SOIL DYNAMIC PROPERTIES ASSESSMENT BY USING GEOPHYSICAL METHODS

ALYAA NADHIRA BINTI SALLEH

UNIVERSITI SAINS MALAYSIA

2021

SOIL DYNAMIC PROPERTIES ASSESSMENT BY USING GEOPHYSICAL METHODS

by

ALYAA NADHIRA BINTI SALLEH

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

October 2021

ACKNOWLEDGEMENT

First and foremost, I would like to thanks Allah the Almighty for allowing me to finish this work. I want to express my deep gratitude to my supervisor Dr Nordiana Muztaza and my co-supervisor, Prof. Dr Rosli bin Sa'ad for the guidance and support during this work. Also, their encouragement, valuable advice, help and kind supervision are highly appreciated.

Million thanks to my parents, Salleh bin Said and Hanisah binti Hassan, for their prayers, love, care, encouragement, understanding and support throughout the completion of this thesis, from beginning till the end. To my siblings, Nurin Irdina and Inas Sofea, thank you for lending your shoulder and encouraging me to do my best. To Megat Shahirul Iqram, thank you for always being there and never failed to help me, no matter in what terms.

I would also like to thank all the technical staff in the Geophysics lab for their help in both field and laboratory work during my research - Mr Yaakub Bin Othman and Mr Shahil Ahmad Khosini. I have been blessed with helpful friends Nazirah Mahmud, Iffah Zalikha and Dr Taqiuddin Zakaria, Fariszatul Erna Zubir, Farah Eliani Soleh, Farid Najmi Rosli and Nabila Husna in my daily work for their encouragement and assistance towards my study. My deepest gratitude goes to Ministry of Higher Education Malaysia for Fundamental Research Grant Scheme with Project Code: FRGS/1/2018/STG09/USM/03/2 entitle Development of 2-D linear inversion algorithm from geophysical approach for soil or rock characteristics and also Research University grant entitle Integrated geophysical characterization of geothermal exploration and strategy for a sustainable use of geothermal resources' with account no. 1001/PFIZIK/8011110.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

A	Area
a	Electrode spacing
Cf	Phase velocity
E	Young's modulus
F	Force
f	Frequency
G	Shear modulus
I	Current
K	Bulk modulus
k	Wave number
Ks	Subgrade reaction coefficient
L	Length
Lo	Initial length
n	Factor of safety
n	n times
P	Pressure
Qa	Allowable bearing capacity
Qult	Ultimate bearing capacity
R	Resistance
SV	Vertical shear wave
v	Poisson's ratio
V	Potential difference
V_P	Compressional wave velocity
V_S	Shear wave velocity
v-w	Velocity frequency domain
x-t	Time domain
γ	Unit weight
γ_o	Reference unit weight
ΔL	Change in length

ΔP	Change in pressure
ΔV	Change in Volume
Δx	Change in distance
ε	Strain
λ	Wave length
Π	Pi
ρ	Bulk density
$\mathrm{\rho}$	Resistivity
σ	Stress
Ω.m	Ohm meter
$<$	Less than
$>$	More than
$\surd$	Square root
1-D	One-dimension
2-D	Two-dimension

LIST OF ABBREVIATIONS

C1	Current 1
C2	Current 2
CPT	Cone Penetration Test
DC	damage control
ERM	Electrical resistivity method
ES 10-64	Electrode Selector 10-64
g/cm^3	Gram per cubic centimetre
GPa	Giga pascal
GPR	Ground Penetrating Radar
Hz	Hertz
kN/m^3	Kilonewton Per Cubic Meter
m	Meter
MASW	Multichannel analysis of surface wave
kPa	kilo pascal
ms^{-1}	Meter per second
ms^{-2}	Meter per second squared
NPP	North Penang Pluton
NSV	New Sonic Viewer
N-values	Blow count
P1	Potential 1
P2	Potential 2
RMS	Root Mean Square
RQD	Rock Quality Designation
SAS 4000	Signal Averaging System 4000
SPT	Standard Penetration Test
SR	Seismic refraction
USM	Universiti Sains Malaysia

LIST OF APPENDICES

PENILAIAN CIRI – CIRI TANIH DINAMIK MENGGUNAKAN KAEDAH – KAEDAH GEOFIZIK

ABSTRAK

Ciri-ciri dinamik tanih merupakan ciri geoteknik yang kritikal dalam menentukan kestabilan struktur di atas mahupun didalam bumi. Maklumat mengenai sifat tanah dapat digunakan dalam reka bentuk awal asas bagunan. Secara konvensional, kaedah – kaedah geoteknik digunakan dalam menilai sifat dinamik tanah. Walau bagaimanapun, kaedah ini memakan banyak masa untuk mendapatkan hasilnya. Oleh itu, penyelidikan ini menggunakan kaedah geofizik untuk mengkaji sifat dinamik tanah dari pelbagai jenis litologi melalui keberintangan elektrik (ERM), pembiasan seismik (SR), dan kaedah analisis gelombang permukaan (MASW). USM, Gelugor dan Paya Terubong dipilih sebagai lokasi kajian kerana terdapat beberapa kes kegagalan asas pada masa lalu. USM terdiri daripada pasir dan kelodak berpasir dengan nilai ketahanan 1754 – 2182 Ω.m dan 90 – 1938 Ω.m. Paya Terubong terdiri daripada pasir berkrlodak dan granit terluluhawa dengan nilai keberintangan 40 – 380 Ω.m dan 400 – 1800 Ω, Gelugor dengan nilai keberintangan < 200 Ω.m untuk zon tepu, 140 – 824 Ω.m untuk zon terluluhawa dan lapisan keras dengan nilai keberintangan > 3000 Ω.m. Ciri sinamik tanih menunjukkan bahawa Paya Terubong mempunyai permukaan bawah tanah yang kompeten dengan 113 – 856 kPa untuk nilai Qa. Gelugor dengan 72 – 462 kPa untuk Qa, sementara USM mempunyai daya nilai paling rendah dengan < 200 kPa untuk nilai Qa.. Sebarang permukaan dengan nilai Qa kurang dari 200 kPa adalah tidak sesuai untuk menyokong sebarang jenis asas bangunan. Nilai Qa untuk kelodak berpasir < 200 kPa; pasir berkelodak berkisar antara 113 – 615 kPa, dan granit terluluhawa > 700 kPa. Taburan saiz zarah juga

mempengaruhi sifat dinamik tanih kerana USM dan Gelugor menunjukkan nilai daya galas yang lebih rendah kerana mempunyai taburan saiz zarah yang lebih halus. Paya Terubong secara dominan terdiri daripada taburan saiz zarah kasar; oleh itu, daya galas yang lebih tinggi diperolehi. Kesimpulannya, gabungan kaedah geofizik yang digunakan dalam kajian ini menunjukkan bahawa Paya Terubong, yang dominan terdiri daripada taburan saiz zarah kasar, dan mempunyai keadaan tanah yang stabil. USM dan Gelugor mempunyai kestabilatan tanah yang kurang untuk asas bangunan dan memerlukan penambahbaikan tanah seperti pemadatan untuk meningkatkan daya galas. Oleh itu, kaedah geofizik disyorkan untuk penyiasatan tapak untuk memberikan parameter reka bentuk asas kepada jurutera struktur.

