DEVELOPMENT OF PENTA-AXIAL GEOPHONE FOR P- AND S-WAVE IN SEISMIC DOWNHOLE METHOD

RAIS BIN YUSOH

UNIVERSITI SAINS MALAYSIA

2020

DEVELOPMENT OF PENTA-AXIAL GEOPHONE FOR P- AND S-WAVE IN SEISMIC DOWNHOLE METHOD

by

RAIS BIN YUSOH

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

May 2020

ACKNOWLEDGEMENT

Praise to Allah, the Most Gracious and the Most Merciful for giving me health, strength and determination to complete my research. Alhamdulillah, all praises to Allah for His blessing in finishing this thesis. Special appreciation goes to my supervisor, Prof. Dr. Rosli Saad, for his supervision and continuous support. His invaluable help of constructive comments and suggestions throughout the experiment and thesis works have contributed to the achievement of this research. My gratitude also to my co-supervisor, Dr. Mohd Ashraf Mohamad Ismail, for his supports and advices and providing me with his knowledge in the field of this research. I would like to express my appreciation to the Dean of School of Physics, Prof. Dr. Azlan Abdul Aziz for their supports and help towards my postgraduate affairs. My appreciation goes to all academic and technical staffs for their co-operations especially to Dr. Nordiana Mohd Muztaza, Dr. Nur Azwin Ismail, Mr. Yaakub Othman, Mr. Shahil Ahmad Khosaini, Mr Zulkeflee Ismail, Mr. Ahmad Halmi Ghazalli, Mr. Azmi Abdullah, and Mr. Abdul Razak Noh @ Che Ngah. Sincere thanks to all my friends; Sabrian Tri anda, Sabiu Bala Muhammad, Muhammad Nazrin A Rahman, Kiu Yap Chong, Mark Jinmin, Amsir Taib, Fauzi Andika, Tarmizi, Zul Fadhli, Yakubu Mingyi Samuel, Mohammed Mustapha Adejo, Adamu John, Mohd Firdaus Adul Razak, Mohd Hanis Mohamad, Najmiah binti Rosli, Muhammad Taqiuddin Zakaria and others for their moral support during my research. Last but not least, my deepest gratitude goes to my beloved parents; Yusoh Ahmad, my late mother Siti Hawa Abdul Rahman, Rosli Bakar and Asmah Zainuddin and also to my sister and brothers for their endless love, prayers and encouragement. Also to my wife, Ros Nadiah Rosli for her love and care about my health and study. And to those who had indirectly assisted me during the course of my study, thank you very much for your assistance.

TABLE OF CONTENTS

LIST OF TABLE

Page

LIST OF FIGURES

LIST OF SYMBOLS

%	Percent
±	Plus Minus
μ	Shear modulus
cm	Centimeter
D	Depth
DIA	Diameter
Ghz	Giga-hertz
Hz	Hertz
K	Bulk modulus
Kg	Kilogram
m	Meter
mm	milimiter
ms	milisecond
º	Degree
R	Ray path
R^2	Regression
t	Travel time
t_c	Corrected travel time
V_d/V	Interval velocity
V_P	Primary wave velocity
V_S	Secondary wave velocity
ρ	Density

LIST OF ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
ABS	Acrylonitrile Styrenic Butadiene
ASCII	American Standard Code for Information Interchange
CAM	Computer Aided Manufacturing system
CPT	Cone Penetration Test
DC	Direct Current
DM	Direct Method
FDM	Fused Deposition Modeling
GB	Gigabytes
GPR	Ground Penetrating Radar
ixSeg2SegY	Interprex Seismic Shot Conversion
MASW	Multiple Surface Wave Analysis
MB	Megabytes
MRM	Mean Refracted Ray Path Method
P	Primary
PLA	Poliactic Acid
PVC	Polyvinyl Chloride
P-wave	Primary wave/compressional wave
RAM	Random Access Memory
S	Secondary
sCPT	seismic Cone Penetration Test
SH	S-wave propagate horizontally

SPT	Standand Penetration Test
SPT-N	Standard Penetration Test blows counts
SRT	Seismic Refraction Tomography
SV	S-wave propagate vertically
S-wave	Secondary wave/Shear Wave
TEM	Transient Electromagnetic
T-Rex	Triaxial vibroseis
USM	Universiti Sains Malaysia
WGS 84	World Geodetic System 1984

LIST OF APPENDICES

PEMBANGUNAN GEOFON BERPAKSI-PENTA UNTUK GELOMBANG -P DAN -S DALAM KAEDAH SEISMIK LUBANG DASAR

ABSTRAK

Lubang dasar seismik adalah tekni geofizik yang mengukur halaju tanah / sempadan batuan bawah permukaan geologi di sekitar lubang jara. Gelombang sismik yang diterima oleh geofon di dalam lubang jara ditransmisikan dari sumber yang terletak di permukaan tanah bersebelahan dengan lubang jara dalam bentuk gelombang pemampat dan ricih (gelombang-P dan -S). Pengukuran ini dapat dikira dengan lebih lanjut untuk pembangunan tapak, kajian potensi pencecairan dan reka bentuk asas tanah. Walau bagaimanapun, lubang dasar seismik memerlukan pengukuran yang tepat untuk mengaitkan parameter reka bentuk geoteknik seperti nisbah Poisson serta ricih dan modulus Young. Ketepatan lubang dasar seismik bergantung kepada keberkesanan sumber seismik dan isyarat kepada nisbah hingar. Untuk memperoleh amplitud maksimum isyarat gelombang seismik, adalah penting untuk memahami pergerakan arahan sumber gelombang seismik di mana ia seharusnya sejajar dengan sensor geofon. Oleh itu, penyelidikan mengenai pelbagai arah geofon telah dilakukan untuk mendapatkan pelbagai arah gelombang gelombang seismik. Sehubungan itu, tujuan kajian ini diadakan untuk menghasilkn sebuah geofon Penta-axial geofon yang terdiri daripada lima geofon sudut (satu gelombang-P dan empat geofon gelombang-S) untuk mengoptimumkan keberkesanan penerima. Dengan penghasilan geophone Penta-Axial, kedudukan gelombang seismik pada permukaan menjadi tidak mudah, kerana penerima dapat memperoleh pelbagai arah gelombang di dalam lubang jara. Fabrikasi geofon Penta-Axial dibuat menggunakan pencetak 3D yang dihasilkan oleh bahan plastik asid Polatik (PLA) sebagai bekas untuk memegang kedudukan sensor geofon. Selain itu, lembaran kerja pemprosesan data yang betul telah dibangunkan untuk menguruskan data dengan menyusun kedudukan jejak di setiap kedalaman geofon. Geofon Penta-Axial telah diuji di Kampus Kejuruteraan USM dengan lubang jara sedia ada dengan nilai SPT-N termasuk data ujian penusukan kon Seismic (sCPT). Data sCPT digunakan sebagai pengesahan bersama geofon Penta-Axial di mana data sCPT menghasilkan halaju gelombang-S yang tepat disebabkan oleh penderia geofon yang dipandu langsung ke bawah tanah. Cengkaman tegar antara penderia geofon sCPT dan permukaan bawah bumi menghasilkan penerimaan gelombang seismik secara langsung tanpa kehilangan tenaga. Hasil korelasi untuk waktu ketibaan antara geofon sCPT dan Penta-Axial telah mencapai perbezaan 0.61% dan peratus perbezaan untuk halaju gelombang-S adalah 6.8%. Kesimpulannya, geofon Penta-Axial telah memperoleh hasil yang baik kerana korelasi dengan sCPT memberikan hanya sedikit perbezaan dalam keputusan halaju masa dan kedatangan masa pertama untuk gelombang S manakala isyarat gelombang P juga memberikan hubungan yang baik dengan profil lithologi di kawasan kajian kes.

