THE SLOPE ASSESSMENT USING GEOPHYSICAL APPROACHES WITH INTEGRATED ANALYSIS OF 2-D CROSS PLOT MODEL

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by/oleh

MUHAMMAD TAQIUDDIN BIN ZAKARIA

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LIST OF SYMBOLS

A	Cross-sectional area
a	Electrode spacing
c	Cohesion
c′	Cohesion in term of effective stress
C1	Current electrode 1
c_p	Phase velocity
Cr	Critical slope
dx	Receiver spacing of geophones
E	Young’s modulus
f	Frequency
Fa	Failure slope
f-k	Frequency-wave number
g/cm^3	Gram per centimeter cube
G_0	Shear modulus
GPa	Gigapascal
ha	hectares
Hz	Hertz
I	Current
i_c	Critical angle
k	Geometric factor
k	Wavenumber
kg	Kilogram
L	Length
m/s	meter per second

m_0	Initial mass
mA	Milli-ampere
m_d	Dry mass
n	Dipole separation factor
N	Newton
P	Horizontal shear force
P1	Potential electrode 1
R	Resistance
sec	Second
St	Stable slope
t_{cross}	Intercept time at cross-over distance
t_i	Intercept time
t-x	Time-space
V	Volume
V_1	Velocity of the first layer
V_2	Velocity of the second layer
V_g	Voltage
V_{mm}	Volume of mass movement
V_p	P-wave velocity
V_R	Rayleigh wave
V_r	Rayleigh wave phase velocity
V_s	S-wave velocity
V_{sm}	Volume of the mass body below the sliding plane
V_{soil}	Volume of soil
V_{s-v}	S-wave velocity-vertical component
V_{tm}	Volume of total mass body
W_{dry}	Weight of dry soil

x,y	Areal extent of landslide
x_1	Distance of source to receiver
x_c	Critical distance
x_{cross}	Cross-over distance
z	Depth
Ze	Median depth of investigation
Z_{max}	Maximum depth of investigation
λ	Wavelength
λ_{max}	Longest wavelength
μs	Micro-seconds
ν	Poisson's ratio
ρ	Density
ρ	Resistivity
ρa	Apparent resistivity
σ	Normal stress
σ'_f	Effective normal stress
τ	Stress on the surface of shear
ϕ	Angle of internal friction
ϕ'	Angle of internal friction in term effective stress
Ωm	Ohm.meter
τ_f	Shear stress at failure
τ_p	Peak shear stress at failure

LIST OF ABBREVIATIONS

ABEM	Aktiebolaget Elektrisk Malmletning
BD	Bulk density
JMG	Jabatan Mineral Dan Geosains Malaysia
JMM	Jabatan Meteorologi Malaysia
MASW	Multichannel Analysis of Surface Waves
Q	Quadrant
RQD	Rock quality designation
S/N	Signal to noise ratio
SAS	Signal Averaging System
SPT	Standard Penetration Test
1-D	One dimensional
2-D	Two dimensional
3-D	Three dimensional

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PENILAIAN CERUN MENGGUNAKAN PENDEKATAN GEOFIZIK BERSAMA PENGANALISAAN BERSEPADU 2-D MODEL PLOT SILANG

ABSTRAK

Resolusi yang tidak mencukupi dengan kaedah-kaedah yang terhad terdedah kepada kesilapan tafsiran kerana pencirian tanah runtuh memerlukan julat data dan pemerhatian yang luas. Pengesahan dari parameter-parameter yang berbeza diperlukan untuk mengesahkan keputusan bagi mengurangkan kesalahan semasa tafsiran. Analisis plot-silang bersepadu telah diperkenalkan sebagai kaedah alternatif untuk meningkatkan tafsiran subpermukaan berdasarkan kriteria model-model. Kaedah geofizik keberintangan 2-D, pembiasan seismik, dan MASW telah digunakan untuk mencirikan perilaku tanah runtuh dengan data yang disokong dari parameter-parameter geoteknik dan hidrologi. Tiga jenis keadaan cerun dipilih, iaitu cerun stabil (USM *Arkeologi–USM)*), cerun kritikal (Lojing–*LJ*), dan cerun gagal (Hulu Yam–*HY* & Bkt Antarabangsa–*BA*). *USM* mewakili keadaan cerun yang stabil di mana tanah jeleket dikenal pasti pada keberintangan, ρ=400-1000 Ωm dan halaju V_p=800-1800 m/s; V_s= 250-350 m/s pada kedalaman 5-10 m. Modulus anjal menunjukkan kekuatan tanah dengan moduli rendah, (G_0<0.1 GPa; E<0.25 GPa; ν= 0.05-0.45) dengan kedalaman <5 m. Modulus anjal meningkat dengan kedalaman kerana parameter-parameter kekuatan ricih menunjukkan julat nilai yang tinggi (c'=5-29 kPa; ϕ'= 21-28.8°). Dalam cerun kritikal (*LJ*), tanih sisa telah dikenal pasti sebagai bahan peroi/terluluhawa dengan keberintangan, ρ=200-450 Ωm dan halaju, V_p=400-600 m/s; V_s= 150-200 m/s pada kedalaman <5 m. Nilai rendah moduli (G_0<0.1 GPa; E<0.25 GPa; ν= 0.35-0.45) dengan kedalaman <5 m, dikaitkan dengan luluhawa tanah dengan pengurangan parameter-parameter kekuatan ricih. Cerun gagal seperti *HY* dan *BA*

menunjukkan zon luluhawa tinggi (ρ<1200 Ωm; V_p<1200 m/s) dikenal pasti pada kedalaman <5 m. Nilai SPT-N menunjukkan julat rendah 1-15 ketukan, mewakili kekakuan rendah untuk keadaan tanih. Jumlah curahan hujan anteseden yang tinggi (*HY*=267 mm; *BA*=410.4 mm) menunjukkan faktor tambahan mencetuskan kejadian tanah runtuh. Model 2-D plot silang berjaya mendedahkan zon lemah dan kedalaman permukaan gelincir (*LJ&HY* <5 m; *BA* <10 m) tanah runtuh. Model 2-D plot silang memberikan tafsiran komprehensif di mana kuadran, Q1 menunjukkan zon rentan badan tanah runtuh. Satah lemah berjaya dikenal pasti berdasarkan model plot silang dimana zon terluluhawa dan ciri-ciri subpermukaan ditentukan. Penganggaran isipadu pergerakan jisim berjaya dihitung untuk cerun kritikal dan gagal menggunakan peta isopak berdasarkan penentuan satah geluncur. Penganggaran isipadu masing-masing adalah 13657.26 m^3, 554057.83 m^3 dan 167963.71 m^3 untuk *LJ*, *BA* dan *HY*.

THE SLOPE ASSESSMENT USING GEOPHYSICAL APPROACHES WITH INTEGRATED ANALYSIS OF 2-D CROSS PLOT MODEL

ABSTRACT

Inadequate resolution with limitation of the methods vulnerable for misinterpretations as characterisation of landslide required a wide range of data and observations. Validation from different parameters necessary to substantiate the result as to reduce erroneous during interpretations. Integrated cross-plot analysis was introduced as an alternative method to enhance the subsurface interpretations based on the models' criteria. Geophysical methods of 2-D resistivity, seismic refraction, and MASW was utilized to characterize the landslide behaviour with supported data from geotechnical and hydrological parameters. Three types of slope conditions were selected, which are the stable slope (USM *Archaeology–USM*), the critical slope (Lojing–*LJ*), and the failure slope (Hulu Yam–*HY* & Bkt Antarabangsa–*BA*). *USM* represent the stable slope condition where cohesive soil were identified at resistivity, ρ=400-1000 Ωm and velocity, V_p=800-1800 m/s; V_s= 250-350 m/s at a depth of 5-10 m. Elastic modulus shows the strength of soil with low moduli (G_o<0.1 GPa; E<0.25 GPa; ν = 0.05-0.45) with a depth of <5 m. The elastic modulus increases with the depth as shear strength parameters show high range values (c'=5-29 kPa; ϕ'= 21-28.8°). In critical slope (*LJ*), the residual soil was identified as unconsolidated/weathered material with resistivity, ρ=200-450 Ωm) and velocity, V_p=400-600 m/s; V_s= 150-200 m/s at depth of <5 m. The low values of the moduli (G_o<0.1 GPa; E<0.25 GPa; ν= 0.35-0.45) at a depth of <5 m attributed to soil weathering with reducing shear strength parameters. The failure slope of *HY* and *BA* shows a highly weathered zone (ρ<1200 Ωm; V_p<1200 m/s) was identified with a depth of <5 m. The SPT-N values show a

low range of 1-15 blows, which represent the low stiffness of the soil condition. A high amount of antecedent rainfall (*HY*=267 mm; *BA*=410.4 mm) shows an additional factor triggering the landslide event. The 2-D cross plot model successfully revealed the weak zone and depth of the slip surface (*LJ&HY* <5 m; *BA* <10 m) of the landslides. The 2-D cross-plot model gives a comprehensive interpretation where quadrant, Q1 shows the vulnerable zones of landslide body. The plane weakness was successfully identified based on the cross-plot model as the weathered zone, and subsurface features is determined. The mass movement's estimated volume was successfully calculated for critical and failure slope using the isopach map based on the sliding plane's determination. The estimated volume is 13657.26 m^3, 554057.83 m^3 and 167963.71 m^3 for *LJ*, *BA* and *HY*, respectively.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Landslides or unstable slopes are complex geological events with high socio-economic impacts in populated regions of many countries causing severe damages in term of lives lost and facilities destroyed. Landslides are known as 'mass-wasting' which occurs due to the down-slope movement of soil and rock in a large variety of shapes and volume (Rahman & Mapjabil, 2017; Morelli et al., 2019). Although the impact of this geo-hazard is inevitable, it can be significantly reduced by increasing the capacity to assess and predict the risks using different mitigation methods (Morelli et al., 2019). In the past decades, numerous modelling methods have been designed to assess slope stability, predict slope response to various triggers and evaluate slope deformation (Morelli et al., 2019). Investigation of subsurface landslide features is necessary to provide preliminary input for forward modelling and subsequent predictions of potential failure events (Malet et al., 2005; Rosso et al., 2006). However, such models still require access to detailed information of geological, mechanical, hydrogeological properties and boundaries conditions. Identification of the factors which control the landslide mechanism with a high spatial resolution becomes one of the challenges in landslides characterisations (Travelletti & Malet, 2012). The behaviour of slope involves the mechanical properties of soil which is an essential aspect that needs to be considered. Slope failures analysis and stabilisation require an understanding and evaluation of the processes that govern the behaviour of the slopes (Ozcep et al., 2010). Comprehensive result with proper numerical modelling helps to develop the predictive model, especially for complex landslides event.

Hence, several geophysical approaches with soil mechanics laboratory analysis were applied to study soil characteristic of failure zones. 2-D resistivity, seismic refraction and multichannel analysis of surface wave (MASW) were used to delineate the soil properties. Geotechnical and hydrological parameters were used as supporting information in providing realistic data interpretation. In this research, three major conditions of slope behaviour were classified based on the slope condition; stable, critical and failure slope. The classification was based on the geomorphology observations where slope with no active slope modification occurred was considered as stable slope for. The critical condition was defined as where there is active slope/soil movement exhibit the instability whereas the failure slope refer to condition where the slope is already failed due to landslide activity. The outcome highlights the advantages of considering the geophysical parameters and deriving elastic moduli in defining the subsurface behaviours. The study provides insights into how spatial distributions of geophysical properties used to minimise the uncertainty in the ground models. Besides that, cross-plot analysis with the development of 2-D cross-plot model was introduced based on the integration of resistivity and velocity values in order to enhance the subsurface resolution besides providing comprehensive subsurface images.

1.2 Landslide overview

There are numerous landslide tragedies in Malaysia recorded and involved a high number of fatalities and economic loses. Slope failure events occurred are mostly triggered by heavy rainfall due to the tropical rainforest climate with relatively high temperature and rainfall throughout the year. In a tropical region like Malaysia, rainfall-induced landslide becomes common geohazard phenomenon where the soil typically deposits by residual soils (Huat et al., 2005; Rahimi, 2010). The significant thickness of the unsaturated zone with deep groundwater table shows the features of residual tropical soil (Rahardjo et al., 2009). Malaysia experiences hot and humid climate all year round with temperature 22-32 degree Celsius with annual rainfall from 200–250 cm and extremities during southwest (April-October) and northeast (October-February) monsoons (Yusoff et al., 2016). The formation of residual soil is caused by intense chemical weathering due to the combination of climatic parameters. Under certain geological and topography effect, the rainfall becomes a major factor that triggered the occurrence of landslides involving both natural and cut slopes. The intense precipitation in highland area causes the situation to become more hazardous. Although the hilly area is stable of a certain range of water saturation, under critical limit, the shear resistance is enhanced due to effect of suction which creates an apparent cohesion between particles (Springman et al., 2003). Major landslides at local slope failure occur due to water saturation exceeds a critical limit in certain parts of the slope (Friedel et al., 2006). Based on a study conducted by Chigira et al. (2011), granitic rock is known to be very sensitive to weathering and vulnerable for mass sliding.

In a tropical region like Malaysia, deep weathering profile undergo a thickness up to 100 m. The nature of weathered material and mass structure highly control the failure mechanism. The extensive weathering effect causes the soil at the top layer to form loose layer and resulting it to slide. The high erodibility with the existence of relict discontinuities, sharp soil-rock boundary, dynamic weathered material under the saturated condition and the inhomogeneity of weathering structures will lead to frequent slope failure events. The presence of a fracture and structural discontinuity causes the cohesion and internal friction decreases or reduced by severing bonds between particles and created the discrete failure surfaces (Terzaghi, 1962; Carson & Kirkby, 1972). The understanding of the unsaturated soil mechanics is important in investigation of rainfall-induced landslide mechanism, as shown in Figure 1.1. The phenomena occur mainly initiated by loss of matric suction in the unsaturated zone during rainfall infiltration as resulting in reducing in shear strength (Lu & Godt, 2008; Travis et al., 2010). Therefore, evolving scientific comprehension of the geological and physical process of earth's rheology is vital to assess and develop a predictive model for hazard problems.

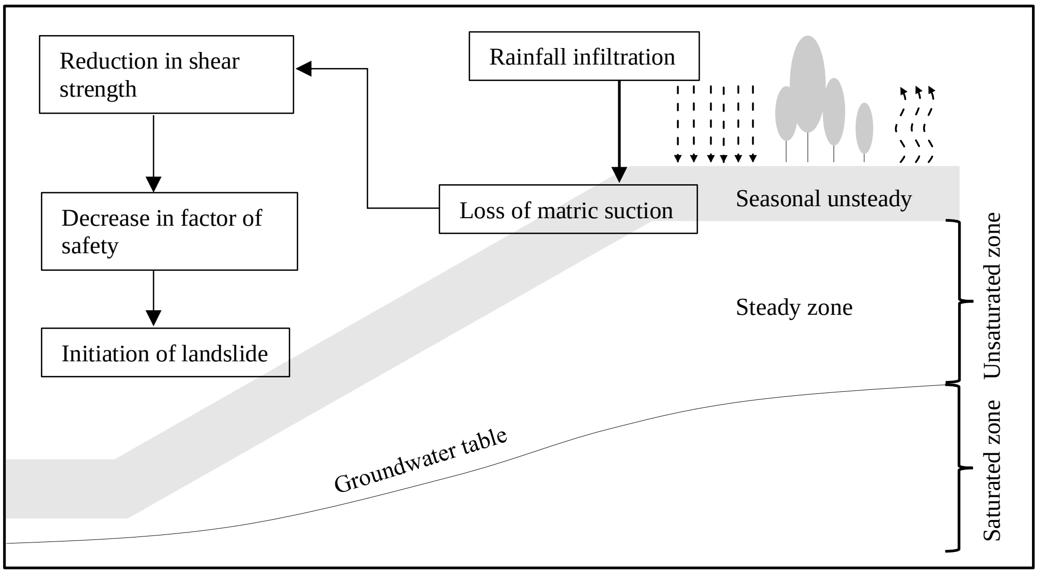

Figure 1.1 An overview of rainfall-landslide mechanism (Yeong, 2012)

1.3 Problem statement

Slope failure or landslides has been studied for several decades using multidisciplinary approaches (Ventura et al., 2011; Guzzetti et al., 2012; Travelletii et al., 2013; Pazzi et al., 2017). The methods provide comprehensive knowledge of the slope behaviour including characterisation of failure area, affected volume and factor of controlling mechanism. Conventional assessment like geotechnical investigations and remote sensing provide particular characteristic of the subsurface based on the parameters and the limitations of the methods. Geotechnical investigations give verifiable information on the subsurface features but in a limited point-scale as it requires more boreholes for the wider area. Remote sensing has been proven to provide large scale information regarding surface features of the slope but inadequate resolution in characterising the subsurface geometries, which plays a vital role in landslide mechanism. Therefore, geophysical approaches were implemented to provide comprehensive data resolution in characterising the subsurface properties of the geomaterials with high level of accuracy. Due to the ability of the methods which provide a significant depth of investigation with promising data resolution such as defining plane weakness of the geomaterial, it shows high efficiency for methods to be considered. The justification of the geophysical parameters with geotechnical and hydrological properties is needed to provide comprehensive interpretations where those properties play an important role in landslide mechanism. However, without any correlation and validation with supported data, the results are vulnerable to misinterpretation. Hence, a cross-plot analysis was introduced as an alternative method to integrate two or more different parameters as to reduce the ambiguity of the data. The analysis provides direct visual interpretations based on the integrated parameters which enhance the subsurface images. The 2-D cross-plot model provides insights into how the spatial distribution of landslide mechanism was identified with the volume of mass sliding successfully determined. The accurate identification of a sliding plane reduces the error during the volumetric estimation.

1.4 Objective of the research

The research involves several geophysical methods with validation of several supported data from geotechnical and hydrological parameters in order to study the subsurface of the landslides area based on the following objectives:

i. To characterise the slope/landslide body using 2-D resistivity, seismic refraction and MASW methods based on different types of slope condition;

ii. To validate the results from geophysical methods with supported data from geotechnical and hydrological parameters; and

iii. To integrate different geophysical parameters using cross-plot analysis with the development of 2-D cross-plot models for enhancing subsurface images and volume evaluations of mass sliding.

1.5 Scope of the research

This research involves geophysical approaches in characterisation of the subsurface features of the body of the landslide based on different slope conditions which are stable, critical, and failure slope. The USM-Archaeology and Lojing-Cameron Highland study areas represent the stable and critical slope condition, respectively. Meanwhile, the failure slope was represented by study area of Hulu Yam and Bkt Antarabangsa. The geophysical methods, which are 2-D resistivity, seismic refraction, and MASW were applied in the study area. The research aims to provide insight into the landslides/slope mechanism based on the geophysical parameters and validate the data using geotechnical and hydrological parameters. The laboratory analysis and elastic modulus derivation were involved in providing exhaustive and realistic interpretations. Furthermore, this research frameworks also introduced a comprehensive and integrated method between different geophysical parameters using 2-D cross-plot models. A test model was analysed to obtain initial interpretation and validation from borehole information. The cross-plot analysis was applied at the selected study areas, and the results obtained were used to analyse the properties of the subsurface with the estimation of the landslide volume.

1.6 Novelty of the research

Geophysical approaches were applied to study the soil characteristics of failure zones in order to create an image of the soil properties by providing realistic data interpretation. The outcome of the works highlights the advantages of considering geophysical parameters in defining the subsurface behaviours to be cost-effective and provided a high spatial resolution of the sliding mass geometry with validation from geotechnical and hydrological data. This research also introduces an alternative integrated method with development of 2-D cross-plot model using different geophysical parameters. The models successfully mapped the subsurface properties as the vulnerable layers were identified. The study provides insights into how spatial distributions of elastic properties can be used to minimise the uncertainty in the ground models. Besides that, the cross-plot models between the integration of resistivity and seismic results show an informative technique in enhancing subsurface resolution with the volume of mass sliding were successfully calculated.

1.7 Thesis outline

In this thesis the research framework, data analysis, interpretation and the outcome of this research were presented with the following chapter as described below.

Chapter 1 briefly describes the background of the study, the problem statement, the research scope, and the objectives of the research with the significance of the research outcome. It also describes the general overview of the landslides in Malaysia region with previous research findings. Chapter 2 discusses the general theory of geophysical and geotechnical method with the background of the methods and previous research related to the landslides study cases. Furthermore, Chapter 3 defined the methodology and typology of the research framework, including the study area, data acquisition and processing stages with a general overview of fundamental background. This chapter also discusses the required information and data needed for cross-plot analysis as well as to develop the 2-D cross-plot model. Next, chapter 4 discusses and explains all the collected information and results for each case study. The subsurface of landslide characteristic with the correlation of geotechnical and hydrological parameters were briefly explained. The integrated geophysical parameters using cross-plot analysis were presented with the volumetric of mass sliding were well defined. Lastly, the conclusion and recommendation are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The destabilisation and mass movement of soil and rock on slopes occurs as a common phenomenon across the globe and causes loss of life and severe damage to the property and infrastructure in the affected areas (Petley, 2012; Froude & Petley, 2018; Whiteley et al., 2019). A detailed investigation on the landslides provides essential information including soil and rock characteristics, landslide geomorphology and other parameters. The investigations of subsurface landslide features are indispensable for performing a forward modelling and subsequently predicting the potential slope failures including the run-out distance of the mass movement and the mobilised volume (Malet et al., 2005; Rosso et al., 2006). The geophysical approaches were capable of identifying the spatial variations of physical parameters of the landslide subsurface by physical property contrasts, including the physical extent of the landslide, slip surface, lithological contact and distribution of the movement of moisture throughout landslide body (Everett, 2013; Parsekian et al., 2015; Whitley et al., 2019). The features of a typical landslide mechanism which can be identified and assessed using geophysical method are shown in Figure 2.1. Nowadays, the application of geophysical approaches in landslides characterisation has become increasingly common. The multi-approach method for landslide investigation allows an even better evaluation of the internal structure by overcoming the limitations of single-method approaches (Schrott & Sass, 2008).

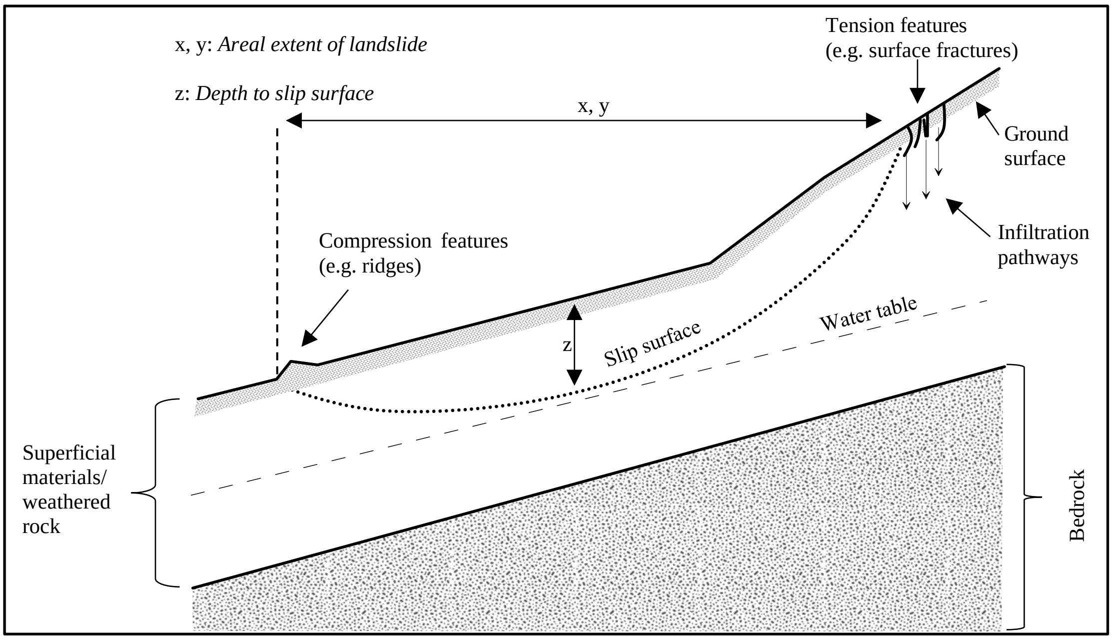

Figure 2.1 Schematic diagram of a landslide system, showing the major landslide setting features that can be investigated and assessed using geophysical methods (Whitley et al., 2019)

2.2 Basic theory of resistivity

The resistivity of the material is defined as resistance of a cylinder with a cross-section of unit area per unit length. Figure 2.2 shows the resistance, R of conducting cylinder with length, L and cross-sectional area, A. The resistivity, ρ of the conductor and its relationship with the geometric parameters are expressed using Equation 2.1. Resistivity survey is generally used to characterise the subsurface resistivity distribution based on the measurements on the ground surface. The resistivity value is related to some of the geological parameters, including porosity, fluid content and degree of water saturation in rock. In the resistivity method, electric currents are passed through the surface of the electrodes that are inserted into the ground, thereby resulting in a potential difference. The differences in the patterns of potential difference in the homogenous ground provides information and electrical properties of the subsurface inhomogeneities (Kearey et al., 2013).

$$R = \rho L/A \tag{2.1}$$

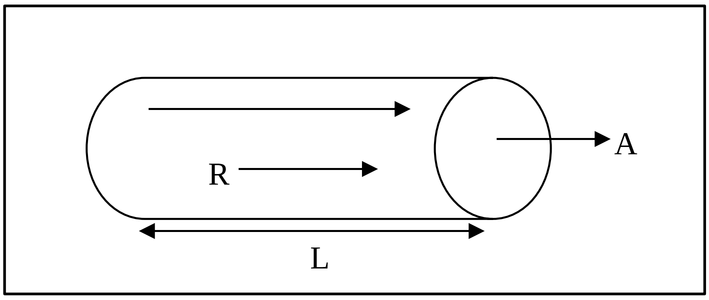

Figure 2.2 Electrical resistivity with the relation of resistance (R), area (A), and length (L)

The Equation 2.1 shows that the resistance, R is proportional to the length, L, and inversely proportional to the cross-sectional area, A, of the conductor. The SI unit of resistivity is ohm.meter (Ωm). According to Loke (2015), in the resistivity method, the current is injected into the ground through two current flowing electrodes: C1 and C2. The potential difference is measured using two potential measurement electrodes, namely P1 and P2. Figure 2.3 shows the configuration of a four-electrode array.

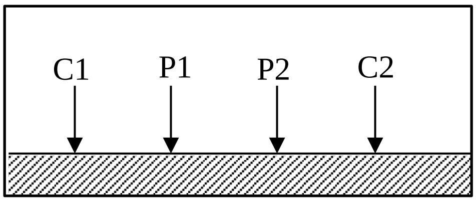

Figure 2.3 A conventional four-electrode array (Loke, 2015)

The apparent resistivity, ρa is calculated based on Equation 2.2.

$$\rho a = kV_g/I \qquad (2.2)$$

where k is a geometric factor that depends on the arrangement of the four electrodes. In resistivity survey, the value of 'k' plays an important role, wherein the depth of penetration of resistivity sounding depends on the spacing of electrode, which is referred to as 'k' value. Figure 2.4 shows the common electrode array used in the 2-D resistivity survey for different electrode spacing.

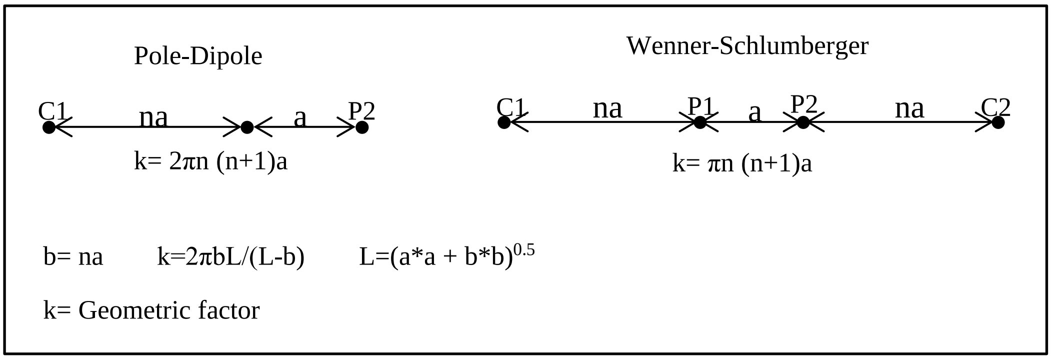

Figure 2.4 Common array used in an electrical survey with different geometric factor (Loke, 2015)

According to Loke (2015), the calculated value is not the true resistivity but refers to an apparent value. In order to obtain a true subsurface resistivity, an inversion process must be carried out using computer software. In the homogenous ground, the current is allowed to flow uniformly across a hemispherical shell centered on the source, as shown in Figure 2.5. The depth of penetration is proportional to the electrode spacing. The resistivity value of the homogenous ground should be constant and independent of electrode spacing and surface location. When non-homogenous subsurface exists, the resistivity will differ relative to the electrode position. The value of calculated resistivity is known as apparent resistivity (Kearey et al., 2013).

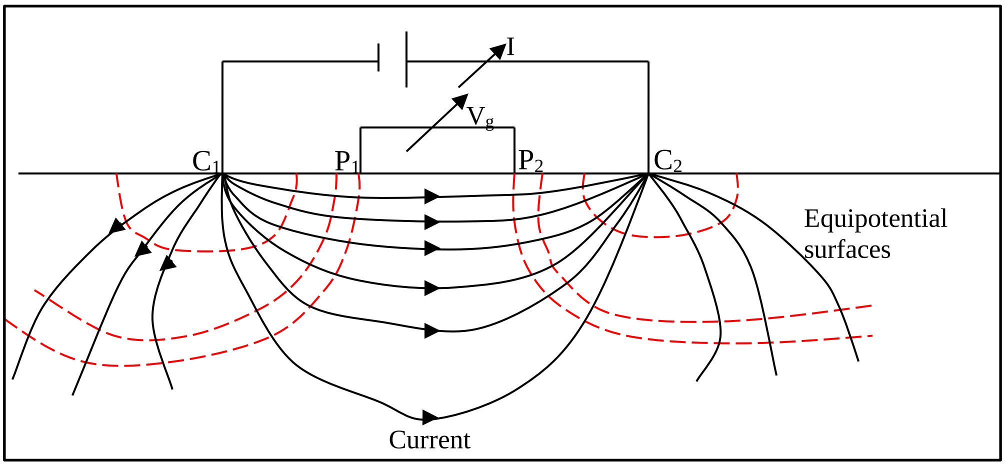

Figure 2.5 Illustration of current flow in the homogeneous subsurface (modified from Loke, 2015)

2.3 Basic theory of seismic refraction

The seismic refraction method is one of the geophysical methods applied to study the earth's behaviour in identifying the characteristics, lithology, and other properties. This method involves the estimation of P-wave velocity (V_p) of the earth near-surface material and has also been used to investigate landslides since the early 1960s (Narwold & Owen, 2002). Refraction survey has been used to estimate the depths to the failure and lateral extent of the landslide (Al-Saigh & Al-Dabbagh, 2010; Abidin et al., 2012a; Yilmaz & Kamachi, 2018) based on the differences in the physical properties of the sliding materials and the underlying undisturbed sediments or bedrock that result in different seismic velocities (Abramson et al., 2002). The underlying principle behind the seismic refraction method is the measurement of travel times of the seismic waves refracted at the interfaces between the subsurface layers of different velocities. The seismic energy generated by a seismic source ('shot') located on the surface radiates outward from the shot point spreading in all directions. The wave travels directly through the upper layer (direct arrivals), or it may travel down to and then laterally along with the high-velocity layers (refracted arrivals) before bouncing up and coming back to the surface (Figure 2.6). A critical refracted wave travels along the interface between layers and is refracted back into the upper layer at the critical angle. The waves refracted back into the upper layer are called head waves. The thickness and velocity of the material above and below an interface can be calculated by determining the arrival times of the direct and refracted waves from the seismic section (Saad et al., 2017). Hence, the final output comprises a depth profile of the refractor layers and a velocity model of the subsurface.

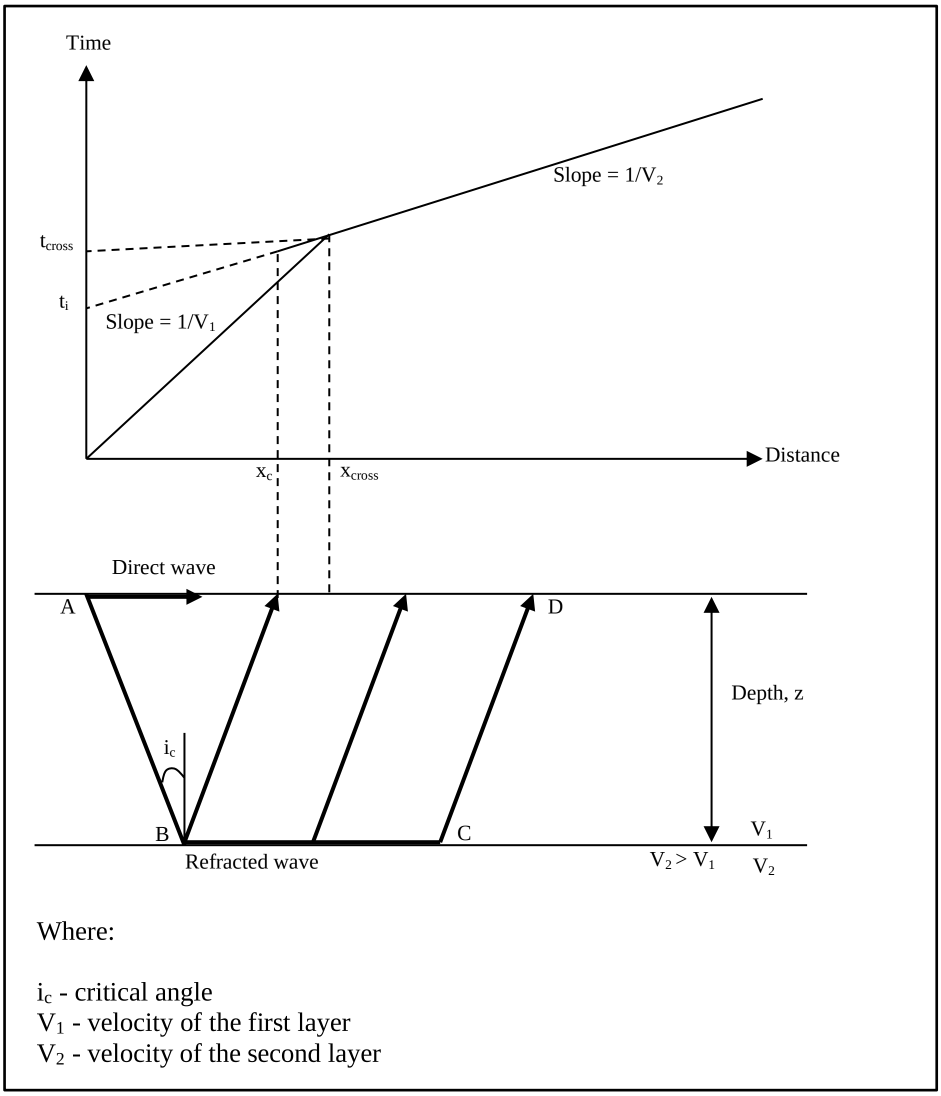

Figure 2.6 Travel time of seismic waves

2.4 Basic theory of multi-channel analysis of surface wave (MASW)

Surface wave analysis methods are based on the dispersive properties of surface waves in a vertically heterogeneous medium. Generally, the analysis is carried out utilizing Rayleigh waves as they were easy to be generated and be detected on the ground surface by low-frequency geophones (Socco et al., 2010) as a result of the interaction of P-waves (V_p) and S_v-waves ($V_{s-v)}$) with the surface of the earth (Aki & Richards, 1980). Rayleigh waves velocity is generally observed to increase with depth (i.e., waves with longer wavelength (lower frequency) propagate faster than the shorter wavelength (high frequency). The relationship between frequency (f), Rayleigh wave phase velocity (V_r), and wavelength (λ) is given in Equation 2.3 (Kramer, 1996).

$$f = \frac{V_r}{\lambda} \tag{2.3}$$

The phase velocity of a Rayleigh wave component propagating through a layered medium is determined by the average stiffness and the average density of the soil layers that it travels (Everett, 2013). Figure 2.7 shows a schematic diagram of wave propagation.

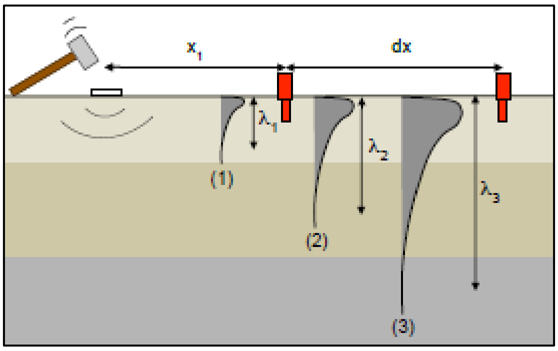

Figure 2.7 Rayleigh wave component with different wavelength propagating through a layered medium. Wave components with different frequency reflect soil properties at diverse depth

Multi-channel analysis of surface waves (MASW) is a non-invasive method of estimating the shear-wave velocity profile from surface wave energy. The method has been increasingly applied to geotechnical and engineering geology (Rehman et al., 2016; Arisona et al., 2017; Anukwu et al., 2018a, Anukwu et al., 2018b) and various shallow geophysical sounding (Bajaj & Anbazhagan, 2017; Pamuk et al., 2016; Mi et al., 2017). The most common uses of the surface wave's dispersive properties are to obtain V_s profiles by analysing plane waves, while fundamental Rayleigh waves carry more than 2/3 of total seismic energy generated. In a layered media, the frequency of a surface wave is related to the elastic and physical properties of the material (Lee et al., 2002). In such a context, the inversion technique was developed to retrieve information measured from surface wave dispersion. Dispersion is a term that describes the change of phase velocity with frequency. In the case of elastic half-space (i.e., no velocity changes with depths), no surface wave dispersion will occur. Dispersion will occur only when velocity changes vertically. At high frequencies, the wavelengths are short, and the propagation velocity is controlled by the wave-speed of the shallow soil layers (which are usually of low speed). As the frequencies decrease, the wavelengths increase, causing the wave to penetrate to deeper layers with higher velocities (Khalil et al., 2017).

2.5 Elastic moduli for subsurface characterisation

The body wave velocities of soil, which are the compressional wave (V_p) and shear wave (V_s), can be directly related to the medium of wave propagation's elastic moduli. The relationship between the elastic moduli and body wave velocities is widely utilized in the geophysical survey to obtain information on the spatial distribution of mechanical properties of the subsurface (Everett, 2013). The most commonly used moduli to characterize soil are the small strain shear modulus, $G_{0,}$ and Young's modulus, E (either express in terms of undrained/total stress or drained/effective stress). Both of these moduli provide the measurement of material's stiffness and are defined as the ratio of stress to resulting strain along an axis resulting from shear (G_0) or loading (E) (Clayton, 2011; Mavko et al., 2020). Shear modulus also reflects the rigidity of the material that describes the ability of the material to resist shearing (i.e., change of the shape without change the volume). Thus, the shear modulus is equal to the ratio of shear stress to shear strain, while Young's modulus, E, is referred to as the compressibility behaviour. Both G_0 and E are frequently used in the estimation of soil consolidation (Braja, 2008), deformation analysis (Clayton, 2011) as well as physical landslide modelling (Lacroix & Amitrano, 2013). Equations 2.4 and 2.5 show the relationship of shear modulus and Young's modulus with the density, ρ of the material. Table 2.1 lists the general values of shear modulus for several types of soil.

$$G_0=\rho v_s^2 \tag{2.4}$$

$$E = \frac{\rho V_s^2(3V_p^2-4V_s^2)}{(V_p^2-V_s^2)} \tag{2.5}$$

where;

v_s= S-wave velocity
v_p= P-wave velocity
ρ= density

Table 2.1 General values of shear modulus for several soil types (Sabatini et al., 2002)

Soil Type	Shear modulus, G_0 (GPa)
Soft clays	0.00275-0.01375
Firm clays	0.0069-0.0345
Silty sands	0.0276-0.138
Dense sands and gravels	0.069-0.345

Another commonly used parameter in slope stability analysis is the Poisson's ratio, ν (Martel & Muller, 2000; Ulehman et al., 2016a), which is linked to the stress field in the slope and degree of saturation of the soil material (Huang et al., 2012). In contrast to the shear and Young's moduli, no density estimation was required for the calculation of ν, which highlights the benefit of considering Poisson's ratio (Equation 2.6) by eliminating the potential uncertainties rising from an assumed density. Table 2.2 lists the general values of Poisson's ratio for several types of soil.

$$\nu=\frac{V_p^2-2V_s^2}{2(V_p^2-V_s^2)} \tag{2.6}$$

where;

v_s= S-wave velocity
v_p= P-wave velocity

Table 2.2 General values of the Poisson′s Ratio for several soil types (Braja, 2008)

Soil type	Poisson's Ratio
Loose land	0.2-0.4
Medium sand	0.25-0.4
Dense sand	0.3-0.45
Silty sand	0.2-0.4
Soft clay	0.15-0.25
Medium clay	0.2-0.5

2.6 Shear strength of the soil

Shear strength of the soil mass refers to the internal resistance per unit area that the soil mass can offer to resist failure and to slide along any plane inside it (Braja & Sivakugan, 2015). It measures the soil resistance to deformation by continuous displacement of its soil particles. In 1900, Mohr presented a theory for rupture of a material relating the normal stress and shear stress on a failure plane as a linear function (Equation 2.7 and Figure 2.8). Saturation of soil slope will reduce the soil strength, which will lead to numerous collapses and failures of the slopes. Strength is the measure of the maximum stress state that can be induced in a material without it failing; fundamentally, it is the ability to sustain shear stress that provides the strength (Whitlow, 2004). The shear strength within a soil mass is essentially due to the development of frictional resistance between the adjacent particles. Shear strength in soils depends primarily on the interactions between the particles, and a failure occurs when the stresses between the particles are high as they slide or roll past each other. Soil derives its shear strength as cohesion and frictional component. Table 2.3 shows typical drained shearing angles of friction for different soil types (Whitlow, 2004).

$$\tau_{f} = c + \sigma \tan \phi \qquad (2.7)$$

where;

c = cohesion
ϕ = angle of internal friction
σ = normal stress on the failure plane
τ_f = shear stress at failure

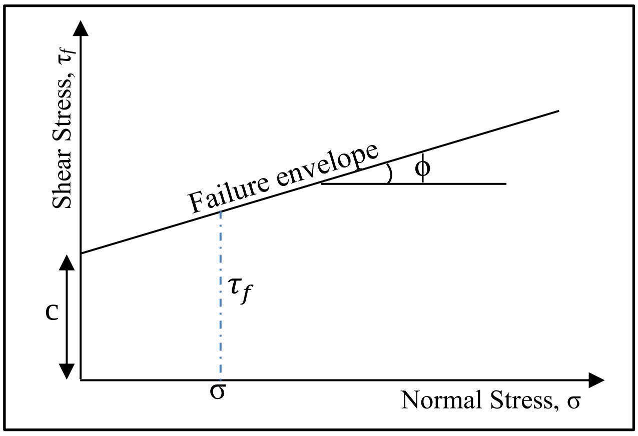

Figure 2.8 Mohr-Coulomb failure criterion

Table 2.3 Shearing angle of friction for soil types (Whitlow, 2004)

Soil types	ϕ (deg)
Sand: Rounded grains	
Loose	23-30
Medium	30-35
Dense	35-38
Sand: Angular grains	
Loose	30-35
Medium	35-40
Dense	40-45
Gravel with some sand	34-48
Silts	26-35

2.7 Overview of landslide in Malaysia

Malaysia is located in the Southeast of Asia, occupying about 330200 km^2. The entire country is divided into two main regions, Peninsular Malaysia and East Malaysia. The geographic position subjects the country to a steamy, hot, and humid climate throughout the year with yearly monsoons from the southwest from April to October and from the northeast from October to February. Also, Malaysia has not experienced strong/major earthquakes, but large-scale landslides still occur due to mainly gravity-induced events at times of heavy and prolonged rainfall. Due to rapid development since the 1980s, strategic and suitable low-lying areas have become increasingly unavailable for development. The development of highland or hilly terrain has increased, particularly in areas adjacent to densely populated cities, thereby exposing urban communities to increased landslide occurrences. The development of hill land leads to severe irreversible effects on its immediate environment and the surrounding environment downstream (Rahman & Mapjil, 2017).

In the report titled 'National Slope Master Plan (2009-2023)', a total of 49 cases of massive landslides have been reported, out of which is 88% were attributed to the manmade slope (JKR, 2009a,2009b). The hills, which are usually categorized into dangerous slopes (20-30 degrees) and critical slopes (>30 degrees), should be avoided from development. Mohktar (2006) highlighted that the main factors contributing to slope failure/landslide at several sites in the hillside are rainfall and stormwater activities. The most common type of landslide in Malaysia is a shallow landslide where the slide surface is usually less than 4 m deep and occurs during or immediately after intense rainfall (Rahman & Mapjil, 2017). The high temperatures throughout the year with prolonged rainfall cause intense chemical weathering and favours the formation of thick residual soil profiles. With this set of climate and geological conditions, combined with other causative factors, landslides are thus one of the most destructive natural disasters in Malaysia (Bujang et al., 2008). The statistics of the cases reported by Gue and Tan (2007) mentioned that incompetency would lead to landslide events in addition to the poor design of the slope structures (Table 2.4). The underestimation of the existing groundwater tables and inadequate surface drainage capacity also weighed in among the factors causing landslides.

Table 2.4 Reported cases of landslide in Malaysia in year of 2000-2006 (Gue & Tan, 2007)

Causes of Landslides	Number of Cases	Percentage (%)
Design error	29	60
Construction errors	4	8
Design and constructions errors	10	20
Geological features	3	6
Maintenance	3	6

2.8 Previous study

The previous study was discussed based on the assessment of landslide from multi-disciplinary approach with the implementation of cross-plot analysis for subsurface characterization based on the following subsection.

2.8.1 Overview of landslide assessment

Slope failure is a complex phenomenon that may trigger the occurrence of landslides due to several factors and become one of the major geomorphic processes that affect the evolving landscape of the mountainous region, favouring disastrous phenomena. The broad or small scale of landslide refers to a widespread natural process resulting from the downward and outward movement of slope-forming materials, including sculpting the landscape. The characterization of landslides in heterogeneous conditions becomes one of the biggest challenges as the assessment requires extensive data ranging from multidisciplinary approaches as the measurement of geological and hydrological parameters (Pazzi et al., 2019). Conventional methods of geomorphology survey, geotechnical investigation, and more recent methods of remote sensing, aerial photography, and synthetic aperture radar interferometry, can be employed to obtain and analyse the information required regarding the landslides properties (Travelletii et al., 2013; Pazzi et al., 2017). Each method allows the study of specific triggering factors or particular physical features based on the parameter and the method's ability. Satellite and airborne methods (i.e., GPS and digital aero photogrammetry) are also helpful in providing useful information regarding the surface characteristics of the slope including the geomorphological features, areas of extension of the landslide body, superficial displacement, and velocity (Ventura et al., 2011; Guzzetti et al., 2012). However, in most cases, all of this information does not include the subsurface features, which play a vital role in landslide characteristics. Direct ground-based techniques (i.e., piezometer and inclinometer) give verifiable and reliable information on the mechanical and hydraulic characteristics of the terrains affected by the landslides but at discrete points of the subsurface (Marcato et al., 2012). The application of geophysical approaches has witnessed an exponential increase for detailed subsurface characterization, localization of sliding surface, evaluation of the emergence and growths of fractures, and the understanding of water dynamics and possible reactivation by rainfall (Pazzi et al., 2019). The information obtained from geophysical surveys is used as an input for defining ground models of landslides and, consequently, to perform slope stability assessment (Whiteley et al., 2019).

Landslides activities in weathered granitic rocks are strongly affected by weathering types and have been documented for tropical and humid regions. Based on a study conducted by Chigira et al. (2011), granitic rock is known to be very sensitive to weathering and vulnerable to mass sliding. In a wet tropical region in Malaysia, a deep weathering profile will exhibit a thickness of up to 100 m. The mechanism of failure is highly controlled by the nature of weathered material and its mass structure. In 1993, Malaysia witnessed major slope failure disasters of Bkt Antarabangsa involving loss of lives and property damages. Komoo (1997) shows that weathered granitic materials may contribute as a major factor for a landslide to occur. The material was classified as porous, easy to crumble, and inherited the plane of the parent rock's weakness. An extensive weathering profile of soil changed the condition, transformed the granite into residual soil, and weathered granite materials. The unstable condition with loose materials and increased accumulation of water triggered the occurrence of a landslide. In a revisit study at Bkt Antarabangsa by Lim et al. (2019), there were numerous evidence showing that the lands had significantly been battered and modified since the last 50 years before the landslides occurred. Extensive land exploitation, construction practices, construction on landslide affected terrains, or previously modified land slope had significantly contributed to recurring instances of landslide occurrence. The study shows that climate-induced geological factors (weathered granitic terrain) and lithological relics contributed to the predisposing factor, and the changes in land-use ascribed to disturbances in the terrain due to human habitation may also affect the occurrence of landslides. The site is an example of human-induced landslide disasters, which is a consequence of improper land use management and construction practices.

The infiltration of rainfall into the soil and its effect on slope failure has been of particular interest for the past few years (Irfan et al., 2017; Chen et al., 2018,2019; Jing et al., 2019). Rahardjo et al. (2007) conducted a series of parametric studies to understand the hydrological and geotechnical parameters on rainfall-induced instability. The study inferred that rainfall intensity, soil properties, groundwater table, and slope geometry played an important role in the rain-induced instability of the slope. The continuous infiltration of rainwater will increase the pore-air pressure and decrease the matric suction, compromising slope stability (Sun et al., 2015, 2016). The process causes a change in effective stress, which produced variations in the porosity of the soil (Sun et al., 2016).

According to Collins and Znidarcic (2004), two distinct failure mechanisms have been observed in the event of rainfall-induced landslides. For the first mechanism, a significant build-up of positive pressures was observed in a low area on the slope or along with the soil/bedrock interface. Movements along the sliding surface lead to liquefaction along with it, resulting in rapid movements, long run-out distances, and finally, complete liquefaction of the failed mass occurred (Wang & Sassa, 2001). In the second mechanism, the soil was in an unsaturated state, and slope failure was mainly due to rainfall infiltration and a loss in shear strength when soil suctions are decreased or dissipated (Fourie et al., 1999). Infiltration and near-surface flow increased pore water pressure, causing the stress path to move nearly horizontally to intersect a failure envelope, initiating a slope failure. In unsaturated loose soils, suction decreases, and coupled volumetric collapse may involve the failure process (Olivares & Picarelli, 2003). Landslides in weathered granitic rocks for tropical and humid regions have been well understood as the phenomenon is strongly affected by the type of weathering.

Furthermore, the geophysical methods were included in landslide evaluations since this method was beneficial in identifying the petrophysical properties of subsoil, such as seismic wave, electrical resistivity, and dielectric permittivity (Travelleti & Malet, 2012). In-situ geophysical methods, of resistivity and seismic refraction measurements, are capable of evaluating the physical parameters directly or indirectly, including the lithology of the subsurface, hydrology, and geotechnical characteristics (Perrone et al., 2014). These methods are less invasive and provide comprehensive information on a large soil volume, thus overcoming the point-scale features of geotechnical measurements. The successful geophysical methods were evident with significant contrast present among the physical properties of different lithological units (Pazzi et al., 2019).

Nowadays, the geophysical method has been extensively utilized in slope failure assessments. Dostal et al. (2014) and Ng et al. (2015) conducted 2-D resistivity measurement intending to characterize the subsurface layer of the slope for remedial works to identify the shear zone. The outcome shows that low resistivity zones face the risk of slope failure, which demand remedial measures. The prospection zone of loose soil with high resistance was clearly visible and indicated that the landslides in history consisted of cohesive deposit materials in relic landslide as conducted by Kaczmarek et al. (2014). The 2-D resistivity and geotechnical method was successfully applied to estimate the geometry, thickness, and depth of the landslide's failure zone (Maniruzzaman et al., 2017). The relationship between friction angles for various soil properties was established by simple regression analysis from apparent resistivity data. The results revealed that the increase in water content in the slide zone reduced the shearing resistance's effectiveness and increased the sliding movement. Abidin et al. (2017) and Muztaza et al. (2017) showed that the 2-D resistivity study could determine the subsurface geometry with the factors contributing to landslide events. The existence of weak zones represented low resistivity values due to high water content or highly conductive materials (Abidin et al., 2017). The study showed that heavy rainfall and existing geological structure (weakness zone) played a critical role in contributing to the landslide occurrence. This finding proved that this method could predict the landslide's features to assist the conventional borehole data. The presence of weathered granite, fracture, and boulders would be an indicative factor for landslide events (Muztaza et al., 2018).

In 2011, Clarke and Burbank conducted a seismic refraction study to calculate the depth, densities, and gradient of the bedrock fracture. It revealed two subsurface scenarios: the bedrock that uniformly fractured with depth and the bedrock fractured