THE CORRELATION OF SEISMIC P- AND S-WAVES FROM REFRACTION AND DOWNHOLE METHODS FOR SOIL PROPERTIES VERIFICATION

SABRIAN TRI ANDA

UNIVERSITI SAINS MALAYSIA

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THE CORRELATION OF SEISMIC P- AND S-WAVES FROM REFRACTION AND DOWNHOLE METHODS FOR SOIL PROPERTIES VERIFICATION

by

SABRIAN TRI ANDA

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LIST OF SYMBOLS

ρ	Density
μ	Shear modulus
<	Less than
σ_p	Poisson's ratio
D	Depth
E	Young's modulus
G	Shear modulus
h	Thickness
Hz	Hertz
K	Bulk modulus
m	Meter
m/s	Unit meter per second
>	More than
R	Distance between source to detector
R	Coefficient of correlation
R^2	Coefficient of determination
t	Time
t_i	Intercept time
t_c	Corrected travel time
V	Velocity
Vp	Compressional wave velocity
Vs	Shear wave velocity
X_{co}	Crossover distance
θ_i	Incidence angle
θ_r	Refracted angle
θ_{ic}	Incidence critical angle

LIST OF ABBREVIATIONS

BH	Borehole
CGAR	Centre for Global Archaeological Research (CGAR)
CPT	Cone Penetration Test
CPTU	Piezocone test
GPS	Global Positioning System
L	Seismic survey line at USM, Pulau Pinang
MASW	Multichannel Analysis of Surface Waves
P-wave	Primary wave
SASW	Spectral analysis of surface wave
SB	Seismic survey line at Sungai Batu
SCPTU	Seismic piezocone
SH	Secondary Horizontal
SP	Shot point
SPT	Standard Penetration Test
SRT	Seismic Refraction Tomography
SV	Secondary Vertical
S-wave	Secondary wave
USM	Universiti Sains Malaysia

KORELASI GELOMBANG SEISMIK -P DAN -S DARIPADA KAEDAH PEMBIASAN DAN LUBANG DASAR UNTUK PENENTUSAHAN SIFAT-SIFAT TANAH

ABSTRAK

Dalam mengenali kerumitan mendapatkan halaju in-situ, korelasi empirikal telah diterbitkan dalam kajian ini untuk menentukan halaju in-situ dengan menggunakan seismik pembiasan. Begitu juga, terdapat beberapa kesukaran dalam mendapatkan data gelombang–S seismik pembiasan termasuk pemprosesannya. Atas sebab ini, korelasi empirikal telah dibangunkan antara halaju gelombang mampatan (Vp) dan gelombang ricih (Vs) untuk menetukan Vs daripada Vp. Tambahan pula, korelasi antara kaedah geoteknik dan geofizik telah dibuat untuk meningkatkan interpretasi data dan menentusahkan sifat-sifat tanah. Kajian telah dijalankan dengan menggunakan dua kaedah seismik (pembiasan dan lubang dasar) di dua kawasan berbeza dengan ketetapan geologi berbeza. Tapak pertama terletak di Kampus USM, Pulau Pinang yang dilapisi oleh batuan granit, sementara tapak kedua terletak di Sungai Batu, Kedah yang dilapisi oleh batuan sedimen. Berdasarkan korelasi empirikal yang telah dibangunkan dalam kajian ini, didapati bahawa data lubang dasar adalah berkait secara linear dengan data pembiasan dengan nilai-nilai R^2 adalah, 0.62 – 0.66. Perbezaan antara kaedah seismik pembiasan dan lubang dasar juga telah dikira dan mendapati secara amnya <19%. Informasi ini membawa kepada kesimpulan bahawa data seismik pembiasan boleh diguna pakai sebagai alternatif untuk menetukan data lubang dasar kerana cepat, kurang musnah dan jimat kos. Kajian ini juga telah mendapati bahawa Vs adalah berkait secara linear dengan Vp, dengan nilai-nilai R^2, 0.52 – 0.79. Nilai-nilai tersebut menunjukkan bahawa sehingga 52 – 79%

variasi dalam Vs adalah diterangkan oleh Vp. Baki peratusan dalam kevariasian boleh diterangkan oleh factor-faktor lain yang hanya tipikal kepada Vs, seperti kandungan cecair subpermukaan. Akhir sekali, interpretasi keputusan yang telah diperoleh menunjukkan bahawa tiga dan dua lapisan subpermukaan telah ditentukan berdasarkan halaju, jenis tanah dan pengkelasan nilai-N di Kampus USM dan tapak Sungai Batu.

THE CORRELATION OF SEISMIC P- AND S-WAVES FROM REFRACTION AND DOWNHOLE METHODS FOR SOIL PROPERTIES VERIFICATION

ABSTRACT

In recognition of the complexities in obtaining in-situ velocity, empirical correlation was established in this study to estimate the in-situ velocities by using seismic refraction. Similarly, there are several difficulties in obtaining seismic refraction S-wave data including its processing. For this reason, empirical correlation was also developed between compressional waves (Vp) and shear waves (Vs) velocities in order to estimate the Vs based on Vp. Furthermore, the correlation between geotechnical and geophysical methods was made to enhance data interpretation and to verify the soil properties. The study was carried out using two seismic methods (refraction and downhole) in two different areas with different geological setting. The first site located at USM Campus, Pulau Pinang which is underlain by granitic rocks, while the second site located at Sungai Batu, Kedah which is underlain by sedimentary rocks. Based on the empirical correlation established in this study, it is found that the downhole data is linearly related with refraction data with R^2 values of 0.62 – 0.66. The different between seismic refraction and downhole method were also calculated and found to be generally <19%. This information led to the conclusion that the seismic refraction data can be used as an alternative way to estimate the downhole data for it is fast, less-invasive, and less cost. The study has also found that Vs is linearly related to Vp with R^2 value of 0.52 – 0.79. The values indicated that up to 52 – 79% of variations in Vs are explained by Vp. The remaining percentage in variability could be described by other factors typical to Vs only; such as fluid content of subsurface. Finally, interpretation of the data obtained showed that three and two layers of subsurface was determined based on velocity, soil type and N-value classification at USM Campus and Sungai Batu site respectively.