DEVELOPMENT OF PENTA-AXIAL GEOPHONE FOR P- AND S-WAVE IN SEISMIC DOWNHOLE METHOD

ABSTRACT

Seismic downhole is a geophysical method that measures the soil/rock velocity of geological subsurface boundaries in the proximity around borehole. Velocity of seismic wave captured by geophone inside the borehole is transmitted from a source located on the ground surface adjacent to borehole in the form of compressional and shear wave (P- and S-wave). These measurements can be further calculated for site development, liquefaction potential studies and earthwork foundation designs. However, seismic downhole needs an accurate measurement to correlate with geotechnical design parameters such as poisson's ratio as well as shear and Young's modulus. The accuracy of seismic downhole depends on the effectiveness of seismic source and the signal to noise ratio. To acquire the maximum amplitude of seismic wave signal, it is important to understand the directional movement of seismic wave source where it should be aligned with geophone sensors. Hence, research on multiple direction of geophone has been performed to retrieve various directions of seismic wave source. Therefore, the aim of this research is to develop the Penta-Axial geophone, consists of five angles geophone (single P-wave and four S-wave geophone) to optimize the effectiveness of receiver. By producing the Penta-Axial geophone, positioning of seismic wave source on surface become effortless, since the receiver is able to acquire various wave direction inside the borehole. Fabrications of Penta-Axial geophones were made using a 3D printer produced by Polyactic Acid (PLA) plastic material as a chassis to hold the geophone sensors position. In addition, a proper data processing spreadsheet was developed to manage the data by sorting the position of traces for each geophone at every depth. Penta-Axial geophones were tested in USM

Engineering Campus with the available existing borehole with SPT-N value including Seismic Cone Penetration Test (sCPT) data. The sCPT data was used as a validation with Penta-Axial geophone where the sCPT data produce an accurate S-wave velocity due to the direct driven of geophone sensors into the ground subsurface. A firm grip between sCPT geophone sensors and ground subsurface resulted in a direct receive of seismic wave without energy loss. The correlation result for the arrival time between sCPT and Penta-Axial geophone has achieved 0.66 % difference, and percentage difference for S-wave velocity is 6.8 %. It is concluded that the Penta-Axial geophone acquires a good result since the correlation with sCPT gives a slight difference in first arrival time velocity result for the S-wave, while the P-wave signal also gives a good relation with the lithology profile at the case study area.

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Geophysical methods are used for shallow and deep earth exploration, usually reach several meters of depth, and may expand to a thousand of meters in acquiring earth subsurface information. These methods become one of the leading fields for geotechnical engineering application to overcome various engineering problems including slope failure, geohazard, soil/rock ripability during excavation, ground subsurface strength for piling design, subsurface treatment, detecting cavities/sinkholes, characterize soil/rock and abandoned mines. There are conventional methods commonly used, such as electrical resistivity, seismic method, ground penetrating radar (GPR), multichannel analysis of surface wave (MASW), transient electromagnetic (TEM), gravity and magnetic. However, the geotechnical engineering requires a reliable data to determine the parameters for geotechnical design. Hence, in order to achieve a reliable data, seismic method becomes popular and it is the most dependable geophysical method in geotechnical engineering. There are two type of seismic methods which are surface and downhole seismic method. The seismic downhole provides a good accuracy for geotechnical engineering parameters. The conventional method of seismic downhole method used is mainly to receive P- and S- wave inside borehole, where it consists of horizontal and vertical geophone (Crice, 2002; Fang and Chen, 2019; Kim et al., 2004). Nevertheless, despite seismic downhole method becomes mostly common method used, but this method is still having problem to acquire a good data due to unknown direction of geophone direction especially in S-wave signal. The S-wave exhibited highly sensitive to angle direction of seismic geophone in order to acquire the maximum amplitude of S-wave signal.

Therefore, this research aims to obtain a reliable data accuracy by improving the conventional seismic downhole method. In this chapter, the problem statement, research objectives and scope of study are discussed as a guideline to oversee the research purposes which provide benefit to the industrial improvement related to seismic downhole method.

1.2 Problem statements

Site investigation is a part of geotechnical engineering that plays an important role in identifying the ground subsurface conditions. It might have a significant impact on the proposed development and provides an accurate knowledge of the site and of the surrounding environment. Cohesive and shear strength of ground subsurface are the most important parameters used in designing geotechnical earth work. The ground subsurface parameter commonly computes from compressive wave (P-wave) and shear wave (S-wave) velocities using surface or downhole seismic. The surface seismic measures the wave velocities of the ground subsurface in 2D image by data interpolation based on obtained result, which result in low accuracy for deeper penetration.

The seismic downhole measures a seismic velocity using in-hole geophone with borehole as a medium, resulting in a good accuracy of seismic velocity of ground subsurface. To prevent miscalculating the compressional and shear strength of material based on P- and S-wave velocities, an improvement on seismic downhole is necessary. The P-wave usually has less issues in receiving the maximum amplitude of seismic wave signal due to the vertical geophone position, as the seismic source can be generated with earth gravity which is automatically aligned with geophone direction inside borehole.

