DEVELOPMENT OF TESTING SYSTEM BASED ON SURFACE WAVE SPECTRAL ANALYSIS (SASW) TECHNIQUE

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Seismic waves are waves of energy that travel through the core of the earth such as soil or other elastic bodies generated from earthquake, explosion, or some other process that involve the low-frequency acoustic energy. There are two types of seismic waves which are body and surface waves. Body waves travel through the interior of the Earth follow ray paths refracted by the varying density and stiffness of the Earth's interior while surfaces waves travel only on the surface of the Earth. Furthermore, in Civil Engineering, the term of stiffness is the ratio of the force divided by the displacement which is applied to materials or structures. High stiffness means that a large force produces a small displacement. When discussing the stiffness of a material, there is a relationship between the seismic waves and the surface wave velocity which is called seismic geophysical technique that important to ensure the durability of the structure or building to be built. Each ground improvement method needs to take into account the types of improvement and the deficiencies that are to be remedied. Thus, assessment of the effectiveness of ground improvement is critical to determine whether the quality of the works meets the prescribed requirements(Madun, 2012).This technique offers the method to surface wave velocity parameter in a cost effective way. The analyzing of the seismic waves is to obtain the phase velocity of the wave travelled through the propagation medium. The velocity then can be transformed to dispersion curve profile of the material. This surface wave technique had been used by many researchers, in various applications such as (Moxhay *et al.*, 2000) in monitoring of soil stiffness during ground improvement using seismic waves. (Mesures *et al.*, 1994) in surfaces wave velocity methods that are used to for determining moduli of the ground in situ at low strain.

1.2 Problem Statement

Soil characteristics of earth control the responses to earthquake and dynamic motions for building or structure. Therefore, stiffness profile of the soil must be determined correctly in order to get the optimum design in engineering. Lately, seismic wave methods have been introduced in geophysical engineering. There are many types of seismic waves, body wave, surface waves, S-waves and P-waves. These are commonly used to help petroleum engineers decide where to drill for oil. This method also helps civil engineers determine the thickness of a soil deposit over bedrock. The different type of seismic wave has been gaining importance for civil engineers which is the surface wave. A very valuable aspect of the surface wave is in a horizontal layered system, it will exhibit dispersion which the velocity will vary with frequency or wavelength. The variation of surface wave velocity with wavelength correlates to the variation of the earth’s stiffness with depth (Votano *et al.*, 2004). The dispersion curve profile parameter is crucial for predicting the deformation of material and foundation that may arise from loads imposed by civil engineering structures. However, existing method only focus using P-wave such as coring test to determine the structure properties profile and destructive testing will be conducted. Therefore, surface wave method approached in this study is important to ensure the integrity of the foundation on which the structure is to be built without damaging the material. In this research spectral analysis surface wave (SASW) technique will be applied to characterize dispersion curve material profile by varying the frequency via surface wave testing system. Thus the testing and data analysis steps are will be established at the end of this research.

1.3 Aim and Objectives

The aim of this project is to develop a testing system based on surface wave spectral analysis technique. This system should be applied on material or soil thus to evaluate the dispersion curve profile.

In order to achieve this aim, the objectives of the study are formulated as follow:

1. To develop surface wave system based on SASW technique.
2. To identify suitable data processing technique such as data acquisition in order to determine the dispersion curve profile of phase velocity material profile.
3. To identify suitable surface wave testing system for laboratory scale experiment

1.4 Scope of study

This research will focus on the source signal, which is propagated by piezoelectric transducers and studying the effect and relationship between source and data acquisition in order to measure the dispersion curve of phase velocity material profile.

CHAPTER 2

LITERATURE REVIEW

2.1 Seismic Wave

When mechanical energy is introduced to a medium, it induces the propagation of seismic waves (Phillips, 2004). Seismic waves are predicted during the 19th century. It is similar to sound waves except that the periods of oscillations are far longer. The frequency range of these waves is large from as high as the audible range to as low as the free oscillations of the entire earth. There are two types of seismic waves which is body and surface waves. P-wave or Primary wave and S-wave or Shear wave are also known as Body wave. In surface wave, there are two types of wave which are Rayleigh wave and Love wave. Figure 2.1 below shows the chart type of seismic wave.

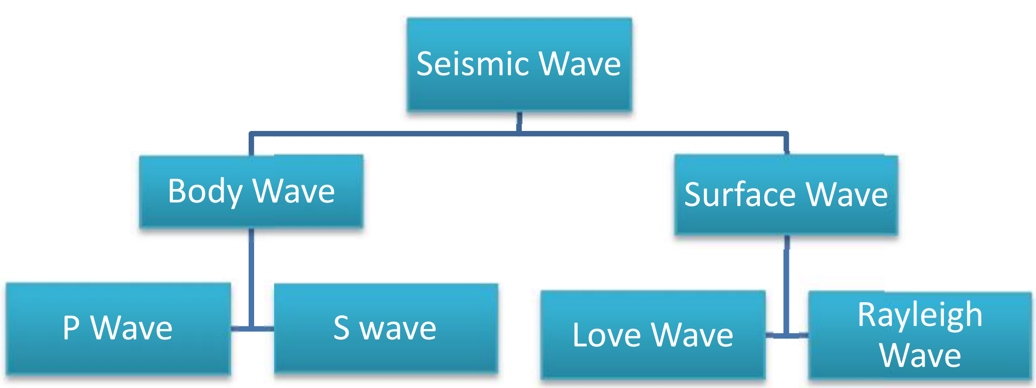


Figure 2.1: Type of seismic wave chart

2.2 Seismic Energy Sources

A seismic source can be derived as a tools or devices that controlled the seismic energy. Seismic source are widely used in seismic surveys such as investigate shallow subsoil structure or to study deeper structure. The requirement of using seismic source are listed in Table 1 below. 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. An overview about the difference types of seismic source have been given by Miller *et al*., (1986).