SOIL DYNAMIC PROPERTIES ASSESSMENT BY USING GEOPHYSICAL METHODS

ABSTRACT

Soil dynamic properties are the most critical geotechnical property of soils, help in the stability of structures on or below the earth. The information on soil properties can be used in the preliminary design of the foundation. Conventionally, the geotechnical method is used in assessing the dynamic properties of soil. However, this method consumes much time to get the result. Thus, this research utilises geophysical methods to investigate the soil dynamic properties of various lithology types via the application of the electrical resistivity method (ERM), seismic refraction (SR), and multichannel analysis of surface wave (MASW) methods.USM, Gelugor, and Paya Terubong were selected as a site of interest as there had been few cases of foundation failure in the past. USM comprises SAND and sandy SILT with resistivity values of 1754 – 2182 Ω.m and 90 – 1938 Ω.m. Paya Terubong comprises silty SAND and weathered granite with resistivity values of 40 – 380 Ω.m and 400 – 1800 Ω.m. Gelugor with resistivity values < 200 Ω.m for the saturated zone, 140 – 824 Ω.m for the weathered zone, and hard layer with a resistivity value of > 3000 Ω.m. The soil dynamic results show Paya Terubong has the most competent subsurface with 113 – 856 kPa for Qa. Gelugor with 72 – 462 kPa for Qa, while USM has the slightest bearing capacity values with < 200 kPa for Qa. Any subsurface with Qa values < 200 kPa is not suitable to support any type of building foundation. The Qa values have been established based on soil type; sandy SILT is less than 200 kPa, silty SAND between 113 – 615 kPa, and highly weathered granite is more than 700 kPa. The grain size particle also influences soil dynamic properties as USM and Gelugor showed lower

bearing capacity values due to finer grain size particles. Paya Terubong is dominantly made up of coarse grain particles; thus, a higher bearing capacity is obtained. In conclusion, the combination of geophysical methods used in this study shows that the Paya Terubong, dominantly made up of coarse-grained, has the most stable ground condition. USM and Gelugor are less stable for foundations and require ground improvement such as compaction to increase the bearing capacity. Hence, geophysical methods are recommended for site investigation to provide information on the subsurface's stability and competency before constructing a new building.

CHAPTER 1

INTRODUCTION

1.1 Background

Building performance over its lifespan cannot be separated from the foundation contribution, which provides support and stability. Foundation transfers the loads from the superstructure by spreading them over a large area to the soil layers with the slightest deformation and high bearing capacity. When all the forces and loads are transfer to the underlying soil; thus, it will result in some movement, allowable movement. The foundation that undergoes movement more than its ability to resist will cause subsidence and excessive settlement failures (Figure 1.1). Therefore, detailed information of the underlying soil is required to prevent foundation failure and understand the soil dynamic properties of ground conditions (Poulos, 2016).

The geophysical methods have been used widely for soil investigation and engineering foundations; Telford et al., 1990; Sharma, 1997; Bery et al., 2017 supplied the relationship between soil lithology and electrical resistivity method. The main aim of electrical resistivity imaging is to map the electrical resistivity of the subsurface vertically and laterally. It measures the differences in electric potential to identify subsurface material. The geotechnical borehole was used to validate the electrical resistivity result and study the factor that influenced the resistivity values based on soil types (Bery et al., 2017). Besides, electrical resistivity is also capable to reveals any subsurface features such as boulders and fractures that may lead to foundation failures (Muztaza et al., 2017).

The seismic methods become a cost-effective tool to determine the subsurface structure's depth and bedrock for the engineering and construction project (Reynolds, 1997). The seismic refraction method employs the acoustic seismic waves that travel through the ground subsurface and return to the surface after critical refraction. The first arrivals of the compressional wave (V_P) are essential in seismic refraction, leading to a time-travel graph. The time-travel graph processing will produce the V_P with depth of subsurface. The multichannel analysis of surface waves generated a shear velocity profile by analysing Rayleigh waves to evaluate the ground's elastic condition (Reynolds, 2011). When the energy is transmitted, the Rayleigh wave frequency component has different velocity propagation called phase velocity (Cf) at each frequency (f) that result in different wavelength (λ). This property is called dispersion. The 1-D model is produced from the inversion result of the dispersion curve. The parameters obtained are shear wave (V_S) velocity, indicating the subsurface's stiffness.

Besides delineating the subsurface layers, seismic methods also calculate the soil dynamics properties (Schulze, 1943). V_P and V_S from both seismic techniques can provide the subsurface's information of soil dynamic properties. Soil dynamic properties are critical parameters in foundation engineering. It is because soil dynamic properties such as bulk density, Poisson's ratio, Young's modulus, bulk modulus, shear modulus, subgrade reaction coefficient, ultimate and allowable bearing capacity are essential to determine the deformation and competency of soil (Tezcan & Ozdemir, 2011). This research attempts to characterize soil dynamic properties variation in some areas in Penang Island. Realizing the part of geophysics in engineering fields, many studies are conducted to integrate the geophysical method and geotechnical method (Ismail et al., 2015). Geotechnical methods such as borings in this research are used to validate the geophysical data interpretation. The integration of geophysical and geotechnical methods provides a better approach to understand the ground condition better.