However, the S-wave had encountered an issue in receiving maximum amplitude of shear wave signal inside borehole. This is because the source needs to be parallelly aligned with geophone direction inside borehole to provide a similar polarity for both left and right directions. The direction of geophone was unknown when being inserted into the borehole, and thus resulting in acquiring a lower amplitude of seismic wave due to limited of mechanical movement inside geophone sensors. To acquire the maximum amplitude of seismic wave signal, it is important to make sure the direction movement of seismic wave source should be aligned parallel with geophone sensors.

Hence, a research on multiple direction of geophone has been performed to retrieve various direction of seismic wave source. Therefore, the Penta-Axial geophone has been developed, which consists of five angles geophone (single P-wave and four S-wave geophone) to optimize the effectiveness of receiver. By producing the Penta-Axial geophone, positioning of seismic wave source on surface become effortless, since the receiver is able to acquire various wave directions inside the borehole.

1.3 Research objectives

The objectives of this research using newly developed multiple axial geophone prototype are as follows;

- To develop the optimum multiple directions of seismic downhole receiver
- To develop the algorithm of data arrangement for the Penta-axial geophone
- To validate the modified multiple axial geophone prototype with sCPT data

1.4 Scope of study

This work focuses on improving the seismic downhole acquisition data by reducing error in angle of seismic wave receiver. This work involves the understanding of the optimum angle of receiver to develop the multiple angles geophone (Penta-Axial geophone) consists of one P-wave and four angle S-wave detectors that will be used for seismic downhole method. The Penta-Axial geophone receives the P- and S-wave signals from all source directions by enhancing the S-wave signal. Since the geophone was newly build, the data processing algorithm is developed using Microsoft Excel software as a data arrangement in order to obtain sorted data for further processing. The downhole data is recorded using ABEM Terraloc MK8 seismograph and a seismic downhole test is conducted at Universiti Sains Malaysia (USM), Engineering campus to validate the effectiveness of Penta-Axial geophone prototype.

1.5 Novelty

This research is focusing on the development of multiple angles of geophone which provides advantage as an improvement of its advancement in acquiring a multiple direction of wave signal in seismic downhole method without losing the amplitude signal due to rotation of geophone when inserting into borehole. Due to newly developed prototype, a proper data sorting is developed by designing the algorithm using Microsoft Excel software to re-position the data signal.

1.6 Limitation

a) The aim of the development of Penta-Axial geophone is to improve the data acquisition of seismic wave for Seismic downhole method.

However, there are a few of limitions faced on this development related to data acquisition process which are listed below:

b) The size of borehole for testing is limited for minimum size of 3-inch diameter

c) The designated length of data acquisition was only 20-meter depth

d) Difficulty in reading the S-wave signal if the borehole is drilled not in vertical direction.

e) The designated length of data acquisition was only 20 meter depth

f) Difficulty in reading the S-wave signal if the borehole were drilled is not in vertical direction.

1.7 Thesis Layout

The following is the outline of this thesis;

This thesis was organized to present the Chapter 2 refers to the literature review, comprising previous work on the seismic method. Most of the earlier works concern with various type of seismic downhole and ground surface seismic, the accuracy of data acquisition and the geophysical method correlation with soil properties. This chapter also describes the fundamental theory of seismic downhole, P-wave and S-wave propagation and site investigation. The materials and methodology implemented in this research is discussed in Chapter 3. The detailed on Penta-Axial geophone design and manufacturing are also discussed including the principle of seismic downhole data acquisition and processing. Chapter 4 presents the results and discussion of seismic downhole using Penta-Axial geophone and soil properties of the study region, and data analysis including empirical correlation is also discussed. Chapter 5 discusses the findings of the research, objectives and includes some recommendations and suggestions for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Geophysical methods such as seismic, Ground Penetrating Radar (GPR) and resistivity, are tools applied for environmental and engineering applications used to improve soil/rock characterization study. Geophysical methods have been used over the past decades in determining the engineering properties such as elastic modules, shear strength, compressional strength and density, used in turn to solve geotechnical and environmental problems. It also used for the detection of utilities, tanks, pipes, and groundwater contaminant plumes, and characterization of landfill borders (Cardarelli et al., 2008; Cossu et al., 1990; Griffin, 1995; Zungalia et al., 1989). The application of the seismic method is widely used in engineering and environmental of structure due to its capability (Strack, 2013). Seismic method is important as a recommendation technique before conducting a drilling which can be used to optimize the interest area. There was two types of seismic method available in geophisic which are seismic refraction and seismic downhole. The basic principle for the seismic refraction method is that the source and receiver (geophone) are located on the earth surface, while for the seismic borehole method, the source is either located on the earth surface or inside the borehole, whereas the receiver is located inside the borehole. Normally the seismic source is performed by producing seismic wave using sledgehammer, weight drop or explosive.

The seismic downhole method is an in-situ study to determine the velocities of P- and S-wave velocities, to produce the soil Young modulus that can be estimated using laboratory testing such as triaxial test or oedometer test. The velocities are used to analyze a geotechnical foundation, soil statically and dynamically and liquefaction. In this chapter the fundamental theory of seismic downhole including previous work were discussed to evaluate the information to provide justification of this study.

2.2 Seismic waves

Seismic wave is an energy traveled through the layers of the earth from seismic source such as man-made explosions, earthquakes, volcanic eruptions, and enormous landslides producing low-frequency acoustic energy. The seismic waves are generated from the sources and propagate through the ground subsurface while the waves reflected/refracted at each geological boundary and create a secondary wave received by a geophone. The seismic wave velocity of ground subsurface depends on density, elasticity of the medium, while the velocity increases with depth through the subsurface (Lee and Balch, 1982).

Waves that travel through subsurface are divided into two types; body waves and surface waves. Body waves is the waves that travel through the interior of the earth where the particle vibration and wave propagation differences produce two different types of wave which are primary waves (P-wave), in other word is compressional wave, and secondary waves (S-wave), i.e. is shear waves (Figure 2.1). Movement of the P-waves particles are vibrated along the wave propagation while the S-waves particles are vibrated perpendicularly to the wave propagation. The P-wave has a greater velocity than S-wave and it arrives first before the S-wave. The S-wave consists of the particle vibration; horizontally and vertically referring to the earth surface which are called SH and SV respectively (Burger et al., 2006).

