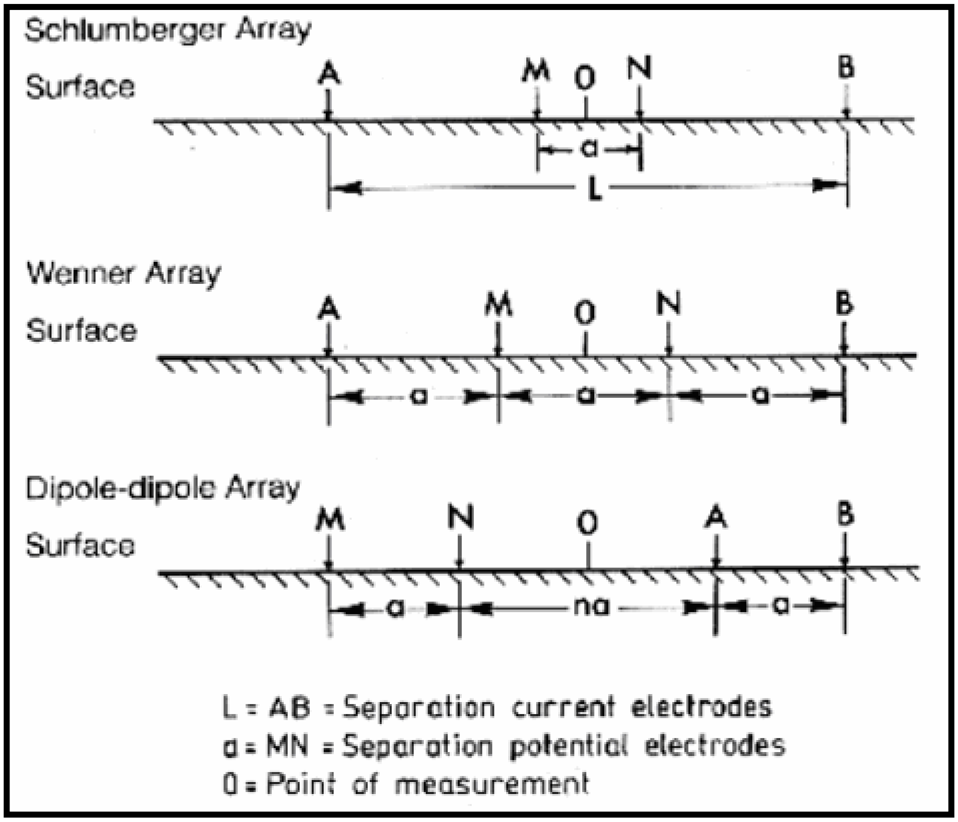

Figure 1.4: Types of electrode array/configuration

(Source taken from www.geophysik.uni-koeln.de)

This theory is applied in resistivity imaging where the data of the electrical properties of earth can be derived. In turn, from those electrical properties, geologic properties of earth can be identified. Resistivity data is generally interpreted using the 'modeling' process. A hypothetical of the earth and its resistivity structure is generated. The theoretical electrical resistivity response over that model is then calculated.

1.4 RESEARCH OBJECTIVES

The objectives of this research are outlined as follows:

- To characterize slope based on the effect of the physical properties of the slope materials on resistivity.
- To detect the presence of water on slope.
- To identify geological features underneath the ground of slope.
- To predict the probability of the occurrence of landslide on the study area.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

Most current landslides are recurrences of previous landslides. The main factors in triggering these landslides are rainfall and snowmelt, which bring about an increase in pore water pressure at the slip surface, erosion at the landslide toe, etc. Several other factors relating to the landslide generation mechanism must be studied in order to predict the type of disaster that may arise because of a slide, and to formulate measures for preventing slides. In order to obtain necessary data for landslide mechanism analysis, such as the shape and position of the slip surface, subsurface conditions, and groundwater distribution in the landslide area, most landslide experts make use only of borehole information. However, there are many cases in which such data are insufficient, so there is a need to design appropriate technology for predicting landslides (Matsuura, 1998). To overcome some of these problems, electrical resistivity surveys have increasingly been used as a survey technique for landslide studies. The resistivity method helps by revealing the resistivity characteristics of the subsurface, thereby providing valuable information on the geological structure of the subsurface (Konishi, 1998).