Table 1: Seismic source type (Source from Reynolds, J.M book "An introduction to applied environmental geophysics")

Source Type	On Land	On Water
Impact	1. Sledge Hammer 2. Drop weight 3. Accelerated weight	
Impulsive	1. Dynamite 2. Airgun 3. Detonating cord 4. Shotgun 5. Borehole Sparker	1. Water gun 2. Steam gun 3.Gas gun
Vibrator	1. Vibroseis 2.Vibrator Plate 3. Rayleigh wave generator 4. Multipulse 5. GeoChirp	

2.3 Seismic Surface Wave Technique

Surface waves can only be generated at free boundary which is divided into two types such as Rayleigh wave and Love wave. Rayleigh waves are named after Lord Rayleigh (John William Strutt, 3rd Baron Rayleigh, OM) who predicted their existence in 1885.
The Rayleigh wave is a function of frequency and this dependence is strictly related to the mechanical parameters of the medium (Geotecnica, 2000). Furthermore, the properties of Rayleigh waves indicate that it can always be generated on a free surfaces. Rayleigh waves, which are characterized as high amplitude and low-frequency surface waves, are usually dispersive in a non homogeneous medium (Min & Kim, 2006). The particle motion of this Rayleigh wave is a combination of longitudinal and vertical vibration that give elliptical motion to the structure are illustrated as figure 2 below. Rayleigh wave show dispersion and its velocity is not constant but varies with wavelength. Therefore, Surface wave technique is very powerful tools that have been used by many researchers. For example, surface wave testing such as a spectral analysis of surface wave (SASW) method (Alam & Mcclellan, 2003) and continuous surface wave (CSW) method (Moxhay *et al.*, 2000).

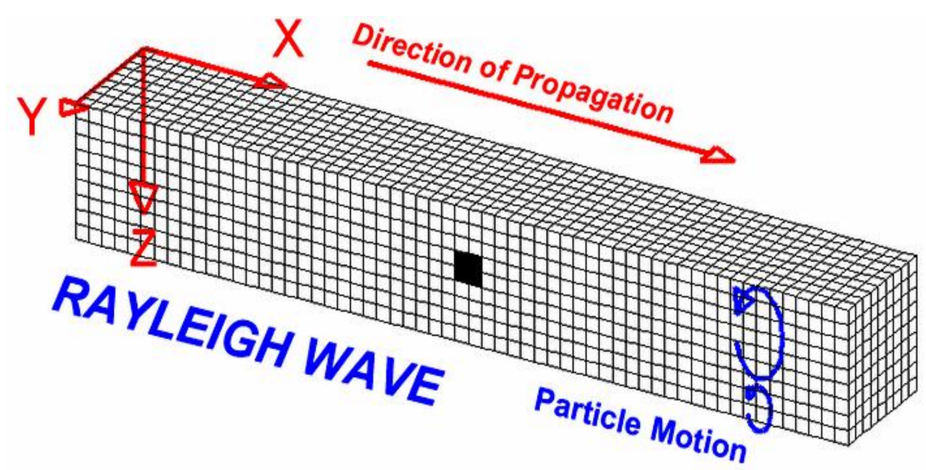


Figure 2.2: Rayleigh wave motion. Source:(www.geo.mtu.edu/UPSeis/waves.html)

2.4 Spectral Analysis Surface Wave Method

Spectrum Analysis of surface waves (SASW) is one of the most effective non-invasive methods for soil characterization (Alam & Mcclellan, 2003.). SASW typically used in site investigations for foundation engineering design and settlement prediction in geotechnical technology. SASW is a non destructive and in situ method used for determining the thickness and elastic properties of pavement and soil sites using the dispersion characteristic of surface wave (Al-Hunaidi, 1993). The energy of Rayleigh waves from the source propagate mechanically along the surface of media and their amplitude decrease rapidly with depth (Rosyidi, 2004). The technique that is used in determining the dispersion curve (Phase velocity VS Frequency) was introduce by SASW method which is possible to calculate the parameter of the medium either on free surface of the boundary. SASW methods are followed by two aspects of procedures which is considered as relative phase angle unwrapping and source-to-near-receiver distance (Al-Hunaidi, 1993). Figure 3 and Figure 4 show the application of SASW technique.