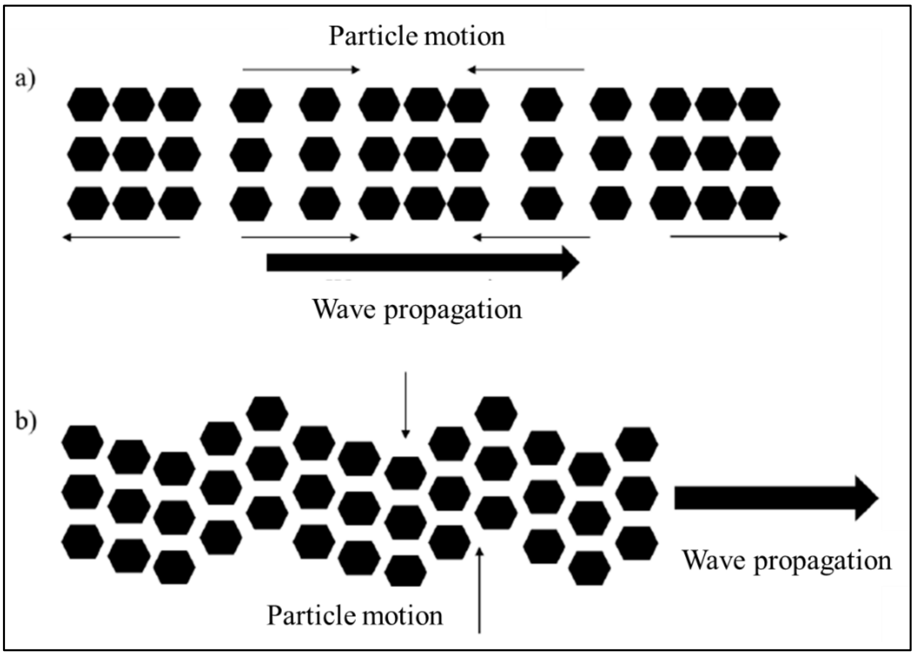

Figure 2.1 Particle movement; a) P-wave and b) S-wave (Burger et al., 2006)

The seismic wave velocity is influence by some factors caused by non-homogenous subsurface characteristics including temperature, mineral content, porosity, weathering, confining pressure, and fluid content (Schultheiss, 1982). The P- and S-waves' velocity is important in geotechnical engineering field which has a potential in terms of wave propagation velocity for material characterization such as density, shear strength and elastic coefficients of subsurface material. Relation between the P- and S-waves with geotechnical engineering parameters are described in Equation 2.1.

$$V_P = \sqrt{\frac{K+4\mu/3}{\rho}} \tag{2.1}$$

where;

V_P= P-wave velocity

K = Bulk modulus

μ = Shear modulus

ρ = Density

and,

$$V_S = \sqrt{\frac{\mu}{\rho}} \tag{2.2}$$

where;

V_S= S-wave velocity

μ = Shear modulus

ρ = Density

The S-wave cannot travel through liquid medium and is proven by Equation 2.2. Assuming the propagation medium is liquid, which means that the shear modulus, μ is equal to zero, the S-wave velocity, V_S is also zero which also means that no shear movement in liquid medium. Referring to Equation 2.1, the P-wave velocity decreases when passing through liquid. As a conclusion, the P- and S-waves velocity is effected by the density, ρ of subsurface medium and the wave velocity reduces when propagating through fresh rock to highly fractured rock and porous material. In accordance to Equation 2.1 and 2.2, a standard of typical seismic wave velocities for common subsurface material has been made as shown in Table 2.1 (Mavko, 2005)

2.3 Seismic signal receiver

There are two types of seismic signal receiver which is hydrophone and geophones. Hydrophone is a device for the detection of seismic energy in the form of water pressure changes during marine seismic acquisition (Figure 2.2). It measures pressure changes with the assistance of a piezoelectric material when the deformation generates a voltage (Marzetta et al., 1988). Hydrophone are mostly used in underwater to detect wave vibration and converting the acoustic energy into electrical energy.

Table 2.1 Standard velocity of common subsurface material (Mavko, 2005)

Type of formation	P-wave velocity (m/s)	S-wave velocity (m/s)
Vegetal soil	300 – 700	100 – 300
Dry sands	400 – 1200	100 – 500
Wet sands	1500 – 2000	400 – 600
Saturated shales and clays	1100 – 2500	200 – 800
Marls	2000 – 3000	750 – 1500
Saturated shale and sand sections	1500 – 2200	500 – 750
Porous and saturated sandstone	2000 – 3500	800 – 1800
Limestone	3500 – 6000	2000 – 3300
Chalk	2300 – 2600	1100 – 1300
Salt	4500 – 5500	2500 – 3100
Anhydrite	4000 – 5500	2500 – 3100
Dolomite	3500 – 6500	1900 – 3600
Granite	4500 – 6000	2500 – 3300
Water	1450 – 1500	-

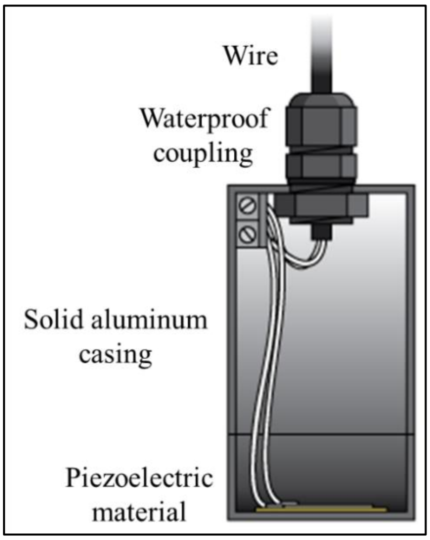

Figure 2.2 Hydrophone receiver mechanism (Zendehboudi and Bahadori, 2016)

However, geophone is used to receive seismic signal data acquiring on land. The device designed consists of magnet, surrounded by wrapped wire coil hanging on spring in the middle (Figure 2.3). When the seismic source applied, seismic wave will shake the magnet up and down but a mass of wired coil remain motionless creating an electrical voltage proportional to wave velocity. In certain geophones, the components are reversed; a magnetic core is connected to the spring and core is covered by a coil. A normal ground geophone was built with a plastic case, which usually has a spike at the bottom to anchor/penetrate firmly into the ground to perform a direct contact to the ground (Zhenlin and Guokun, 1986)