CHAPTER 1

INTRODUCTION

1.0 Preface

Nowadays, implementation of geophysical methods for engineering and environmental application has become one of prominent disciplines since these methods can be used to achieve the need for advanced characterization in geotechnical works (Stokoe & Santamarina, 2000). The utilization of geophysical methods for geotechnical work is usually conducted for shallow depths of investigation; typically, less than several hundred meters, but can be extended to several thousand meters in some instances. According to Anderson and Croxton (2008), geophysical surveys for geotechnical engineering purposes are performed on top of the ground surface, within boreholes and in water and air media. Several applications of geophysical methods for geotechnical engineering and environment include: rippability estimation for excavation, soil and rock characterization (soil and rock type, bedrock depth, layer boundaries, fractures, weak zone, clay type and water table), detecting cavities, sinkholes and abandoned mines, bridge/dam foundation analysis, in-situ material testing, mapping and locating utilities, seismic hazard, etc. Several geophysical methods that are commonly used for geotechnical purposes include seismic method (reflection/refraction), multi analysis of surface waves (MASW), downhole seismic, cross-hole seismic, ground penetrating radar (GPR), electromagnetic (EM), electrical methods, gravity and magnetic.

This study will focus on the use of seismic refraction method, since rock and soil properties are closely related to wave velocity and mechanical properties of rock and soil such as Bulk modulus, Shear modulus, Young modulus and Poisson's ratio (Soupios, 2005). The seismic wave velocity also depends on soil and rock type; sedimentary, granitic or metamorphic. The study was conducted at a granitic area in USM, Pulau Pinang and a sedimentary area in Sungai Batu, Kedah using seismic refraction and downhole methods by applying P- and S-waves.

1.1 Problem statements

Soil profile classifications are commonly determined using field measurements such as soil blow counts, unconfined compressive strength or in-situ shear wave velocity. According to Williams et al. (2003), engineers still need alternative ways to measure these parameters in a non-invasive and less expensive manner compared to traditional borehole methods. Based on this, shear wave velocity can be one of the easiest parameters to be measured using non-invasive methods such as seismic refraction, reflection, MASW and spectral analysis of surface waves (SASW). However, there are some limitations on depth penetration due to constraints in availability of space and the restrictions of energy source. This notwithstanding, the aforementioned geophysical methods are still considered fast, less costly, less invasive and can be extended within the area of investigation. Another problem associated with this method is the difficulty in acquiring surface seismic refraction to generate mostly the shear waves and the ambiguities involved in its processing.

Therefore, this research will attempt to find an alternative way of determining in-situ velocity using the correlation of seismic refraction and downhole methods, and the correlation between shear wave and compressional wave velocities in order to determine shear wave velocities using compressional wave velocities. Furthermore, the correlation between geotechnical and geophysical methods were made to enhance the data interpretation and verify the soil properties.

1.2 Research objectives

The objectives of this study are:

i. To characterize the seismic velocities with geotechnical parameter (N-value).
ii. To correlate the velocities of compressional (P) and shear (S) waves.
iii. To correlate of velocities resulted from seismic downhole and refraction method.
iv. To verify the equation which established from empirical correlation between seismic downhole and refraction velocities.

1.3 Scope of study

The investigations were done by carrying out the seismic refraction and seismic downhole to delineate subsurface at two different geologic areas; residual soil (USM campus, Pulau Pinang) and sedimentary (Sungai Batu, Kedah). The seismic refraction and downhole method (P- and S-wave) were carried out across an existing borehole to achieve the objectives drawn. There are some limitations in this research such as:

i. The correlation of velocities resulted by seismic refraction and downhole methods, and the correlation of velocities based on wave applied are made by considering the velocities only. Other elastic parameters were not investigated.

ii. The shear wave velocities (Vs) are expressed in terms of compressional wave velocities (Vp) models.
iii. The correlations are made based on empirical approach.
iv. Furthermore, the correlation with the geotechnical parameters (SPT-N value) are made to enhance data interpretation.

1.4 Thesis outline

The arrangement of this thesis consists the following;

Chapter 1 discussed the introduction of the thesis in which the research background, problem statements, scope, and the objectives of the study are elaborated.

Chapter 2 is the literature review; which consists of previous works related to seismic method. Most of the previous works described the comparison of velocities resulted from borehole and surface seismic, the relation between compressional and shear wave velocities and the correlation of geophysical method with soil properties. Basic theory of seismic refraction, downhole and boring method are also described in this chapter.

Chapter 3 discussed the methodology applied in this study. This chapter are including the principle of seismic refraction and downhole data acquisition to data processing. Method for data analysis are also briefly discussed in this chapter.

Result and discussion regarding the seismic refraction, downhole measurement and soil properties in the study area are presented in chapter 4. Data analysis including empirical correlation are also briefly discussed in this chapter.

In chapter 5, the conclusions of objectives achieved are discussed and some suggestions and recommendations for further study are also included.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The application of geophysical methods for engineering and environmental applications were aimed to improve the quality of site characterization by increasing the data resolution of the study area. In last few decades, the application of geophysical methods has been used to determine engineering properties, such as elastic moduli, electrical resistivity, magnetic and density which are in turn used to assist and suggest the solution for most engineering and environmental problems. Geophysical methods are also used for utility detection such as buried tanks and pipe, contaminant plumes, and landfill boundaries characterization (Griffin, 1995). The utilization of seismic method is favorable in determining an oil-bearing formation and now has been used increasingly for engineering and environmental application (Bery, 2013). It is recommended to conduct the seismic methods in the first stage of geotechnical site characterization. It is better to do so before drilling and excavation activities with the aim to detect the critical zone for more detailed invasive follow-up investigation, such as boreholes. Generally, the seismic method is conducted by applying seismic waves (body or surface waves) which are generated from a seismic source such as sledgehammer, weight drop or explosive. This method can be categorized into two types which are surface and borehole (downhole) seismic methods. Basically, the rule is the same for both methods except the surface seismic method utilizes source and detectors located on the ground surface while borehole seismic method uses source located on the ground surface and detectors located inside the well or borehole.

This chapter discussed the basic theory of seismic refraction, downhole and geotechnical method including the several works related to; the correlation between seismic refraction and downhole method, correlation of compressional and shear wave (P- and S-wave) velocities, and the correlation of seismic study with geotechnical.

