A NOVEL TECHNIQUE TO PREDICT SOIL DEFORMATION

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ABSTRACT

The geophysical method such as seismic surface wave offered advantages in the geotechnical site investigation via non-destructive testing. The geophysical methods have been widely used to detect any spatial material property changes which cannot be seen using naked eyes of human. Therefore, this research focused on a development of the seismic wave technique of surface wave with in situ non-destructive testing. The method presented in this research is by obtaining the surface wave phase velocity of a material in order to develop the graph of phase velocity versus wavelength. These researches utilize two different seismic surface wave techniques in one seismic complete system. The two seismic surface wave technique used is the Spectral Analysis Surface Wave (SASW) and Continuous Surface Wave (CSW). This research explores the effect of the relationship between source and receiver distance for both methods. The practical testing has been conducted on known materials; where the CSW system has been used on a concrete mortar. The ratio for this concrete mortar is 1:15; cement and sand and 1m x 1m x 1.5m for its dimension. Meanwhile, the SASW system has been used to test for soft soil conducted at RECESS soft soil test site in UTHM. The CSW method is based on generating a mono-frequency source using piezoelectric transducers in order to produce a seismic energy. For SASW method an impact source using a hammer is used to generate the seismic energy. The seismic recording used in this research includes a pair of accelerometer sensors and National Instrument data acquisition system. The collected data were stored, and processed after the completion of a data acquisition session. The portable personal computer with the developed Matlab programmed has been used to control the SASW and CSW system and the data acquisition during site investigation. The experimental result for phase velocity obtained in this research for concrete mortar is average at 374.29 m/s between 0.5m to 0.6m wavelength. Meanwhile, for SASW system the phase velocity of soil at a wavelength of 0.34m to 3.5m is average at 75.03 m/s.

ABSTRAK

Kaedah geofizikal seperti teknik gelombang seismik mempunyai kelebihan didalam penggunaanya di tapak uji kaji dengan menggunakan teknik yang tidak memusnah. Kaedah yang digunakan di dalam projek ini adalah dengan mendapatkan halaju fasa untuk mendapatkan anggaran lengkung serakan. Permukaan gelombang elastik boleh merambat sepanjang permukaan bahan elastik. Amplitud akan berkurangan dengan cepat mengikut kedalaman dan tenaga mereka hanya merambat pada lapisan cetek. Pengujian gelombang permukaan boleh diklasifikasikan sebagai ujian bukan pemusnah. Objektif kajian ini adalah untuk membangunkan sistem pengujian gelombang permukaan berdasarkan teknik (CSW). Kajian ini memberi tumpuan terhadap sumber isyarat dan kesan hubungan di antara sumber isyarat dan jarak penerima untuk menentukan anggaran lengkung serakan bahan. Ujian ini telah dijalankan ke atas konkrit mortar dengan nisbah 1:15 simen dan pasir. Konkrit mortar ini dibina dengan dimensinya 1m x 1m x 1.5m. Kaedah (CSW) menggunakan mono frekuensi sebagai sumber tenaga seismik oleh piezoelektrik sebagai sumber isyaratnya. Dua sensor penerima digunakan untuk menangkap isyarat pengujian dalam kaedah ini. Pembangunan perisian yang digunakan dalam kajian ini ialah dengan menggunakan pengaturcaraan perisian Matlab untuk berkomunikasi dengan sistem gelombang permukaan seismik. Ukuran eksperimen diproses menggunakan sistem perolehan data untuk mendapatkan halaju fasa sebagai fungsi panjang gelombang. Hasil daripada percubaan akan menyediakan maklumat daripada profil halaju gelombang permukaan. Hasil uji kaji ini, halaju yang diperolehi untuk konkrit mortar ialah 300 m/s hingga 400 m/s manakala halaju tanah untuk ujian SASW ialah 67.94 m/s hingga 94.61 m/s untuk kedalaman 0.34 m hingga 3.64m. Oleh itu sistem ini telah dibuktikan dapat digunakan bagi tujuan penentuan halaju fasa bagi bahan yang telah diketahui.

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CHAPTER 1

INTRODUCTION

In this sophisticated era, the construction process is increasing, especially in an emerging country. Before any construction, the geophysical engineers may help to conduct a site investigation in order to understand the soil characteristic. This is an important task before any construction works.The main purpose of the site investigation is to identify the profile and strength of the soil layers.

Conventionally, the measurement of soil profile is carried out using a combination of the in-situ invasive field test and the laboratory test. The standard penetration test, cone penetration test and field vane shear are examples of the traditional field tests techniques. All these methods provide a good site investigation result however, it is time consuming and expensive. Meanwhile, the laboratory testing requires the sample retrieval and thus introduces additional difficulties associated with sample disturbance and the reliability of the sample as a representation of the entire site (Madun et al., 2012). Thus,geophysical offered non-invasive and non-destructive method to identify the soil stiffness profile and thus able to overcome these problems.

Amongst the geophysical methods, seismic surface wave method offered an advantages in the geotechnical site investigation via providing the soil profile as well as anelastic parameters such as young modulus, bulk modulus and shear modulus (Madun et al., 2012). In addition, the seismic surface wave techniques are quick to deploy for a preliminary method to study the conditions of the soil before any construction work.

This is an advantage of the seismic surface wave technique which the measurements are conducted on the surface of the testing area or material and thus any extra work prior testing are not involved. Moreover, the seismic surface wave technique can be used as a monitoring system in the building or infrastructure for the purpose of forensic inspection and thus increase the safety to the public user.

1.1 Problem Statement

The geophysical seismic surface wave method has three main techniques; the Spectral Analysis Surface Wave (SASW), Continuous Surface Wave (CSW) and Multi Channel Surface Wave (MASW). All these three method have their own specialty; however among the three, the MASW is more expensive due to the high numbers of receiver used in testing. Meanwhile, the SASW and CSW techniques basically required minimum two receivers prior to perform a testing. The CSW and SASW techniques adopted a vibratory and transient seismic source respectively. Thus, the SASW technique having no selective control over the frequency generated given by impulsive seismic source. Therefore, measurement using SASW is limited to certain frequencies and will affect the lack of information in the medium. Meanwhile, the CSW technique is using a selective frequency control of the vibration seismic source. The range of frequency can be easily generated and provide accuracy on measurements.

Due to the crucial of the frequency in the seismic surface wave testing, thus a combination of these two techniques (SASW and CSW) was developed in this research in order to obtain better accuracy of the measurements. This system is designed to allow two different techniques into one system can lower the operating cost. Therefore, a combination of these two techniques can further lower an operating cost. Currently, the system in the market is ultrasonic wave technique, which is focused on estimating the overall stiffness of the tested material. The proposed seismic surface wave technique offers a non-destructive testing, which performs a testing on the surface of the material and is able to determine the stiffness in function of depth. In addition, this technique is very suitable for inspecting the integrity of the structure of the heritage buildings. In a few cases, the structure deterioration cannot be seen with naked eyes. Therefore, to overcome these matters, the non-destructive technique should be adopted to identify the affected areas quickly and in a cost effective way. Thus, the equipment of the test must be affordable to Malaysian's engineer. Currently, the seismic surface equipment needs to be purchased from overseas and the price is expensive therefore for some reason cause small companies could not afford the system.