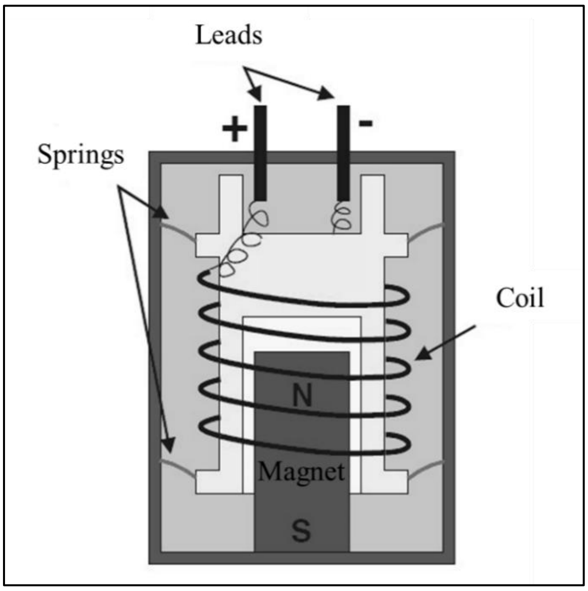

Figure 2.3 Geophone receiver mechanism (Zendehboudi and Bahadori, 2016)

2.4 Seismic downhole method

The common seismic methods applied for shallow application are seismic refraction and seismic downhole. Seismic refraction method is used for shallow subsurface to investigate the subsurface profile for engineering and environmental issues. There is a time requirement for an acoustic wave to travel through the ground and refracted to the ground surface and detected by receiver (geophone). Regarding on Snell's Law, wave propagation shall be subjected with an arrival time and geophones interval distance for analysis to interpret subsurface information (Fang and Chen, 2019).

The seismic downhole method is applied to measure a single place/spot of in-situ subsurface profile with high accuracy of the P- and S-wave velocity of soil/rock for each depth (Crice, 2002). It is considered to be less expensive and easier than cross-holes method, which requires more than one borehole. This method acquire data by placing the geophone/hydrophone inside borehole while the seismic source strikes on ground surface near to the borehole, and the seismic waves are received by geophone/hydrophone are transferred to seismograph for recording (Figure 2.4).

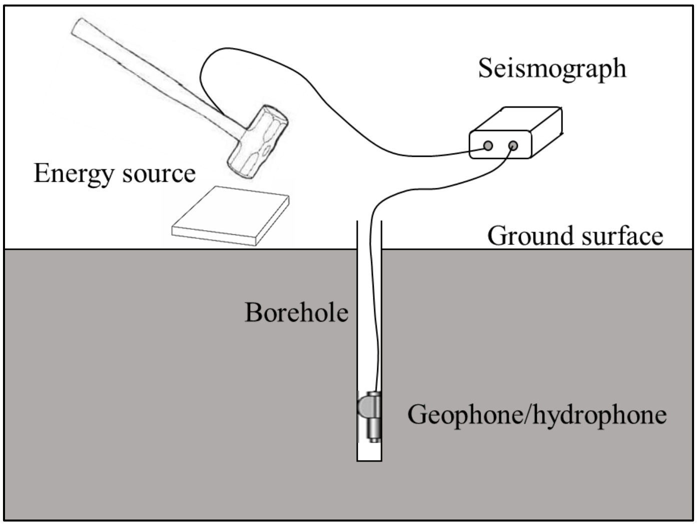

Figure 2.4 Illustration of seismic downhole acquisition (Crice, 2002)

The travel time of seismic waves passing through the ground surface and received by geophone/hydrophones is used to calculate the P- or S-wave velocity profile (Fang and Chen, 2019). The relevance of seismic downhole method is that the acquired seismic wave velocity data seem to be relevant with subsurface material where the seismic downhole method offers true velocity of subsurface material. Special software, such as SeisImager, Downhole GeoStru software, etc. is use to process seismic downhole information. The seismic downhole test information are interpreted by two prevalent techniques: direct and interval measurements (Kuo et al., 2017).

2.4.1 Direct measurement

Direct measurement technique is applied by assuming the travel time (*t*) of inclined path by correcting to the vertical path (t_c) using time correction as described in Equation 2.3. The velocity of each depth is calculated using Equation 2.4 using the difference of depth range between top and bottom, and dividing with a difference of corrected travel time (Kim et al., 2004).

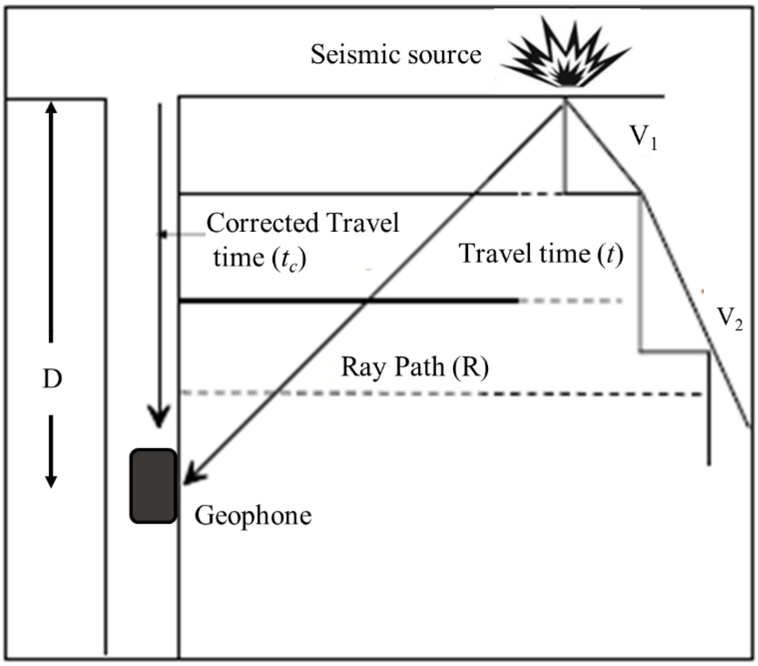

Figure 2.5 Mechanism of direct method (Kim et al., 2004)

$$t_c = D\,\frac{t}{R} \tag{2.3}$$

and,

$$V_d = \frac{\Delta D}{\Delta t_c} \tag{2.4}$$

where;

t_c = Corrected travel time

D = Depth

t = Travel time

R = Distance between seismic source to receiver

V_d = Interval velocity

2.4.2 Interval measurement

Figure 2.6 shows a schematic diagram of the interval measurement technique. This technique determines the interval wave velocity based on the difference of distance of direct wave between two geophones which is then divided by time difference (Equation 2.5). However, seismic velocities derived from the technique often differ significantly from the correct hypothetical values compared to direct measurement technique, where the difference is only at several meter at top surface and reducing the gap when reaching a greater depth (Kim et al., 2004).

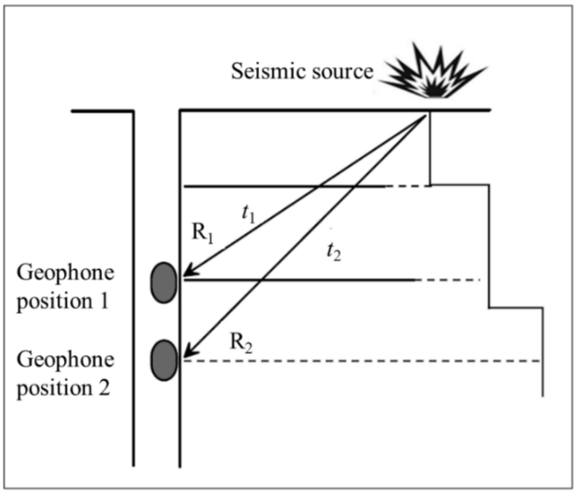

Figure 2.6 Mechanism of interval method (Kim et al., 2004)

$$V = \frac{R_2 - R_1}{t_2 - t_1} \tag{2.5}$$

where;

R_1 = Distance between seismic source to detector 1

R_2 = Distance between seismic source to detector 2

t_1 = Travel time at geophone 1

t_2 = Travel time at geophone 2

2.5 Geotechnical investigation

Geotechnical investigation is usually needed to collect and evaluate site conditions information to design and create the basis for a structure, such as a building, plant or bridge. However, information on properties of soil and rock gathered from geotechnical investigation can be correlated with geophysical data as an ancillary data to support the geophysical result which can be subjectively interpreted without real physical properties information. Mostly, wash boring and Cone Penetration Test (CPT) are commonly used to correlate with geophysical data which provide various information including Standard Penetration Test (SPT) value and soil behavior type. A new CPT technique has been introduced, called sCPT technique, where a geophone sensor is added to detect the S-wave signal, which can be correlated with geophysical seismic data including surface refraction or seismic downhole methods.

2.5.1 Wash boring method

The practical opportunity to obtain visual descriptions and index tests of the subsurface samples is a direct observation such as boring. The boring procedure is carried out on relatively un-cemented soil. Various boring methods usually performed at in-situ area include auger, wash boring, and light-percussion drilling. Auger technique is categorized as easy, light, versatile and suitable for soft to cohesive soils investigation (Yusoh et al. 2015). Wash boring is a combination of wash boring and rotary drilling technique, which performed to observe the encountered soil strata (Figure 2.7). Even though the wash boring is an old method, but it is well known as quick and easy technique obtaining soil subsurface information for all types of soils except boulders and rock (Singh et al., 2015).

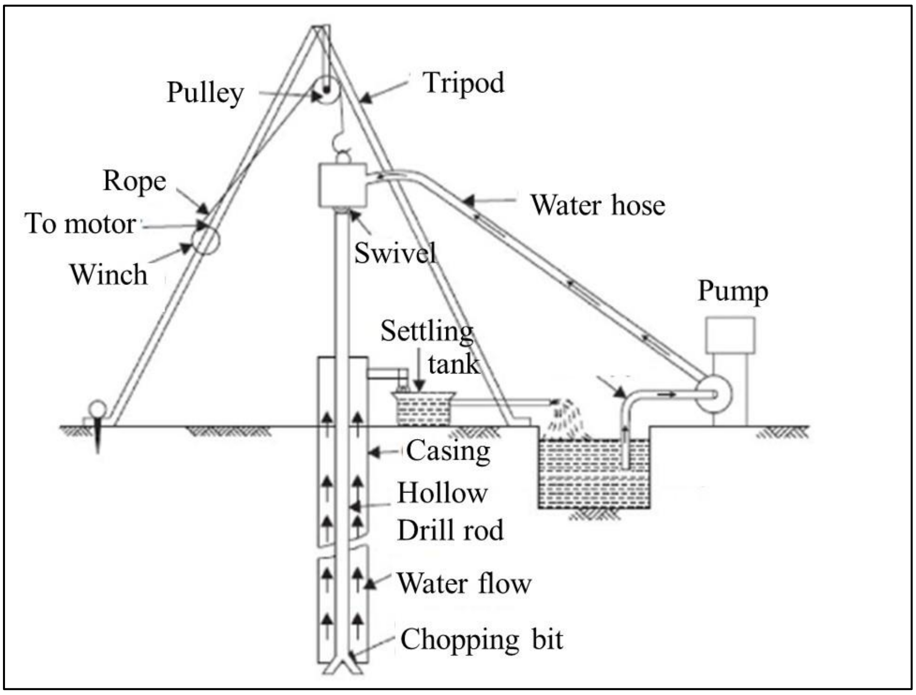

Figure 2.7 Illustration of wash boring method (Hvorslev, 1948)

2.5.2 Seismic Cone Penetration Test (sCPT)

A CPT has become globally widely used and is a reliable technique to determine geotechnical properties of soil including soil behavior type. At some places, the data obtained using CPT is used to acquire information whether the subsurface layers are likely to liquefy under different levels of earthquake shaking. Besides that, the CPT sensors can be equipped with geophone sensor which used to obtain the S-wave signal, and this technique is called Seismic Cone Penetration Test (sCPT) (Figure 2.8). The sCPT is a technique for calculating the soil's small strain shear modulus by evaluating the velocity of the S-wave through the subsurface.

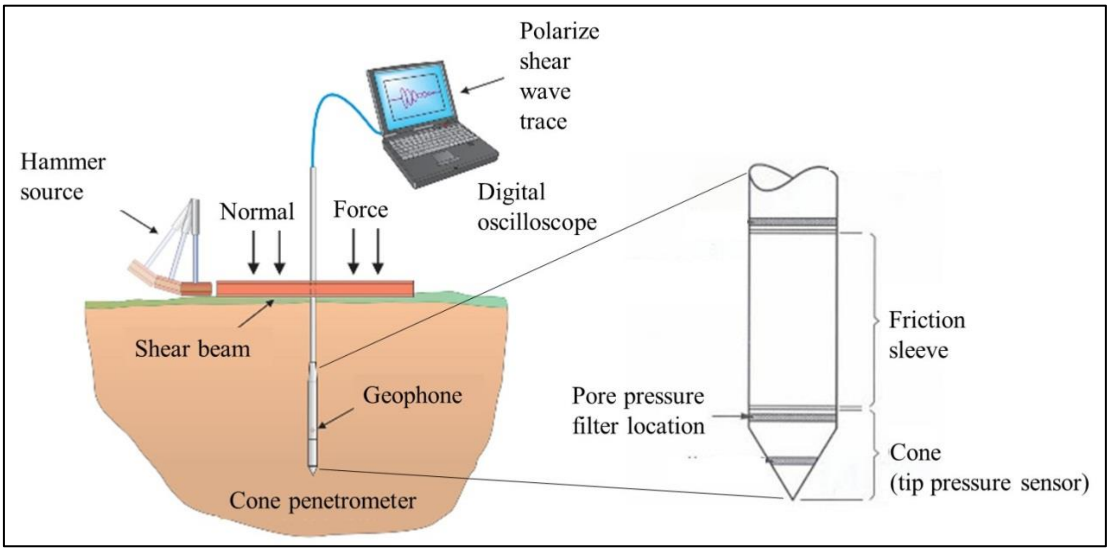

Figure 2.8 Mechanism of CPT and sCPT implementation (Lunne et al., 2002)

