APPLICATION OF 2-D RESISTIVITY IMAGING AND SEISMIC REFRACTION METHODS IN IDENTIFYING SUBSURFACE GEOLOGICAL STRUCTURES

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by

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LIST OF SYMBOLS

A	Ampere
cm	centimeter
E	Elastic coefficients
F	Force
F/A	Stress
h	Thickness
Hz	Hertz
I	Current
I	Current density
K	Bulk modulus
k	Geometric factor
km	kilometer
m	Meter
R	Configuration resistance
r	Distance between the current electrodes
V	Potential
v	Velocity
V_P	P-wave velocity
V_S	S-wave velocity
Φ	Angle of deformation
ρ_a	Apparent resistivity
ρ	resistivity
ε	Electric conductivity
θ_{ic}	Incidence critical angle

$<$	Less than
$>$	More than
Ωm	Ohm-meter
π	Pi
σ	Poisson’s ratio
$\partial V / \partial r$	Potential difference
θ_i	Refraction angle
$\Delta L/A$	Strain

LIST OF ABBREVIATIONS

BH	Borehole
C	Current electrode
DC	Direct current
ENE	East north east
ESE	East south east
GPR	Ground penetrating radar
GPS	Global positioning system
GRM	Generalized reciprocal method
HER	Enhancing horizontal resolution
MTFC	Møre-Trøndelag Fault Complex
NE	North East
NW	North West
P	Potential electrode
RES2DINV	Resistivity 2-D Inversion software
RES2DMOD	Resistivity 2-D Modeling software
SAS4000	Signal Averaging System 4000
SE	South East
SEISOPT2D	Seismic optimization two dimensional
SPT	Standard penetration test
USM	Universiti Sains Malaysia
1-D	One dimensional
2-D	Two dimensional

APLIKASI KAEDAH PENGIMEJAN KEBERINTANGAN 2-D DAN SEISMIK PEMBIASAN DALAM PENGENALPASTIAN SUB-PERMUKAAN STRUKTUR GEOLOGI

ABSTRAK

Struktur geologi boleh mempengaruhi landskap sub-permukaan, kadar potensi kejadian tanah runtuh, penemuan sumber tenaga, dan menjadi saluran untuk pengumpulan bahan logam seperti emas dan perak. Kesedaran mengenai kepentingan struktur geologi telah mendorong kajian ini untuk menumpukan kepada aplikasi kaji selidik geofizikal yang melibatkan dua gabungan aktif yang berlainan; pengimejan keberintangan 2-D dan seismik pembiasan. Kedua-dua kaedah ini telah dilaksanakan untuk mengenal pasti ciri-ciri struktur geologi sub-permukaan dengan lebih tepat. Oleh itu, ciri-ciri struktur permukaan geologi seperti sesaran, sentuhan, lipatan, retakan, lapisan, dan bahan sub-permukaan dikaji dengan parameter geofizik berkaitan keberintangan, ρ dan halaju, v. Terdapat dua bahagian utama dalam kajian ini iaitu kerja lapangan dan ujian lapangan. Pengenalpastian struktur geologi pada kerja lapangan telah dilengkapkan dengan pemetaan singkapan. Kawasan kajian yang dipilih untuk kerja lapangan adalah Bukit Kukus (mempunyai struktur sesaran, sentuhan, dan lipatan), Guar Jentik (mempunyai struktur sentuhan dan retakan), dan Bukit Chondong (mempunyai struktur sentuhan, retakan, dan lapisan). Hasil daripada kerja lapangan telah menggariskan ciri-ciri khas bagi struktur geologi. Sesaran dan retakan telah dikenalpasti daripada perbezaan nilai keberintangan dan nilai halaju yang tinggi. Ciri-ciri zon sentuhan dikenalpasti melalui perubahan yang ketara terhadap nilai keberintangan dan halaju. Struktur lipatan menyebabkan kontur tomogram dari kedua-dua kaedah untuk berada dalam corak yang berlapis-lapis (mengikut nilai yang

paling rendah kepada nilai yang tinggi). Setelah berjaya mengaplikasikan kedua kaedah ini di kerja lapangan, kaedah yang sama turut digunakan untuk aplikasi di ujian lapangan. Kawasan ujian lapangan yang dipilih ialah di Krueng Raya, Aceh (Indonesia). Kawasan kajian ini berhampiran dengan sistem sesar yang aktif dikenali sebagai zon sesaran Seulimeum. Objektifnya adalah untuk mengenalpasti lineamen daripada zon sesaran dengan menggunakan ciri-ciri khas struktur sesaran yang didapati dalam kajian di kerja lapangan. Bagi kedua-dua kaedah yang digunakan dalam kaji selidik, jarak antara elektrod dan geofon telah diselaraskan untuk memastikan ketepatan aplikasi kerana kedua-dua bidang kajian ini mempunyai skala dan kedalaman sasaran yang berbeza. Pemetaan lineamen geologi dari sesaran Seulimeum ini berjaya diperolehi daripada aplikasi kaedah pengimejan keberintangan 2-D dan seismik pembiasan.