2.1 Theory of seismic waves

In seismic exploration, a controlled source is applied to generate seismic waves and the waves will propagate through the subsurface. At the geological boundaries within the subsurface, the seismic waves will return to the surface after being refracted or reflected. Seismic surveying was first conducted in early 1920s; the method itself is derived from the earthquake seismology. The earthquake seismology presents information of subsurface on a large scale but in fact the resolution is less than presented. Similarly, seismic exploration can provide a high resolution and detail of subsurface geology but in a smaller scale.

There are two types of waves which travel through the subsurface based on the medium traveled. The first is called body waves, which is the waves that travel through the interior of the Earth (Telford et al., 1990). Based on particle vibration and wave propagation, body waves can be divided into two types of waves (Figure 2.1). The first is P-wave or known as primary wave where the particles vibrate along the propagation of the wave. The longitudinal waves, called primary waves have the greatest velocity and on the illustrated arrival waves, the P-wave also shows up first.

The other wave is S-wave, known as secondary or shear waves because the wave has less velocity than the P-wave and appears after the P-wave. The particles of the waves move transversely or perpendicularly to the propagation of wave. S-wave movement is distinguished into two parts; horizontally and vertically on ground surface and are called SH and SV respectively (Burger et al., 2006).

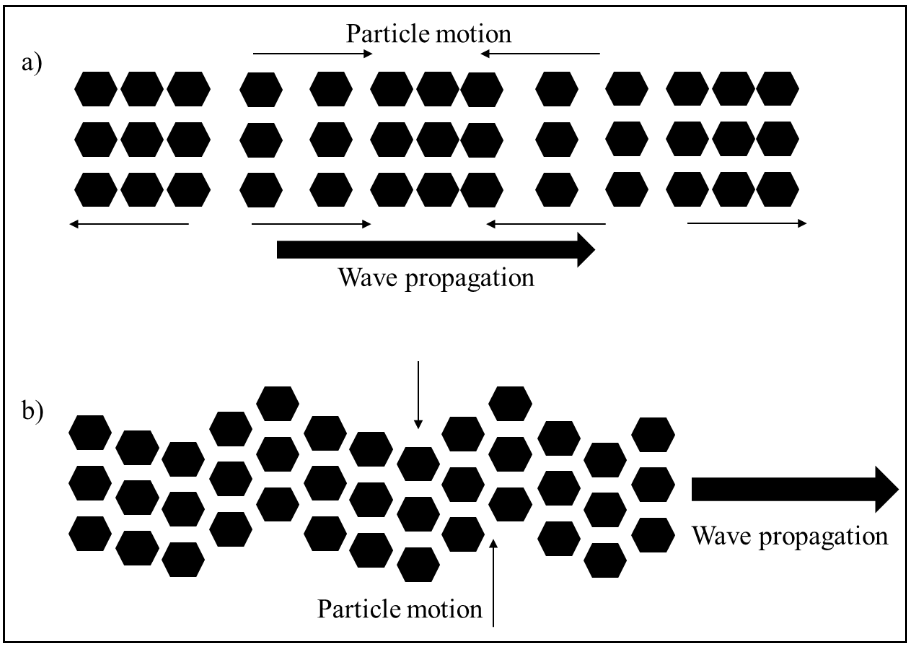

Figure 2.1: Body waves particles and waves propagation; a) P-wave, and b) S-wave (Sharma, 1997)

Basically, P- and S-waves velocity are described regarding the elastic coefficients and density of a subsurface material. Several factors that influence the actual seismic velocity include temperature, mineral content, porosity, weathering, confining pressure, and fluid content (Ismail, 2015). The P- and S-waves velocities are described by Equation 2.1 and 2.2 respectively. In view of the fact that elastic moduli are positive, it is believed that P-wave velocity (Vp) are always greater than S-wave velocity (Vs).

$$V_p = \sqrt{\frac{K + 4\mu/3}{\rho}} \qquad (2.1)$$

where;

K = Bulk modulus
μ = Shear modulus
ρ = Density

and,

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

where;

μ = Shear modulus
ρ = Density

Following Equation 2.1, when $\mu=0$ (liquid medium), the P-wave velocity decelerates. It is the evident that P-wave is reduced when traveling through the highly fractured and porous rocks. Meanwhile, since the shear moduli, $\mu=0$ for liquids, the velocity of S-wave becomes zero or simply said that shear wave cannot travel through liquid medium. Table 2.1 shows the typical velocities of common materials.

Table 2.1: Common velocity of materials (Bourbie et al., 1987)

Type of formation	P-wave velocity	S-wave velocity
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	-

While the body waves travel through the elastic medium of the Earth, there is another type of wave that only travels along the free surface of an elastic medium or through an interface between two mediums, called surface waves. Surface waves appear after the body waves. There are two types of surface waves; Rayleigh and Love waves (Figure 2.2).

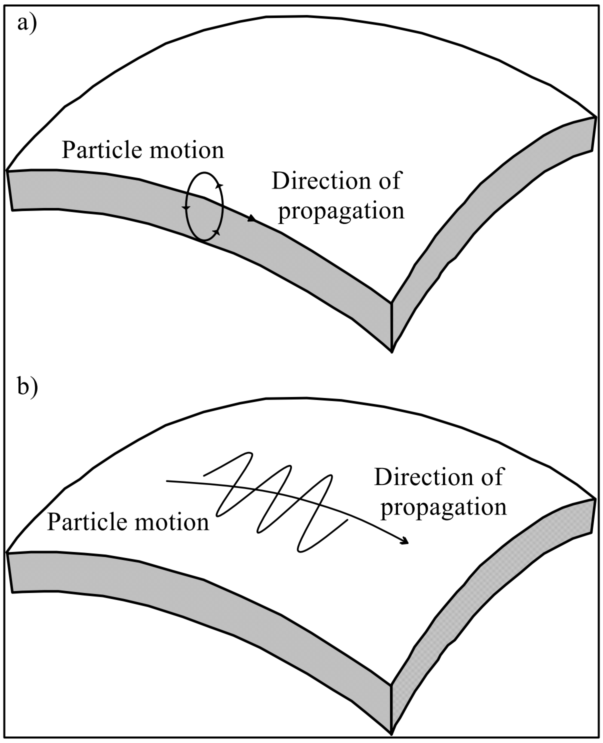

Figure 2.2: Surface waves particles motion and wave propagation; a) Rayleigh waves and b) Love waves (Sharma, 1997)

Rayleigh wave is the most important surface wave that is used in the exploration of seismology (ground roll). The wave is a combination of longitudinal and transverse movements and have certain phase relation to each other. The Rayleigh wave velocity is contingent with the elastic constant near the surface and the velocity is always less than the S-wave. In several investigations, the velocity of Rayleigh wave is used to estimate the S-wave velocity.