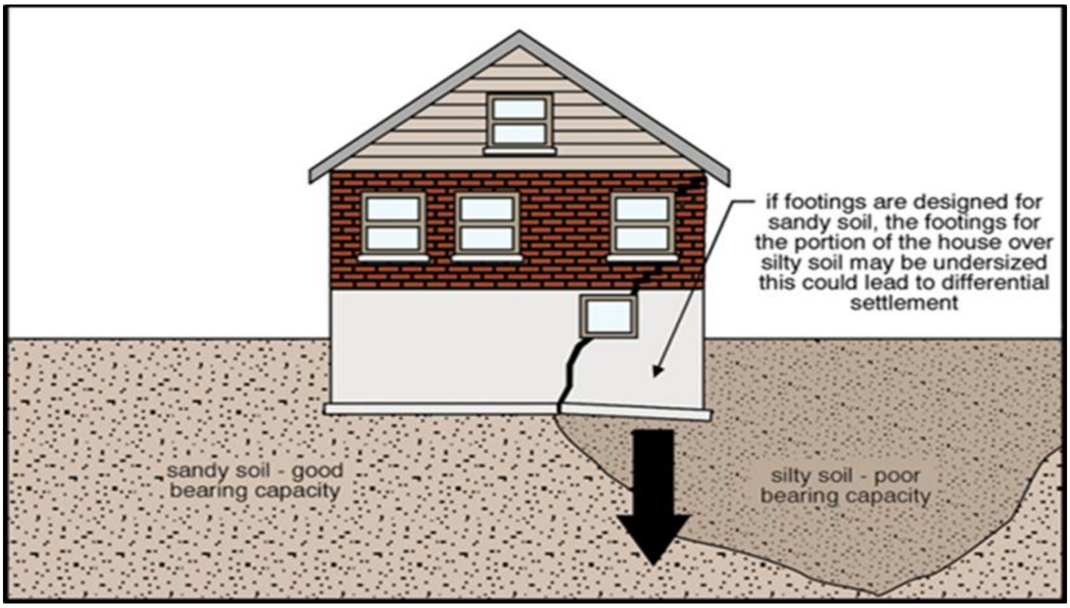

Figure 1.1 The non-uniform variation of soil properties that cause structural damage (Grant et al., 1974)

1.2 Problem statements

In a most general sense, electrical resistivity may effectively-identified soil types. However, the previous researchers' theoretical ranges are in the values of a broad range and overlap between soil value classes that may lead to misinterpretation (Seaton & Burbey, 2002). Hence, this study performed a field electrical resistivity method at different soil types with supporting data from the borehole record to find the factors influencing the electrical resistivity values (Abidin et al., 2017).

The standard method of evaluating the soil dynamic properties are plate load testing and laboratory testing. However, this method has limitations such as a long time consuming, prohibitive cost, and only limited to a particular point (Pfaffhuber et al., 2019). Hence, the non-destructive geophysical method such as seismic refraction and multichannel analysis of surface waves are used in this study to overcome this issue since it provides a large area of subsurface information (Schulze, 1943). In addition, the integration can be a guide in determining soil properties at the construction site. Therefore, it enhances geophysical data interpretation with less time-consuming.

1.3 Research objectives

The objectives of this research are;

i. To identify electrical resistivity values of soil base on soil type.

ii. To determine the soil dynamic properties using seismic velocities.

iii. To establish the soil dynamic properties values based on soil types.

1.4 Scope of study

The study evaluates the competency and stability of the subsurface by using the inversion profile of geophysical methods and numerical calculations. The research was carried out in three different locations in Penang Island with different types of soil conditions. The resistivity parameter obtained from ERM is then correlated with soil lithology from the borehole record to study the factors influencing the resistivity values. Apart from that, ERM is also used to identify weak zone which may lead to ground failure (Muztaza et al., 2017). SR and MASW methods play a vital role in delineating the subsurface layers and calculating the soil dynamic properties. Therefore, soil dynamic properties can give information of the subsurface condition, such as stability and competency. Besides, the research also might help give the information of the deformation and capacities of soil based on the types.

1.5 Significance of the study

The electrical resistivity method provides the distribution of soil's resistivity laterally and vertically. Compressional and shear wave velocities obtained from seismic refraction and multichannel analysis of surface wave were used to calculate the soil dynamic properties of the subsurface. Thus, the result obtained was not solely based on the inversion profile but also the calculation of soil dynamic properties. Additional information from the borehole record will help validate and verify the soil's lithology, while SPT-N values from the borehole record will enhance the soil dynamic result. Hence, the competency of the subsurface will be evaluated based on the values of soil dynamic properties. The research provides insight into the importance of geophysical parameters to evaluates soil dynamic properties of subsurface layers. Besides, it will help the engineers in the preliminary foundation design based on the ground condition information.

1.6 Thesis layout

Chapter 1, the background of this research, is introduced. Problem statements and research objectives to be achieved related to this research are highlighted. Furthermore, this chapter presents the scope of the study, significance of the study, and layout of the thesis.

Chapter 2 includes the fundamental theory of electrical resistivity method, seismic refraction, multichannel analysis of surface wave and soil dynamic properties. The previous study related to the soil dynamic using geophysical method such as electrical resistivity, seismic refraction, multichannel analysis of surface wave are also being discussed in this chapter.

Chapter 3 explained the methodology of the research. It includes the research flowchart. This research applied electrical resistivity, seismic refraction and multichannel analysis of surface wave at several locations in Penang Island. The data acquisition, data processing and the calculation of soil dynamic properties were discussed in this chapter.

In Chapter 4, the final data is presented. The values of soil dynamic properties were calculated using the mathematical equations based on their soil types.

Finally, Chapter 5 concluded that the geophysical methods are able to determine the soil dynamic properties. This chapter also provides the recommendation related to the soil dynamic properties evaluation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Geophysical methods have been used widely in evaluating the subsurface's soil dynamic properties. A preliminary study using the geophysical method provides the necessary information to understand the subsurface better. In this study, the electrical resistivity method (ERM), seismic refraction (SR), and multichannel analysis of surface wave (MASW) have been integrated to achieve the objective of the research. The ERM measures the resistivity material of the ground surface as the parameters. The electrical resistivity method parameter is essential in determining the resistivity of different soil types. The seismic methods (SR and MASW) depend on acoustic wave energy and the elasticity properties of the subsurface (Haeni, 1986). The parameter from seismic refraction is compressional wave velocity (V_P), while shear wave velocity (V_S) is generated from the multichannel analysis of surface wave method. The soil dynamic properties such as bulk density, Young's modulus, Poisson's ratio, shear modulus, Bulk modulus, the allowable and ultimate bearing capacity have been calculated from V_P and V_S using a relative formula.