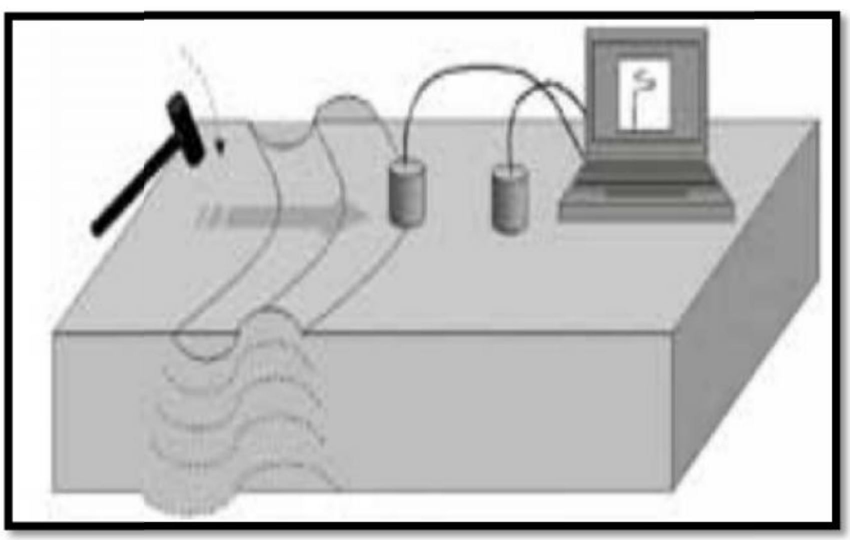


Figure 2.3: SASW Principle testing Kit. Source; (http://www.forcetechnology.com)

Figure 2.4: Testing SASW kit on soil. Source; (http:// www.gdsinstruments.com)

2.5 Data Acquisition

Data acquisition is the process of sampling signals to determine the conditions of the signal and converting the resulting samples into digital that can be manipulated by a computer. Data acquisition systems actually convert analog waveforms into digital values for processing by using computer. The components of data acquisition systems can be divided into three as follows:

i) Sensors that convert physical parameters to electrical signals.

ii) Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values.

iii) Analog-to-digital converters, which convert conditioned sensor signals to digital values.

DAQ hardware is what usually interfaces between the signal and a computer. National Instruments DAQ is the most trusted computer-based measurement hardware available. Innovative DAQ hardware and NI-DAQmx driver technologies gives better accuracy and maximized performance. Regardless of our application, whether for basic measurements or complex systems, NI has the right tools for the job. The two-station acquisition pioneered by Jones (1958, 1962) and Ballard (1964) developed to become the SASW test (Nazarian and Stokoe, 1984; Stokoe et al., 1994) has been widely used for geotechnical characterization and for pavement assessment (Socco & Strobbia, 2004).

2.6 Preceding study

In this part, Table 2 below shows the previous research about the development of spectral analysis of surface wave technique studied by using different method.

Table 2: Method from previous research

AUTHOR	TITLE	METHOD
N. Gucunski and R.D. Woods	Numerical Simulation of the SASW test	Evaluation of dispersion curve.
Longzhu Chena, Jinying Zhub, Xishui Yanc, and Chunyu Songa	On arrangement of source and receivers in SASW testing	Rayleigh transient wave
S.A. Rosyidi, K.A.M. Nayan and M.R. Taha	Measurement of subgrade stiffness using the SASW method	Fast Fourier Transform (FFT Analysis)
M.O Al Hunaidi	Insights on the SASW nondestructive testing method	Relative phase angle unwrapping and source to near receiver distance
Goh, TL Samsudin, AR Rafek, AG	Application of spectral analysis of surfaces waves (SASW) method: Rock mass characterization	WinSASW 3.1.3 software

2.6.1 Numerical Simulation of the SASW test (Gucunski & Woods, 1992).

This paper proposed the seismic wave SASW method in order to obtain and evaluate the dispersion curve on several of soil condition. The SASW method basically operates with the dispersion of Rayleigh wave in layer systems which are propagated in different frequency and velocity. The SASW test basically has three basic development such as collection data, evaluation of Rayleigh wave dispersion curve and also inversion of dispersion which is manually conducted by user. This paper actually produced the numerical modeling of SASW test on various situation of soil profiles or condition. Average dispersion curves have been combine which are the dispersion curves for several receiver spacing and two direction of dispersion curve. Moreover, they have compared the inversion process to theoretically defined as solution. In this paper, the author proposed the receiver spacing range of 0.5 till 1 s. However, source near to the receiver distance had the least affected on the scattering the dispersion curve. The dispersion curve from SASW test can differ significantly. That can cause Heisey's criteria to only accept the wavelength that is too close to the source which is still in process and possible interference that are more near or closer to the source. The coherence function has been used in this paper as a corrector to the ambient noises which are from attenuation signal when constructed the testing field. Finally, this paper shows the dispersion curve that is only affected by the source to near receiver spacing. Thus, the approach of this paper will be applied in this study for example the evaluation of dispersion curve in order to get the stiffness profile of the material.

2.6.2 On arrangement of source and receivers in SASW testing (Chen et al., 2004)

This paper investigated the arrangement of source and receiver on Rayleigh Wave dispersion curve by SASW testing. To overcome the error of Rayleigh wave phase velocity measurement, this paper proposed difference Poisson's ratio of soil or saturated soil. According to the elastic wave theory, Rayleigh wave V_R is related to shear wave velocity Vs of the material by Poisson's ratio, v. Therefore, if Rayleigh Wave can be measured, the shear wave velocity can be easily determined. In real situation, ideal of surface wave is difficult to generate. So, SASW method is used to apply the transient wave on the surface of the soil. The Rayleigh wave assumption is valid only when the source and receiver arrangement meet certain criteria which are affected by Poisson's ratio. In order to achieve this study, the Rayleigh wave method that approach from this paper will be applied in order to differ or compare the result each of the materials or samples.