2.6 Previous study

Numerous researchers have published their works on geophysical method especially in seismic study of P- and S-wave characteristics. Seismic refraction and downhole methods were implemented worldwide including in developing an enhancement from the conventional method by improving the settings, handling technique and also manufacturing an advance equipment.

Moffat et al. (2016) has conducted a test to compare the mean shear wave velocity (V_S) using Multichannel Analysis of Surface Waves (MASW) and seismic downhole for the depth of <30 m from ground surface. The MASW data are acquired with available information from site investigation and downhole tests, using a total of 12 active geophones with nominal frequency of 4.5 Hz. The shear wave velocity, V_S was extracted from MASW result obtained from inverted dispersion curves. The downhole test was conducted at 5 locations within the study area and obtained direct shear wave velocity value of <30 m in depth. The V_S values identified from the MASW and downhole were correlated and the average velocity of each station was calculated.

The research outcome identified that the V_S values obtained from MASW and downhole seismic methods are almost similar up to 30 m depth which conclude that both method provide the same seismic classification of the soil.

Maheswari et al. (2010) explained that the S-wave velocities (V_S) was used in representing the stiffness of soil layers for their work at Chennai, India, where the V_S value was used as input for geotechnical engineering parameters to interpret the soil shear strength. Estimating the Vs at study area is recommended in every site investigation site to reduce inaccurate of construction design. Thus, a reliable correlation between V_S and standard penetration test blows counts (SPT-N) are applied to improve the interpretation of subsurface shear strength. Empirical correction was developed between V_S and SPT-N values with different types of soils around Chennai city which consist of different soil conditions. The V_S data was acquired using Multi-channel Analysis of Surface Waves (MASW) method at all available existing SPT-N data. Result indicates a good correlation between V_S and SPT-N as shown in Figure 2.9

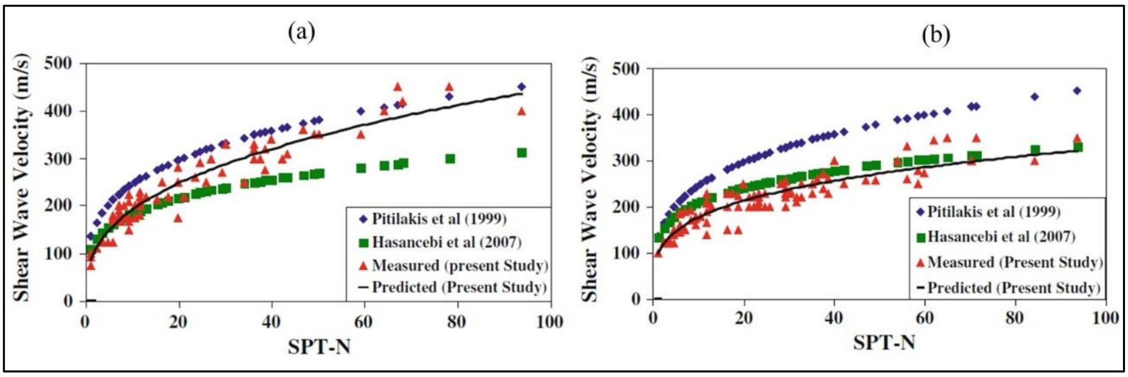

Figure 2.9 Correlation between measured, previous and predicted V_S with N_{60}; (a) clay and (b) sand material (Maheswari et al., 2010)

Signanini and Torrese (2004) has applied a high resolution shear wave seismic method to investigate a geotechnical problem. Seismic refraction and seismic downhole methods were applied in allowing the work to cover a large area of study.

The geophysical method has been utilized to clarify the soil subsurface properties and characterize lithology profiles. Study results show that seismic downhole is possible to resolve geotechnical issue. For slope failure case study, it was found that seismic downhole study is a useful method in recognizing a hidden layer which the lower velocity was hidden under the high velocity of subsurface. This issue will cause high risk in sliding of slope surface due to unstable subsurface related to loose material which was hidden under the ground surface. The study has revealed that the limitations of velocity inversion for seismic refraction is able to overcome the ambiguity and also obtain high resolution image of subsurface with hidden layer of lower seismic velocity surface, due to small variations in the rock's seismic rigidity as shown in Figure 2.10.

The seismic refraction and seismic downhole have their advantage and disadvantage that has been discussed by Tabakov and Baranov (2008). They have summarized that the seismic refraction method is not producing true velocity pseudo section and signature because it comes from interpolation processing and also produces low resolution.

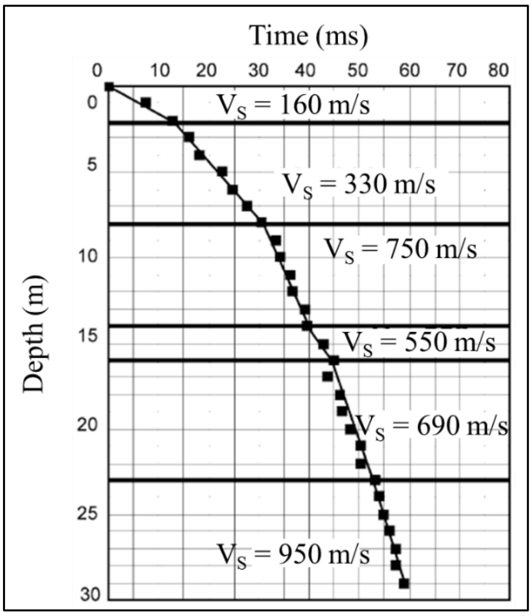

Figure 2.10 S-wave travel time and velocity for seismic (Signanini and Torrese, 2004)

On the other hand, the measurements of the seismic downhole provide the user with true velocity with high resolution result, but it is quickly losing efficiency when it is close to ground surface. Mok (1987) has used crosshole and seismic downhole methods as tools to determine the variation of elastic moduli with different depths. These methods commonly used in engineering field as a dependable means to determine in-situ compression and shear strength parameters. However, crosshole is an expensive method compared to seismic downhole since the former requires a minimum of two monitoring boreholes to conduct the crosshole survey and seismic source need to be blown inside the hole which require a proper equipment to produce the compression and shear wave but it is easier to evaluate the seismic results (Figure 2.11). Nevertheless, if a soft layer is sandwiched between the hard layers, it is often difficult to identify the first arrival of the direct shear wave in crosshole records. Theoretical seismogram was produced to solve this problem based on ray theory and also from Interference of refracted and reflected waves of the direct shear wave. This study showed that the crosshole seismic is very accurate and very detailed in profiling subsurface seismic velocity.