APPLICATION OF 2-D RESISTIVITY IMAGING AND SEISMIC REFRACTION METHODS IN IDENTIFYING SUBSURFACE GEOLOGICAL STRUCTURES

ABSTRACT

Geological structures reflect the impact on the landscape of the subsurface, determination of the degree of landslide hazard, discovery of hidden energy and act as host to many economic minerals or metals such as gold and silver. Awareness on the importance of geological structures has motivated this study to focus on the application of geophysical surveys involving a combination of two different active methods; 2-D resistivity imaging and seismic refraction. Both methods were executed to identify signatures of subsurface geological structures precisely. Therefore, the signatures of geological structures including fault, contact, fold, fractures, bedding, and subsurface materials were investigated in terms of geophysical parameters such as resistivity, ρ and velocity, v. There are two main part in this study which are field works and a field test. Identification of geological structures at field works accompassed with outcrops mapping. The study areas for field work is known as Bukit Kukus (with the structures of fault, contact, and fold), Guar Jentik (with the structures of contact and fracture), and Bukit Chondong (with the structures of contact, fracture, and bedding). The results of field work have outlined the typical features of geological structures. Fault and fracture were identified from the high contrast in the resistivity and velocity values. The signatures of contact zone were identified from the distinct change of resistivity and velocity values. The folding structures cause contouring tomograms from both methods to be in layered pattern (from lower to higher values). After successfully applied at the field works, both methods will be applied to the field test. Krueng Raya,

Aceh (Indonesia) were selected as the field test location. The study area is located near to an active fault system known as Seulimeum fault zone. The objective was to identify the lineament of the fault zone by using the special features of fault structure from the field works. For both methods used in the surveys, the spacing between electrodes and geophones were standardized to ensure accurate application for all study areas because the field works and field test have different scale and depths of the target. A geological lineament mapping of Seulimeum fault was successfully carried out using 2-D resistivity imaging and seismic refraction methods.

CHAPTER 1

INTRODUCTION

1.0 Background

The study about geological structures is crucial in the economic geology including petroleum and mining geology. The examples of common geological structures are fault, fracture, fold, bedding, and contact zone. Fault and fold structures in the subsurface may indicate the existence of hydrocarbon, mineral depositional and hydrothermal potential. The geological structures also contribute to engineering problems. For example, the structures of fault and fold provides internal weakness of the rock stability and affect the safety of facilities on the top surface such as houses, dam, road cuts, and tunnels.

Geophysical methods were established to support the data for the engineers to enhance their interpretations on the subsurface structure. Besides than comparatively cost-effective, the geophysical methods also can quickly provide data with high accuracy. There are several methods used for geophysical surveys such as 2-D resistivity imaging, seismic refraction, gravity, magnetic and ground penetrating radar (GPR) methods. Different methods used will provide different parameters such as resistivity and velocity that are needed to study the subsurface geology. However, there are a few important aspects need to be considered before conducting a geophysical survey such as the objective, budget, and accessibility on the study area.

Out of five methods as listed above, the first two methods which are 2-D resistivity imaging and seismic refraction methods were used in this study to investigate the geological structures. Both methods are reliable in providing the detailed information of the subsurface such as depth of bedrock, characteristic of overburden material and near surface structures such as bedding, faults, fold, fracture, and contact zone. The 2-D resistivity imaging quickly provides data with high accuracy and easier to interpret. The array used for 2-D resistivity survey was a pole-dipole array because this array can provide good resolution and very well subsurface coverage. While, seismic refraction enables the surveyor to estimate the soil strength by measure the velocity for each layer of the subsurface.

Each geophysical method has their own advantages and limitations. Thus, the combination of several methods could help in enhancing the data interpretation. In other words, the correlation of two or more methods is very effective and could solve some interpretation ambiguities (Comina et al., 2002).

1.1 Problem statements

The study on geological structures is very important because it was closely related to the engineering and environmental problems such as landslides and liquefaction. Hence, the geophysical methods were developed alongside with the geotechnical methods to accommodate the needed in this field. Geophysical methods can investigate the subsurface of the earth. However, there are some ambiguities about the geological structures from the results of geophysical methods. The lack of information related to the geological structures becomes the main problem in the interpretation of geophysical data. Generally, the geophysical methods will only provide the results in terms of an image that could not signify accurate signatures of the geological structures. The geological structures could not be identified precisely because the contouring of the results is solely based on the subsurface materials without identifying the geological structures at the subsurface layer. Hence, a new research is needed to enhance the knowledges about the geological structures by applying the geophysical methods on the outcrops. Usually, one method used in geophysical surveys could not confirm the signatures of structures. The geophysical methods are non-standalone methods as the data from a survey could lack datum points and can be affected by the surrounding parameters such as noise. The 2-D resistivity imaging method can map the subsurface of the earth in terms of resistivity. The addition of seismic refraction method will enhance the information of the subsurface image with respect to the physical parameters which is velocity.

1.2 Research objective

The main purpose of this study is to apply the different geophysical methods to study geological structures. Other objectives of this research include:

i. To visualize the geological outcrops using 2-D resistivity imaging and seismic refraction methods.

ii. To assess the distinctive features of geological structures from the geological outcrops based on the results of 2-D resistivity imaging and seismic refraction methods.

iii. To identify the lineament of Seulimeum fault using typical features of geological structures understood from the 2-D resistivity imaging and seismic refraction methods.

1.3 Scope of study

In this research, 2-D resistivity imaging and seismic refraction methods were conducted at all study areas to assess the distinctive features of geological structures from both methods. The visual inspection of the outcrops was also used to match with data obtained from geophysical surveys. In addition, some information from the geological map is also gathered to assist the interpretation. The needed of this study was to obtain details information about geological structures of the subsurface. Hence, all the significant shows in the results will be discussed accordingly to each criterion meet with geological structures such as fault, fold, contact, bedding, fractures, and subsurface materials.

There are two parts of study in this research which are field works and field test. For field works, both methods were applied to three different study areas with the assist of outcrops and geological map information. Three outcrops in Peninsular Malaysia were selected as the field works which are Bukit Kukus, Hill B, and Bukit Chondong. Both geophysical methods were applied to the field works and conducting on the same profiles (2-D resistivity imaging survey lines were on the same line with the seismic refraction method survey lines). The special signatures of geological structures that are obtained at field work and will be used as guidelines to study the possible structures that may found in the field test.

The field test was a regional study on a large-scale area that is conducted at Krueng Raya, Aceh in Sumatra Island, Indonesia. Boreholes records and geological map were used to support the result obtained from the surveys. The geological map has confirmed that this study area was underlain with the main active fault system known as Seulimeum fault. Both geophysical methods were applied to cover the whole study area to investigate the lineament of Seulimeum fault. However, there is some limitation occurs during conducting the surveys. Both methods are failed to conduct on the same line due to the limited accessibility of the study area. Hence, all survey lines were planned to cover as wide as possible and must be nearer to the fault system. The identification of the signatures and significant of geological structures are obtained from the combination of data set with refers to the special features of geological structures obtained from field works.

1.4 Significance and novelty of the study

The combination of 2-D resistivity imaging and seismic refraction methods in this research will produce a better interpretation on the results obtained from the surveys. The research was supported by the information provided from the visual inspection on the outcrops at three field works. Thus, the results obtained was not solely based on the contouring profile but also with the lateral view of the outcrops to validate the signatures of geological structures. The structures found at field works includes with fault, fractures, contact, fold, and bedding. These structures will have different signatures and give special features in the resistivity and velocity values. Hence, the features of geological structures obtained from field works can be used to investigate the structures at other study area. The additional information such as borehole records and the geological map will enhance the results in terms of ambiguities reduction and assist in interpretation for the field test. Hence, the lineament of Seulimeum fault can be identified using the results from field works as the references. This research has a potential to contribute to the progress of knowledge in the application of the geophysical methods to study about the features of geological structures such as fault, fracture, fold, bedding, and contact zone by refers to the parameters of resistivity and velocity. Besides that, this research will help in generating an up to date geological map of the Seulimeum fault system at Aceh, Indonesia by using geophysical approach.

1.5 Thesis layout

The thesis chapters are organized as follows:

Generally, chapter two consists of two parts. The first part discussed on the theoretical part from both methods, which are 2-D resistivity imaging and seismic refraction methods. The second part is on the previous studies of the geophysical methods in various scopes such as mineral exploration, environmental and engineering problems. All previous study has shown significant impact from both methods used in determining the geological structures. Research gaps of the previous study were also being discussed briefly in this chapter.

Chapter 3 is devoted to the location and geology of the study areas. The research methodology for both methods which are 2-D resistivity imaging and seismic refraction methods were discussed briefly in this chapter. The research has been divided into two parts which are field works and field test. The selection of field works was based on the objective of the research which is to assess the distinctive features of geological structures from the geological outcrops based on the results of 2-D resistivity imaging and seismic refraction methods to obtain the signature of the fault, fracture, fold, bedding, and contact zones. Meanwhile, a field test was chosen based on the availability of location of fault zone from the geological map coupled with the statements by the several previous studies. The data acquisitions and main apparatus used for the study are also provided in this chapter. Finally, the data will be processed using RES2DINV software for 2-D resistivity imaging. The software used for seismic refraction method is Firstpick and SeisOpt2D software. The final interpretation will be done in Surfer8 software.

Chapter 4 presents the results from this research which mainly consist of the outcome and interpretations. The results were divided into two main parts which are field works and field test. The field works include Bukit Kukus, Hill B, and Bukit Chondong. The results obtained from three field works were supported by the geological mapping of the outcrops and geological maps. Only one field test was used to study the same methods in identifying the lineament of Seulimeum fault system at Krueng Raya, Aceh Besar (Indonesia). The interpretation of the results were done with some additional information from boreholes records and geological map to support the results obtained from the field test. Both parts show that this study has successfully obtained the signatures of geological structures by describing the subsurface materials and contouring models.