2.6.3 Measurement of subgrade stiffness using the SASW method (Rosyidi, 2004)

This paper has developed the SASW method to estimate the stiffness of pavement profile foundation. The accurate parameter information such as the elastic moduli and thickness of the various pavement layers are used to calculate the load capacity and also estimate the properties of road itself in order to predict the performance and design of the pavement profiles. In this paper, the SASW method is based on Rayleigh Wave dispersion curve in order to determine the shear wave velocity, modulis, and depth of each layer. This paper has discussed the theory, role and method of SASW in order to evaluate the pavement profile. The test of SASW has been conducted at Universiti Kebangsaan Malaysia (UKM), Bangi. All data that have been tested are transformed into frequency domain by using Fast Fourier Transform (FFT) analysis method of spectrum analyzer. There are two functions of frequency domains which are the coherence function and the phase information of transfer function. The coherence functions are used to inspect or evaluate the quality of signal by Signal to Noise Ratio while transfer function spectrum is used to obtain the relative phase shift between two signals. All the data are unwrap in order to get the dispersion curve. This paper is able to characterize the stiffness of pavement profile in term of shear wave velocity by using SASW method. Thus, the FFT analysis method approach by this paper will be applied for this study in order to get the dispersion curve of stiffness profile.

2.6.4 **Insights on the SASW nondestructive testing method (Al-Hunaidi, 1993)**

This paper proposed the procedures of the SASW technique which are the relative phase angle unwrapping and source to near receiver distance. These methods have major advantages in performing the test in a short period and also cause no physical damage to tested material. A vertical vibration placed on the surface of the sublayer or soil is used as a source. The vibration transducer will produce certain frequency by tuning the source. Computer simulation of surface waves test have been conducted in this paper. The purpose of the simulations is to clarify the errors in the dispersion curves when the SASW test and data analysis are performed with the procedures. By the way, the phase unwrapping procedure may be not reliable or suitable for some surfaces of material. However, another alternative procedure is needed such as to calculate the time delay between the SASW receivers. By using the simulated wave at the surface, this study demonstrated that source near the receiver distances taken to be equal to the spacing between the receiver and the wavelength should be greater than ½ the receiver spacing insufficient to ensure the condition that the measured wave only for considered site or material. In other hand, the procedure approach from this paper can be used in this study in order to determine the phase velocity or dispersion curve.

2.6.5 **Application of spectral analysis of surfaces waves (SASW) method: Rock mass characterization (GOH et al., 2011)**

This paper is proposed to determine the Rock Quality Designation (RQD) by using spectral analysis of surface wave (SASW). Soil and rock engineering usually perform the Standard Penetration test (SPT) and seismic test. The SPT test normally involved drilling and laboratory works and in high cost, while seismic test are fast, cheap, non destructive and easy to operated for rock mass characterization. In this study, WinSASW 3.1.3 was used for inversion processing of SASW data to get the shear wave velocity versus depth profile. The impacted from hammer are used to generate Rayleigh wave, detected by two receiver and recorded by a spectrum analyzer. After performing the test, the difference between RQD value from SASW test and those discontinuity surveys are less than 10%. In other hand, the SASW test is valid in seismic application for RQD measurement. Thus, the steps, procedures and approach that have been used in this paper will be used in the study. However, data acquisition DAQ will be used to analysis of the data.

CHAPTER 3

METHODOLOGY

3.1 Research Flowchart

The step and flow of this research are shown from the research flow chart as in figure 3.1 and 3.2. This research can be divided into two part which are the hardware and software development.