There are two parts of Chapter 2; the first part is about the theory of geophysical method (electrical resistivity method, seismic refraction, and multichannel analysis of surface wave) and soil dynamic properties (bulk density, Young's modulus, Poisson's ratio, shear modulus, bulk modulus, allowable and ultimate bearing capacity). The second part is about the previous studies related to the soil dynamic properties using different geophysical methods.

2.2 Electrical resistivity method

The electrical resistivity method has been widely used to measure subsurface electrical resistivity. This method is beneficial in detecting the vertical and lateral changes of electrical resistivity in subsurface materials. A few factors affected the value of subsurface resistivities, such as lithology, degree of water saturation, porosity, degree of fracturing, and concentration of dissolved salt (Loke, 1999).

The resistivity measurement is usually conducted by injecting current (I) into the ground. Apparent resistivity is calculated by using the potential difference (V). The electrical resistance is calculated by using Ohm's Law as in equation 2.1. Current is directly proportional to voltage and inversely proportional to resistance (Burger, 1992).

$$R = \frac{V}{I} \tag{2.1}$$

Where;

R: Resistance of conductor

The SI unit for resistance is volts per ampere or Ohm (Ω). The resistivity can be calculated using equation 2.2

$$R = \rho \frac{L}{A} \tag{2.2}$$

Where;

ρ: Resistivity of the conductor material (Ω.m)
L: Length of the conductor (m)
A: Cross-sectional area (m^2)

Two current electrodes were injected into the ground (C_1 and C_2), and the resulting potential difference between two potential electrodes (P_1 and P_2). The modified current flow in the subsurface (Milsom, 2003) is shown in Figure 2.1.

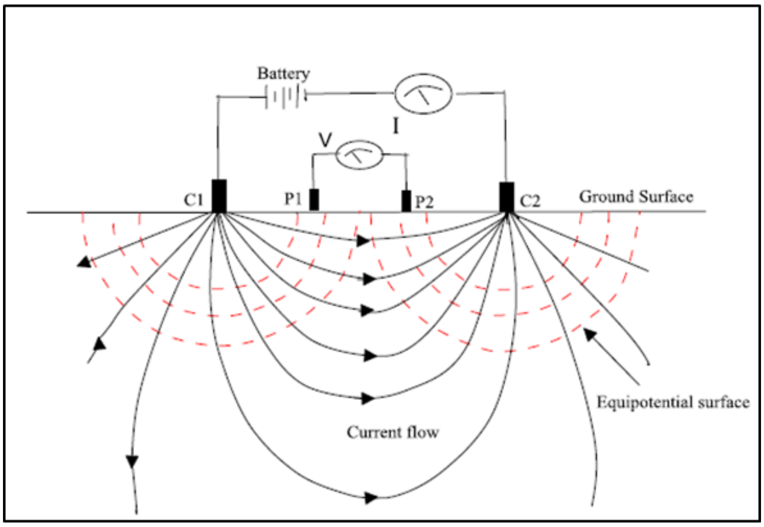

Figure 2.1 Electrodes array for subsurface resistivity measurement and current flow in the homogenous ground (Burger et al., 2006).

2.2.1 Wenner-Schlumberger and Pole – Dipole array

Several electrode arrays can be used for resistivity surveys. The aim and the interest of the target will help in choosing the most suitable array. The arrays have different sensitivity to vertical and horizontal changes in the subsurface resistivity, the depth of investigation, the horizontal data coverage, and the signal strength (Loke, 1999). The most common array for the electrical resistivity method are Wenner, Schlumberger, Dipole – Dipole, Pole – Dipole and Wenner – Schlumberger.

Wenner-Schlumberger is the new hybrid between Wenner and Schlumberger array (Pazdirek & Blaha, 1996). It can be used in the system with a constant spacing of electrode arrangement shown in Figure 2.2. The array is moderately sensitive to the vertical and lateral structures due to the slightly greater concentration of high sensitivity values below the P1- P2 electrodes. Wenner-Schlumberger has better signal strength compared to another array (Seaton and Burbey, 2002). The Pole – Dipole array has relatively good horizontal coverage, but it has significantly higher signal strength, and it is an asymmetry array (Loke, 1999). In some situations, the asymmetry in the measured apparent resistivity values could influence the model obtained after inversion. By combining the measurements with the "forward" and "reverse" Pole – Dipole arrays, any bias in the model due to the asymmetrical nature of this array would be removed (Loke, 2004). Moreover, the Pole – Dipole array is more sensitive to vertical structure. One advantage of the Pole – Dipole array is good depth penetration, and good data cover near the end of layouts, which is essential when operating in confined space (ABEM, 2009).

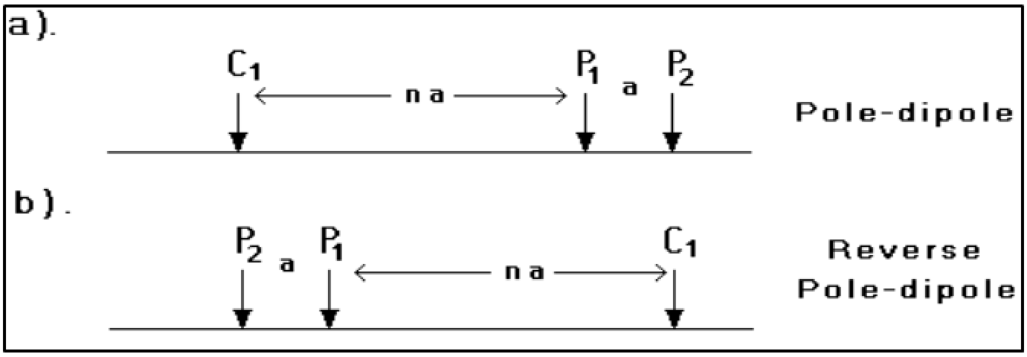

Figure 2.2 Forward and reverse Pole – Dipole array (Loke, 1999)

2.2.2 Electrical resistivity of soils and rock

The resistivity value of soils and rocks is in a broad range and overlapping between the classes of soil and rocks. The same soil or rock may have different resistivity values, and different soil or rock also can have the same resistivity value. For example, clayey and silty soil, classified as cohesive soil, typically have a lower resistivity value than sandy and gravelly soil that is non-cohesive (Abidin et al., 2017). The resistivity of a rock or soil sample depends on several factors, such as the porosity, the degree of water saturation, and the concentration of dissolved salts. Table 2.1 shows the resistivity value of some rocks and minerals.

Table 2.1 Resistivities of some common rocks and minerals (Keller and Frischknecht 1966, Daniels and Alberty 1966)

Material	Resistivity (Ω.m)
Granite	$5x10^3$ - 10^6
Basalt	10^3 - 10^6
Slate	$6x10^2$ - $4x10^7$
Marble	10^2 - $2.5x10^8$
Quartzite	10^2 - $2x10^8$
Sandstone	8 - $4x10^3$
Shale	20 - $2x10^3$
Limestone	50 - $4x10^2$
Clay	1 - 100
Alluvium	10 - 800
Groundwater (fresh)	10 - 100
Sea water	0.2

2.3 Seismic methods

Seismic waves are generated by energy caused by a sudden movement of soil or rocks within the Earth. Therefore, the wave may travel differently through different materials of the Earth.

Seismic waves are divided into two basic types; body wave and surface wave. A body wave is a seismic wave that travels through the Earth's inner layers rather than across its surface (Aki & Richards, 1980). Body waves divide into compressional waves (primary wave or V_P) and transverse waves (secondary wave or V_S). The surface wave travels slower and usually have higher amplitudes and longer wavelength (Gubbins, 1990). Surface waves divide into two types; Rayleigh wave and Love wave.

V_P is also known as compressional waves (longitudinal/primary wave). It propagates by compressional and dilational strains in the direction of wave travel (Figure 2.3). V_P is the fastest traveling seismic wave, and therefore, the first to be felt or recorded during an earthquake (Milsom, 2003). A sound wave is an example of a V_P wave.

Most seismic surveying has focused on using V_P. It is because it only detects vertical ground motion and is not sensitive to horizontal motion. In addition, V_P reaches the detectors first, so it is easier to recognize.

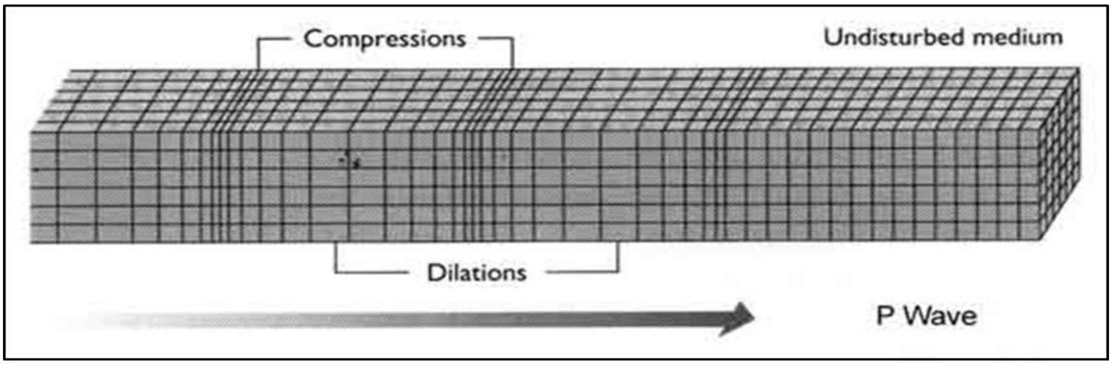

Figure 2.3 Particle moves parallel to the direction of V_P propagation (Rubin and Hubbard, 2005).

V_S is shear waves (transverse, secondary wave). It is propagated by pure shear strain perpendicular to wave travel (Figure 2.4). The wave moves through elastic media, and the main restoring force comes from shear effects. V_S is the second wave felt in an earthquake. V_S is slower than V_P and can only move through solid rock, not through any liquid medium (Gubbins, 1990).

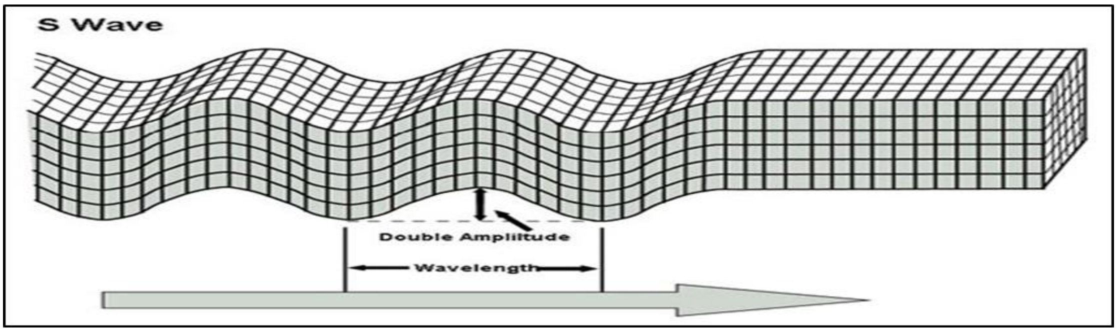

Figure 2.4 Particle move perpendicular to the direction of V_S propagation (Rubin and Hubbard, 2005).

The elastic moduli determine the velocities of V_P and V_S and the density of the material; thus, it can be expressed as (Equation 2.3 and 2.4).

$$\mathrm{Vp} = \sqrt{\frac{\mathrm{K} + \frac{4}{3}\mu}{\rho}} \qquad (2.3)$$

Where;

K = Bulk modulus
μ = Shear modulus
ρ = Density

$$\mathrm{Vs} = \sqrt{\frac{\mu}{\rho}} \qquad (2.4)$$

Where;

μ = Shear modulus
ρ = Density

When μ = 0 (as in gaseous and liquid medium), V_P velocity is decreased, and V_S velocity becomes zero (Burger et al., 2006).

Surface waves travel across the Earth's surface as opposed to through it. Surface wave usually has larger amplitudes and longer wavelengths than body waves; they travel more slowly than body waves. Love waves and Rayleigh waves are types of the surface wave.

There are two types of the surface wave; Rayleigh and Love wave. Surface wave has both longitudinal and transverse wave characteristic. The particles move in a parallel and perpendicular direction to the direction of wave motion. Rayleigh waves travelling around the Earth's surface are observed to be dispersive. The particle motion consists of a combination of compressional and vertical shear (SV) wave vibration, giving rise to an elliptical retrograde motion in the vertical plane along the travel direction (Figure 2.5).

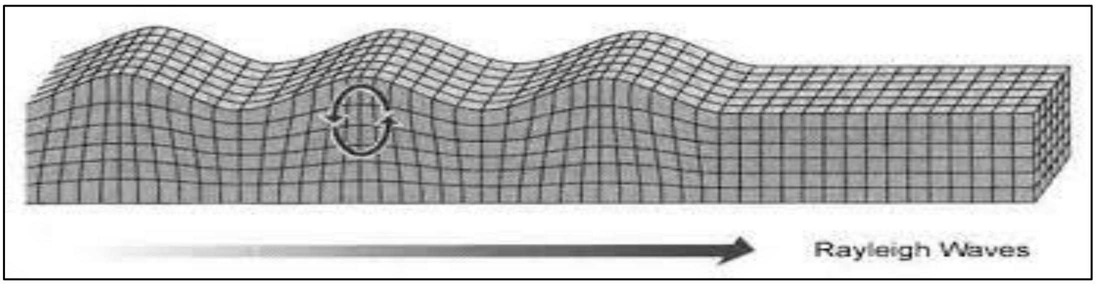

Figure 2.5 Rayleigh wave; particle experience elliptical retrograde motion due to the combination of compressional and vertical shear (SV) waves (Rubin and Hubbard, 2005).

Love waves are polarised shear waves with particle motion parallel to the free surface and perpendicular to wave propagation. It is the fastest surface wave and is confined to the surface (Sheriff & Geldart, 1995). Inherently dispersive (velocity dependent on wavelength). Propagation of the Love wave causes the ground particles to move side-to-side, perpendicular to the direction of the wave (Figure 2.6).

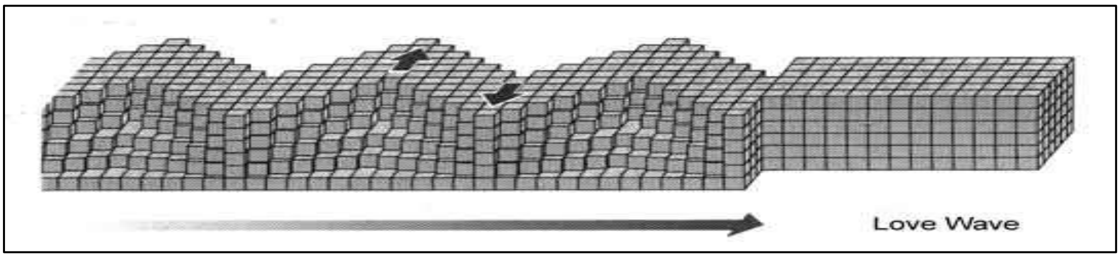

Figure 2.6 Ground particles move side-to-side, perpendicular to the Love wave's propagation (Rubin and Hubbard, 2005).

2.3.1 Seismic refraction

Seismic refraction is widely used in the fields of engineering geology, geotechnical engineering, and exploration geophysics. The seismic refraction method utilizes the refraction of seismic waves on geologic layers and soil/rock units to characterize the subsurface geologic conditions and geologic structure. The seismic refraction technique is based on the refraction of seismic energy at the interfaces between subsurface/geological layers of different velocities (Burger et al., 2006). The seismic refraction method uses similar equipment to seismic reflection, typically utilizing geophones in an array and a seismic source.

The schematic diagram illustrates the path of seismic waves propagating from a source at the surface (Figure 2.7). Some of the seismic energy travels along the surface in the form of a direct wave. However, when a seismic wave encounters an interface between two different soil and rock layers, a portion of the energy is reflected, and the remainder will propagate through the layer boundary at a refracted angle (Sheriff, 1989). At a critical angle of incidence, the wave is critically refracted and will travel parallel to the interface at the speed of the underlying layer (Haeni, 1986). Energy from this critically refracted wave returns to the surface in the form of a head wave, which may arrive at the more distant geophones before the direct wave.

By picking the time of the first arrival of seismic energy at each geophone, a plot of travel-time against distance along the survey line can be generated. The final output is a velocity/depth profile for the refractors.

The methods depend on the fact that seismic waves have differing velocities in different soil or rock types. Besides, the waves are refracted when they cross the boundary between different soil or rock types (or conditions). Thus, the methods enable the general soil types and the approximate depth to strata boundaries or bedrock.

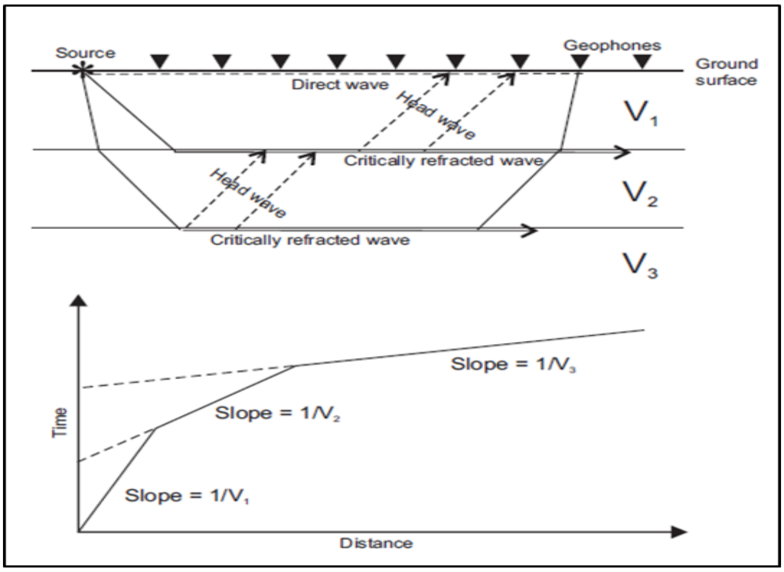

Figure 2.7 Refracted ray path for a single subsurface interface (Burger et al., 2006).

2.3.2 Multichannel analysis of surface wave

MASW is one of non-invasive of geophysical method that introduced by Park et al. (1999). It measures the ground stiffness using shear velocity (Vs) of the subsurface with a depth of more than 30m depending on site conditions and seismic sources (Reynolds, 1997). The MASW method measures the seismic wave of the surface wave velocities from various seismic sources and estimates the V_S using the Rayleigh wave of dispersion through mathematical inversion (Miller et al., 1999). There is a particular type of wave that propagates along the surface when a seismic wave is generated. This unique wave is called a surface wave which penetration depth depends on the wavelength. The longer the wavelength, the deeper the penetration depth, as shown in Figure 2.8. The surface wave is usually dispersive; the waves of different wavelengths travel at different phase speeds.

The fk-spectrum method is the most commonly used for the dispersion curve measurements related to the characteristics of surface wave data, or those data analyzed to transform into the fk-domain. (Gabriels et al., 1987). The analyzed data can then be used to create the Phase velocity frequency spectrum as in equation 2.5.

$$cf = \frac{dx}{dt} = \frac{2\pi f}{k} \quad (2.5)$$

Where:

Cf: the phase velocity,

f: the frequency,

k: the wave number

λ: the wavelength

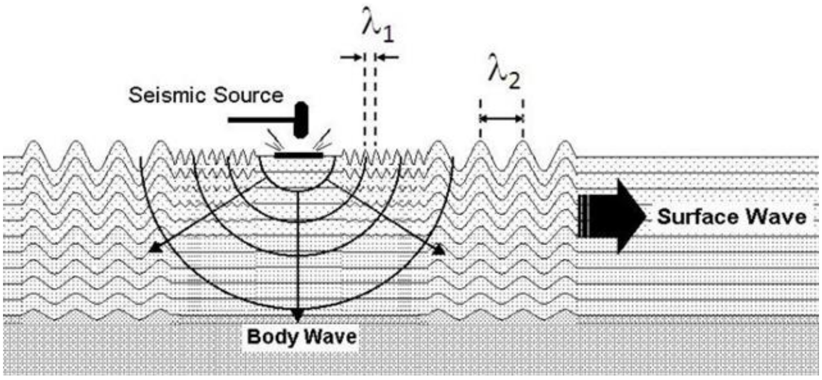

Figure 2.8 Schematic diagram for surface wave (Park, 1999).

2.4 Soil dynamic properties

The compressional and shear wave velocities obtained from SR and MASW were used to determine the soil dynamic properties for each layer delineated. Elasticity is defined as the material's ability to temporarily deformed due to pressure/an external action to return to its original form (Landau & Lipshitz, 1970). There are two crucial elements in the definition above: external pressure (stress) and changes in a material due to external pressure (strain) (Daintith, 2005). Stress is force per unit area and can be expressed as in equation 2.6:

$$\sigma = \frac{F}{A} \quad (2.6)$$

Where:

σ: Stress (N/m^2)

F: Force (N)

A: Area of object (m^2)

Every material that undergoes pressure/stress will change/deform its shape, angle, or volume. It is known as strain. It can be expressed as in equation 2.7:

$$\varepsilon = \frac{\Delta L}{Lo} \tag{2.7}$$

Where:

ε: Strain

ΔL: Elongation or compression (offset) of the object

L_o: Initial length of the object.

2.4.1 Bulk density

Bulk density is vital to reflect the ability of soil to support the structural load from the entire building. Bulk density is a measurement of the amount of solid + water per unit volume. The bulk density can be calculated by using equation 2.8. Where γ is the unit weight of the soil and g is the acceleration due to gravity which is given by 9.8 m/s^2 (Tezcan & Ozdemir, 2011)

$$\rho = \frac{\gamma}{g} \tag{2.8}$$

Where;

γ: Unit weight of soil (kN/m^3)

g: acceleration due to gravity (m/s^2)

The value of the unit weight of soil measures the weight of a unit volume of material. It can be calculated from the V_P value by using equation 2.9 by Tezcan &

Ozdemir, 2011. Where V_P in m/s while γ_o, the reference of unit weight value in kN/m^3. The reference of unit weight values for soil and rock types are given as follows:

γ_o = 16 (loose sandy, silty and clayey soils)

γ_o = 17 (dense sand and gravel)

γ_o = 18 (mudstone, limestone, claystone., conglomerate)

γ_o = 20 (cracked sandstone, tuff, greywacke, schist)

γ_o = 24 (hard rock)

$$\gamma = \gamma_o + 0.002\ V_P \tag{2.9}$$

2.4.2 Poisson’s ratio

The negative ratio of lateral strain to longitudinal strain. Poisson's ratio defines how much the material will deform in lateral directions (Figure 2.9). Poisson ratio is a dimensionless material property that determines how much a given material will contract in the lateral direction when the material stretches in a longitudinal direction. It can be expressed as in equation 2.10:

$$v = \frac{-\varepsilon\ \text{lateral}}{\varepsilon\ \text{longitudinal}} \tag{2.10}$$

Where:

v:	Poisson’s ratio
ε lateral:	Lateral strain
ε longitudinal:	Longitudinal strain

Poisson’s ratio can be measured on the field, such as V_P and V_S wave velocities as in equation 2.11 by Tezcan and Ozdemir 2011. Poisson’s ratio plays a vital role in estimating any engineering calculation. It defines the negative ratio of transverse to axial strain.

$$v = \frac{\left(\frac{Vp}{Vs}\right)^2 - 2}{\left\{2\left[\left(\frac{Vp^2}{Vs}\right) - 1\right]\right\}} \qquad (2.11)$$

Where:

V_P: Compressional wave velocity (m/s)

V_S: Shear wave velocity (m/s)

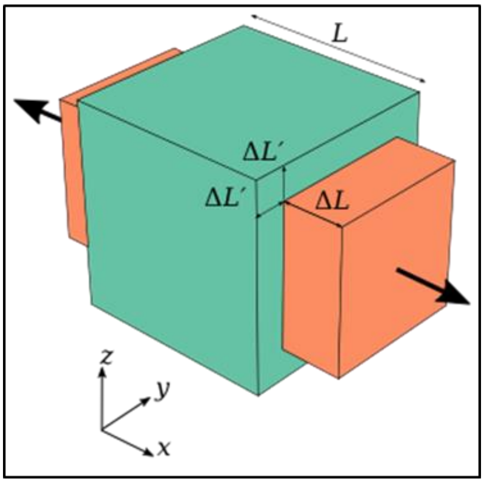

Figure 2.9 Poisson's ratio diagram (Hicher, 1996)

2.4.3 Young’s modulus

Young's modulus in Figure 2.10 measures how much material to withstand changes in length under compression. It is also known as the ratio between tensile stress and tensile strain. Young's modulus can be expressed as in equation 2.10:

$$E = \frac{F}{A} = \frac{\Delta L}{Lo} \qquad (2.12)$$

Where:

E: Young's modulus,

ΔL: Change in length

L_o: Original length.

Young's modulus can be expressed in terms of a compressional wave, bulk density, and Poisson's ratio as in equation 2.11:

$$E = \frac{\rho Vp^2(1-2v)(1+v)}{(1-v)} \quad (2.13)$$

Where:

ρ: Bulk density (kg/m^3)

V_P: Compressional wave (m/s)

v: Poisson's Ratio

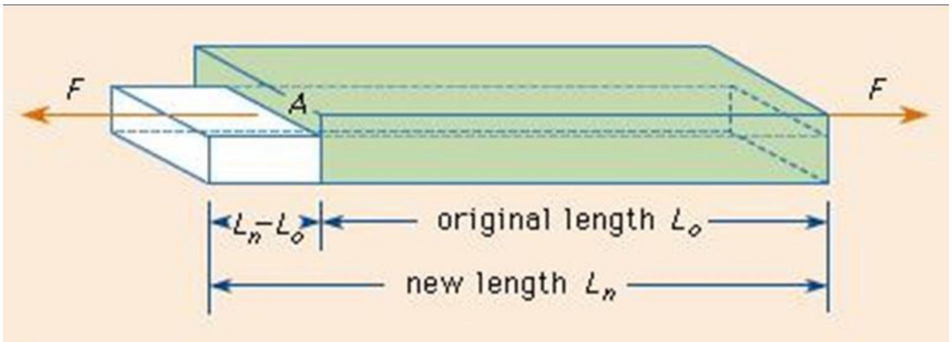

Figure 2.10 Young's modulus diagram (Hicher, 1996)

2.4.4 Bulk modulus

Bulk modulus indicates how difficult it to be compressed. One object is subjected to force act equally in all its faces (Figure 2.11). The object will not change its shape, but the volume is changing. The Bulk modulus is related to the propagation of V_P, and it can be express as in equation 2.14:

$$K = \frac{\Delta P}{\left(\frac{\Delta V}{V}\right)} \quad (2.14)$$

Where:

K: Bulk Modulus (N/m^2)

ΔP: Change of the pressure (N/m^2)

ΔV: Change of the volume of the material due to the compression (cm^3)

V: Initial volume of the material (cm^3)

Bulk modulus also can be defined in terms of Young's modulus and Poisson's ratio as in equation 2.15:

$$K = \frac{E}{3(1-2v)} \quad (2.15)$$

Where:

K: Bulk modulus (GPa)

E: Young's modulus (GPa)

v: Poisson's ratio

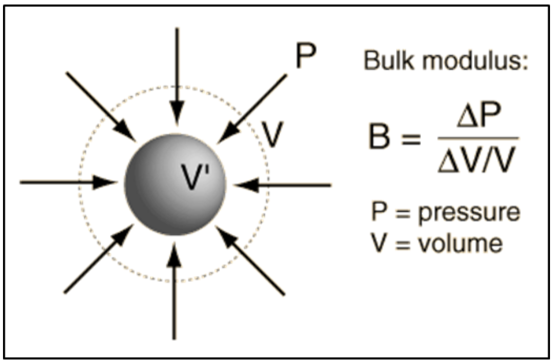

Figure 2.11 Bulk modulus diagram (Hicher, 1996)

2.4.5 Shear modulus

Shear modulus is the measure of the ratio of shear stress to shear strain. For example, two opposite forces exerted on a body of different planes are subjected to a tangential force to one of its faces while the opposite face is held fixed by another force, the produced strain is the horizontal distance of sheared face by the height of the object as shown in Figure 2.12. The shear modulus can be expressed as in equation 2.16:

$$G = \frac{F}{A} = \frac{\Delta x}{L} \quad (2.16)$$

Where:

G: Shear Modulus

F: Tangential Force

A: Area of being sheared

Δx: Horizontal distance sheared face moves

L: Height of objects

Shear modulus can be defined in terms of Young's modulus and Poisson's ratio as in equation 2.17:

$$G = \frac{E}{2(1+v)} \tag{2.17}$$

Where:

E: Young's Modulus

v: Poisson's ratio

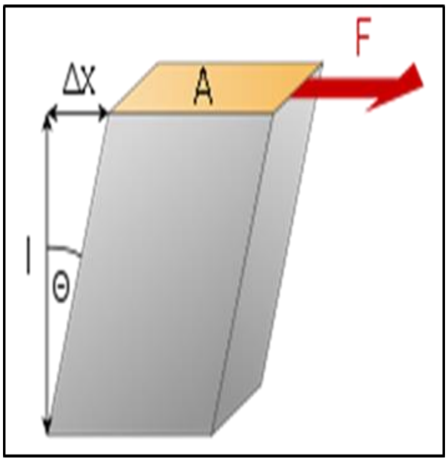

Figure 2.12 Shear modulus diagram (Hicher, 1996)

2.5 Geotechnical borehole

Borehole investigation is one of the common drilling technique tests to acquire the physical characteristic of soil/rock. This method is constructed for many different purposes, such as environmental site assessment, groundwater study, and site investigation. To obtain the subsurface soil's detailed information, some samples were taken out from the borehole to perform laboratory testing.

This study utilizes the existing borehole record at the study area. The parameter from the borehole that is considered for this study is soil lithology.

2.5.1 Soil lithology

The soil's lithology in the borehole record is determined based on the undisturbed sample taken out from the borehole. Soil lithology is used in the study to obtain information on the soil types and soil consistency which then can be used to correlate with the resistivity values.

2.5.2 Standard penetration test

The Standard Penetration Test is an in-situ test that is useful in site exploration and foundation design. It produces an N-value, representing the number of blows of a standardized sampler driven into the soil at a standardized distance. The N-value from the borehole record is used to determine the stiffness of the subsurface. The consistency of N-value for cohesive soil (silt and clay) and non-cohesive soil (sand and gravel) are different. Table 2.3 shows the Consistency of soil based on N-values

Table 2.2 Consistency of soil based on N-values (Terzaghi & Peck, 1967).

Cohesive Soil		Non-cohesive soil	
Consistency	N-values	Consistency	N-values
Very soft	0-2	Very loose	0-4
Soft	3-4	Loose	5-10
Medium	5-8	Medium dense	11-30
Stiff	9-15	Dense	30-50
Very stiff	16-32	Very dense	> 51
Hard	> 32		

2.6 Bearing capacity

There is a limit to the amount of weight that soil can support due to applied loads without failing. The bearing capacity of soil plays a vital role in knowing whether a particular soil can withstand the amount of load acting on a structure or not (Poulos, 2016). If a structure is constructed on soil that cannot bear the load, it will result in structure settlement, resulting in crack and damage to the structure. Soil bearing capacity will help in footing design which can withstand the loads.