Electrical resistivity studies in geophysics may be understood in the context of current flow through a subsurface medium consisting of layers of materials with different individual resistivities. For simplicity, all layers are assumed to be horizontal. The resistivity of a material is a measure of how well the material retards the flow of electrical current. Resistivities vary tremendously from one material to another. For example, the resistivity of a good conductor such as copper is on the order of 10^{-8} Ω m, the resistivity of an intermediate conductor such as wet topsoil is ~10 Ω m, and the resistivity of poor conductors such as sandstone is ~10^{8} Ω m. Due to this great variation, measuring the resistivity of an unknown material has the potential for being very useful in identifying that material, given little further information.

Table 2.1: Resistivity of soil and rock masses. Left columns show ranges and right columns show dependency on water content (values marked with (1) after Telford et al., 1990, with (2) after Vogelsang, 1994).

Material	Resistivity range (Ohmm = Ωm)	Material (Ohmm = Ωm)	Resistivity
Dry sand (2)	800–5000	Coarse grained sandstone (0.18% water) (1)	1×10^{8}
Clay (2)	3–150	Coarse grained sandstone (0.39% water) (1)	9.6×10^{5}
Slate (1)	6×10^{2}–4×10^{7}	Dolomite (0.96% water) (1)	8×10^{3}
Limestone (2)	500–3500	Dolomite (2% water) (1)	5.3×10^{3}
Sandstone (2)	300–3000	Granite (0.0% water) (1)	1×10^{10}
Granite (1)	300–1×10^{6}	Granite (0.31% water) (1)	4.4×10^{3}
Debris and dumped soil (2)	200–350	Basalt (0.0% water) (1)	1.3×10^{7}
Domestic garbage (2)	12–30	Basalt (0.49% water) (1)	9×10^{5}
Natural water in sediments (1)	1–100	Basalt (0.95% water) (1)	4×10^{4}
Sea water (1)	0.2	Siltstone (0.38% water) (1)	5.6×10^{8}
Scrap metal (2)	1–12	Siltstone (0.54% water) (1)	1.5×10^{4}

2.2 FACTORS AFFECTING RESISTIVITY

There are several factors that will affect resistivity such as:

2.2.1 ARCHIE'S FORMULA

Formulas that relate the resistivity of the different components to the bulk resistivity of the conducting medium are referred to as mixing law, and the simplest of these is Archie's formula. Archie's formula relates the electrical resistivity of saturated soil ρ to the electrical resistivity of its pore fluid ρ_w and the geometry of the pore spaces in the soil by the relationship:

$$\rho = a\,\rho_w\,n^{-m}$$

where n = porosity of the soil, and a and m are constants that depend on the type of soil or rock (Abu-Hassanein, 1996). For unconsolidated soil a = 1, and m is dependent on soil type. m is a measure of pore tortuosity, or the path water must take in order to move around particles. This formula shows that the electrical resistivity of saturated soil is sensitive to the porosity, the electrical resistivity of the pore fluid, and the soil fabric and type. For a given soil with a constant a and m, as the porosity decreases, the electrical resistivity of the soil increases, and as the electrical resistivity of the pore fluid increases, the electrical resistivity of the soil increases. Archie's formula has been recognized as an oversimplification, but is still valid as long as the pore fluid resistivity is low and there are relatively small quantities of conducting clay minerals present in the soil.

2.2.2 SOIL TYPE

Matrix solids resistivity is the result of electron conductance through the grain to grain contacts of contiguous sand grains of the aquifer (Faye and Smith, 1994). Electrical conduction in clean sands and gravels occurs almost exclusively in liquid contained in the pores, because quartz sand is virtually a nonconducting material and matrix solids resistivity is considered infinitely large. In clayey soils and clay-bearing rocks, however, electrical conduction occurs in the pores and on the surfaces of electrically charged clay minerals. For clays, surface conductance can be a significant factor affecting the bulk electrical resistivity of the soil.

2.2.3 IONIC CONTENT OF PORE FLUID

Ionic content of the pore fluid determines its electrical resistivity. An increase in ionic content or the amount of dissolved solids in the pore fluid will produce a decrease in electrical resistivity. If insulating contaminants are present in the pore water, resistivity will increase. The influence of the conductive contaminants is greater than that of nonconducting contaminants (Campanella and Weemees 1990).

2.2.4 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is dependent on several factors, many of which are the same that influence resistivity. Because ions flow through some of the same paths as water, the electrical resistivity and hydraulic conductivity of soils are expected to be affected by similar variables. Among these variables are fluid viscosity, pore-size distribution, grain-size distribution, void ratio, roughness of mineral particles, and degree of soil saturation. In clayey soils, structure, ionic content, and thickness of the water layers held to the clay play an important role in determining hydraulic conductivity.

Also influencing the hydraulic conductivity in compacted clays are factors such as changes in density, void ratio, molding-water content, compactive effort, and compaction method, all of which are variables affecting the size, shape, and connectivity of the pores (Abu-Hassanein., 1996). It is important to note that the relationship between electrical resistivity and hydraulic conductivity varies with different soils, and contradictory results have been reported (Abu-Hassanein, 1996).

2.2.5 COMPACTION VARIABLES

Measurements of electrical resistivity can be used to determine if a soil is compacted wet of optimum-water content, or wet of the line of optimums, provided the compactive effort is known (Abu-Hassanein, 1996). The degree of compaction is measured by its dry unit weight. Water is added to soften the dry soil, and particles are able to slide past one another and create a denser soil until the soil reaches the optimum moisture content. This value is reached when the most possible void space is taken up by solid particles. After this point, too much water separates particles that were previously more densely packed. The proctor compaction test measures this variable in the laboratory (Das, 1994).

As the compaction effort is increased, the maximum dry unit weight of compaction is also increased. As compaction effort is increased, the optimum moisture content is decreased to some extent. However, hydraulic conductivity decreases with the increase in moisture content. It reaches a minimum value at approximately the optimum moisture content. Beyond that point, the hydraulic conductivity increases slightly (Das, 1994). High resistivity can be expected for soils compacted with low water content and/or high air-filled porosity. Thus, field measurement of resistivity is potentially a useful indicator of high hydraulic conductivity from less then desired compaction due to inadequate water content or compactive effort (Kalinski and Kelly1994).

2.2.6 SATURATION

For constant water resistivity, resistivity differences between unsaturated sediments, such as a fine gravel and silt, are generally much larger than for the same sediments in a saturated condition, with finer sediments being less resistive than coarser sediments (Kelly 1985).

2.2.7 PARTICLE-SIZE DISTRIBUTION

With an increase in percentage of fines in sandy soils, electrical resistivity is affected in three ways. First, porosity will be decreased, since the fines will occupy void space between sand grains, and decreasing porosity has the effect of increasing the resistivity (Campanella and Weemees 1990). Secondly, the presence of fines in the soil generally indicates the presence of conducting clay minerals, which would result in a decrease in the resistivity. Thirdly, soils with higher fines content also generally have higher specific surface, which improves surface conductance (Abu-Hassanein, 1996). In general, surface resistance increases as soils become increasingly coarsegrained (Abu-Hassanein, 1996).

2.2.8 TEMPERATURE

The viscosity of the pore fluid affects the conductivity of a particular ion in an electrolyte. The most important factor affecting viscosity, and hence conductivity, is the pore fluid temperature (Campanella and Weemees 1990). Electrical resistivity decreases with increasing temperature. (Abu-Hassanein, 1996).

2.2.9 INDEX PROPERTIES

Electrical resistivity is also correlated with index properties. Soils with a higher liquid limit or plasticity index have lower electrical resistivity (Abu-Hassanein, 1996).

2.3 USES OF RESISTIVITY MEASUREMENT

Here are some of the examples regarding the uses of the resistivity measurement:

2.3.1 GEOENVIRONMENTAL

Geoenvironmentalists use resistivity data along with CPT (Cone Penetration Test) data. With the recent increase in urban development and development of reclaimed land such as landfill sites, design consultants are becoming increasingly aware of the problems other than foundation design, especially soil contamination, both pre-existing and time-dependent. Resistivity data is an effective way to identify and quantify the extent of contamination. It is also a nondestructive tool helpful in evaluating compacted soil liners for landfills (Horsnell 1998; Kalinski and Kelly 1994). Piezocones are capable of detecting small variations in soil stratigraphy with great accuracy. This may not be necessary in foundation engineering, but a thin sand seam may be a pivotal piece of information in finding cross-contamination or migration paths on or off-site. No cuttings or samples are produced during cone penetration testing, which is advantageous in geoenvironmental applications where contaminated soils may be a concern.

2.3.2 STRUCTURAL ENGINEERING

Structural Engineers use resistivity data along with piezocones to gain a better understanding of the subsurface in order to design foundations. Rapid identification of soil type, pore fluid and perma frost conditions greatly assists engineers in arctic drilling platform and oil and gas pipeline planning and design (Woeller, 1991). Knowledge of