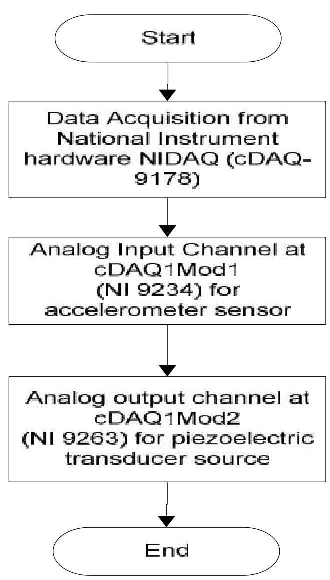


Figure 3.1: Flow chart of hardware setup

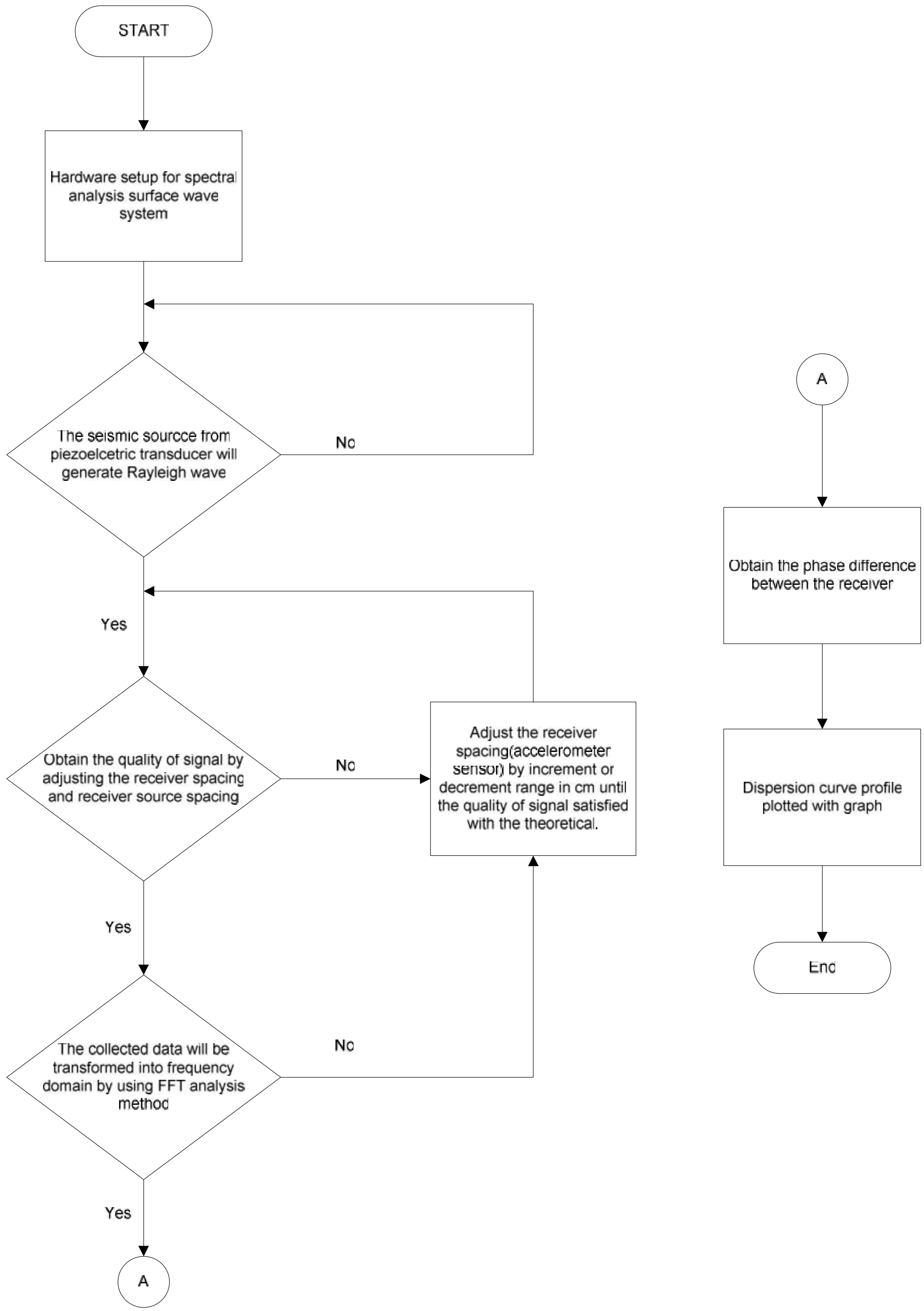


Figure 3.2: Flowchart of data analysis by SASW technique from seismic source software

The hardware part is by using DAQ tools by National Instruments to collect the data from the seismic wave source via piezoelectric transducer. The data will be used to conduct the analysis of the surface wave system which consists of two main process such as adjusting the receiver spacing and varying the frequency. The recorded signal from transceivers or source will be transformed into frequency domain using Fast Fourier Transform (FFT) analysis method and develop the dispersion curve (wavelength VS phase velocity). The result will be determined and discuss after these two of main data processing have been analyzed.

3.2 Hardware Development

Figure 3.3 below shows the diagram of the hardware setup in the laboratory in order to develop the seismic surface wave system.

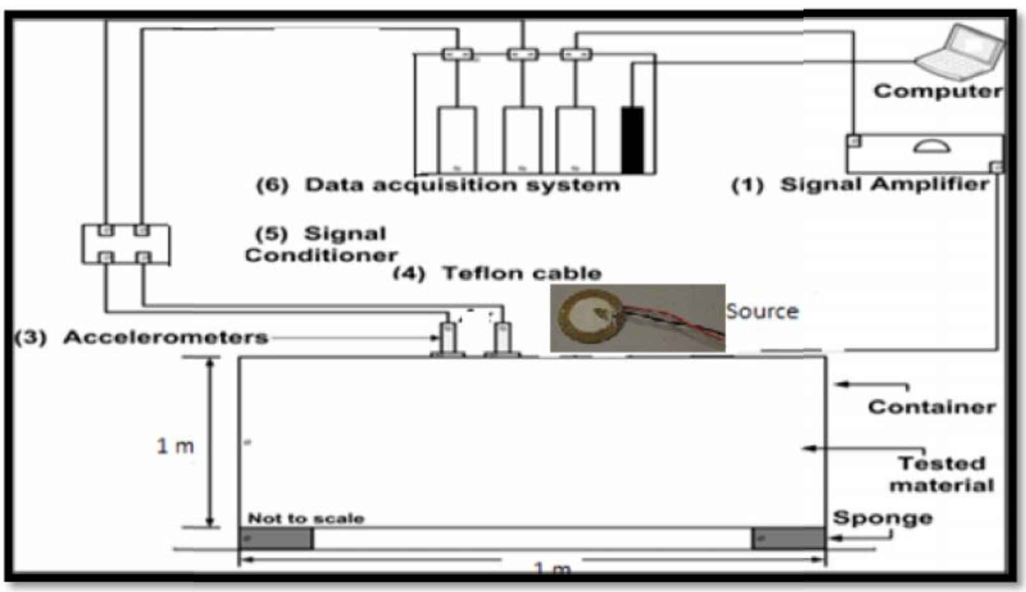


Figure 3.3: Hardware set up for seismic surface wave in the laboratory

Based on Figure 3.3, a source with a piezoelectric transducer is applied on the tested material which, in this research, is the concrete block to perform the test. An impact source on a tested material is used to generate the Rayleigh waves. The development of more powerful computers for signal processing and for numerical analysis has enabled the SASW method to be more practical (Ismail *et al.*, 2012). The experiment will be carried out by using computer system with Matlab platform.