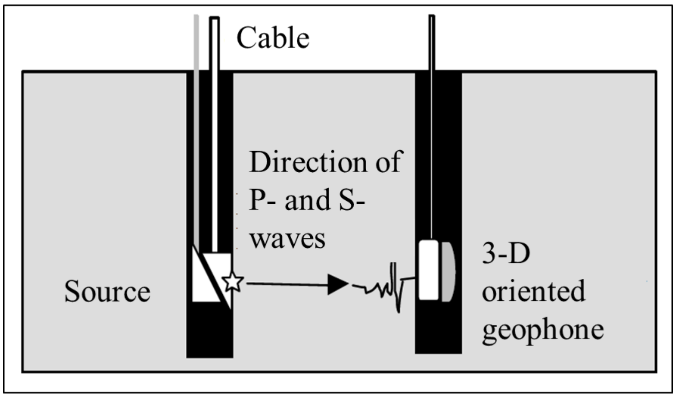

Figure 2.11 Crosshole seismic test with two boreholes (Mok, 1987)

Suspension logging also another type of borehole seismic technique which was conducted by Nigbor and Imai (1994). This technology is the latest addition to the range of forage methods that have been available over the past two decades. Figure 2.12 shows the suspension logging system schematically and includes a tool that contains an energy source, isolation pipes and two biaxial receiver. The source of energy is made of solenoid which activates the tool case by a small-hammer, causing the fluid - filled borehole to produce an impulsive water pressure wave. The wave transfers energy to the borehole wall that produces P- and S- waves that propagate through the geological formation. The distance between the energy source and the nearby receiver is about 2 to 3 m while the receiver distance is approximately 1 m. The tool is about 7 m long and the center point between both receivers is about 3 to 4 m above the bottom. Figure 2.13 shows the result of Suspension logging acquired at Golden Gate Bridge. The result shows a hidden layer at 240 to 270 ft depth where the velocity become 6300 ft/s while obtaining at depth of 180 to 250 ft theS-wave velocity of 7400 ft/s.

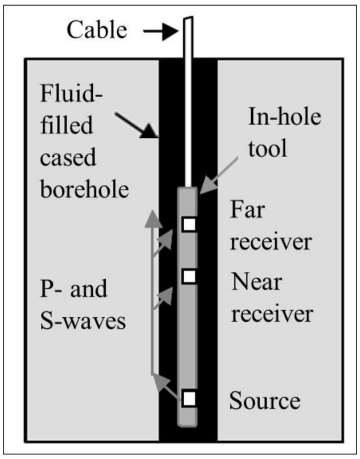

Figure 2.12 Schematic diagram of suspension logging (Nigbor and Imai, 1994)

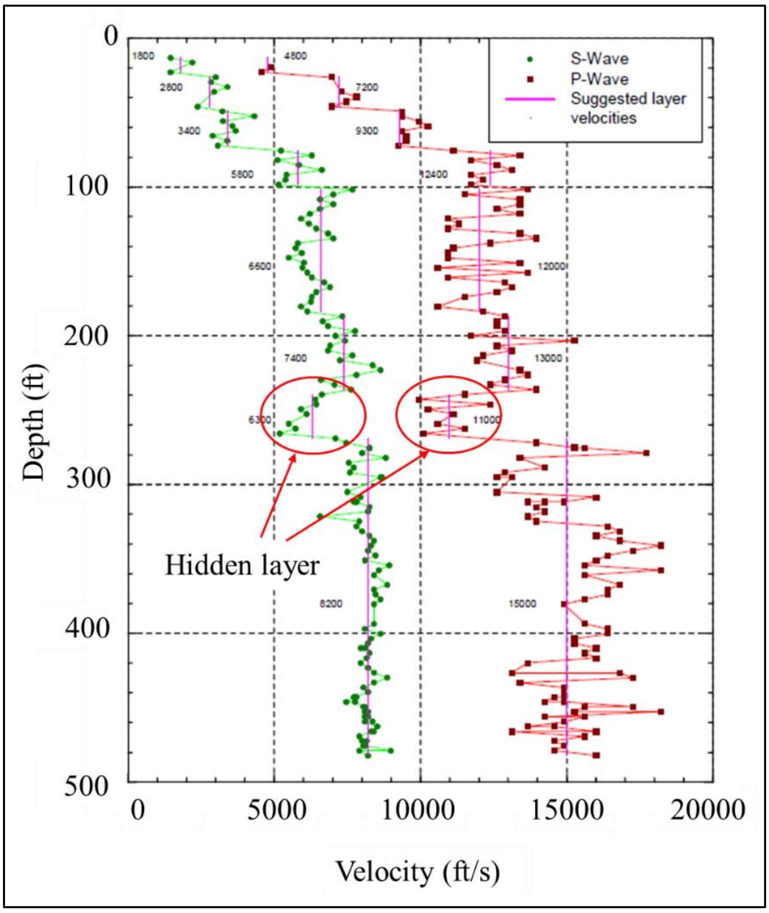

Figure 2.13 The P- and S-wave velocity using suspension logging acquire at Golden Gate Bridge (Nigbor and Imai, 1994)

Geophysical investigation conducted by Thomas et al. (2016) uses shear wave seismic downhole to study geotechnical site characterization. For subsurface investigation, high-resolution of subsurface profile is an important exploration in development sites which involves designing a mega structure buildings. In-situ measurement of primary wave (P-wave) was measured to predict the strength and density of subsurface which is directly related to lithological structure. Nevertheless, utilization the P-wave in deriving geotechnical parameters is highly influenced by groundwater table due to its characteristics. In order to solve the problem, the development of geophone for shear wave velocity (V_S) of subsurface detection was applied and it has become widely used in geotechnical engineering study. This study has tested a new developed equipment by measuring the P- and S-waves velocity using