ISSN 2278-3091
Volume 8, No.1.6, 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse0481.62019.pdf
https://doi.org/10.30534/ijatcse/2019/0481.62019

# Soil Compaction Testing using Piezoelectric Sensor

**Nurul Afiqah Izahar**[1], **Siti Zarina Mohd Muji**[2], **Mohd Helmy Abd Wahab**[2] , **Muhammad Jaysuman Puspanathan**[3]
[1]ZTE (Malaysia) Corporation Sdn Bhd (642514-X) Suite 18-08, Level 18 G Tower, 199, Jalan Tun Razak, 50400 Kuala Lumpur
[2]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, szarina@uthm.edu.my,helmy@uthm.edu.my
[3]Sport Innovation and Technology Centre (SITC), School of Biomedical Engineering & Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Johor 81310, Malaysia
jaysuman@utm.my

## ABSTRACT

This paper presents the soil compaction testing using piezoelectric sensor. In this study, the shear wave velocity and small- strain shear modulus, Gmax value were measured and has been used as parameters for soil compaction testing. The experiment has been conducted on two different specimens, A and B. Specimen B are denser than specimen A. In this project, ±20V sine pulse of frequencies ranging around 3 kHz until 20 kHz is injected to the transmitter of bender element (piezoelectric sensor) to make it vibrated and caused a shear wave propagation in soil. Then, the receiver of bender element (piezoelectric sensor) receives the waves and convert the motion of that wave into electrical signals. As a result, there is a relation between the frequency injected and the shear wave velocity. It shows better linearity in specimen B compared to specimen A in both shear waves velocity and travel time. Based on the test results obtained in this experiment, a clear difference in the small-strain shear modulus, Gmax values for the tested soil specimens was observed using the shear waves velocity result. It is proven that the piezoelectric sensor can be employed for determining the shear wave velocity in soils efficiently.

**Key words :** Soil, compaction, piezoelectric, shear wave velocity

## 1. INTRODUCTION

Buying a house is the largest financial investment for people nowadays. Normally, houses are built in the location where the soil conditions are not perfect. The land selection factor include availability, cost and proximity to schools and the industrial areas. In fact, the main reason for selecting a certain land to develop, of course, there is a strong demand of people who want to buy homes in that area and a profit can be made from selling the houses. People should know that there is soils with the potential to shrink or swell are found throughout the Malaysia. Construct buildings and housings on soils with shrink or swell potential will create a lot of difficult problems. Hence, potential problems and costly mistakes can be avoided by the developer and buyers if a study of the soil and site characteristic was made before construction begins or before a house is purchased by doing the compaction testing.

There were many different types of soil that can be encountered at construction sites. Characteristics of soil such as the size and nature of particles, its density and structural properties were very important and it is required when to make design and construction decisions.

Physical properties of soil will affect its strength and stability. Soils with good structures were more stable. Clay textures were more stable than sand textures because they have better structures. However, mixes of particles sizes were best for engineering construction. Note that soils were stable through cycles of wetting and drying. Therefore, there is no crack on the roads or foundations that cause from expanding soils.

Good soils have the ability to capture precipitation, so that runoff and erosion do not damage its structures. In fact, good soils for infrastructure should have balanced chemistry so that there will no building material corrosion occurs. Hence, testing the soil condition is important before any development of construction taking place. In this paper, S wave will be investigated as a way to test the soil compaction.

Based on wave definition, it state that wave is a vibration that transfers energy from one place to another in matter such as solid, liquid or gas [1]. Light and sound both travel in this way. During an earthquake, energy has been released and travels in the form of seismic waves around the Earth. There were two types of seismic wave exist which is P and S waves. They were different in the way that they travel through Earth. P-waves which stand for primary wave arrived at the detector of seismometer first. P-waves are also known as compression wave. The longitudinal waves is when the vibrations are along the same direction as the direction travel.

S-waves are stand for secondary wave that arrived at the detector of a seismometer. S-waves are also known as shear wave. The transverse waves is when the vibrations are at right angles to the direction of travel. Both types of seismic wave can be detected near the earthquake centre but only P-waves can be detected on the other side of the Earth.

Some researcher discover the prediction technique to measure the soil condition as did by [2] and [3]. However this technique is not measuring the real situation. The result obtained would change depend on many factors. Ultrasonic can become a tool for testing the soil condition as did by Wang et. al [4]. They prove that ultrasonic tests can be suitably exploited for the mechanical study of soil using P wave piezoelectric transducer with frequency 130kHZ and 500kHz.

Disk shaped Piezo-ceramic transducers was capable to measure both P and S waves in a soil specimen. Experimental studies has been done using two types of Piezo-ceramic elements. The P-waves and S-waves were placed together in a metal housing for measurement purpose. Both worked as a wave measuring transducer installed in a triaxial apparatus [5]. The disk transducer was not inserted into the specimen in order to free out from the difficulties of preserving the integrity of the material around it. However, it needs a good contact between the transducer surface and specimen. In this research, it was recommended to use the frequencies which less than 8 KHz in order to successfully transmit the S-waves [5]. The disk transducer was effective wave measurement technique for wave measurements in soil specimens.