The computer will be connected to the National Instruments data acquisition system, in which an analogue output module (NI-9263) will generate the transmitted waveforms. On the receiver side, the sensors consist of two piezoelectric accelerometers. The accelerometer was connected via cable to an analogue signal conditioner. The seismic signals are then sampled by analogue-to-digital converter module (NI-9239). Table 3 below shows the general properties each of the hardware used in this research. Figure 3.4 below shows the hardware cDAQ-9178 that has been used in order to develop the seismic surface wave system via SASW technique.

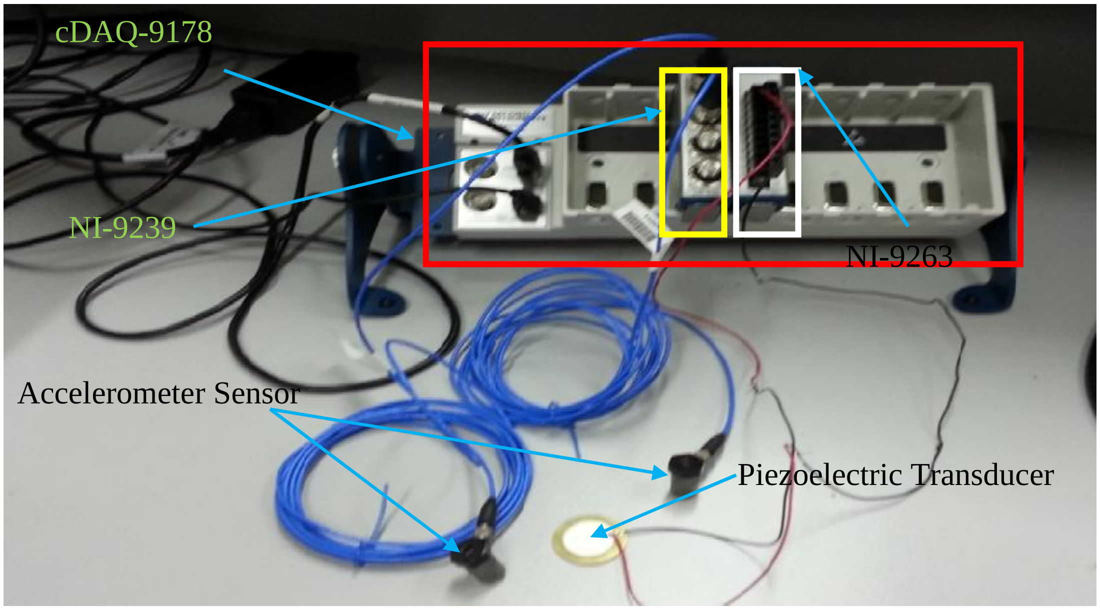
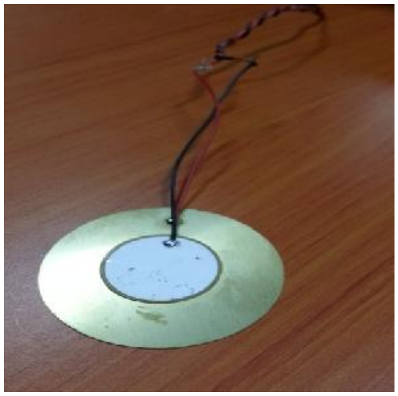


Figure 3.4: NIDAQ hardware setup with cDAQ-9178

Collected data were stored, and then will be processed after the completion of a data acquisition session. The two receivers placed along a straight line will detect the transient signal produced by the vertical impact source. The signals are recorded using data acquisition system. The next process is to transform the time domain signals to frequency domain using Fast Fourier Transforms to have better analysis with the measurement. The coherent between the signals and the phase information of the transfer function are evaluated from the output.

Table 3: List of Hardware with Description

No.	Hardware	Description
1.	Sensor 	• Piezoelectric accelerometers (model 352C42 from PCBpiezotronics) with a frequency range of 1 Hz to 10 kHz
2.	DAQ Platform (cDAQ - 9178) 	• The computer will be connected to a National Instruments data acquisition system, in which a 16-bit analogue output module (NI-9263) will generate the transmitted waveforms. • The input seismic signals are then sampled by a 24-bit sigma-delta analogue-to-digital converter module (NI-9239) with a sampling rate of 50 kHz.
3.	Signal conditioner 	• The accelerometer was connected via cable to an analogue signal conditioner (model482C05) • The signal conditioner purpose to filter the noise incoming from the signal

<table>
<tr>
<td>4.</td>
<td>Piezoelectric Transducer
</td>
<td>• These ceramic piezo transducer elements generate a range of audible tones and frequencies when energised
• Piezo transducer generate the Rayleigh waves.
• They withstand severe environmental conditions and prove durable in domestic appliances without causing RF interference.</td>
</tr>
<tr>
<td>5.</td>
<td>NI-9234
</td>
<td>• The NI 9234 have four-channel with signal acquisition module for making high-accuracy measurements from integrated electronic piezoelectric (IEPE) and non-IEPE sensors</td>
</tr>
<tr>
<td>6.</td>
<td>NI-9263
</td>
<td>• The NI 9263 have 4-channel, 100 kS/s simultaneously updating analog output module for any NI CompactDAQ
• The NI 9263 also features ±30 V overvoltage protection and short-circuit protection.</td>
</tr>
</table>

3.3 Software Development

Based on Figure 3.5 below, the test required a vertically oriented impact source from piezoelectric transducer enabling the generation of Rayleigh wave over a wide frequency bandwidth. The receivers are arranged to be in line with the source (Hunaidi *et al*., 2002).