1.2 Objectives of the Research

The aim of this research is to develop a low cost operation of seismic surface wave testing system by combining two different kinds of seismic of surface wave technique in one system.This research has focused on the use of seismic surface wave,a method which is more versatile and considered as an economical in terms of field operation (Matthews et al., 2000). Wave propagation integrates the properties of the material from the source to the receiver. The developed system can be adopted for attaining and utilize the data taken from in situ testing where this data will provide information regarding the quality and reliability of the tested material.

To achieve the aim of this research, the following objectives are established:

1. To propose and develop a surface wave testing system by utilizing two different seismic surface wave techniques in one system.
2. To design the completeness seismic surface wave testing system.
3. To evaluate the performance of the developed system.

The achievement of this research product is winning in innovation competition as follows;

i. Gold medal in Seoul International Invention Fair (SIIF), 27th November – 1st December. 2014, COEX, Seoul, South Korea for product "Building Structure Health Monitoring Inspection Kit (BISMIK).

ii. Bronze medal in Malaysia Road Conference Invention & Innovation Exhibition (MRC-IIE) Organized by Ministry of Works Malaysia, 10th – 12nd November 2014, Sunway Pyramid Convention Centre, Malaysia for the invention of "Building Structure Health Monitoring Inspection Kit (BISMIK)".

iii. Gold medal in 25TH International Invention, Innovation and Technology Exhibition (ITEX 14) Festival Organized by Malaysian Invention and Design Society (MINDS). 8th – 10th May 2014. Kuala Lumpur Convention Centre, Malaysia for the invention of "Building Structure Health Monitoring Inspection Kit (BISMIK)".

1.3 Scope of the Research

The two different techniques procedure used in this research are Spectral Analysis Surface Wave (SASW) and Continuous Surface Wave (CSW). These techniques can be distinguished based on the types of seismic sources used; one is from the transient impact source (SASW) and the other one is from steady-state vibration source (CSW). The selection of appropriate seismic source is very important for particular surveys to ensure sufficient frequencies generated. For the purpose of validating the seismic surface wave testing system,CSW technique was tested on the concrete mortar (high seismic velocity) while the SASW technique was tested on soil (slow seismic velocity). CSW used a piezoelectric transducer as a seismic source, which produce surface wave frequencies in the range of 500 Hz to 20 kHz. Therefore, it is suitable for testing at high velocity materials, such as concrete or rock. Meanwhile, SASW used 5 kg hammer source which is able to generate the seismic frequency ranges between 20 Hz to 500 Hz, thus it is suitable for slow seismic velocity material testing In order to integrate this system, a variety of seismic sources are required. For examples, variety of hammer size and mechanical vibrator is usedto overcome the issue of generating the variety of seismic frequencies.

This research is focused on investigation of arrangements between source to receiver spacings to attain sufficient and reliable data for both techniques.Both techniques use different arrangements of source to receivers spacing, due to its limitations of test equipment and the developed material sizes. The proposed completeness seismic surface wave testing system is design by developing a signal generator and signal detector as the main part. A written Matlab software programmed is developed and used to conduct the testing. The collected data are captured and stored using data acquisition National Instrument devices.

1.4 Thesis Outline

This thesis is organized in five chapters. Chapter 1 introduces the main objectives and problem statements of the research undertaken. It also states the aim and the scope of the research. Chapter 2 provides an overview of the literature relating to the research which includes geophysical testing and seismic surface wave technique. This chapter also discussed the important parameter used in collecting the data from seismic surface wave testing. The basic of seismic surface wave testing system is discussed in Chapter 2. Chapter 3 presents the methodology of this research which consisted of the development of seismic surface wave testing system for both techniques; SASW and CSW where the development of seismic surface wave system is based on the signal generator and signal detector. The seismic surface wave experimental work using two different materials, concrete mortar model and on soft soil is discussed. The works, regarding sample preparation, and development of the test equipment and measurement procedures according to its types of techniques are explained. Chapter 4 presents the findings obtained during this research and discussion of the measured results. Finally, Chapter 5 concludes with a summary of the research and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A surface wave is a geophysical method that has a number of advantages because it is able to assess variation for both width, depth and across the area in a cost effective way so that improvements can be examined in detail (Madun et al., 2012). Since the late 1950s the seismic surface wave has been developed for various applications. The surface wave; which a wave that travels at free boundary is a function of frequency and this dependence is strictly related to the mechanical parameters of the medium. The potential of geophysical seismic method in geotechnical engineering was first highlighted by Terzaghi (1943) as a tool of the future. It was followed by many researchers, especially in recent decades, various applications such as; Luna and Jadi (2000) in investigating of soil property; Abbis (2001) in landfill deformation properties and long-term settlement prediction; Moxhay et al. (2001) in ground-improvement monitoring technique; Rhazi et al. (2002) investigations of concrete non-homogeneity effects; Socco and Strobbia (2004) in near surface characterization; Tran (2009) in soil characterization; M.N.Omar (2011) prediction of long term settlement on soft clay; Madun et al. (2012) characterization and quality control of stone columns.

2.2 The Seismic Based Method

The seismic based method can be divided into two; Borehole method and Surface method as shown in Figure 2.1. The borehole methods can be classified as invasive techniques which are divided into four types, Up hole, Down hole, Seismic cone and Cross hole. Meanwhile, for the surface methods are non-invasive that consists of three types of techniques; they are refraction, reflection and surface wave. The surface wave data collection uses the surface method, which is more versatile than other methods in determining of soil profiling because it is not constrain by any ground models (Madun et al., 2012) and considered more economical in terms of field operation (Matthews et al., 2000). A seismic surface wave is a part of geophysical method conducted in identifying the structural layer of soil on the surface without having to do excavation works throughout the soil layer.

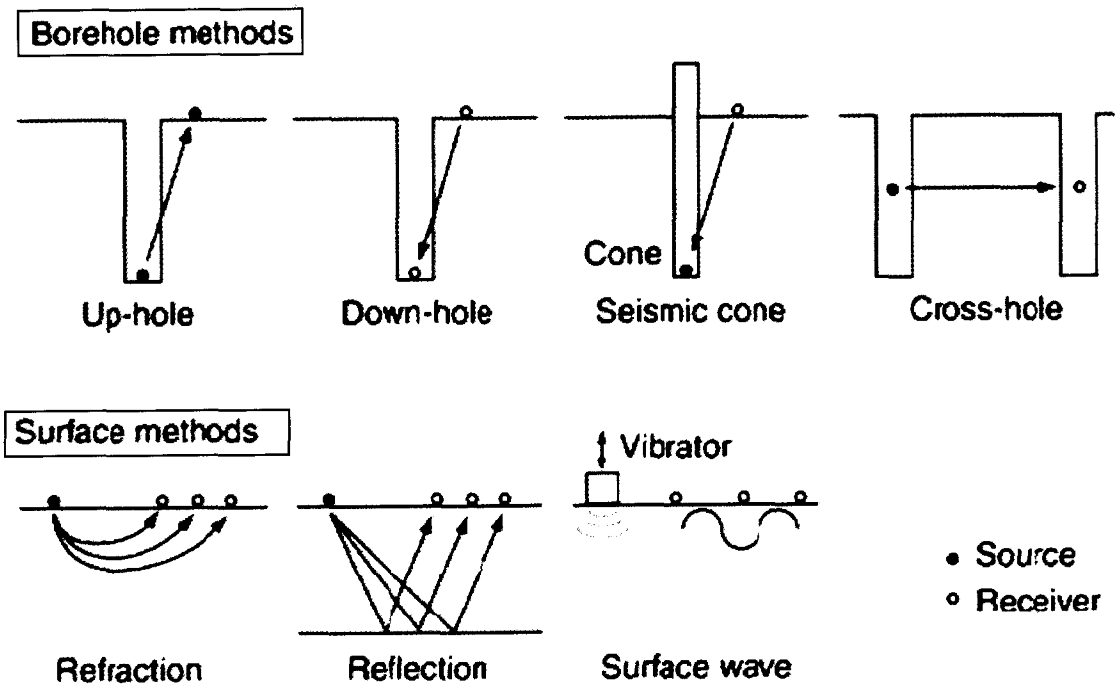


Figure 2.1: Schematic diagram for the borehole invasive method and surface non invasive methods (Madun et al., 2012)

The geophysical seismic based method utilized mechanical wave to evaluate the material stiffness and to make use of two types of seismic wave: (a) body waves and (b) surface waves as shown in Figure 2.2. Stiffness is the rigidity of an object to the extent which it resists deformation in response to an applied force. Body waves are usually non-dispersive which travels through the Earth interior and having two types; Compressional wave (P-wave) and Shear wave (S-wave). P-waves can travel through any kind of materials, whether it is a solid, liquid or gas because of their wave movement. S-waves on the other hand, can only move through solids and are stopped by liquids and gases. This can be proved as stated in Madun et al. (2012) which concluded that the velocity of a P-wave in water is 1450 m/s meanwhile, S-wave velocity in water is 0 m/s.

Surface waves arrive after the P-waves and S-waves, because they travel along the surface layers of the Earth where velocities are lower. When the ground surface is vibrated with a vertical load, two-thirds of the energy is transformed into surface waves and propagated parallel to the ground surface, (Socco and Strobbia, 2004). The surface wave consists of Rayleigh wave or Love wave which only propagated through a solid medium with the depth of penetration being a function of their frequency and wavelength (Reynolds, 1997). Rayleigh waves are widely used for materials characterization in non-destructive testing to discover the mechanical and structural properties of the object being tested like the presence of cracking, and the related shear modulus. The Rayleigh surface wave can be used at different length scales because they are easily generated and detected on the free surface of solid objects. Since they are confined in the vicinity of the free surface within a depth linked to the frequency of the wave, different frequencies can be used for characterization at different length scales.

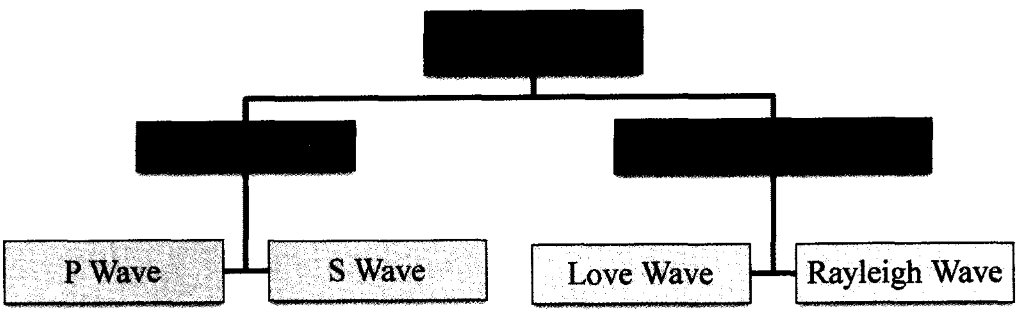


Figure 2.2: Types of seismic waves (Matthews et al., 1996)

Figure 2.3 shows the schematic elastic wave propagation in the ground. The P-waves are longitudinal waves that involve compression and expansion in the direction that the wave is travelling. Particle motion is parallel to the direction of propagation. The S-wave which is slower than a P-wave propagates as perpendicular to the direction of the wave travel. This wave moves a rock up and down, or side-to-side. A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean, and its move both vertically and horizontally in a vertical plane pointed in the direction in which the waves are travelling, because it rolls, it moves the ground up and down and side-to-side in the same direction that the wave is moving. The Love wave moves the ground from side-to-side.

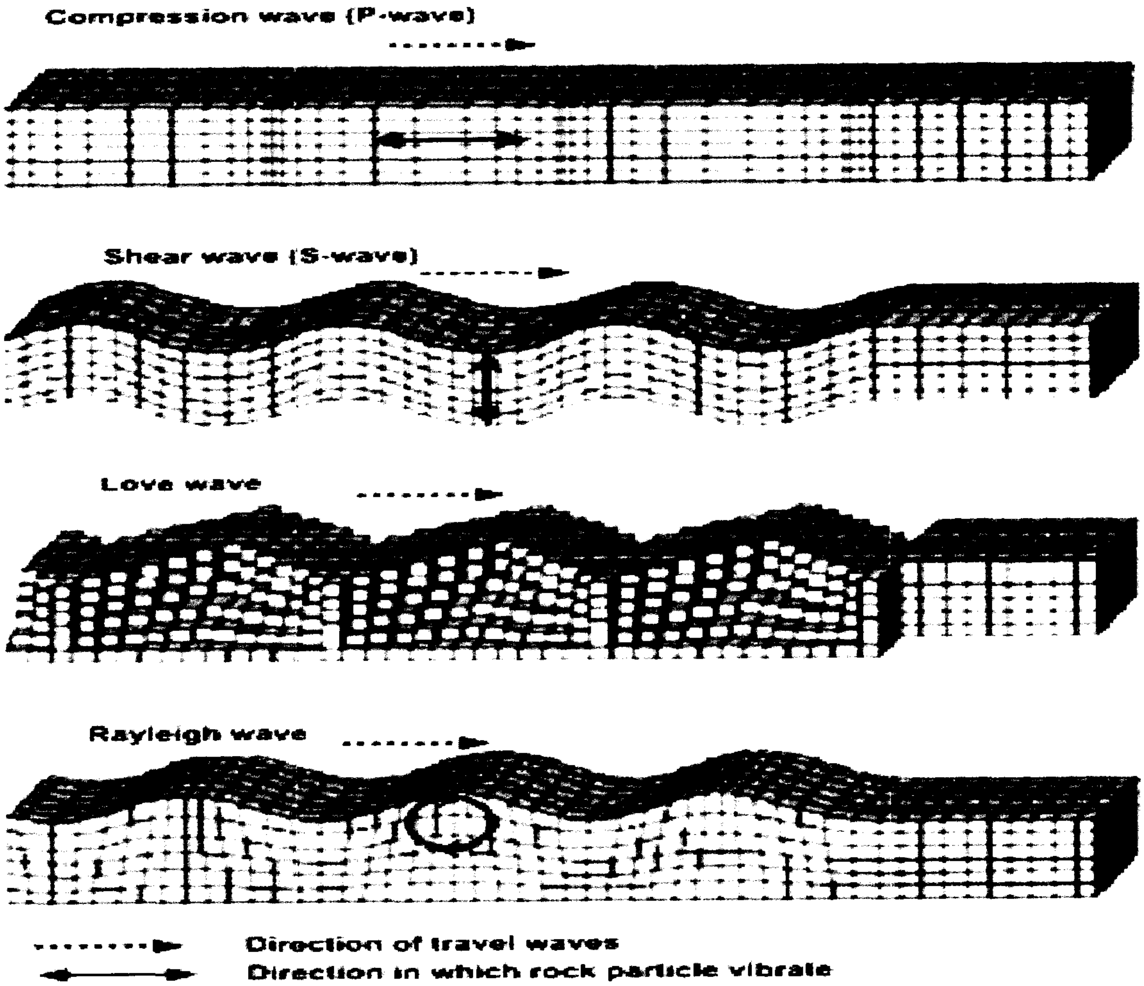


Figure 2.3: Types of Surface wave (Menzies, 2001)

The surface waves are relatively less attenuated as a function of propagation distance as compared to body waves. Therefore, research has evaluated the application of seismic surface wave with the testing method. Surface waves are usually dispersive in a non-homogenous medium, which gives the characteristic that their velocities are a function of frequency (Pasyanos.,2013 and Min & Kim, 2006). Dispersion occurs since the penetration depth of surface waves into the layered medium increases with increasing wavelength. The dispersive characteristics of these waves can be utilized in layered media where information on the variation of material properties with depth can be obtained (Al-Hunaidi et al., 1992).

Surface waves represent a convenient alternative for material characterization because they dominate the ground motion at any distance from the source. The surface wave method has advantages in several respects (Park et al., 2007) which are:

1. The field survey is easy because of the strong nature of surface wave energy that can be generated using a simple impact source; such as sledgehammers.
2. The data processing procedure is usually simple that it does not require highly experienced personnel for reliable determination of optimum processing parameters. This also indicates the potential for full automation of the entire processing procedure.
3. Surface waves respond most effectively to various types of near-surface anomalies that are common targets of geotechnical investigation.

Table 2.1 shows the comparison between Body wave and Surface wave. Geometrical attenuation is smaller for surface waves than for body waves because the wave front is cylindrical and has a smaller area than the spherical wave front of body waves (Phillips C, 2004). In a solid and homogeneous medium, the velocity of surface waves does not fluctuate significantly as a function of distance propagation (Madun et al., 2012).

Table 2.1: Comparison between Body wave and Surface wave (Al- Hunaidi et al., 1993)

Body wave	Surface wave
A seismic wave that travels through the Earth rather than across its surface	A seismic wave that travels across the surface of the Earth as opposed to through it.
Body waves usually have smaller amplitudes and shorter wavelengths than surface waves and travel at higher speeds	Surface waves usually have larger amplitudes and longer wavelengths than body waves, and they travel more slowly than body waves do
Usually non-dispersive	Usually dispersive in non-homogenous medium

2.3 Seismic Energy Source

A seismic source can be derived as a tool or devices that controlled the seismic energy. The selection of appropriate seismic source is very important for particular surveys to ensure a large amount of signal produced sufficient energy to penetrate the ground or material sub surface. Overviews about the different types of seismic source have been given by Miller *et al.* (2000). Table 2.2 shows the types of seismic source. The seismic source can be divided into two types which are the impact source and the vibrating source. The impact source, for example, hammering is commonly used in SASW method. The most common type of non impulsive source is a vibrator. The choice of source (transient or continuous) affects the details of the way in which the field data are acquired and subsequent processed.

Table 2.2: The types of seismic source (Reynolds, J.M, 2012)

	Impact	Continuous
Source Type	1. Sledge Hammer 2. Drop weight	1. Mechanical vibrator 2. Piezoelectric transducer

2.4 Spectral Analysis Surface Wave (SASW)

The Spectral Analysis Surface Wave (SASW) is types of seismic surface wave technique which makes use of transient vertical impact source. In general, heavier weights generate signals predominated by lower frequencies and generate a longer wavelength which is much needed when it is intended to analyze the deeper depth material profile (Madun et al., 2012). The high frequency waves have a shorter wavelength and thus penetrate the shallow layer of soil. Meanwhile the low frequency waves have a long wavelength that can penetrate deeper layer of soil. The SASW technique uses a single pair of receivers that are placed collinear with the impact point of the transient source to yield one-dimensional results of phase velocity versus depth.

The SASW method reduces the testing time by using an impact device to generate a disturbance with wide frequency content. In reality, the ideal plane surface wave is difficult to generate. When the SASW method is used in field, a transient load is applied at a point on the surface of soil (Chen et al., 2004). Vertical motion induced by the source at the free surface of the material is detected by the two receivers and recorded in the time domain.

2.4.1 SASW Analysis

The SASW method uses a spectrum analyzer to capture signals from ground motion receivers usually in the time domain signals. The receivers are placed collinear with the impact point to measure surface vibration reflected along the surface. The time domain data are transformed into the frequency domain using Fast Fourier Transform (FFT) process for further analysis. Figure 2.4 shows in details each step involved in collecting and processing data on the SASW testing system by Rhazi et al 2002. The resulting ground motion is detected at the receivers and digitized at the analyzer. The first step is to filter the signals data, to remove the late arriving reflected energy from the captured signals and then to perform a FFT process. The information of the frequency domain analysis provides the cross power spectrum, which represents the amplitude and phase spectra of the signals. The amplitude spectrum gives information on the frequency bandwidth of the Rayleigh wave energy in the waveforms. The range of frequency bandwidth has been calculated for 20% of the highest peak in Rhazi et al 2002 paper. This percentage was determined following numerous experiments and helps in rejecting low-energy frequency components that might be contaminated by noise while retaining a significant of the frequency bandwidth. Thus, the minimum and the maximum of the frequency bandwidth can be determined and useful in spectral analysis.

Meanwhile, the information from phase spectral data can be used to determine the phase difference between the signals at each receiver sensor. The phase spectrum gives the relative phase difference between the two recorded waveforms for each frequency component (Rhazi et al., 2002). The SASW method measures the phase difference of surface waves as they travel between two receivers (Stokoe and Nazarian, 1983). A graph of surface wave velocity versus wavelength (dispersive curve) can be obtained by calculating the surface wave velocity using the given information from the FFT analysis.

The seismic technique is analyzed to obtain the velocity of the wave travelled through the propagation media. The data of the phase angle can be unwrapped from the transfer function where a composite of the phase velocity versus wavelength (dispersion curve) for the entire receiver spacing can be generated. The phase velocity is computed as the distance over travel time, where distance is given by the receiver spacing and travel time is computed from the phase difference at each frequency component. The velocity then can be transformed to information stiffness of the material. However, if there is a variation in the mechanical properties of the medium with depth, the velocity of Rayleigh waves will depend on the wavelength (Rhazi et al., 2002). The depth penetration of surface waves is proportional to the wavelength. In a layered medium, surface waves become dispersive, causing different wavelengths to travel at different velocities (Phillips et al., 2004).

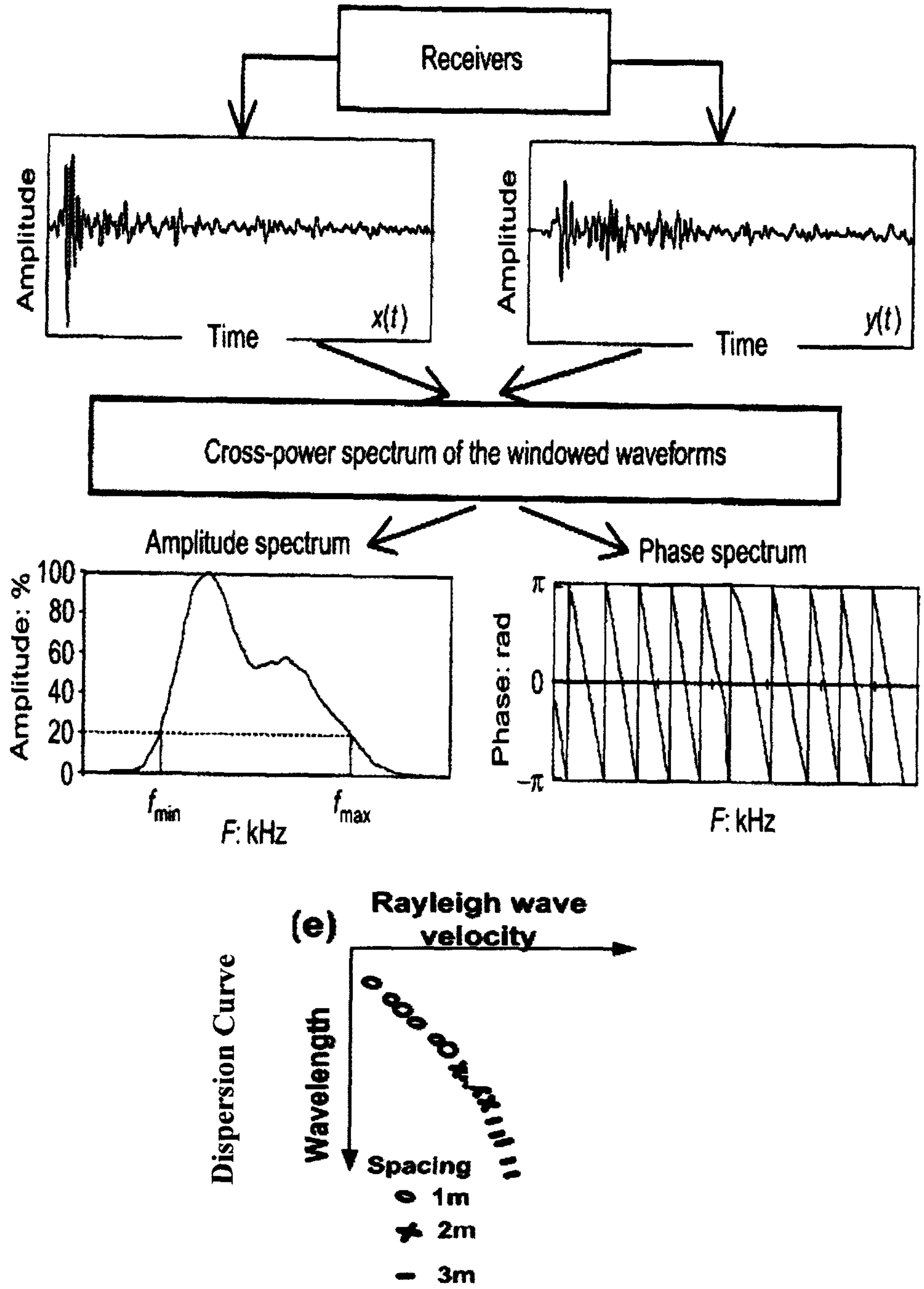


Figure 2.4: The processing data on SASW testing system (Rhazi et al., 2002)

2.4.2 Preceding study

This preceding study explains the previous research using the SASW system. The SASW method has been widely applied in many engineering projects because of its advantages. Table 2.3 shows the use of the SASW system in various applications.

Table 2.3: SASW method from previous research

Author / Title	Method
Rhazi et al 2002 Effect of concrete non-homogeneity on Rayleigh wave dispersion	This research uses SASW technique to study the correlation between Rayleigh wave propagation velocity and concrete mechanical quality and the ability of the SASW technique to characterize the variation of concrete quality with depth. This research makes use of the impact source from a 250g hammer on weight, which produces the frequency bandwidth between 4 to 28 kHz. From the arrangement of source to receiver spacing, and distance between two receivers is same; the authors use 0.45m. Author use a piezoelectric accelerometers (PCB model 353B16). The collected data were transformed into the frequency domain by FFT process. The dispersion curves were constructed by using the cross power spectrum at which the amplitude is greater than 20% of the maximum amplitude of the spectrum. The Rayleigh wave velocity was assumed as 2000m/s in this paper. Finally, this paper shows the dispersion curve is increased with increasing wavelength, due to the fact that the last layer having a better mechanical properties in this research.
Al-Hunaidi et al 1993 Insights on the SASW nondestructive testing method	The SASW method in this research has been used for determining the thickness and elastic properties of pavement and soil sites using the dispersion characteristics of surface waves. A vertical vibration generator is used as a source which produces excitations 2 to 500 Hz. The distance between the nearest receiver and the source; and the distance between two receivers is equal. The vibrations are picked up by two vibration transducer in line array with the source and transform the collected data to the frequency domain by FFT process. Distance from profiling pavements site are 0.5m, 1.0m, and 2.0m.
Matthews et al 1996 The use of surface wave in the determination of ground stiffness profile.	The SASW and CSW system are used to obtain the ground stiffness profile. The SASW system uses a hammer blow meanwhile the CSW system uses a steady state vibrator as an energy source. Two geophones with 4.5Hz is used to detect the seismic source. Five arrangement of geophones spacing; 0.3, 0.6, 1.2, 2.4 and 4.8m which by equating the source to near receiver and the distance between two receivers. A spectrum analyzer is used for recording the captured signals in time domain and then will transform to the frequency domain by using FFT process. For a field dispersion curve of the London Clay and Chalk represents the profile of increasing Rayleigh wave velocity and hence stiffness with dept. Finally, the author had concluded that, the surface wave method provides a rapid means of determining stiffness-depth profile in near surface soil without the need for boreholes.

Rosyidi et al 2004 Measurement Of Subgrade Stiffness Using The SASW Method	The SASW method has been used in order to estimate the stiffness of the pavement foundation which is conducted at UKM, Bangi. An impact source on a pavement surface is used to generate Rayleigh waves. The FFT has been used to analyze the collected data. Two functions in a frequency domain between the two receivers are of great importance (1) the coherence function and (2) the phase information of the transfer function. All the data of the phase angle from transfer function need to be unwrap in order to determine a composite experimental dispersion curve for all receivers spacing. Finally, the research able to characterize the stiffness of pavement profile in term of shear wave velocity by using the SASW method.

In this research, the SASW system will be developed with different setup equipments compare to previous studies. This SASW system will be tested to evaluate the soil profile. The site where the field testings are conducted is located at RECESS UTHM. The impact source of 5 kg hammer is used in order to produce a seismic source in this system. The pair of accelerometer sensors of PCB 352C42 with 30 kHz resonant frequency is used as receiver sensors to detect the data. Generally, other research uses a geophone for the receiver sensors. The best geophones used on most surfaces based on geophysics typically have a natural frequency of approximately 4.5 Hz, which limits their usefulness in surface wave surveys.

In order to overcome these matters, the accelerometer sensors (PCB 352C42) which is capable of 1Hz to 10 kHz for its frequency is use in this research in order to maximize its accuracy in measurements. This range of frequency is very useful to help in the investigation of shallow layers using highest frequency and the lowest frequency is required in order to obtain the deepest layers. Data acquisition system from National Instrument is used instead of using a spectrum analyzer for collecting the seismic data in time domain signal. In addition, the arrangements of source to receivers spacing in this system is arranged on the soil at 0.5m, 1m, 1.5m and 2m by equating the distance of the nearest receiver to the source (d) and the distance between the two receivers (Δx) which is best explain in Figure 2.5. The distance d, between the nearest receiver and the source is suggested by Heisey et al (1982) to be approximately equal to the distance, Δx, between the two receivers. The variety of receivers spacing is to avoid practical consideration such as attenuation, sometimes require that different receivers spacing be used. This is necessary in order to cover the wavelength range required to sample the various layers of a site (Al-Hunaidi et al 1993). Based on Figure 2.5, the layout for conducting the SASW method on soil materials in this research has been shown. Two accelerometer sensors were placed in collinear with the seismic source; hammer on a soil. A personal computer with written Matlab software is used to connect the data acquisition system to the system.

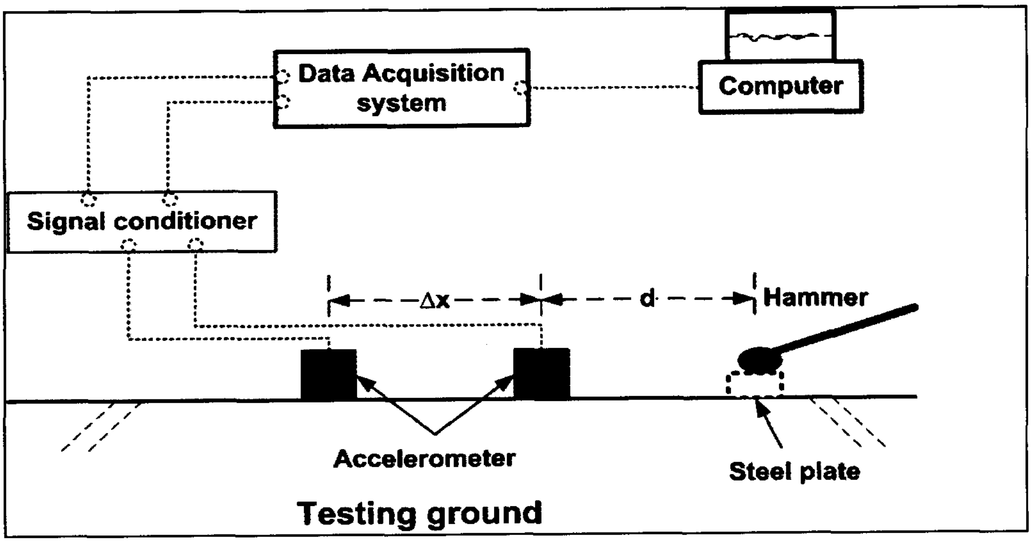


Figure 2.5: Layout for SASW testing method

2.5 Continuous Surface Wave (CSW)

The Continuous Surface Wave (CSW), technique is another type of surface wave method that has been successfully used to produce stiffness parameters in many projects such as in the assessment of ground treatment without the need to provide a borehole. The advantage of using a seismic method is that it is not affected either by insertion effects or by sampling disturbance. The seismic source used in CSW method is a vibratory seismic source which is able to produce selective frequency control. A vibration source generates continuous sinusoidal waves dominated by a single frequency. CSW method is an improved technique, where the source produces a longer duration excitation making it less vulnerable to ambient noise. A sinusoidal input signal generated by an electromagnetic vertical vibrator, that produces a series of finite duration pulses, each at a single frequency over a range of frequencies. At least two receivers are required seismically contacted with the exposed surface of the tested structure to capture the vibration source.

The frequencies of the continuous wave generated by the vibrator and allow velocity measurements can be changed and made over a range of depths. Because the penetration depth of the surface wave technique depends on the frequency of the waves under test, this is where the ground vibrator comes into its own function. It can be specifically set to vibrate at lower frequencies. The main advantage of the CSW test is that the operator has full control over the frequencies being produced and may therefore target the depth of interest by selecting the required frequency range. Thus, this advantage will maximize the accuracy of the measurements without experiencing a loss or inadequacy signal on materials.

2.5.1 CSW Analysis

The CSW processing technique is summarized in Figure 2.6. The captured data are in a time domain. The data collected in the field are in the time domain, and must be transferred to a computer for transformation into frequency domain in preparation for the determination of phase shifts between the signals in the two receivers by using FFT process. The frequency domain data is used to determine the phase of the generated signal at each receiver location (Moxhay et al 2000).The difference phase angle between sensor pair is called phase difference. It is then used to calculate a phase velocities in order to construct the graph of phase velocity versus wavelength (dispersive curve).

The difference between SASW and CSW is the transient impact seismic source generating a swept frequencies meanwhile vibrator seismic source formed a single-frequency sinusoidal force respectively (Madun et al., 2012). The selective mono-frequency in CSW method brings a result that there is no frequency misses and unwanted background noise is more easily recognized, avoided and filtered in the CSW technique (Clayton, 2011).

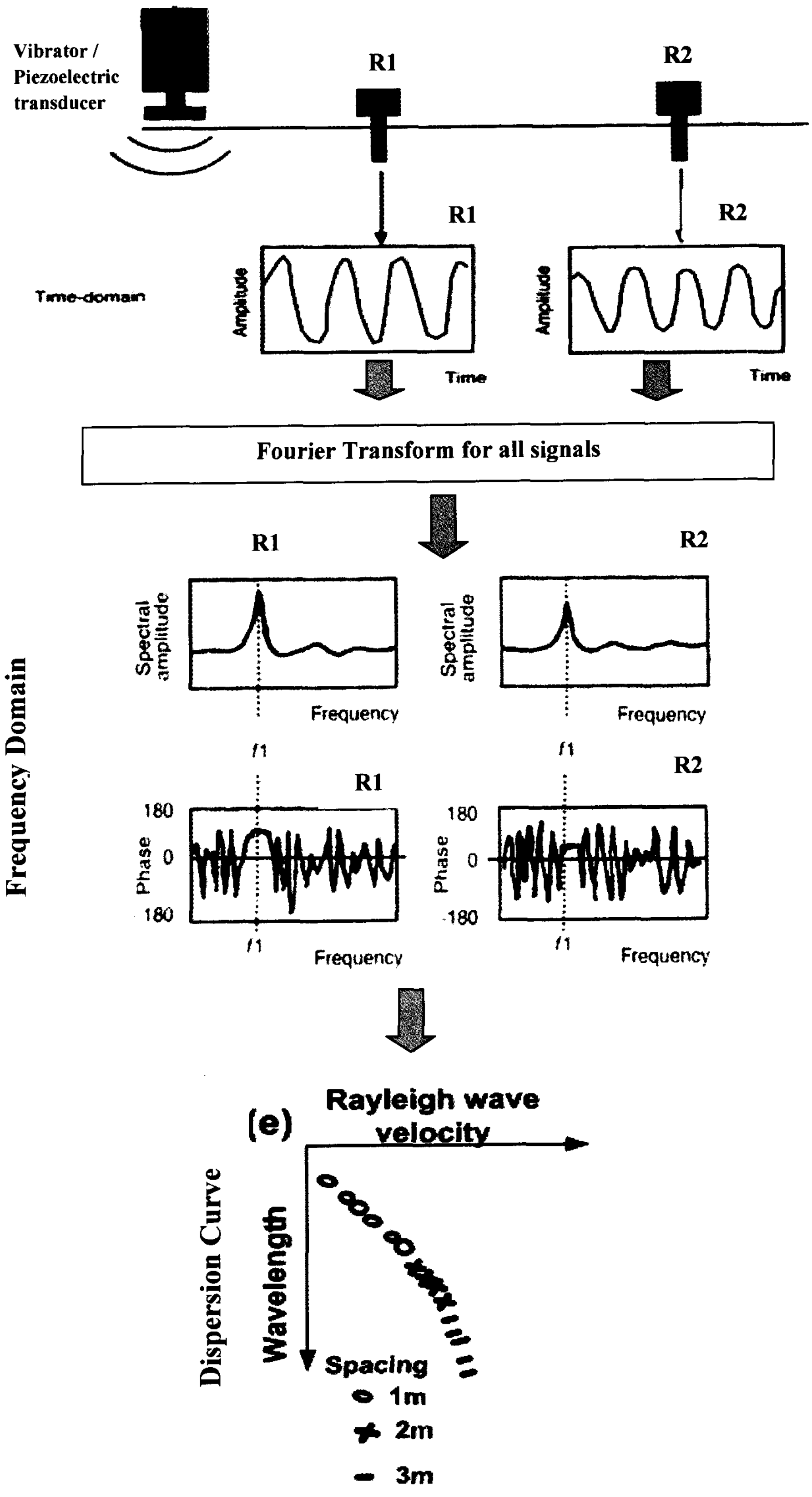


Figure 2.6: The processing data on CSW testing system (Matthews et al., 1996)

2.5.2 Preceding study

This preceding study discussed the previous research that uses CSW system. Table 2.4 shows the use of CSW system in various applications.

Table 2.4: CSW method from previous research

Author / Title	Method
Moxhay et al (2001) Monitoring of Soil Stiffness During Ground Improvement Using Seismic Surface Waves	This research uses a CSW system for monitoring the soil stiffness during ground improvement. The source is an electromagnetic vibrator capable of exerting a peak sine force of 498N. The vibrator is energized at discrete frequencies form 5 and 600 Hz. The waves generated are detected between three and six 2Hz geophones, the outputs of which are passed through signal conditioning amplifiers and then to a high speed 16-bit data acquisition unit. The signals received at geophones are recorded in time domain and subjected to FFT process. From the case histories in this research, the CSW system is capable of monitoring soil stiffness on ground improvement sites and can produce positive results.
Sutton & Snelling (1998) Assessment of ground improvement using the continuous surface wave method.	The Continuous Surface Wave (CSW) method in this research is used to assess the ground improvement. CSW tests have been performed on a representative area of a commercial site immediately prior to ground improvement. The ground improvement was performed by the installation of vibro-replacement stone columns. The energy source (an electro-mechanical vibrator of peak force 498N) is placed on the prepared ground surface. A row of six 2Hz geophones was placed on a line which is co-linear with the vibrator. The vibrator was energized using the controller and drive unit at single known frequencies between 5 and 100 Hz specified to within 0.1Hz. The range of frequencies and the frequency increment are set by the operator using a laptop PC connected to the control unit. The portable generator used for powering the equipment was positioned at least 30 m away from the vibrator on a line which is perpendicular to that of the line of the geophones. CSW tests were carried out before and after the stone columns were placed in order to gauge the improvement in the stiffness of the site. Finally, as a result from the CSW data alone the improvement in the top four meters of the sand is immediately obvious and verified by CPT testing which also obtained a result down to 4m depth.

At an early stage of testing, the seismic surface wave equipment and system were tested for their suitability and robustness to deliver a result. In this research, the CSW system will be developed with different setup equipments compare to the previous study and then use the system to tested on concrete mortar materials. The properties of concrete mortar are reasonably constant after curing within 28 days of casting. Moreover, this approach was used by Khan et al. (2006) and Nasseri-Moghaddam (2006), thus the results using concrete mortar could be compared for verification.

The vibratory source in CSW is from piezoelectric transducer which is capable to produce surface wave frequencies in the range of 500 Hz to 20 kHz. The signal can be controlled via signal amplifier. Vibration sources generate a continuous sinusoidal signal dominated by a single frequency which, within limits, can be varied in a controlled and systematic manner. The lower frequencies correspond to the long wavelength Rayleigh waves, and it is these waves which provide information about the ground at depth (Matthews et al., 1996). Therefore, it is proved that the choice of source; transient or continuous affects the details of the way of field test and the field data acquired. Figure 2.7 shows the layout of CSW method conducted in this research on concrete mortar materials.

Two accelerometer sensors (PCB 252C42) are used in this CSW method and placed with the exposed surface of the tested structure in line with the piezoelectric transducer. The receivers produce an electric signal in response to seismic waves travel through the material. Signal conditioner is used to eliminate the noise and captured in data acquisition system. The CSW system can be controlled using a personal computer with written Matlab software. The collected data are stored and then will be processed via FFT analysis method. The arrangements of source to receivers spacing in this system was arranged on the concrete mortar at 0.05m, 0.1m, 0.15m and 0.2m by equating the distance of the nearest receiver to the source (d) and the distance between the two receivers (Δx).

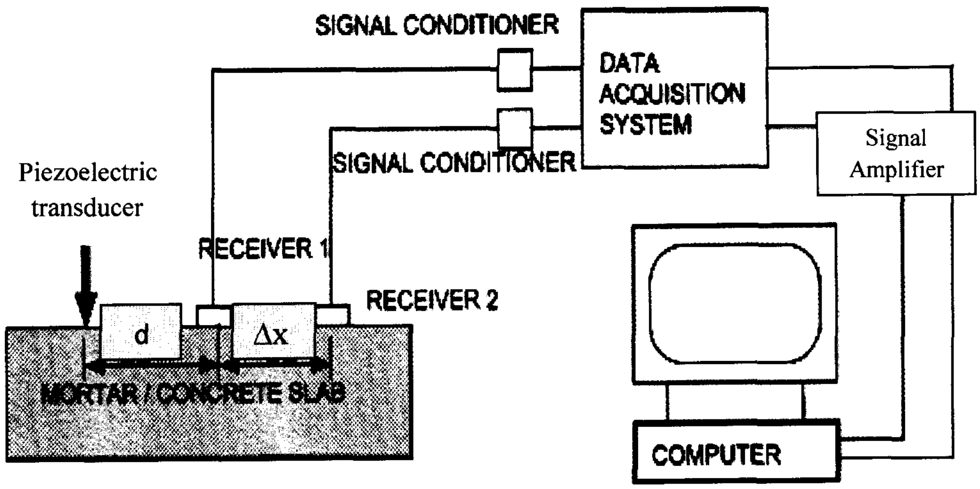


Figure 2.7: The layout for CSW testing system

Briefly, the SASW and CSW techniques can be differentiated according to their source and system set up in the field. Based on Table 2.5, the SASW and CSW technique has been summarized. The CSW system uses a ground vibrator as the source of the energy; meanwhile the SASW uses an impact source, usually a sledgehammer in order to produce seismic source. The difference in performance between the two systems is the depth of penetration that can be achieved. This will depend on the source used and the material under test.

Table 2.5: Summary of SASW and CSW seismic surface wave technique (Ganji et al., 1997; Sutton et al., 1998)

Types of common seismic surface wave method	
SASW	• SASW is a spectral analysis surface wave. • This method makes use of a hammer as an energy source. • The SASW method relies on the frequency spectrum of the energy source used. • No borehole required. Field method is quick and relatively simple. • No selective control over the frequencies generated, therefore measurements are limited to those frequencies, which can be generated in medium by a given impulsive seismic source. It may be necessary to use a number of different impulsive energy sources. • Real time waveform display while testing
CSW	• CSW is a continuous surface wave. • The CSW system uses a vibrator to couple a ground motion into the ground at a specific frequency. • The vibrator generates a predominantly vertical ground motion at a constant frequency. The frequency can be progressively incremented to obtain the phase velocity for different frequencies. • No borehole required. Selective frequency control of vibratory seismic source.

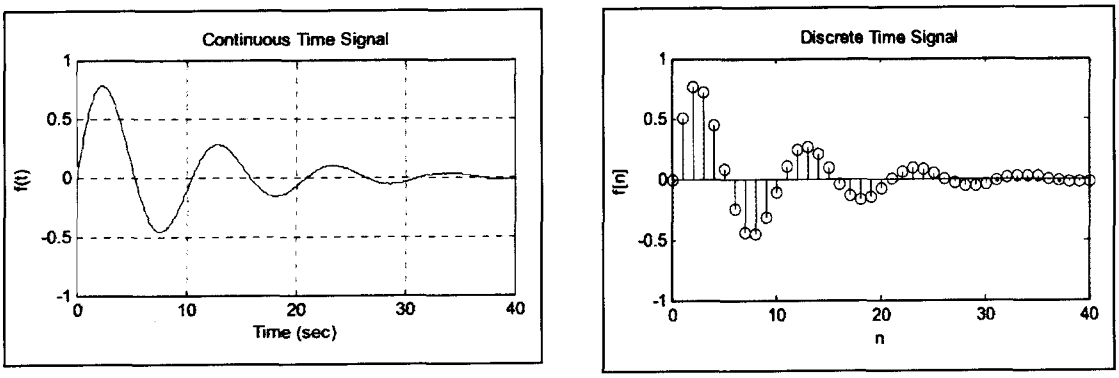
	• Field method is relatively quick and simple. Preliminary result stiffness-depth profile may be viewed on the site. • Depth of investigation is currently limited to about 10 m unless large lorry mounted vibrations are employed to excite low frequency.

2.6 Data processing technique

In signal processing, time frequency analysis comprises a technique to study a signal in both; the time domain and frequency domain simultaneously, using various time frequency representations. Time domain and frequency domain are two modes used to analyze data. A time domain graph shows how a signal changes over time, whereas a frequency domain graph shows how much of the signal lies within each given frequency band over a range of frequencies. In a time domain analysis, the variable is always measured against time. In most of the engineering applications, signals are collected in time domain using a data acquisition system (DAQ).

Frequency domain analysis is widely used in fields such as control systems engineering, electronics and statistics. This refers to analyzing a mathematical function or a signal with respect to the frequency. Frequency domain analysis is mostly used for signals or functions that are periodic over time. A signal is any time varying quantity. A signal contains information about the nature of the phenomenon. For example, in geophysical techniques the displacement or velocity of the ground is measured and recorded as a function of time. These recorded signals carry valuable information about the geological structure of the earth. Signals can be classified into two; continues time signal and discrete time signal as shown in Figure 2.8. A discrete time signal is a time series, a signal that has been sampled from a continuous time signal; furthermore it is a time series that is a function over a domain of integers.

Meanwhile, a digital signal is a discrete time signal that takes on only a discrete set of values. For processing digital systems, the discrete time signals are represented in digital form with each discrete time sample as binary word. Therefore, the analog to digital (ADC) and digital to analog (DAC) interface circuit is required in order to convert the continuous time signals into discrete time digital form and vice versa.



(a) (b)

Figure 2.8: (a) Continuous time signal graph and (b) Discrete time signal graph (Electrical signals in detail Analog and Digital signals http://www.indiastudychannel .com/resources/160259-Electrical-signals-in-detail-Analog-and-Digital-signals.aspx).

In order to convert a signal in the form of continuous time to discrete time a process called a sampling is used and as shown in Figure 2.9. In signal processing, a sampling process is a reduction of a continuous signal to a discrete signal. The value of the signal is measured at certain intervals in time. Each measurement is referred to as a sample.

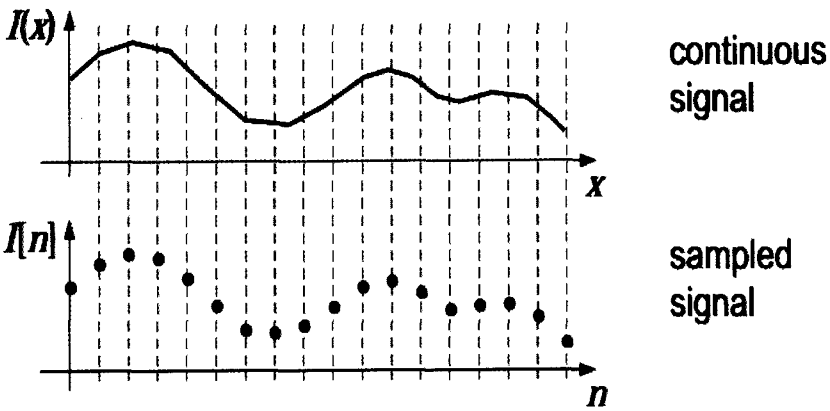


Figure 2.9: The sampling process of converting a continuous signal to discrete time (Electrical signals in detail Analog and Digital signals http ://www.indiastudychannel.com/resources/160259-Electrical-signals-in-detailAnalog-and-Digital-signals.aspx).

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