Love wave appears when the surface layer with lower velocity overlies the medium with greater velocity or when in non-uniform medium. Love wave consists of transverse motion of particles that move parallel to the surface of the ground. Love wave is not important in common seismic exploration since it cannot be significantly generated in seismic field work. The velocity of Love wave is in-between the S-wave velocity at the surface and at the deeper layer.

2.1.1 Propagation of seismic waves

Christian Huygens, a Dutch mathematician, physicist, and astronomer, generated a formula when he tried to develop the wave theory of light. The principle mentions that all the points on wave front can be a source to generate spherical secondary wavelets. After a particular time *t*, the new spot of the wave front is the surface of tangency to these wavelets. Figure 2.3 shows the time, t_1 has been applied using this principle and the wave front at t_2 can be constructed. Assuming that the velocity of wave that travels through the medium is constant, the elapsed time, Δt can be estimated and subsequently the secondary wavelets can be calculated.

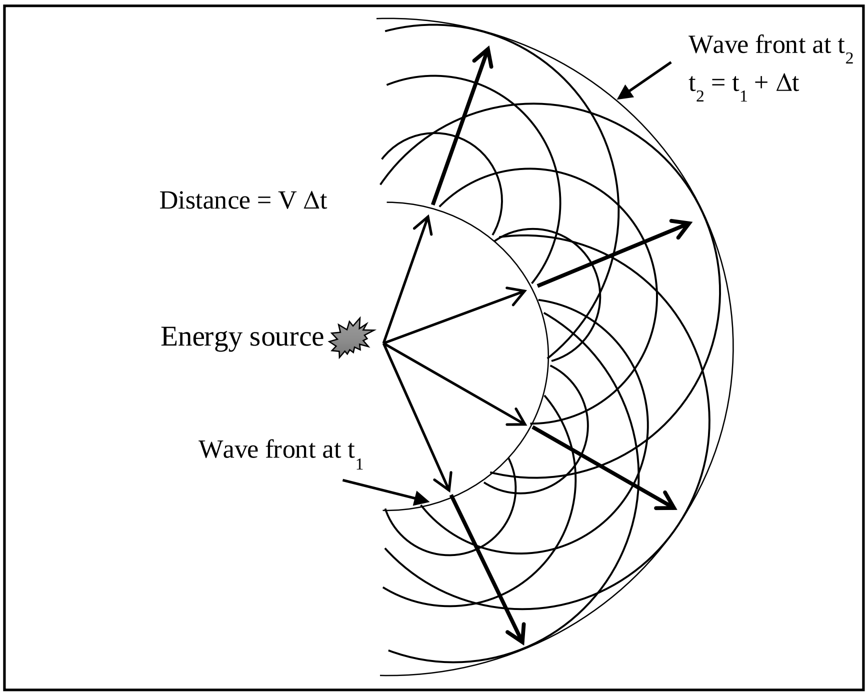

Figure 2.3: Determining the position of t_2 after an elapsed time Δt using Huygens's principle (Burger et al., 2006)

In order to construe the subsurface relationship regarding the refraction and reflection of seismic waves, Snell's Law is used as the basic principle. The relation of angle of incidence and angle of refraction is used in Snell's Law (Equation 2.3).

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{V_1}{V_2} \qquad (2.3)$$

where;

θ_i = Incidence angle

θ_r = Refracted angle

V_1 = Velocity of first layer

V_2 = Velocity of second layer

To maintain the ratios of Snell's Law, as angle of incidence increase, the sine value of the refraction angle should be increased. There is a special case when the angle of incidence will be such that sin $\theta_i = V_1/V_2$, which requires that the sine of the angle of refraction is 1.0 at which the angle is 90^o. In physical terms, the ratios of Snell's Law mean that the angle of refraction increases as the angle of incidence increase until rays are refracted parallel to the interface between the two materials. If the incidence rises outside the unique case, then no refraction event happens, and the ray is completely reflected.

2.2 Seismic refraction method

Seismic method is one of the most substantial geophysical method, and is regarded as such due to the high accuracy, high resolution, and great penetration. The exploration of seismic method is a subset of earthquake seismology. Generally, seismic refraction method is widely used in petroleum exploration since 1920s. Presently, as seismic methods are improving, and the equipment are upgraded, the seismic refraction method has been replaced by seismic reflection method for oil exploration. Nevertheless, the seismic refraction method is still being used for shallow subsurface investigation in engineering and environmental study to locate bedrock for building construction, highways and bridge (Burger et al., 2006).

Seismic refraction technique is a measurement of time needed by an acoustics wave to travel through the subsurface and refracted to the detector (geophones) which is planted on top of the ground surface. Snell's Laws regarding propagation of waves is applied using the arrival times and geophones distance and is required to calculate the subsurface information for further interpretation (Haeni, 1988). Generally, the application of seismic refraction for study of the ground subsurface in engineering and environmental is classified into 2 – 3-layer cases.

2.2.1 Homogeneous subsurface

Throughout the homogeneous subsurface, the energy source creates hemispherical wave front that passes throughout the geophones with a constant spacing which records the ground displacements due to this wave. Geophones spacing and the shot offset (distance from shot point to the first geophone) are known so that the time-distance graph can be plotted (Figure 2.4). The velocity of the wave is constant and is displayed in a straight line due to the homogeneous medium.

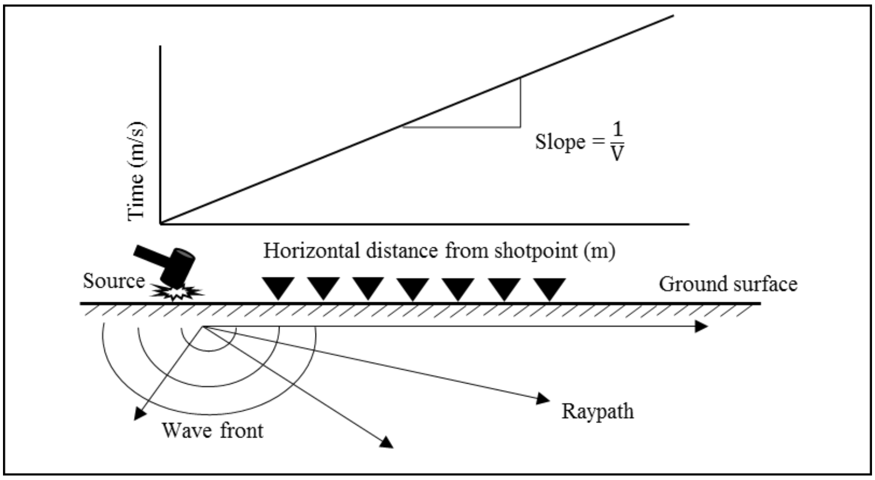

Figure 2.4: Ray paths in homogeneous medium without discontinuity with time-distance graph (Burger et al., 2006)

A straight-line equation is generated from the time-distance graph (Equation 2.4).

$$t = \frac{x}{V_1} \tag{2.4}$$

where;

x = Distance from shot-point to receiver (m)
V_1 = Velocity of first layer (m/s)

The velocity is determined using the equation for homogeneous medium since the distance and time are known. The first derivative of the equation with respect to distance (x) describes the slope of the line (Equation 2.5 – 2.6).

$$\frac{dt}{dx} = \frac{1}{V_1} = \text{Slope} \tag{2.5}$$

Therefore;

$$V_1 = \frac{1}{\text{slope}} \tag{2.6}$$

2.2.2 Two-layer case

In fact, subsurface mostly is not homogeneous and have various interfaces. A ray traveling in two-layer mediums (one interface) produces refraction, reflection, and diffraction of wave. Figure 2.5 shows that a refraction occurs even in a two-layer medium. Refraction wave generated by a source *E* travels at velocity V_1 and hits the interface between two mediums at a different velocity, V_2. At critical angle θ_{ic}, the ray strikes the interface and is parallelly refracted to the interface and travels at velocity of V_2. The ray returns to the surface and is recorded by geophone *G*. Velocity of the two different mediums (V_1 and V_2) and thickness of the layer are generated based on time-distance graph (Figure 2.6).

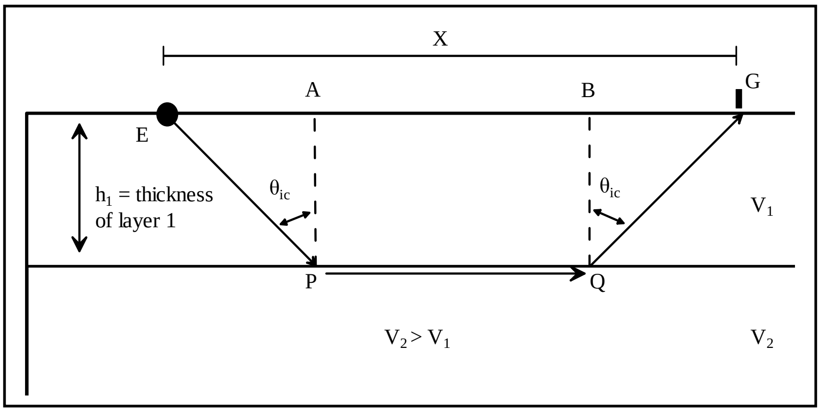

Figure 2.5: Refracted ray path for a single subsurface interface (Burger et al., 2006)

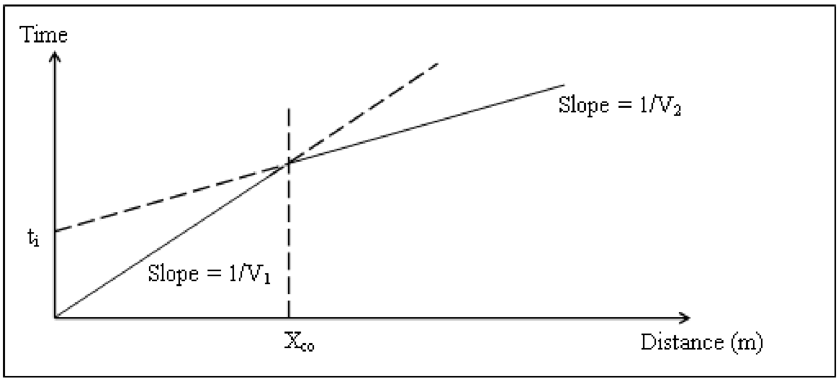

Figure 2.6: Arrival time curve for single subsurface interface (Burger et al., 2006)

The total travel time is described based on Equations 2.7 – 2.13.

$$\text{time} = \frac{EP}{V_1} + \frac{PQ}{V_2} + \frac{QG}{V_1} \tag{2.7}$$

$$\cos\theta_{ic} = \frac{h_1}{EP} \tag{2.8}$$

$$EP = QG = \frac{h_1}{\cos\theta_{ic}} \tag{2.9}$$

$$EA = BG = h_1 \tan\theta_{ic} \tag{2.10}$$

$$PQ = x - 2h_1 \tan\theta_{ic} \tag{2.11}$$

Therefore,

$$\text{time} = \frac{h_1}{V_1\cos\theta_{ic}} + \frac{x - 2h_1\tan\theta_{ic}}{V_2} + \frac{h_1}{V_1\cos\theta_{ic}} \tag{2.12}$$

Equation 2.12 is simplified to Equation 2.13

$$\text{time} = \frac{x}{V_2} + \frac{2h_1\sqrt{(V_2)^2 - (V_1)^2}}{V_1 V_2} \tag{2.13}$$

where;

EP = Distance between points E and P
PQ = Distance between points P and Q
QG = Distance between points Q and G
V_1 = Velocity of first layer (m/s)
V_2 = Velocity of second layer (m/s)
h_1 = Thickness of first layer (m)
x = Distance between points S and G (m)
θ_{ic} = Incidence critical angle

Two methods can be used to determine the thickness of the first layer; intercept time (t_i) and crossover distance (X_{co}). It should be noted that refractions do not occur at the location of energy source. At this point, the refraction time is defined by the intercept time, $t = t_i$ and so, x = 0. Equation 2.13 therefore becomes Equation 2.14

$$\text{time} = t_i = \frac{2h_1\sqrt{(V_2)^2 - (V_1)^2}}{V_1V_2} \tag{2.14}$$

Equation 2.14 can be rearranged in terms of h_1, so the thickness of the first layer is given by Equation 2.15.