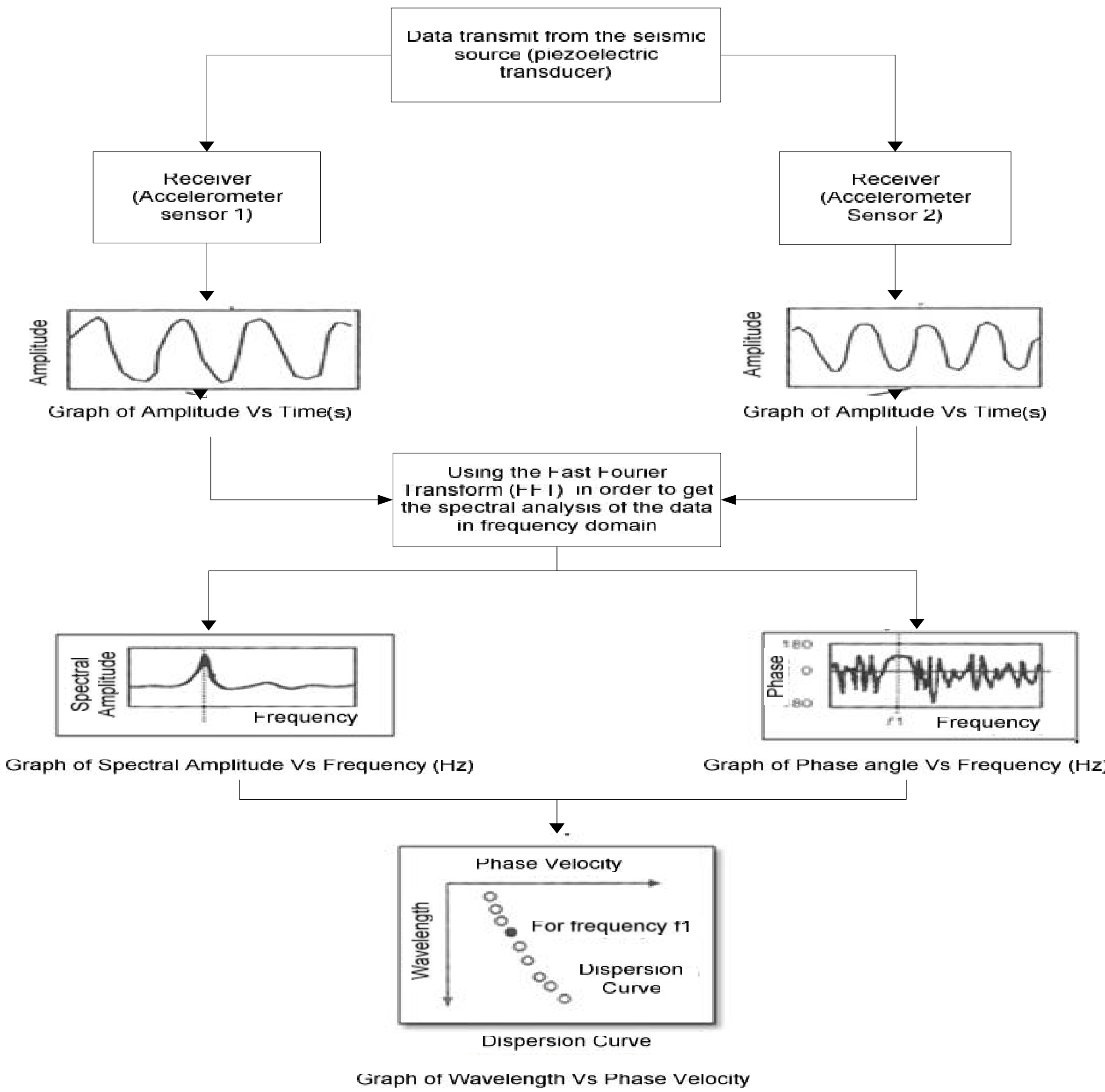


Figure 3.5: Flow of data processing

Vertical motion induced by the source at the free surface of the material is detected by the two receivers or accelerometer sensors and recorded in time domain. The data will be transformed using Fast Fourier Transform (FFT) to get the frequency domain and unwrap the phase angle to get phase velocity versus frequency graph of dispersion curves. The phase differences between the signal captured from two receivers can be determined. The signals picked up by the receivers are recorded and Fourier Transformed by using a Fast Fourier Transform (FFT) analyzer to obtain the relative phase between the receivers as a function of frequency (Al-Hunaidi, 1993). Furthermore, the phase velocity can be calculated by using approximation method but least exact. The amplitude of surface wave is attenuated linearly with depth and can be represent by a direct relationship of equation 2. First, the travel time needs to be measured by using;

$$\Delta t = \frac{\Delta(\emptyset)}{2\pi f} \qquad (1)$$

Where $\Delta(\emptyset)$ = Phase difference at frequency

f= Frequency to which the time difference applied

Relationship between the Δt and Δ (Ø) can determine the phase velocity by using;

$$Vph = \frac{D}{\Delta t} \qquad (2)$$

Where D = Distance between sensor

Δt = Frequency Dependent time difference

If wavelength is required, therefore;

$$\lambda = \frac{V}{f} \qquad (3)$$

Where V = Phase velocity

f = frequency in cycle per second

The approximation method is commonly used as documented in the literature (Jones, 1958; Heukolom and Foster, 1962; Ballard and Mclean, 1975; Abbiss, 1981).