Finally, chapter 5 summarizes the application of 2-D resistivity imaging and seismic refraction methods towards the field works and field test in determining the geological structures. Some recommendations were included for future research in both geophysical and geological studies.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter consists of two sections. The first section is about the theory of 2-D resistivity imaging and seismic refraction methods. The second section is about the previous study on 2-D resistivity imaging and seismic refraction methods which are related to the investigation of the geological structures. The parameters from both geophysical methods such as resistivity (Ωm), and velocity, (v) are important to determine the geological structures of the subsurface. Hence, both selected methods in this study were used to clarify the targets of the research.

2.1 Resistivity theory

The resistivity method is used to investigate the subsurface conditions of an area by injecting the electric current. The current is driven through the ground using a pair of electrodes (C_1 and C_2) and potential is created from the flow of current in a pair of electrodes (P_1 and P_2) as shown in Figure 2.1. The results from the distribution of the potential on the ground was produced by the P_1 and P_2 which is connected to a voltmeter. Data produced from the 2-D resistivity imaging are presented and interpreted in the form of average resistivity that is countered in the heterogeneous underground formation (Sharma, 1986).

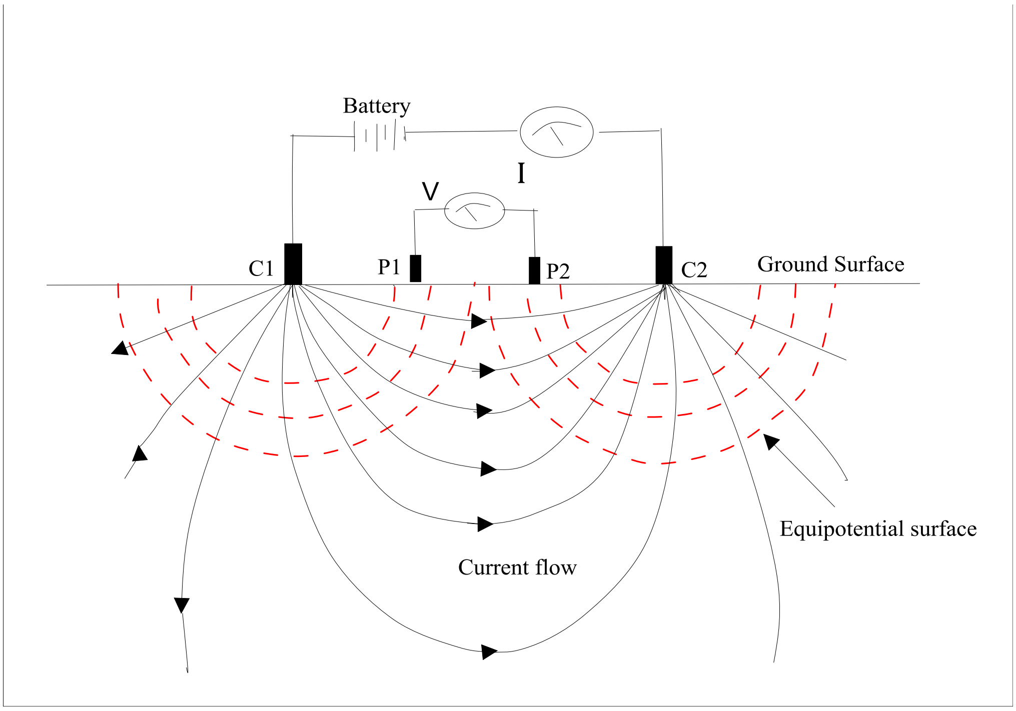

Figure 2.1: Current flow in the homogenous ground (Burger, 1990).

The apparent resistivity, (ρ_a) is measured from the relationship between the applied current and the potential difference from the arrangements of electrodes at constant spacing. Equation 2.1 is explained about the electrode carries a current (I) which is measured in amperes (A) and the potential different (ΔV) created at any point in a medium. The resistivity values vary with the amount of current injected to the ground surfaces (Loke, 1999). Different type of rock and mineral do not have same resistance as they depend on the several geological parameters such as porosity, fluid content, and density (Syukri et al., 2014).

$$\Delta V = RI \qquad (2.1)$$

where,

R: resistance
I: current flow

2.1.1 Resistivity of rocks and minerals

Resistivity (ρ) is measured on the ability of the rock, soil, and groundwater (Loke, 1999) to allow the flow of an electric current (I), in ampere (A). Thus, resistivity can be defined as the resistance per unit volume. The unit used for resistivity is in Ohm meter (Ωm). The resistivity of rock is depending on the resistivity of the contained electrolyte and it is inversely with the porosity and the degree of saturation (Sharma, 1976). Table 2.1 shows the approximate resistivity ranges for several common rock types. Igneous rock and metamorphic rock shows high resistivity due to the fracture and liquid content in their structure but the sedimentary rock has shown low resistivity values due to the high porosity content (Griffiths and King, 1981). Thus, it is concluded that degree of fracture, liquid content and porosity do affect the resistivity value of rock and materials.

Table 2.1: Approximate resistivity of some common rocks and soil materials (Adopted from Griffiths and King, 1981).

Material	**Resistivity (Ωm)**
Igneous rocks	$8 - 1\times 10^6$
Metamorphic rocks	$4 - 1\times 10^6$
Clay	$0.9 - 1\times 10^2$
Soft shale	$0.5 - 1\times 10^2$
Hard shale	$8 - 10 \text{ x } 10^3$
Sand	$20 - 2 \text{ x } 10^3$
Sandstone	$50 - 4 \text{ x } 10^3$
Porous limestone	$1\times 10^2 - 1\times 10^4$
Dense limestone	$1\times 10^3 - 1\times 10^6$

In a homogeneous medium, the theory of potential at point sources of current are defined as the current flow away radially from the point of entry and at any instants, its distributed uniformly over a hemispherical surface. Figure 2.2 shows the method of calculating the potential distribution due to current sources in a homogeneous medium.

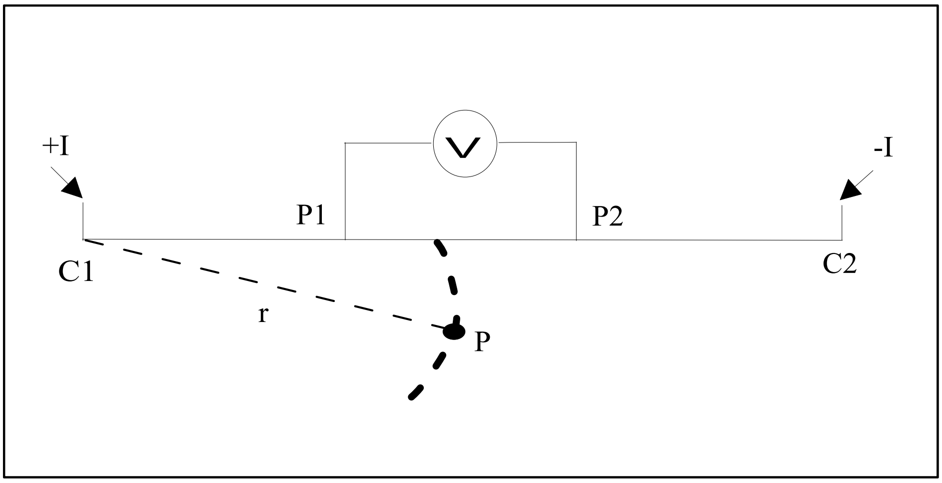

Figure 2.2: Method of calculating potential distribution due to the current source in a homogeneous medium (Sharma, 1986).

2.1.2 Electrodes arrangement

There are several types of electrodes configuration used in the field practice for 2-D imaging surveys. The most commonly used linear array arrangement is illustrated in Figure 2.3, which are Wenner, Schlumberger, and Pole-Dipole arrays. These arrays are practically used for sounding, profiling and scanning survey line at the different study area. The usage of an array for a field practice depends on the advantages of the array which differs in depth of investigation, the sensitivity of the array to vertical and horizontal changes in subsurface resistivity, the horizontal data coverage, and the signal strength.

The important parts in 2-D resistivity imaging are to choose the electrodes array in order to have good results with high resolution and reliable image, data with maximum datum point, fully data coverage and higher signal-to-noise ratio (Loke et al., 2004). In Wenner array, there are four constant electrodes spacing in a line with alternating positive and negative near surface regions cancel, and the main response is from depth which is uniform laterally. This array is good for determining depth variations in 1-D Earth profiles. While the Schlumberger array has an equivalent vertical resolution like Wenner array but it has a deep response. The array is concave upward and becomes sensitive to lateral variation in Earth.

Both Wenner and Schlumberger arrays are relatively sensitive to vertical resolution for horizontal structures and high signal-to-noise data. The pole-dipole array can provide good horizontal coverage with higher signal strength and has lower signal-to-noise ratio. It uses two potential electrodes, P_1 and P_2 separated with spacing, a, which move along the line for n spacing from current electrode C_1. C_2 is used as remote electrodes and must be planted far away from survey line perpendicularly. It has good coverage as this array have multi-electrode resistivity meter systems with a relatively small number of nodes and it is much less sensitive to telluric noise compared with pole-pole array.

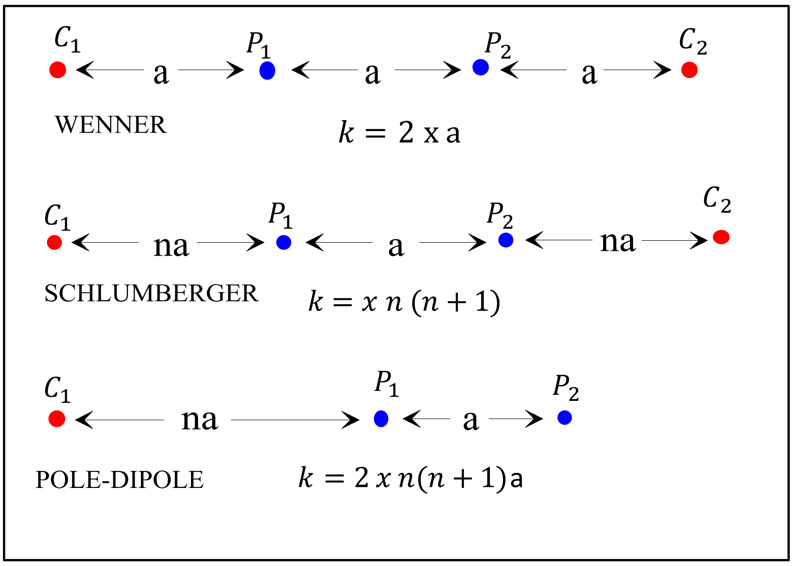

Figure 2.3: Common electrode configurations used in resistivity surveys (Loke, 1999).

2.2 Seismic theory

Seismology is very important in the science of earthquakes. It has been widely used to study the seismic waves generated by the earthquakes. There is a huge possibility of the earthquake to occur every day at any time the wave is strong enough to be felt locally. The distinct seismic wave can be measured with sensitive instruments such as seismometers. A seismic wave can be generated from two major divisions, firstly is from the natural shock waves from the earthquake and other is from artificial explosions.

The seismic method of the subsurface involves the movement of the energy pulse. The pulse of energy measured at ground surface consists of compression, shear, and surface waves as they propagate through the subsurface and may dissipate by reflecting toward the surface or being refracted and travel along the boundaries.

Seismic method is one of the best tools to study layered media of shallow subsurface. This is including two general methods known as seismic reflection and seismic refraction. Seismic reflection method is used to study bedrock mapping, detecting abandoned coal mine, detecting saturated zone and mapping of the shallow faults. Meanwhile, seismic refraction method is used to map the contrast in seismic velocity.

This study focuses on the method used for acquiring critical refraction to deduce the interface depth and velocities of each layer of the subsurface (Ali et al., 2012). Geophones are laid out on the surface as shown in Figure 2.4. Critical refraction is obtained from the differences in velocity of each layer. Once a source is generated at the surface, it forces the wave to travel along the ground surface and wave in the underlying has higher velocity because of the compact layer (Telford et al., 1990). Seismic refraction method is used to map the contrast in seismic velocity. This method uses the critical refraction to deduce the interface depth and velocities of each layer of the subsurface. Equation 2.9 explains the calculation of travel time in two layer cases.

$$time = \frac{x}{V_2} + \frac{2h_1\sqrt{(V_2)^2 - (V_1)^2}}{V_1 V_2} \quad (2.9)$$

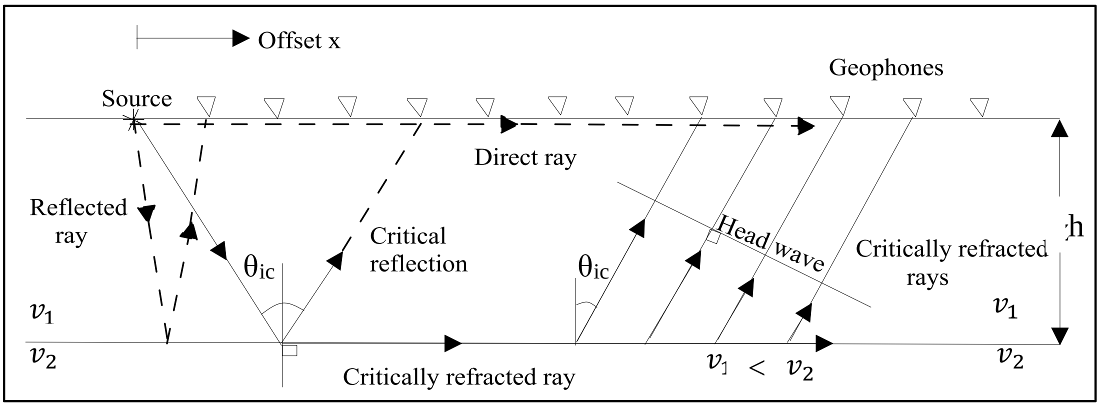

Figure 2.4: Critically refracted rays from multichannel geophones array (Modified from Ali et al., 2012).

2.2.1 Snell's law

When there are two different rock types, the seismic wave will travel across the boundaries by reflected their energy to the surface and the remainder continues its way at a different angle or being refracted. Wave that has been refracted is well explained in Snell's law (Equation 2.16), which describes that the angles of incidence and refraction to the seismic velocities in two media. If V_2 is greater than V_1, refraction will be towards the interface. However, if $sin\ i$ equals to V_1/V_2, the refracted ray will be parallel to the interface and some of its energy will return to the surface as a head wave that leaves the interface at the original angle of incidence. However, at a greater angle of incidence will cause all the energy reflected and refracted ray could not occur (Milsom, 2003).

$$\frac{sin\ i}{sin\ r} = \frac{V_1}{V_2} \tag{2.16}$$

2.2.2 Seismic velocities in rocks

In order to understand seismic velocities of rock, it is important to know the properties of the rock. It is related to the velocity of propagation, particularly to longitudinal waves which are the fastest and the first to be recorded. Seismic velocities of rock material depend on the elastic moduli and density. Both, in turn, depends on properties of rock such as mineral content, temperature, grain size, fabric, porosity, cementation, fluid content, confining temperature and rate of weathering.

The different types of material will give different values of seismic wave velocity. Typical values of the longitudinal velocities, V_P of some rocks are listed in Table 2.2. Besides that, velocities also can be calculated from the measurement of the elastic constant of rock samples by using Equation 2.15. The range of variation in the seismic velocities of rocks is considerably greater than the corresponding variations in their densities.

Seismic velocity, V_P, is the parameter refering to mechanical properties of the rock or materials. The value varies with the types of rock. Jeen et al. (2009) had stated in their study that the measured value of velocity were used to solve several problems regarding the depth variations in seismic velocities, porosity, and permeability. It could also be used to find the relationship between V_P and V_S, identification of the porosity-dependence of P-wave and S-wave velocities and their ratio and porosity-dependence of density. The depth variation also can be obtained from the study of seismic velocities.

Table 2.2: Approximate velocity range of some common rocks and minerals. (Adopted from Sharma, 1986).

Subsurface materials	Longitudinal Velocities, v_P (m/s)
Air	330
Water	1400-1500
Ice	3000-4000
Alluvium, sand	300-1700
Glacial moraine	1500-2600
Sandstones	2000-4500
Slates and shales	2400-5000
Limestones and dolomites	3500-3600
Rock salt	4000-5500
Granites and gneisses	5000-6200
Basalt	5500-6300
Gabbro	6400-6800
Dunite	7500-8100
Peridotite	7800-8400

2.3 Geological structures

The study of geological structures aims to investigate the history of the earth formations including the various types of rocks and minerals. The geological structures such as fractures and discontinuities are mostly found possess at outcrop surfaces. Understanding the earth formations is the key to exploring the geological point of view. Sometimes the geological structures could be the barrier which allows the water flow (Singhal and Gupta, 2010). The discontinuity within earth profiles may include several types such as fault, fold, fracture, and bedding.

In general, a fault occurs when a rock has a significant displacement parallel to the fracture surface. The main causes of faulting are due to the stress and shear movement of plate tectonics. The stress in rocks may come from the deformation in mountain-building tectonic activity. The fault is characterized as the plane zones occurs along the ruptures by three types of normal fault, reverse fault, and the strike-slip fault has moved the opposite walls such as in Figure 2.5 (Rey, 2010).

Some of the criteria used in describing the fault are by observing the displacement of the block such as the bedding changes due to fault mechanism. Locating the fault on the outcrops become easier if the observer could see the displacement by the presence of features of slickensides, mylonite or breccia (Anderson, 1980). If an outcrop has vegetation, the alignment of vegetation also can change. The fault structure will affect the stratigraphy of subsurface because it can break the continuities of stratigraphic units and sometimes repetition in strata. The fault may be easy to recognize on the field and sometimes difficult to see the structures depends on the types of fault which are a normal fault, reverse fault, or strike-slip fault.

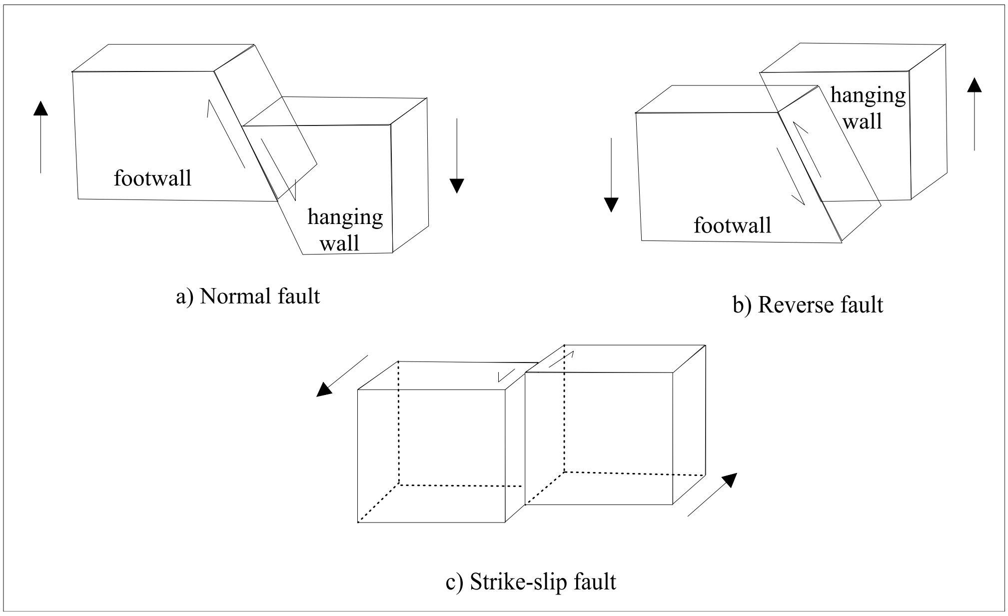

Figure 2.5: The mechanism of fault types with the common term in describing a fault; a) Normal fault, b) Reverse fault, c) Strike-slip fault (Rey, 2010).

The fold is also a common sedimentary rock formation. This structure may form as a result from various mechanisms such as buckling due to lateral tectonic compression and the slip-on trust fault within the subsurface. The classification of fold structures can be divided into several categories which are based on the thickness of folded layers, the angle between limb, the dip of the axial surface, the plunge of the folded axis and the general types of the fold (Rey, 2010). There are two types of fold which are anticlines whose the limbs are dipping away from each other and synclines with limbs dipping towards each other (Singhal and Gupta, 2010). Figure 2.6 shows the two types of folding mechanisms. The simple and easiest way to identify the fold structure is by eye inspection on the fields. The folding structures are recognized by bending of the strata with some repetition.

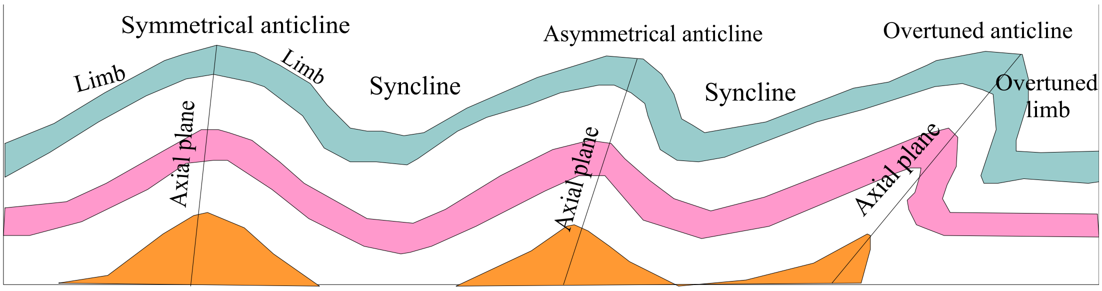

Figure 2.6: Fold types with the common term in describing the mechanism of folding (Rey, 2010).

Fracture is a crack or break that occurs within the block of rock when the plane has experienced an amount of stress that caused partial loss of cohesion in the rock (Singhal and Gupta, 2010). Joint is also a fracture and the occurrence of this structure does not have any displacement along the fracture.

Bedding of sedimentary layer is referring to the significant discontinuity surface in the bodies of rock (Singhal and Gupta, 2010). In other words, bedding is a layer of beds having the same rock and texture form due to the deposition of sediments.

Bedding structure is mostly found with some other structure such as fault, fracture, and fold. The stratification of bedding has different thicknesses; very thick beds until very thin beds.

2.4 Previous study

There are a few case studies to be discussed in this chapter which is involved in mineral exploration, subsurface characterization and groundwater detection using 2-D resistivity imaging and seismic refraction methods. Besides that, a few studies related to the geology of the study areas were also selected for further discussion.

2.4.1 Application of 2-D resistivity imaging and seismic refraction methods

Shawver et al. (2006) designed a research on the application of geophysical methods in a survey along a portion of the southbound retaining wall of Missouri Highway 152 in Kansas City, Missouri. The objective of this research is to map the bedrock geology, structure, and engineering properties of the shallow subsurface. The geophysical methods that had been used in this survey include the 2-D resistivity imaging and seismic refraction methods. Besides that, borehole record was used to interpret the subsurface. The result from 2-D inversion resistivity profiles indicate that bedrock unit strike in a southeasterly direction and dip to the southwest. The inversion model of 2-D resistivity imaging shows the signature of fracture by the presence of conductive zone with low resistivity (<100 Ωm). Detailed analysis of 2-D resistivity imaging has identified the highly-fractured zone within the bedrock units and another potential area of poor rock quality. Data obtained from the 2-D resistivity imaging only indicates the electrical properties of soil and rock that can change within a particular unit. Meanwhile, result from seismic refraction method provided differently and compliments data as it can map the sediment thickness, bedrock velocity, and degree of weathering. The first layer is unconsolidated soil with a velocity value of 300 m/s. The second layer is intermediate velocity sediment layer with velocity >600 m/s interpreted as lower limestone. The higher velocity value for sedimentary rock unit has a value of >2700 m/s. The integration of geophysical methods and geotechnical method has successfully helped in characterizing the geological subsurface.

Muztaza et al. (2012) employed a research on subsurface characterization material that conducted along all 8 km in the North-South direction of in Lenggong, Perak (Malaysia). Two geophysical methods are used which are 2-D resistivity imaging and seismic refraction methods. The purpose of this survey was to map bedrock, structure, and fracture of the shallow subsurface. The results obtained were correlated with borehole log to enhance the interpretation. The result of these studies indicates that the top litho-layer is thinner towards the south and north. The analysis of the field data acquired on 2-D resistivity imaging shows that alluvium part consists of a boulder or weathered granite and granitic bedrock sequences. Besides that, faults and fracture were also successfully determined using 2-D resistivity imaging results, which is by estimates the electrical properties of soil and rocks. The 2-D inversion models has successfully imaging the highly fractured zone provided the suspected zone were filled with fluid or clay. Two major layers were apparent on the seismic refraction analysis with the first layer consisting of alluvium (10 Ωm to 800 Ωm) and boulders of weathered granite (>6000 Ωm). The results from seismic refraction indicate the weathering and rippable of the soil and rocks. The velocity of the first