$$h_1 = \frac{t_1V_1V_2}{2\sqrt{(V_2)^2 - (V_1)^2}} \tag{2.15}$$

When the direct and refracted waves are intersected at one particular point, the location of the horizontal point, X_{co} is called crossover distance (Figure 2.6). The method considers the travel time of direct and refracted waves to be equal, therefore a solution in determining the depth of h_i to the interface can be calculated using Equation 2.16.

$$h_1 = \frac{X_{co}\sqrt{V_2 - V_1}}{2\sqrt{V_2 + V_1}} \tag{2.16}$$

where;

V_1 = Velocity of first layer (m/s)
V_2 = Velocity of second layer (m/s)
X_{co} = Crossover distance (m)

2.2.3 Three-layer case

For shallow subsurface investigation, three-layer case is important in many realistic problems. The wave is thus refracted at two interfaces as depicted in Figure 2.7.

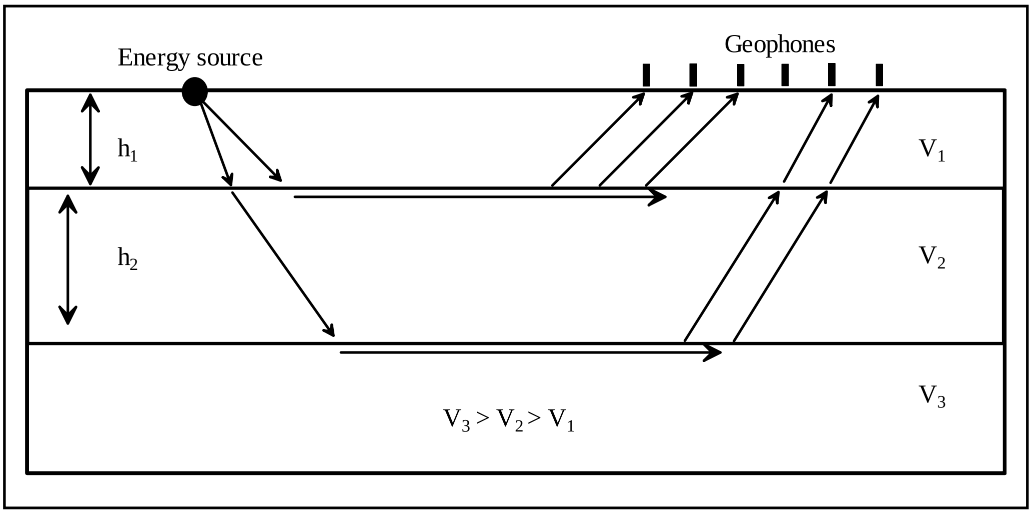

Figure 2.7: Refracted ray path for two subsurface interfaces (Burger et al., 2006)

Thickness of the second layer can be calculated using intercept time and crossover distance methods as well. The modified relationships are given by Equation 2.17 and 2.18 respectively.

$$h_2 = t_{i2} - \left[\frac{\sqrt{2h_1\left(V_3^2 - V_1^1\right)}}{V_3 - V_1} \right] \frac{V_3 V_2}{\sqrt{2\left(V_3^2 - V_2^2\right)}} \qquad (2.17)$$

$$h_2 = 2\left[\frac{h_1\left[\sqrt{V_3\left(V_2^2 - V_1^2\right)} - V_2\sqrt{\left(V_3^2 - V_1^2\right)}\right] + V_1\left(V_3 X_{co1} - V_2 X_{co2}\right)}{\sqrt{V_3^2 - V_2^2}} \right] \qquad (2.18)$$

2.3 Seismic downhole method

The seismic downhole method has been widely used to analyze the profile of in-situ wave velocities for geotechnical investigation. This method employs source placed on ground surface while the detectors (geophones/hydrophones) are placed inside a single borehole (Figure 2.8). The downhole method measures the body wave's travel time from the source to the detector at different depths in a single borehole. This method is considered less costly and easier to operate compared to cross-hole technique which requires more than one borehole.

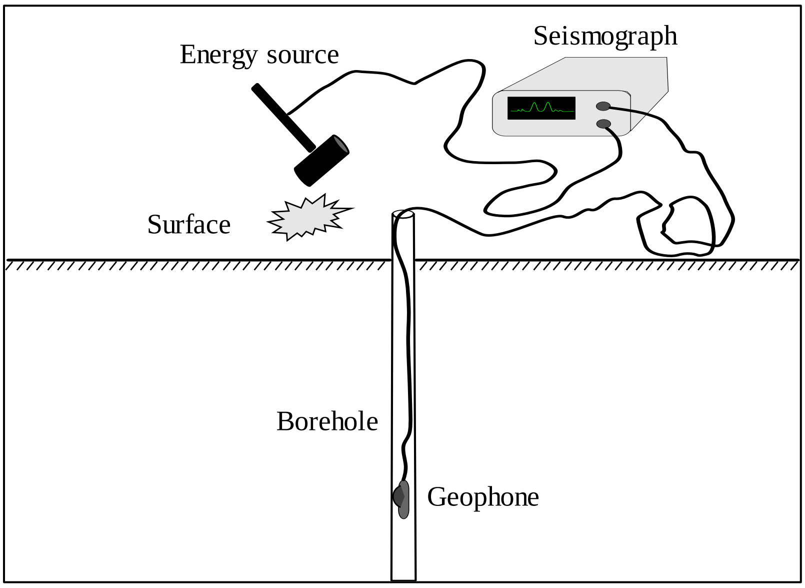

Figure 2.8: Seismic downhole configuration (Crice, 2002)

The travel times either between source and detectors or between receivers are used to calculate the velocity profile (Mok et al., 1988). The significance and use of seismic downhole method is that the seismic velocities information is pertinent to the material in investigations since it is believed that seismic downhole method provides true velocities of materials (Tabakov & Baranov, 2008). For geotechnical investigations, if the velocity and the density of material are known, the elastic properties of the material can be calculated (Crice, 2002). The elastic properties of material include:

- Young’s modulus (E); ratio of applied stress to the fractional extension (or shortening) and the strain of linear change in dimension which is divided by original length of material (Equation 2.19).

$$E = 2G(1 + \sigma_P) \qquad (2.19)$$

- Shear modulus (G); ratio of stress to the rotation of a plane originally perpendicular to the applied shear stress (Equation 2.20).

$$G = \rho V_S^2 \qquad (2.20)$$

- Bulk modulus (K); ratio of confining pressure to the fractional reduction of volume in response to applied hydrostatic pressure (Equation 2.21).

$$K = \frac{1}{3}\frac{E}{1 - 2\sigma_P} \qquad (2.21)$$

- Poisson's ratio (σ_P); ratio of lateral strain that is perpendicular to applied force to the longitudinal strain which is parallel to the applied force (Equation 2.22).

$$\sigma_p = \frac{(V_p/V_s)^2\text{-}2}{2(V_p/V_s)^2\text{-}2} \qquad (2.22)$$

where;

V_p = Compressional wave velocity (m/s)
V_s = Shear wave velocity (m/s)
ρ = Density (kg/m^3)

Seismic downhole data are processed using special software such as SeisImager/DH, Downhole GeoStru software, etc. There are two common methods to interpret the seismic downhole test data; direct and interval measurements (Kim et al., 2004).

a) Direct method

This method assumes that travel time (t) at inclined path is described in vertical path t_c (Figure 2.9). The corrected time is described in Equation 2.23. The velocity of each layer could be obtained by plotting the corrected travel times versus depth and observing the slope of fitting curve. The slope of the fitting curve represents the velocity in each covered range.

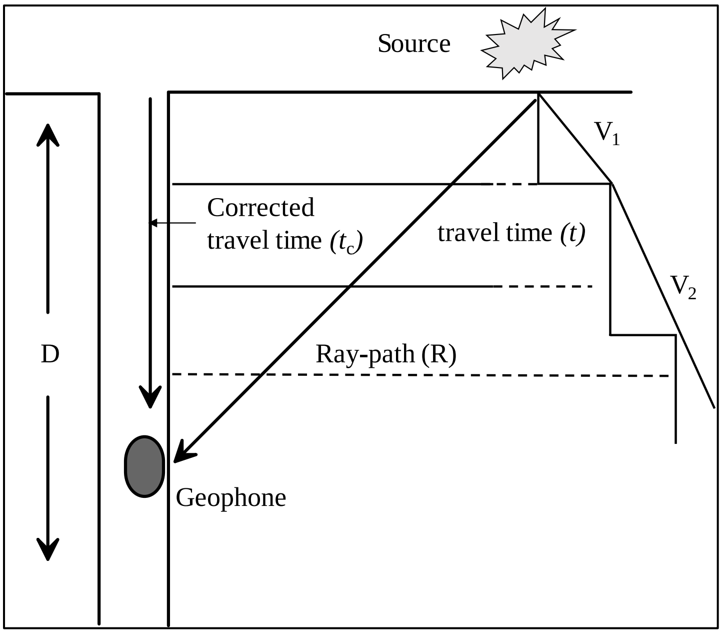

Figure 2.9: Direct method illustration (Kim et al., 2004)

$$t_c = D\frac{t}{R} \tag{2.23}$$

Furthermore, the interval velocity can be expressed by Equation 3.24.

$$V_d = \frac{\Delta D}{\Delta t_c} \tag{2.24}$$

where;

t_c = Corrected travel time
D = Depth
t = Travel time
R = Distance between source to detector
V_d = Interval velocity

(b) Interval method

Figure 2.10 shows two detectors located at different depths inside the borehole. The time travel from source to geophone is considered as direct wave and interval velocity between the detectors is calculated using Equation 2.25.

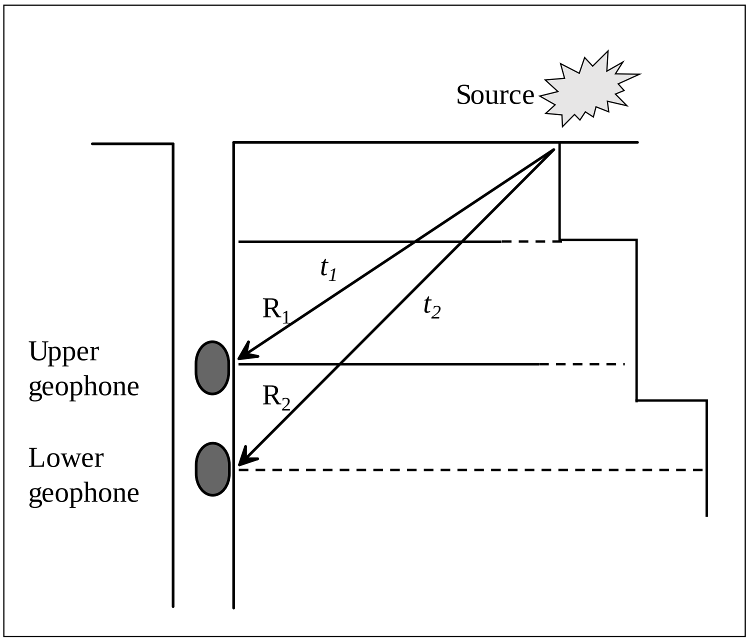

Figure 2.10: Interval method illustration (Kim et al., 2004)

$$V = \frac{R_2 - R_1}{t_2 - t_1} \tag{2.25}$$

where;

V = Interval velocity
R_1 = Distance between source to detector 1
R_2 = Distance between source to detector 2
t_1 = Travel time at geophone 1
t_2 = Travel time at geophone 2

2.4 Geotechnical method

Geotechnical investigation is performed in order to observe the physical properties of soil and rock. Mostly, the investigations are conducted by boring, in-situ test, and soil strata test to characterize the geotechnical parameters related to the construction works. In this study, boring technique; rotary wash boring and solid auger, and in-situ test; standard penetration soil blow count test (SPT) were utilized.

2.4.1 Boring technique

Direct method such as boring provides the practical opportunity to obtain the visual description and index testing of the subsurface samples. Boring method is conducted in relatively uncemented ground. Several boring methods that are usually carried out are augering, wash boring, and light percussion drilling. Augering method is classified as simple and light, using flexible equipment and is suitable for soft to cohesive soils investigations. The rotary wash boring method is a combination of wash boring and rotary drilling in order to observe the soil strata encountered. Wash boring is a relatively old method of boring in fine-grained cohesive and non-cohesive soils (Hvorslev, 1948).

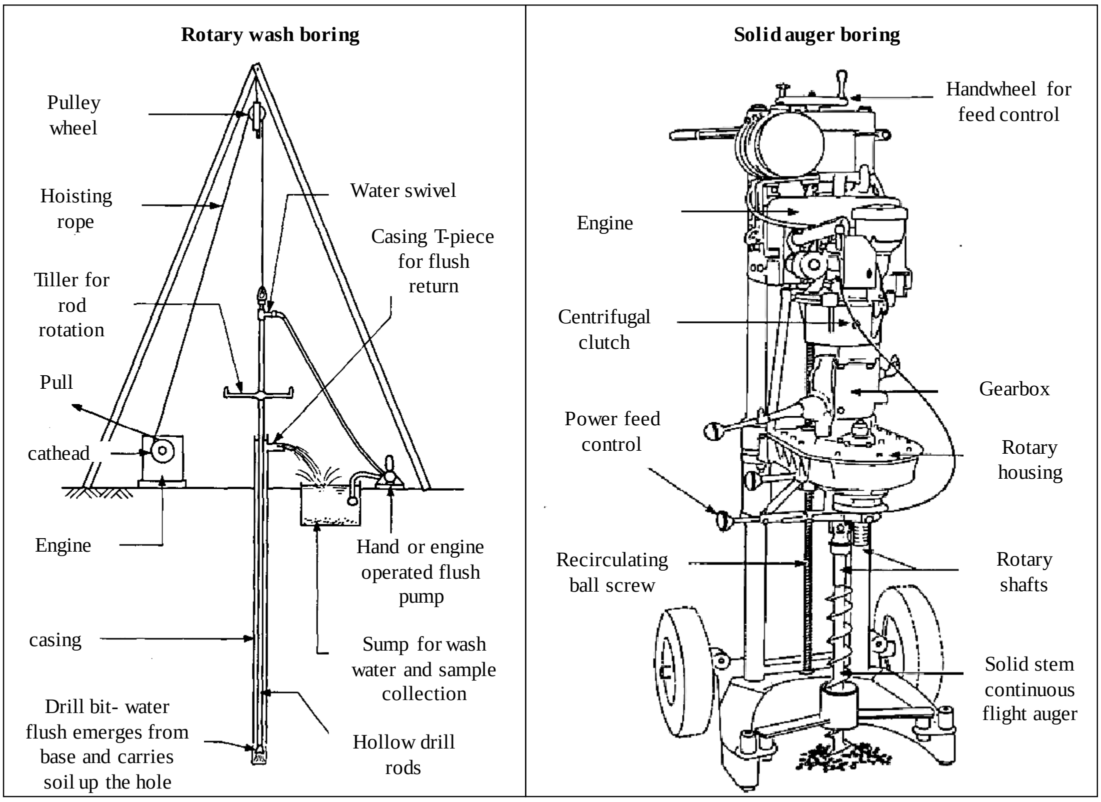

Figure 2.11: Rotary was boring and Solid auger (Hvorslev, 1948)

2.4.2 Standard penetration test (SPT)

The standard penetration test is representative of the disturbed soil sample for identifications and is carried out during drilling process. This method is widely used in many geotechnical exploration projects. The penetration resistance of the soil is determined using split barrel sampler. A hammer with 63.5 kg weight is blown against a sample tube with length of 0.65 m which is then driven to the ground at the bottom of a borehole. The sample is driven up to 0.45 m depth and the number of hammer blows needed for the tube to penetrate every 0.15 m is recorded (N-value). The increment is separated into 3 increments of 0.15 m each. The N-value is determined by sum of the total blows of second and third increment while the first increment is classified as seating drive and is not counted (ASTM, 2008).

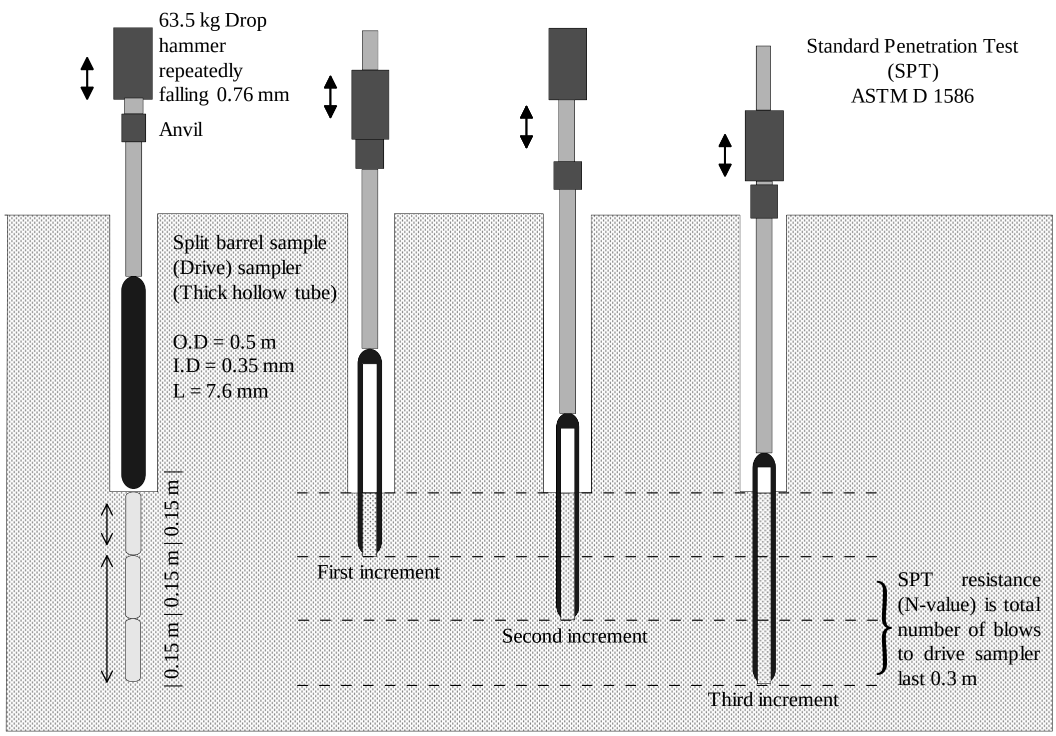

Figure 2.12: Standard Penetration Test (Wazoh & Mallo, 2014)