The known material which is concrete material will be used to verify this system. The types of concrete will be used in this study is concrete mortar. The reason why concrete mortar material has been chosen for this research is because concrete mortar properties such as density and moisture content, is not influenced by the ambient environment such as water effect and duration of time during the experiment. To construct the concrete mortar model, sand, cement and also water are used. The measured concrete stiffness using this system will be verified using theoretical of concrete mortar itself. The surface wave velocity in the concrete mortar block was expected to be approximately 300 m/s -400 m/s.

3.4 Receiver Spacing

The arrangement of receiver and excitation transmitter arrays is subject to the near and far offset constraints (Heissey *et al.,* 1982). These constraints control the wavelength from the signal therefore, it is important to determine the minimum and maximum frequency for spectral analysis using FFT. The empirical study for the near offset constraint of the distance between the source and the first receiver, d_{min} is recommended in the literature (Alhunaidi, 1993; Matthews *et al.,* 1996; Park *et al.,* 1999) as s function of the surface wave wavelength, to be approximately :

$$\mathrm{dmin} > \frac{\lambda max}{3} \qquad (4)$$

When the receiver is far away from the seismic source, then the constraint can be approximately:

$$\mathrm{dmax} < \frac{\lambda min}{2} \qquad (5)$$

So, the spacing between the receivers, Δx, is should be:

$$\Delta x < \frac{\lambda min}{2} \qquad (6)$$

The phase difference between pair of receivers can be determined. To avoid aliasing between the receivers, the λ_{min} and λ_{max} are corresponding to minimum and maximum frequency that can be generated by the seismic source. A more detailed study on the data acquisition of Rayleigh wave was carried out by Xia *et al.*, (2006).

3.5 Experimental Setup and Calibration

To evaluate the viability of this study, a laboratory scale experiment was carried out. The purpose of performing the laboratory scale experiment instead of a field test is that the data collection can be pre calibrated and the truth data regarding the material can be measured. In this study, a concrete mortar box were constructed with dimension 1500 mm x 1000 mm x 1000 mm in length, width and depth such as figure 3.6 below. The mortar concrete were constructed with a mixture of fine sand and cement with ratio 1:15. The mortar was chosen because its geotechnical properties such as moisture content easy to control within the duration of the experiment.

Figure 3.6 : Concrete Mortar Box

A portable ultrasonic velocity profiler was used to measure the P-wave velocity on the mortar concrete and the measurement was in range within the range 600 m/s to 700 m/s. The Rayleigh wave phase velocity of homogenous in concrete mortar block was expected to be approximately 1000 m/s (khan *et al* 2006). However, in this study the ratio 1:15 of the concrete are used, therefore the phase velocity of the concrete mortar approximately within the range of 300 m/s to 400 m/s.

3.6 Experimental Procedure

The array of receiver consisted of two piezoelectric accelerometers. The receiver array was then moved after each measurement in order to obtain the data for each range between the source and the receiver. Firstly, the distance between the source and the first receiver, d was set up as 50 mm such as figure below:

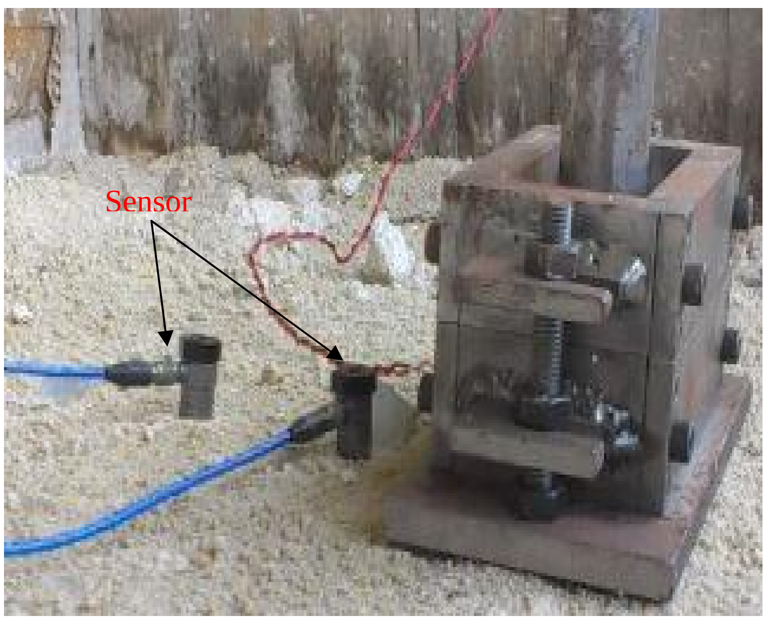


Figure 3.7 : Sensor Arrangements

By using the constraint given in equation 4 and equation 5, and assuming the Rayleigh wave phase velocity as 300 m/s to 400 m/s, the applicable frequency range from the piezoelectric transducer was between the 500 Hz to 10 KHz. More sequence of data collection have been tested shown as figure 3.8 below: