SLOPE FAILURE ASSESSMENT IN PENANG ISLAND USING GEOELECTRICAL METHODS

by

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Thesis submitted in fulfilment of the requirements for the degree of Master in Science

April 2018

ACKNOWLEDGEMENT

I thank Allah S.W.T for His mercy for giving me this opportunity to further study in Master's degree and His guidance for me to face challenges in order to complete this research.

I would like to express my sincere gratitude to my main supervisor, Dr Nur Azwin Ismail for her continuous support, guidance and encouragement that leads me to completing my research. A special thanks to my co – supervisor, Dr Nordiana Mohd Muztaza for her invaluable advices and suggestions. Many thanks also to all Geophysics laboratory assistants for their time and effort in assisting me to conduct my research.

My appreciation also to all my very helpful and supportive postgraduate students for their non – stop encouragement and knowledge sharing that allow me to move forward.

My sincere appreciation toward my beloved parents Mr. Faharul Azman Ahmad Sabki and Mrs. Faridah Md Saad and also my siblings for their prayers and encouragements. Last but not least, Fellowship Scheme of Universiti Sains Malaysia for sponsoring my tuition fees and allowances during my study period.

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LIST OF ABBREVIATIONS

2D	Two dimension
3D	Three dimension
4D	Four dimension
ALERT	Automated time – lapse electrical resistivity tomography
ASTM	American Society for Testing and Materials
BS	British Standard
C1/C2	Current electrode
ERT	Electrical resistivity tomography
FOS	Factor of safety
GIS	Geographic information system
IP	Induced polarization
NPP	North Penang Pluton
NW	Northwest
P – wave	Primary wave
P1/P2	Potential electrode
PSD	Particle size distribution
RES2DINV	Resistivity two-dimension inversion

RMS	Root mean square
S – wave	Secondary wave
SE	Southeast
SK	Sekolah Kebangsaan
SMK	Sekolah Menengah Kebangsaan
SP	Self – potential
SPP	South Penang Pluton
SW	Southwest
TLERT	Time lapse electrical resistivity tomography
USCS	Unified Soil Classification System

LIST OF SYMBOLS

V_m	measured voltage
V_r	residual voltage
ρ_a	apparent resistivity
Δt	length of the time window of integration.
∇	gradient operator
ΔV	Potential difference
C_c	Coefficient of curvature
C_u	Coefficient of uniformity
d	diameter
D	Effective size
E	electric field intensity
e	void ratio
I	current
k	geometric factor
M	chargeability
η	Porosity
r	distance of point in the medium
R	Coefficient of correlation

R	resistance
R^2	Coefficient of determination
V	electric potential
w	Moisture content
$\boldsymbol{\rho}$	resistivity
ρ_{bulk}	Bulk density
σ	conductivity
ϕ	phi unit

PENILAIAN KEGAGALAN CERUN DI PULAU PINANG MENGGUNAKAN KAEDAH GEOELEKTRIK

ABSTRAK

Kegagalan cerun di kawasan berbukit dan kawasan cerun tidak berkurang setiap tahun. Hal ini boleh membahayakan penduduk setempat. Walau bagaimanapun, cerun tidak hanya terhad di kawasan penempatan tetapi juga boleh dilihat di sepanjang lebuhraya dan jalan persekutuan. Kajian ini bertujuan untuk menyiasat cerun di kawasan berisiko tinggi di Pulau Pinang (Sungai Batu, Bukit Relau dan Air Hitam) menggunakan kaedah keberintangan 2D dan polarisasi teraruh serta menganalisa dan mengaitkan keputusan dari keadah keberintangan 2D, kaedah polarisasi teraruh, ujian makmal dan taburan hujan untuk potensi kegagalan cerun. Kawasan – kawasan kajian dipilih berdasarkan kepada kajian terdahulu dan kes – kes kegagalan cerun yang dilaporkan berlaku di Pulau Pinang. Berdasarkan kepada keputusan, kebarangkalian untuk kegagalan cerun di Sungai Batu adalah disebabkan oleh kewujudan zon lemah dengan nilai keberintangan rendah 0 – 400 Ωm and nilai kebolehcasan rendah < 3 ms manakala Bukit Relau pula dijangka mengalami kegagalan cerun disebabkan oleh zon luluhawa dengan nilai keberintangan pertengahan 750 – 3000 Ωm dan nilai kebolehcasan pertengahan 3 – 10 ms. Kewujudan rekahan juga menyumbang kepada kegagalan cerun terjadi. Sungai Batu dan Bukit Relau terletak berhampiran dengan sesar, sekaligus meningkatkan potensi kegagalan cerun disebabkan oleh ciri – ciri batuan yang kekar dan ricih. Air Hitam dikenalpasti terdedah kepada kegagalan cerun disebabkan oleh kewujudan zon lempung tepu berdasarkan nilai keberintangan yang rendah (< 400 Ωm) tetapi nilai kebolehcasan yang tinggi (> 25 ms). Ujian makmal tanah juga dilakukan untuk mengenalpasti kandungan air dan keliangan. Pengamatan

kolerasi antara nilai keberintangan dan nilai kebolehcasan diperoleh dari kaedah geofizik dengan kandungan air dan keliangan dari ujian makmal tanah adalah berkadar songsang antara satu sama lain dengan kekuatan kolerasi kuat sehingga sangat kuat. Analisis taburan saiz zarah berjaya mengenalpasti tanah di Sungai Batu dan Bukit Relau adalah pasir berkelikir. Cerun – cerun dipantau selama beberapa bulan untuk memerhati sebarang perubahan sub permukaan. Berdasarkan keputusan di Sungai Batu, zon lemah dengan nilai keberintangan $< 400\ \Omega m$ ditemui di tengah garis tinjauan manakala zon luluhawa dengan nilai keberintangan 500 – 3000 Ωm dikenalpasti sepanjang garis tinjauan. Kaedah keberintangan 2D mendapati nilai yang menurun, ini menunjukkan zon – zon yang semakin longgar. Rekahan juga dikesan terbentuk semasa tempoh pantauan di jarak 130 – 140 m. Di Bukit Relau, fenomena yang sama dapat diperhati dimana nilai keberintangan menurun dengan masa. Rekahan yang dikesan di jarak 60 m bertambah lebar berbanding di awal tempoh pantauan dan sebuah lagi rekahan dikesan terbentuk di garis tinjauan. Pemantauan cerun membuktikan sub permukaan mengalami perubahan dan ia dipengaruhi oleh pelbagai faktor seperti hujan di sepanjang bulan. Kajian ini berjaya mengenalpasti potensi kegagalan cerun di kawasan – kawasan kajian iaitu zon lemah dan kehadiran bahan lempung di Sungai Batu, zon luluhawa granit di Bukit Relau dan zon lempung tepu di Air Hitam. Faktor yang membawa kepada kebarangkalian kegagalan cerun di kawasan – kawasan kajian ialah keadaan tanah yang telap, taburan hujan yang tinggi dan juga kesan luluhawa.

SLOPE FAILURE ASSESSMENT IN PENANG ISLAND USING GEOELECTRICAL METHODS

ABSTRACT

Slope failures never cease to end in hilly and slope area every year. This is very dangerous especially for those who lives within the proximity. However, slope is not only found in residential area but also alongside highways and federal roads. This research aims to investigate slope at the selected highly suspected area in Penang Island (Sungai Batu, Bukit Relau and Air Hitam) using 2D resistivity and induced polarization methods and to analyse and correlate the results from 2D resistivity method, induced polarization method, laboratory tests and rainfall distribution for slope failure potentials. The study areas were selected based on the previous studies and cases of slope failure reported in Penang Island. Based on the results, Sungai Batu has probability for slope failure due to weak zone with low resistivity value of 0 – 400 Ωm and low chargeability of < 3 ms while Bukit Relau was expected to have slope failure due to the weathering zone with intermediate resistivity 750 – 3000 Ωm and intermediate chargeability 3 – 10 ms. The existence of fractures also contributed to trigger the slope failures. Sungai Batu and Bukit Relau are located near faults and thus, intensified the slope failure potential due to highly jointed and sheared rocks characteristic. Air Hitam was determined to be vulnerable to slope failure due to the presence of clay saturated zone indicated by low resistivity value (< 400 Ωm) but high chargeability value (>25 ms). Soil laboratory tests were also conducted to determine the moisture content and porosity. The empirical correlation of resistivity and chargeability values obtained from geophysical methods with moisture content and porosity from soil laboratory tests indicated that they are inversely proportional to each other with strength of correlation range from strong to very strong. PSD analysis successfully determined that the soil at Sungai Batu and Bukit Relau are gravelly sand. The slopes were also monitored for several months to observe any changes within the subsurface. Based on the results at Sungai Batu, weak zone with resistivity of < 400 Ωm was found at the centre of survey line while weathered zone with resistivity 500 – 3000 Ωm was identified along the survey line. 2D resistivity method recorded decreases in value therefore indicated that the zones were becoming loose. A fracture was also detected formed during the monitoring period at distance 130 – 140 m. As for Bukit Relau, the same phenomenon was observed where the resistivity value decreased with time. Fracture found at distance 60 m is wider since the beginning of monitoring period and another fracture was observed to develop at distance 140 m along the survey line. Monitoring the slope proved that the subsurface experience changes and can be affected by various factors such as rainfall over the months. This research has successfully determined slope failure potentials in the study areas which are the weak zone and presence of clayey material at Sungai Batu, weathered granite zone at Bukit Relau and clay saturated zone at Air Hitam. Factors that leads to slope failures possibilities in the study areas are the permeable soil condition, high rainfall distribution and also weathering effect.

CHAPTER 1

INTRODUCTION

1.0 Preface

Reported from cases of landslides, rockfalls and other types of slope failures never cease to end every year. In the worst case, some of the slope failure repair methods such as retaining walls, rock bolts and geo grid had collapsed together with the slope failures. This perpetual issue will require an amount of money to be taken care of.

Slope is not an uncommon structure in Malaysia. It can be seen alongside the highways, federal roads and also residential areas. About 5000 km of the trunk roads in Malaysia involved many cut slopes and traversed on hilly and mountainous area. Approximately about 75% of the roads are underlain by granitic formation while the other 25% of the roads are underlain by meta – sediments formation such as the mudstone, sandstone and siltstone. Numbers of slope failure occurrences happen on the mountainous roads especially during the rainy season which leads to traffic disruption, injuries and also loss of lives (Singh et al., 2008). Although it happens frequently, an absolute prevention method has yet to be found. Table 1.1 shows the major slope failure occurrences in Malaysia in from 2002 – 2017.

Table 1.1: Series of major slope failure occurrences in Malaysia and consequences in terms of deaths from 2002 – 2017.

Date	Location	Coordinate		Deaths	Sources
		Longitude	Latitude		
20 November 2002	Taman Hillview, Hulu Klang	101.761500	3.175442	8	

Continuation of Table 1.1

29 November 2004	KM 59, Kuala Lipis – Merapoh	101.961883	4.487183	4	Department of Public Works Malaysia
2 December 2004	Taman Bercham Utama, Ipoh	101.135061	4.645389	2	
31 May 2006	Kg Pasir, Hulu Klang, Selangor	101.764778	3.206783	4	
26 June 2006	KM 8.5, Pelabuhan Sepanggar, Kota Kinabalu, Sabah	116.674689	6.095556	1	
30 November 2008	Ulu Yam Perdana, Kuala Selangor	101.674689	3.389919	2	
6 December 2008	Taman Bukit Mewah, Bukit Antarabangsa, Hulu Klang	101.769722	3.186111	5	
16 January 2009	Bukit Kanada, Miri, Sarawak	113.996494	4.393056	2	
29 January 2011	Sandakan, Sabah	118.127078	5.847014	2	
21 May 2011	Rumah Anak Yatim At – Taqwa, Hulu Langat	101.814444	3.138611	16	
7 August 2011	Perkampungan Orang Asli Sg Ruil	101.370464	4.487361	7	
p18 February 2012	Kg Terusan, Lahad Datu, Sabah	118.359314	5.048847	2	
3 July 2013	Ukay Perdana, Selangor	-	-	3	Kazmi et al. (2016)
16 July 2013	Kampung Mesilau, Kundasang	-	-	1	Utusan
30 December 2014	KM Jalan Brinchang – Tringkap	-	-	2	Astro Awani
31 December 2014	Kampung Raja, Cameroon Highland	-	-	1	
22 October 2017	Tanjung Bungah, Penang	-	-	14	Reuters

Shallow slide is the most common type of slope failure in Malaysia where the slide surface is usually less than 4 m depth and occurs during or immediately after intense rainfall (Jawaid, 2000). Other types of slope failure found are deep-seated slide, debris flow and geologically controlled failures such as wedge failures and rock falls.

By definition from Frasheri (2012) slope is a dynamic system of geo-environment phenomena that are related to the movement of soil and rock masses. Some examples of slope failure including avalanche of the rocks, debris and soil flow, collapse of the blocks and landslides. Slope failure phenomena can be defined as an engineering and environmental issue. In order for a slope to fail, there is a process related to deformation of the rock mass, accumulation of stress and mineralogical changes involved. The body movement only occurs as the last stage and associated directly with mechanical and geological condition of the rock mass. The slope become unstable as the rock mass loss mechanical stability due to full compliance of the unstable condition. The rock mass sensitivity to the external force also increased as it become more unstable.

There are many factors that affected slope stability therefore causes slope failure to occur. One of the factor is due to gravitational force which pulls everything to the direction of Earth's centre. Unstable rock or structure will allow the gravitational force to act and end up as landslide or rockfall. Another major factor that influences slope stability is water. Additional of water on the subsurface will results as the slope to increase in weight therefore becomes unstable. Oversaturated soil with water will cause the grain to lose contact to one another and can also change the angle of repose. The nature of Earth material such as clayey type of soil and the presence of structure such as fracture and weathered zone in the subsurface can also cause slope failure to occur. On top of all, the most critical factor for slope failure to occur is triggering events such as heavy rainfall and earthquake (Nelson, 2013).

1.1 Problem statements

Aside from the slope at the roadsides, residential areas and agricultures are developed on the slope areas too. The limited flat land in Penang Island has urged developers to develop buildings on the steep slopes (Teh, 2000). This irreversible action has taken tolls on the hills ecosystems. As the developed slope areas spreads, the effects could be more severe and worse. On top of that, illegal forest clearing and illegal farming on slopes without any consideration of the subsurface condition could accelerate soil erosion and slope failures. Table 1.2 shows the summary of slope failures in Penang Island in 2008 to 2017. This indicates that slope failure in Penang Island is a crucial matter.

Table 1.2: Summary of slope failures in Penang Island.

Date	Location	Remarks
4 October 2008	Persiaran Kelicap, Sungai Ara	Collapsed retaining wall caused flooding and mudslide to resident houses.
7 October 2008	Jalan Teluk Kumbar – Balik Pulau	Landslide caused road closure to traffic
6 April 2009	Pangsapuri Farlim Tower, Bandar Baru Farlim, Air Hitam	Landslide, damage on vehicles
10 June 2010	Pangsapuri Bandar Baru Air Hitam	Landslide
24 June 2010	Batu Feringghi	Mudflow and mudslide from nearby hillslope development project
10 March 2011	Taman Terubong Jaya	Landslide, caused collapsed of retaining wall and buried two cars
September 2013	Penang Hills	Landslide at KM 2.1, KM 2.5 and KM 4.0
29 October 2016	Air Hitam	Landslide near Kek Lok Si Temple heading to Air Hitam Dam
7 November 2016	Jalan Ujung Baru, Teluk Bahang	Landslide forced road closure to traffic
5 November 2017	Tanjung Bungah	Three newly built luxury houses destroyed.

In accordance to slope failure occurrence, Department of Public Work Malaysia will act according to Malaysia Standard Code Practice MS 2038: 2006: Site Investigation – Code of Practice which included the application of boring log, ground water observation and Mackintosh probe test and Malaysia Standard Code Practice MS 1056: 2005: Soil for Civil Engineering Purpose – Test Method which included laboratory test of disturbed and undisturbed soil samples. Slope failure is a perpetual issue in Malaysia, any method that can be in assistance to solve such issue should come to the front. In this research, the ability of geophysical methods in dealing with engineering and environmental issue are tested to determine the slope failure potential.

The common geophysical methods apply for slope failure studies are 2D resistivity method and seismic refraction method (Popescu et al., 2014; Giocoli et al., 2015; Muztaza et al., 2017; Hazreek et al., 2017). In this research, the application of 2D resistivity method is paired with induced polarization method as this combination in slope failure studies is yet to be well-known (Marescot et al., 2008).

1.2 Research objectives

The objectives of conducting this research is listed as follows:

i. To investigate slope at the selected highly suspected area in Penang Island (Sungai Batu, Bukit Relau and Air Hitam) using 2D resistivity and induced polarization methods.

ii. To analyse and correlate the results from 2D resistivity method, induced polarization method, laboratory tests and rainfall distribution for slope failure potentials.

1.3 Scope of research

This research was conducted at Penang Island which is generally made up of granitic rock. The three study areas were chosen based on the landslide distribution in Penang Island obtained from previous studies and also cases of landslide reported.

The geophysical methods used in this study were 2D resistivity method and induced polarization (IP) method by using ABEM SAS4000 Terrameter and ABEM ES 10-64C electrode selector. The resistivity inversion models were produced by using RES2DINV software by Geotomo. Each model inversion was studied and observed so that any slope failure possibilities can be detected.

Aside from geophysical methods, the soil laboratory tests were also conducted in order to measure the soil porosity, moisture content and particle size distribution. Rainfall distribution were also factored, in order to identify the potential of the slope failures.

1.4 Significance of study

People tend to use the ground methods, geotechnical methods and remote sensing over the geophysical methods (Talib, 2003; Ahmad et al., 2006; Khan et al., 2010; Lateh et al., 2011; Department of Public Works Malaysia, 2018). There are many reasons that geophysical method should be chosen when dealing with engineering and environmental issues. The geophysical methods are non – destructive, low cost consumption and have wider area coverage. Geophysical methods also have the potential in dealing with engineering and environmental problem such as slope failures.

This research aims to apply geophysical methods in dealing with engineering and environmental problems Thus, this research is carried out in order to convince the potential lies within geophysical methods in dealing with engineering and environmental problems.

By applying geophysical methods in slope study, the expenditure can be reduced and remedial works will be done in more efficient ways and not blindfolded. The significant of this study is to understand the mechanism of slope failures at highly potential areas in Penang Island as most of the study conducted before were site specific. Another significant of this study is the application of induced polarization method which rarely used for slope study. This aims to detect saturated zone and high moisture area in the subsurface and its origin.

1.5 Thesis outlines

This thesis contained five chapters as follows:

Chapter 1 is the introduction of the research where the preface of study, problem statements, research objectives, scope of study, significance of study, and thesis outline are explained.

Chapter 2 is the literature review. The background of the slope is elaborated, theory of 2D resistivity and IP method is explained and the previous study that related to this research are discussed.

Chapter 3 is the materials and methods chapter. The details about the study area including the geological of the area and the survey lines orientation are shown. This chapter also explained the equipment used and the procedures during data acquisition. Aside from that, procedure that related to soil laboratory tests are explained as it is part of the research element.

The results are discussed in Chapter 4. This includes the soil laboratory tests, particle size distribution results and geophysical results. The results are correlated to the rainfall distribution. Empirical correlation between laboratory test and geophysical results are also shown in this chapter.

Chapter 5 is the conclusion and recommendations. The research findings are concluded and discussed. Some recommendations for future works are also suggested in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

For engineering and environmental purposes, people tend to choose the airborne and satellite methods such as remote sensing and Geographic Information System (GIS) or the direct ground-based techniques such as piezometer and laboratory tests over geophysical method which are also capable in solving the engineering and environmental problems (Talib, 2003; Ahmad et al., 2006; Khan et al, 2010; Lateh et. al, 2011). Fortunately, people had grown interest in geophysical method in order to investigate engineering and environmental problems such as slope stability in the last several decades (Jongmans and Garambois, 2007; Chambers et al., 2011). Each geophysical method has their own specialities on specific targets and environments which will produce good results besides time and cost effective. Several studies on slope failures and the application of geophysical methods on slope stability are included in this chapter.

2.1 Previous studies

A landslide on argillaceous material occurred in Western Cameroon around Kekem area. Geophysical and geotechnical surveys were carried out by Epada et al. (2012) with purpose to understand the triggering processes and mechanism of the landslide and to assess the slope stability. Resistivity survey had been conducted by using electrode configuration of Schlumberger array in order to monitor the behaviour of the landslide in term of resistivity. A zone of low resistivity value was identified as clayey sand-filled aquifer in the subsurface of the landslide. This aquifer was suspected to be the triggering factor of the landslide. Based on the geotechnical sounding result, the aquifer had a thickness of 7.0 m whereas the depth of the landslide crest level to the failure surface reached 3.0 m and 20.6 m. Next, laboratory tests were carried out to evaluate the cohesion of the soil and the angle of internal friction. The tests result shows that the soil has low consistency which is almost doughy. As for stability analysis, the mean value of the factor of safety (FOS) is 1.4 which was lower that the slope stability coefficient which is 1.5. Therefore, the slope was unstable and likely to reactivate at any moment.

A landslide was studied at Buzad village, Timis County, Romania by using electrical resistivity tomography (ERT). The landslide occurred in 2006 was reactivation of an old landslide. Popescu et al. (2014) conducted three resistivity survey over the main body of the landslide by using electrode configuration of Wenner array in 2007, 2012 and 2014 (Figure 2.1). The length of the profile was 90 m in 2014 but 100 m in 2007 and 2012 and achieved depth of about 15.0 m along all longitudinal profiles. The results showed that a section with resistivity value of 0-35 Ωm at the upper half while the middle part ranged from 55 – 100 Ωm. The bottom part recorded as shallow high resistivity zone. This suggest that high water content from the middle part of the profile may be the triggering factor of the reactivation. The hypothesis was confirmed from an in-situ observation of the ground water table appeared to the surface. Whereas the high resistivity value of the bottom part is compact material (sands) embedded in clayey matrix of the old landslide body. Resistivity method allows one to identify high water content area that cause the reactivation and thus reconstruction of the landslide body including the body materials in movement and its volume. Aspect noted in all resistivity profiles, the new and old landslide were located in a zone of obviously changing resistivity values.

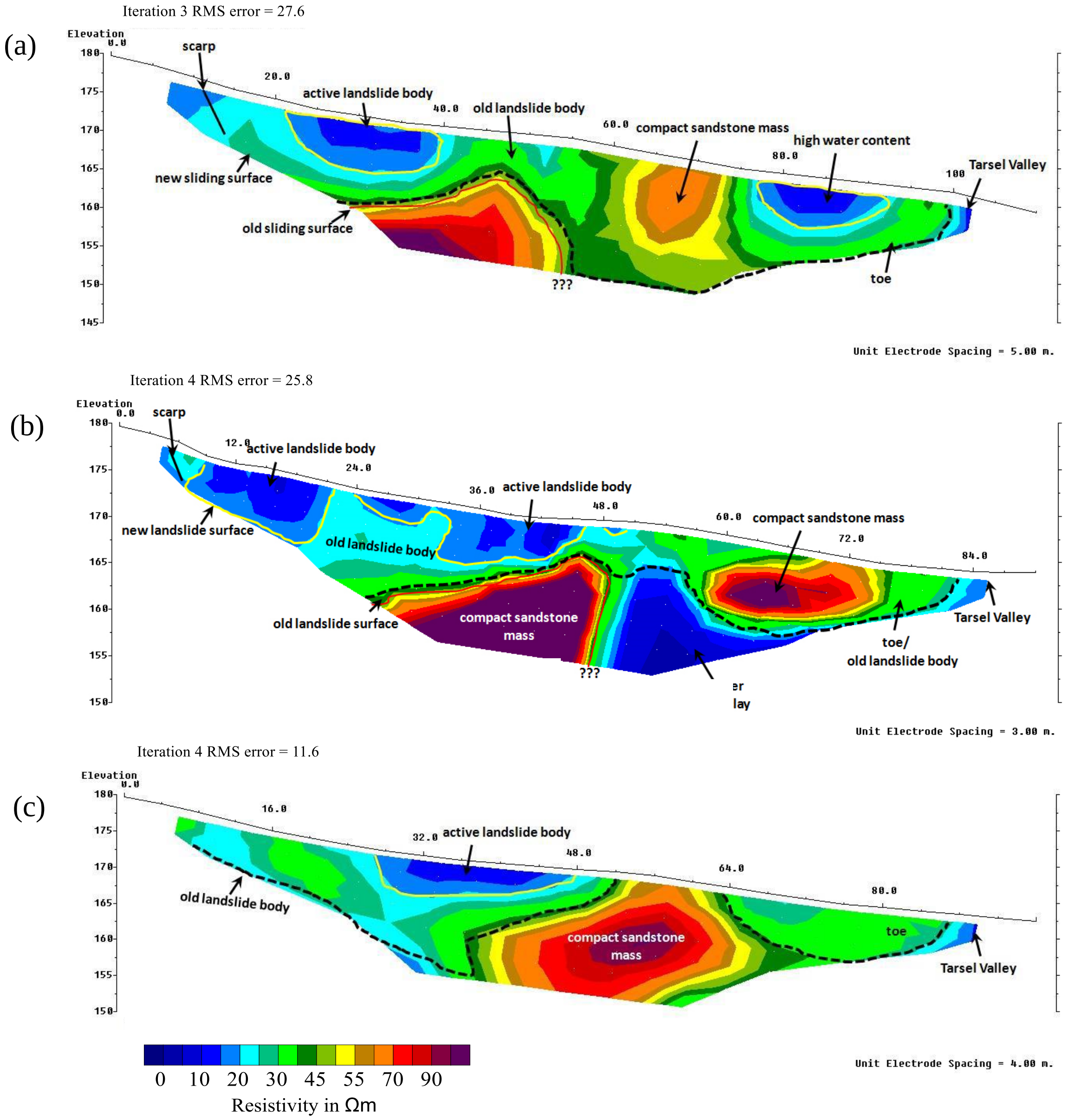

Figure 2.1: ERT profiles through Buzad landslide in (a) 2007 (b) 2012 (c) 2014 (Popescu et al., 2014).

Glacial erosion had produced 'crag and tail' structure at the Edinburgh Castle which is one of the most important heritage site in Scotland. The crag consists of columnar jointed basal that formed a gentle slope protecting the tail of sediment from glacial erosion. An apparent instability was observed in the southern side of the 'tail' between the Edinburgh Castle Esplanade and Johnston Terrace in 1997 which later initiated the geotechnical and geological investigation on the particular slope including electrical resistivity survey. In order to determine the subsurface structures and variations in pore fluid distribution within the slope, Donnelly et al. (2005) conducted six resistivity survey lines with length of 24 m with electrode configuration of Wenner array. Line 1 to Line 5 were positioned down the slope perpendicular with the southern boundary wall of Esplanade whereas Line 6 was positioned across the slope parallel to the Esplanade wall. A shallow slope failure was confirmed based on the result however the initial date of failure is not known but likely since at least 1950's. The resistivity profiles indicated that the instability was due to zones of low resistivity and high saturation. The backscarp also seems to be associated with relatively thin clay layer which apparently not a slip plane but however may cause the local groundwater to flow in as a highly permeable fill material. Similar condition was found to the east and west of the uppermost featured of the landslide lateral continuation.

Giocoli et al. (2015) performed a joint analysis of geophysical surveys, aerial photos interpretation, morphotectonic investigation, geological field survey and borehole data to investigate an area in the Montemurro territory in southeastern sector of High Agri Valley (Basilicata Region, southern Italy). Generally, the area consists of steep slopes, encased streams within narrow and deep land incision and abrupt acclivity change due to tectonic structures or lithological variation. This area has been affected by the hydrogeological instability which included active and inactive landslides. Surficial investigation identified the existing of northwest (NW) – southeast (SE) trending and southwest (SW) facing scraps between villages of Pergola to the north and Voggioni to the south. Geophysical surveys were conducted to unravel the surface expression of the strand. Three resistivity survey lines were carried out across the NW-SE scarp by using Wenner-Schlumberger electrode configuration with 20 m spacing. Survey line ERT1 and ERT3 achieved depth of penetration of 150 m with spread of 940 m length whereas survey line ERT2 achieved the same depth with spread of 1100 m length (Figure 2.2). In the upper of line ERT2, a body associated with the Verdesca landslide was identified between 430 m and 1100 m based on the resistivity values (25 – 70 Ωm). The estimated thickness was derived from borehole data GB1 – GB3 and resistivity contrast from ERT2, varies from less than 10 m and up to 30 m. Another geophysical method done was a high-resolution seismometer with 24-bit dynamic was aimed at the very low amplitude range. Thirty-five ambient noise measurements with each duration of 12-15 minutes with additional measurements overlap with all resistivity profile lines were taken. The results successfully showed the fundamental frequency was related to the depth variation of the seismic impedance differ between the low resistive Quartenary continental deposits (QD) and Albidona Formation (AF) and high resistive Gorgoglione Flysch (GF). These joint analyses succeed in achieving the objectives of the study which is to image the shallow geological and structural setting as well as to verify the nature of the NW-SE scarps and thus interpreting it as surface expression of the Montemurro Fault.

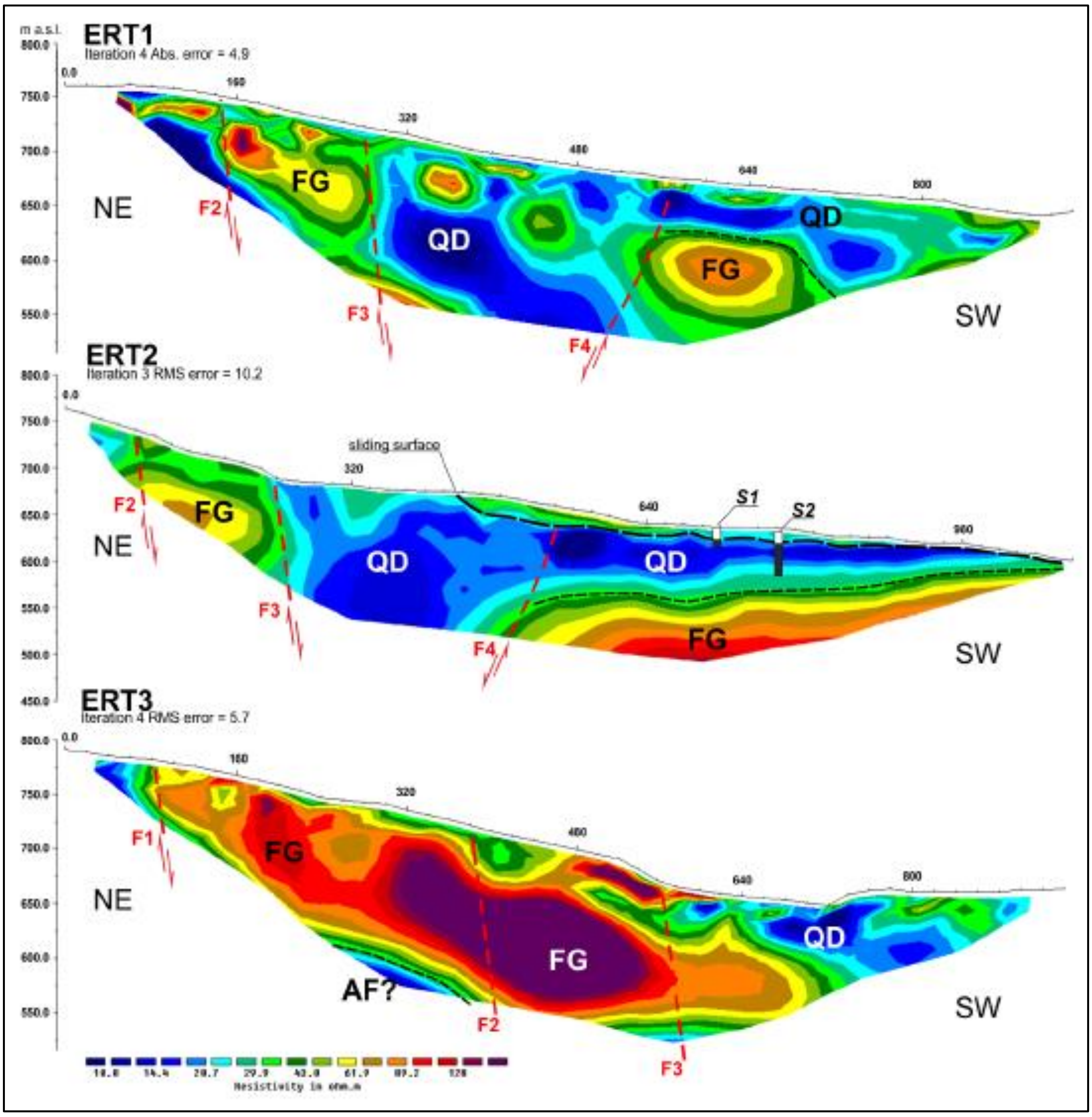

Figure 2.2: Resistivity profiles for ERT1 – ERT3 (Giocoli et al., 2015).

A study of landslide was conducted by Drahor et al. (2006) at district of Aydin, Turkey in 2003 on a slope next to a newly built school building. The slope was unstable due to an excavation work and heavy rainfall. Three resistivity survey lines were conducted over the landslide using Wenner electrode array resulting on the geometry and characteristic of the landslide. Eight boreholes were also carried out on the landslide. Both methods showed a fault presence at the area with addition of a surface rupture indicated by the resistivity profiles (Figure 2.3).

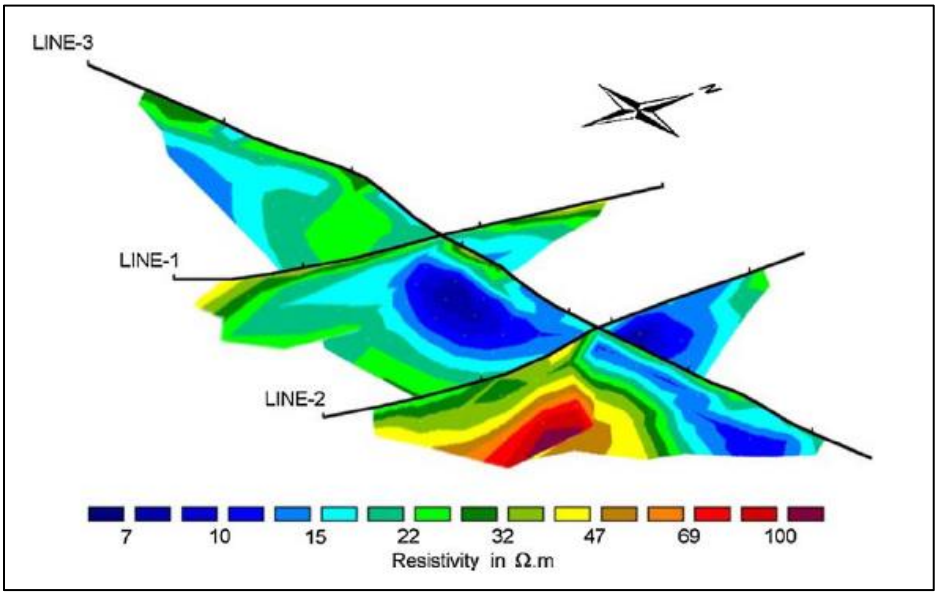

Figure 2.3: 3D fence diagram for resistivity section in Aydin (Drahor et al., 2006).

Resistivity and self-potential methods were applied to study the hydraulics of landslide process as these methods are capable to provide spatial and volumetric information as well as sensitive toward hydraulic changes in the subsurface. A system called Automated Time-lapse Electrical Resistivity Tomography (ALERT) was applied on an active landslide near Malton, North Yorkshire, United Kingdom in order to develop a 4D landslide monitoring system that capable to characterise the subsurface structure of landslide and detecting the hydraulic precursor to movement. According to Chambers et al. (2009), the time-lapse resistivity imaging was able to show the changes related to the seasonal temperature variation, moisture content and ground movement within the landslide. The 4D resistivity imaging was an effective method to investigate the hydraulic of a landslide whilst taking the influence of temperature and electrode displacement into consideration.

One of study conducted in Malaysia is to investigate the influence of natural slope geomorphology on active cut slope failure near Gunung Pass, Simpang Pulai-Lojing Highway by Shuib et al. (2012). Previous studies have found out that there was close correlation between the relict landslide scars on the natural slope and the presence of cut slope instabilities. Hence resistivity and seismic refraction surveys were conducted across the relict landslide scars. Based on the results, the steep relict scarps were connected at the subsurface by a circular slip surfaces which is represent by steep weak zones. The head scarp zone was represented by the topmost slip surfaces with tension cracks suggestive of extensional strains while the toe region was represented by the reversed slip surface suggestive of compressional strains. The failure was due to the head and the upper main body zone sliding roughly orthogonal to the foliation while the middle and toe zone is sliding down and out of the foliation. From the surface and subsurface observation, the natural slope was inferred to be creeping which later induces shallow planar and circular failures at the cut slope.

Based on a study conducted by Chigira et al. (2011), landslides in weathered granitic rocks are greatly influence by the type of weathering and it is site specific. The mechanism of failure in deep weathering profiles in Malaysia are highly controlled by the nature of the weathered material and its mass structure. In Japan, the landslides occurred due to moderately weathered decomposed granite. The rock loosened rapidly as it was exposed to the ground surface and formed loosened layers to slide. The fact of weathered granite is prone to slide was known for many years. However, the landslide mechanism was not yet fully understood due to the weathering profile was site specific and differ among climates. More than 80 landslides occurred along the mountainous main highway to Genting Sempah, Pahang. Most of the landslides occurred in a few hours in June 1995 as there was a continuous rain for more than 72 hours. Majority of the landslide can be categorized as small to medium size with sliding materials less than 500 m^3. Types of slope failure included shallow and deep sliding, rock block sliding and debris flow. This is a region that formed by granite batholiths and the granite has undergone intensive tropical weathering. This resulting in forming weathered profiles with various characteristic and thickness. Most of the landslides are related to the weathered materials. The intense and heavy rain saturate the residual soil thus, triggering two major landslides upstream of a tributary of Sungai Gombak.

A study conducted by Komoo (1997) at Bukit Antarabangsa concluded that the weathered granitic material may contributed to landslide as it was porous, easily crumble and inherited the plane of weakness from the parent rock. Bukit Antarabangsa has marked in the history of Malaysia landslide disasters as there were six major landslides occurred since 1993. The hill was underlain by granite and extensive weathering has transformed the granite into residual soil (grade VI) and completely weathered material (grade V). The weathered material was sandy with average thickness profile of 30 m. The subsurface loose its consistency with increasing amount of water. This condition triggered a collapsed of twelve storey Highland Tower condominium in 1993.

Another study conducted by Komoo and Lim (2003) at the same Bukit Antarabangsa with 100 m distance south from the previous landslide. In 2002, a bungalow was destroyed due to landslide killing eight people. The landslide mechanism was rather complex but it is due to continuous heavy rain that triggered the sliding. That was not all, other factors may also contribute the triggering of the landslide. Factors such as weathered granitic materials that prone to failure, geological lineament that facilitating the sliding. An old landslide landform found nearby also aided the accumulation of groundwater that resulting in the landslide in 2002.

Muztaza et al. (2017) has conducted a slope failure evaluation and landslide investigation by using 2D resistivity method in Selangor. Nine survey lines were carried out at Site A and another six survey lines at Site B with minimum electrode spacing of 5 m were performed using Pole – Dipole electrode array. Alluvium or highly weathered zone with resistivity value of 100 – 1000 Ωm found at depth > 30 m, saturated area with resistivity value of 1 – 100 Ωm and boulders with resistivity value of 1200 – 7000 Ωm. The granitic bedrock was identified with resistivity value of > 7000 Ωm (Table 2.1). From this study, the triggering factors for slope failure was due to the saturated zones, highly weathered zone, highly contain of sand, and boulders.

Table 2.1: Summary of resistivity value with interpretation at the study areas in Selangor (Muztaza et al., 2017).

Resistivity value (Ωm)	**Interpretation**
1 – 100	Saturated zone
100 – 1000	Alluvium or highly weathered zone
1200 – 7000	Boulder
> 7000	Granitic bedrock

A slope failure in Kenyir Lake was evaluated by Hazreek et al. (2017) using resistivity method with a reference to a borehole data. Two resistivity survey line was carried out using electrode array of Schlumberger array. The main factor that triggered the slope failure is the combination of heavy rainfall and the presence weakness zone. The results also successfully detected fault and rock discontinuities which associated by low resistivity value (Figure 2.4). By applying resistivity method, the shape and depth of subsurface landslide that caused ground damage can be determined easier as the resistivity method mapped the subsurface profile based on the resistivity values.

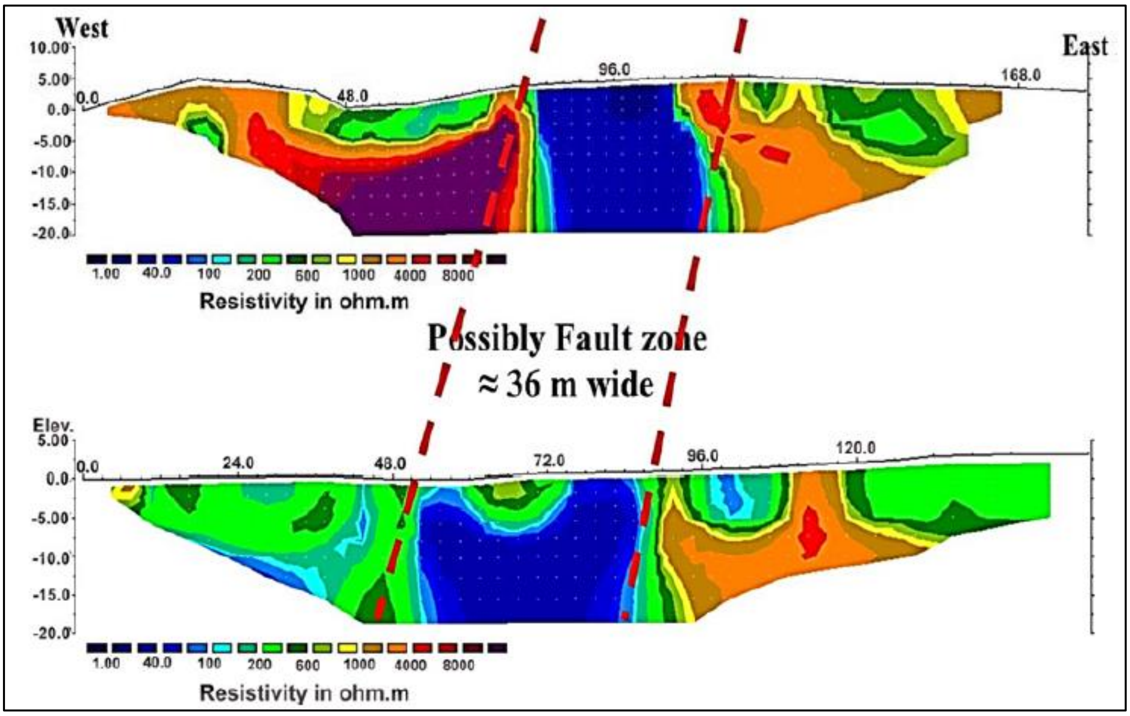

Figure 2.4: Resistivity profiles according to the location (a) top of landslide (b) toe of landslide (Hazreek et al., 2017).

Yaccup and Tawnie (2015) had conducted a comparison between resistivity imaging technique and borehole data on determining depth of granite body as the active quarry site in order to define the accuracy of the resistivity data with borehole information. Eight resistivity profiles were built near to several boreholes with maximum distances of less than 50 m. The result shows that in the tropical region such as Malaysia (Table 2.2), the resistivity value of low weathered granite to fresh granite is more than 5000 Ωm, medium weathered between 1000 – 5000 Ωm and highly weathered granite is lower than 1000 Ωm. Resistivity and borehole recorded accuracy more than 80% with another 20% error due to changing of resistivity due to existence of water, fractured zone and the distance between the survey line and borehole.

Table 2.2: Resistivity range of weathered granite and fresh granite in Malaysia (Yaccup and Tawnie, 2015).

Resistivity value (Ωm)	**Interpretation**
< 1000	Highly weathered granite
1000 – 5000	Medium weathered granite
> 5000	Low weathered – fresh granite

Jinmin et al, (2013) applied 2D resistivity method for subsurface study at Bukit Bunuh. The aim was to identify the bedrock structure, fracture of shallow subsurface and identify the alluvium pattern. Due to large study area, the borehole data is not adequate to measure the subsurface condition. Therefore, the borehole data were used as preliminary information to refine 2D resistivity results. A survey line of 2.065 km was done by applying Pole – Dipole array with 5 m minimum electrode spacing. The results show two major zones in the study area; resistivity value of 10 – 800 Ωm interpreted as alluvium and resistivity value of more than 3000 Ωm as boulder and granitic bedrock.

A study on hill-slope movement was conducted by Khan et al. (2010) to monitor a land movement during rainy seasons in 2008. Two landslides occurred between 23 and 26 km stretched through Gunung Pass, Cameron Highland in April and December 2007 respectively. Based on deduction, the hilly terrain was triggered by the rainfall events. Moreover, the slope at Gunung Pass may experience some movement within the subsurface from the past rainfall events before the failure occurred in 2007. Therefore, a theodolite study was conducted on the slow hill-slope movement to monitor the land movement during rainy seasons of 2008. The results successfully identified a close correlation between the hill-slope displacements and the rainfall amount during the study period. The slow hill-slope movement occurred after a heavy rainfall in 2008. Result from Prism III theodolite showed that the down slope movement was more than 4 m, southward movement of 1.94 m and westward movement of more than 5 m (Figure 2.5). As conclusion, the area was unstable and prone to slide.

(a)

(b)

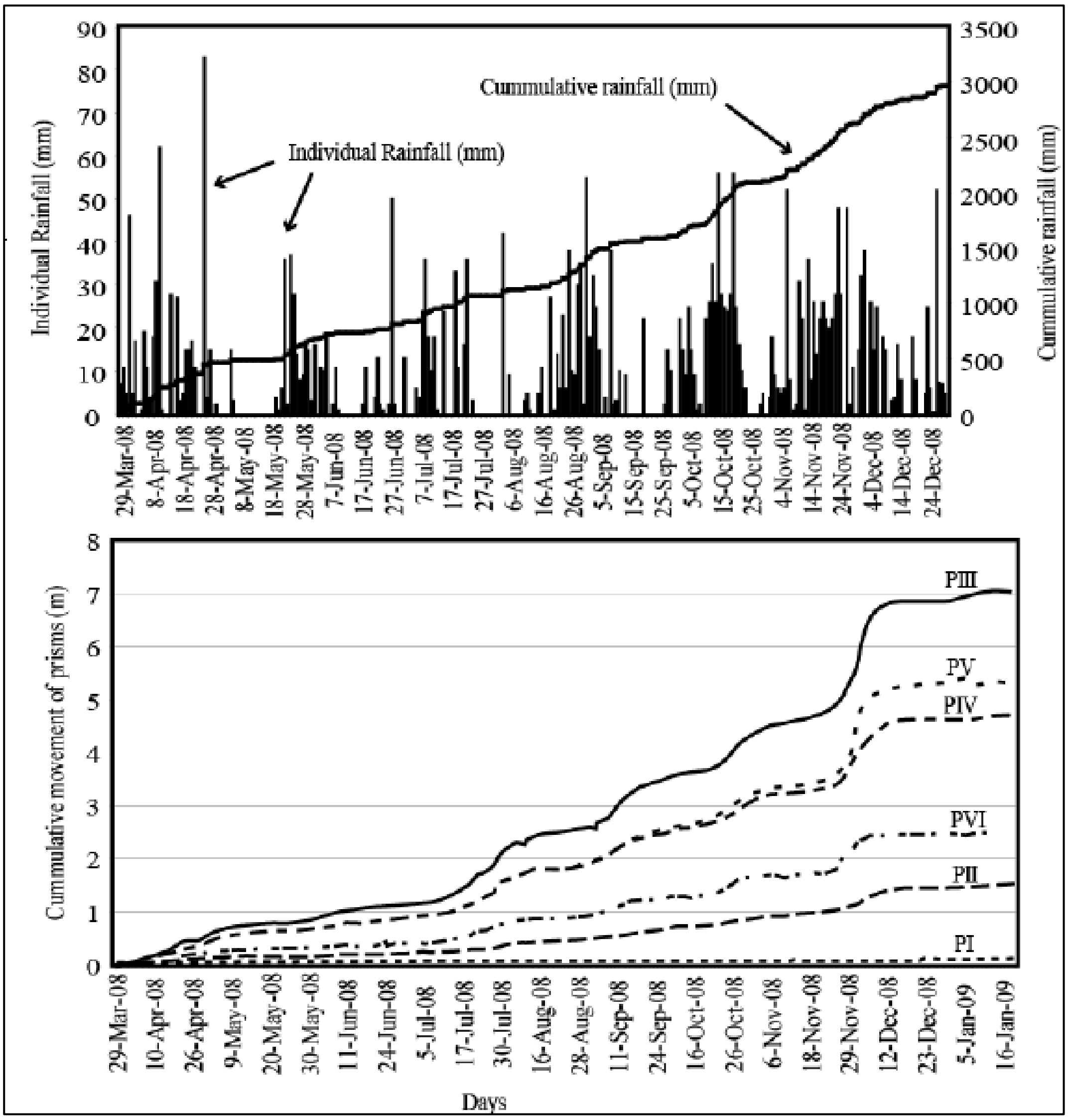

Figure 2.5: a) Average rainfall at Cameron Highland from March 2008 to Dec 2008 b) Observed total displacement at Prisms I-VI (Khan et al., 2010).

Xu et al. (2016) investigate a landslide in southwestern China by using time – lapse electrical resistivity tomography (TLERT) in November 2013 and August 2014. The study aims to investigate the subsurface hydrogeological environmental and evolution of landslides based on the electrical structure and geometry of sliding surface. The landslide mechanism is inferred based on the spatiotemporal characteristic of the surface water infiltration and groundwater flow within the landslide body. The resistivity inversions accurately defined the interface between the Quarternary sediments and bedrock when combined with borehole data. The results show that the surface water penetrates via the fracture zone and fissures into the slipping body and drained as fissure water in the fractured bedrock. This eventually caused the weathered layer to soften and erode. This finding indicated that the TLERT monitoring able to provide preliminary information on critical sliding and can be used for landslide stability analysis and prediction.

A study conducted by Rahardjo et al. (2001) in Nanyang Technology University Campus successfully indicated that the landslides were initiated by the rainfall infiltration. The daily rainfall and the cumulative rainfall both act as the triggering factor for slope failure. A five days cumulative rainfall with more than 60 mm combined with daily rainfall exceeded than 90 mm was sufficed to initiated a landslide.

A water – seepage coupling model and stability analysis was developed to study the effect water on the soil – slope stability by Liu and Li (2015). In order to analyse the effect of water seepage which came from rainwater and water level fluctuation, safety factor of slope by rainfall and water level fluctuation was simulated. The simulated result indication that both rainfall and water level fluctuation decreased slope stability according to the safety factor of the slope (Figure 2.6). The reason for this phenomenon is increased in total soil weight and slight improvement of pore pressure in slip surface. Therefore, slope stability is highly affected by rainfall and water level fluctuation.

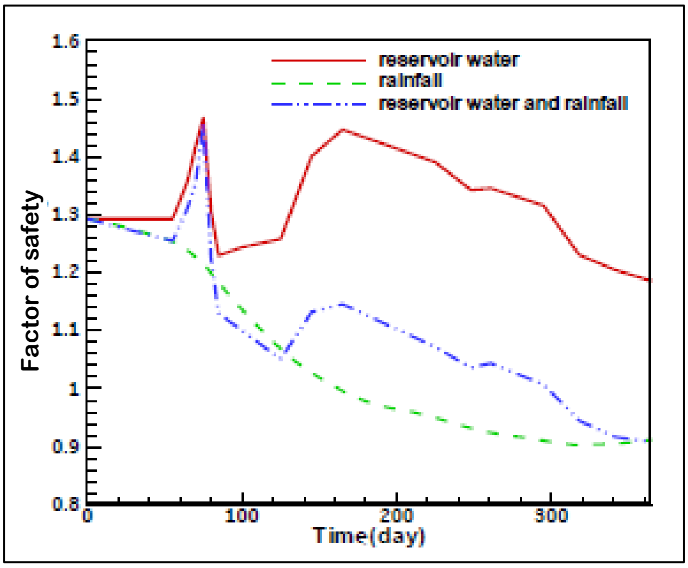

Figure 2.6: Safety factor caused by reservoir water, rainfall and combination of rainfall and reservoir water fluctuation (Liu and Li, 2015).

Lateh et al. (2011) monitored the slope movement before the slope failure occurs by using inclinometer, piezometer and rain gauge at 3.9 km Jalan Tun Sardon, Penang. The soil was detected move on 30th July 2010 and 4th November 2010 due to the intense rainfall before the occurrence. Therefore, the soil movement and rainfall intensity can be related in affecting slope failure occurrence.

A slope investigation was carried out at Fraser's Hill due to a debris flow was found at 9 km of Fraser Hill road by Ghazali et al. (2013). Using resistivity method, three survey lines parallel to the slope and two survey lines perpendicular to the slope were applied at the reported area. Results showed existence of granite body at the central part of the east line and nearest to the ground surface. The presence of resistivity less than 600 Ωm within the granite body is interpreted as highly fractured and water conducting zones. The same zone was detected at east – west and north south lines. Therefore, the fracture granite is virtually floating above the water saturated zone thus, considered as unstable.

Ng et al. (2015) has utilized resistivity method to investigate a slope failure at Precinct 9, Putrajaya with aided by borehole sampling data. Results showed two zones were encountered, high water content zone with resistivity value of 10 – 300 Ωm and dry zone with resistivity value of 300 – 100 kΩm. Borehole sampling recorded subsurface condition was range from fresh to highly weathered granite. Rock quality designation (RQD) indicated value of 0 – 100 % which show the presence of rock fracture that cause seepage flow within the subsurface. Therefore, low resistivity zone face risk for slope failure which demand remedial measures.

Ramadhan et al. (2015) has conducted resistivity method by using electrode configuration of Wenner – Schlumberger at Bendanduwur Gajahmungkur Semarang to identify landslide slip surface. The results of resistivity method reached to depth of 14 m and it shows that the lithology of the location consist of soil, clay, sandstone and breccia. The contact between clay and sandstone found at depth 1.25 to 6.76 m found in the survey lines is interpreted as the slip surface of landslide due to the contact indicated disconnection between the layers also known as weak zone. Landslide can be expected in this location due to the presence of clay, which is impermeable for water to pass through.

A study by Ahmad et al. (2006) at Paya Terubong on a landslide that occurred in 1998. The average thickness of highly to completely weathered granitic soil is found to be approximately 30 m. The sampled residual soil consists of gravel (14%), sand (55%), silt (18%) and clay (13%) which can also represent as course-grained residual soil which is also known to be susceptible to landslide.

Hashim et al. (2015) used shear box test in order to identify slope failure in Penang Island. This study aims to determine the soil shear strength under saturated shear box test for samples taken from slope failure locations. The locations were selected from slope failure tragedy sites along Teluk Bahang – Balik Pulau road. The summary of shear box test and particle size distribution test (BS 5930: 1990) is as in Table 2.3 and Table 2.4 respectively. The results indicated that the slope failures were found mostly in gravelly silt soil and the range of cohesion recorded was largest compare to others soil.

Table 2.3: Saturated peak shear box and particle size distribution tests, BS 5930: 1990 (Hashim et al., 2015).

Soil types	Range of cohesion	Range of angle of shearing resistance
Silt	0.1 – 33.4	22.9 – 47.1
Very silty sand	0.6 – 8.3	30.7 – 62.4
Sandy silt	0.0 – 27	18.6 – 52.9
Very silty gravel	0..8 – 37.5	24.5 – 57.2
Gravelly silt	0.0 – 40.8	18.1 – 65.8

Table 2.4: Result of soil classification and particle size distribution test, BS 5930: 1990 (Hashim et al., 2015).

Soil sample	Slope condition	Percentage (%)				Soil classification
		Gravel	Sand	Silt	Clay	
A	Unfailed	64.88	18.08	17.04	0.00	Very silty gravel
B	Failure mass	37.92	20.67	41.25	0.16	Gravelly silt
C	Failure scar	36.26	30.16	33.53	0.05	Gravelly silt
D	Failure mass	36.88	24.21	38.67	0.24	Gravelly silt
E	Failure mass	26.19	36.88	36.85	0.08	Gravelly silt
F	unfailed	76.93	7.45	15.50	0.12	Very silty gravel

A study conducted by Bery (2016) to identify the empirical correlation of soil properties of shear strength, moisture content, void ratio, porosity, saturation degree and Atterberg's limit with electrical resistivity values from resistivity tomography models. Eleven undisturbed clayey sand soil samples were collected at different distances, depths and both infield and laboratory condition. Based on the results, the electrical resistivity values were highly influence by the soil properties. A good estimation of soil mechanics properties can be obtained from the results of electrical resistivity tomography model.