A research was conducted on the interpretation of shear wave velocity from the bender element test [6]. This research was aimed to investigate the main factors that affected the interpretations of shear wave velocity by using bender element in unconfined specimen. Based on this research, one of the factors that affected the interpretations of shear wave velocity was input frequency [6]. High input frequency introduced interference to the received signal prior to the first positive major deflection. Moreover, strength of the received signals also diminished with increased input frequency. In addition, distortion of a signal also occurred due to interference of reflected waves from the medium boundaries. Observation has been made and it stated that the further the distance of the boundaries in direction of the polarization of shear wave, the less prominent the effect of lateral rebound and distortion of propagating wave [6]. Besides that, specimen geometry was also one of the factors that affecting the interpretations of shear wave velocity. This explained why dispersion plots from the larger specimens displayed better linearity that the other small specimens [6]. These bender element tests were beneficial because it was easily repeatable to test on the same specimen and adaptability of the bender element transducer for installation in existing test apparatus. These research concluded that various factor were found to affect the measurement of shear wave velocity such as input frequency and specimen geometry [6].

A review about modelling of soil compaction and its impact has been done [7]. Experimental studies show that the soil compaction results are depend on soil strength, bulk density, volumetric water contents and field capacity [7]. However, it was decreases in total porosity, soil aeration, water infiltration rate and saturated hydraulic conductivity. The natural causes of the soil compaction was rainfall, plank roots, foot traffic of man or animal and in terms of artificial were some mechanical operations [7]. Nowadays, several models of soil compaction testing were available not only assessed the soil compaction due to traffic load but also calculated the negative effect of soil compaction on different compartment of soil, plant and environment. However, there were no unique models for all types of soil [7].

Meanwhile in Mexico, some researchers had performed a compression and shear wave's velocities measurement on Mexico City clay samples. Based on their work, an experimental has been conducted where the compression and shear wave velocities were measured with piezoelectric crystals in two different soil samples inside in a triaxial cell [8]. The both samples were similar in terms of index properties but show different in regards to stress history, ageing and time-dependent bonding effects [8]. The isotropic compressibility was obtained when testing the reconstituted sample. It displayed an initial yield point upon the application of additional stresses, until reached its virgin consolidation line [8]. In addition, shear wave velocities measured were found to relate linearly to effective stress after each isotropic load increment [8].

An experiment has been conducted to identify the shear wave velocity by using piezoelectric film. The research has measure the shear wave velocity through shear wave propagation [9]. The shear wave was generated and received by piezoelectric sensors that placed at opposite side of the soil sample [9]. Limitations of this piezoelectric film sensor has been found which it is the series connected piezoelectric film sensor was not good to be used as a sending sensor because the sending signal was not strong enough. This limitation was lead to the occurrence of cross talk during shear wave measurement. [9]. The benefits of piezoelectric film sensor such as its light weight, budget and less disturbance during the sensor installation. Despite all that, piezoelectric film technique was still be able to measure the shear wave velocity and the result obtained was similar to the shear wave velocity data from the field test [9].

Meanwhile in Tokyo, Japan, experimental studies to measure the shear wave and compression wave velocities in laboratory triaxial test using disk shaped composite P/S piezoelectric transducer is being done [10]. The wave measurement system performance was conducted by analyse the crosstalk effect, transmission cables quality and recording unit features[10]. The experimental studies showed that crosstalk deterioration was eliminated successfully through a complete grounding and the used of coaxial cables that enhanced signal to noise ratio of the received signals. The identification of near field effect in shear wave receiver signal were found by combined the monitoring of shear and compression waves using the transducer [10]. Based on the experimental results obtained, disk type transducer shown a potential for laboratory determination of shear modulus and constrained compression modulus of soil due to its robustness and non-invasive nature.

A new approach which used crawling wave chirps were found to measured shear wave speed and shears speed dispersion of elastic materials. In this research, biomaterials were scanned while being vibrated with a reciprocal chirp signal over the defined range such that each frame of the acquired movie represents one frequency [11]. The motion slice defined at a certain depth and displayed distinctive straight equal-phase line which simplified the further processing [11]. Doppler processing of an acquired signal produced images of the square of vibration amplitude where the repetitive constructive and destructive interference patterns which called crawling waves were shown [11]. Sweeping the vibration frequency and analysis approach provided more advantages over earlier technique where repetitive measurement were made for each frequency at distance steps over a bandwidth.

At the same time, investigation of piezoelectric bimorph bender transducer that generates and receive shear wave has been done. The piezoelectric bimorph element was demonstrated by housing the bimorph elements in probes and inserted directly into sediments [12]. Measurement were taken in terrestrial environment and it showed that each of the receive signals decayed in amplitude and has delayed time of arrival as a function distance from the source. The attenuation of 45dB/m was reported had a combined loss due to absorption and spreading [12]. It claimed that Piezo-ceramic bimorph bender elements were useful in probe transducer to gather in situ measurement of shear wave and attenuation [12].

There was an imaging technique named transient elastography which implements small frequency shear waves in direction of diffusion of ultrasound waves at a relatively much cheaper manner [13]. This technique was used to visualize and calculate the stiffness of the materials. The piezoelectric crystal in the ultrasound probe was energized using high voltage pulsar which altered the digital pulses into high voltage impulses [13]. This research proved that transient elastography technique was capable to measure elasticity.

Recently in 2016, the research about estimation of small strain-shear modulus of embankment soils before construction using bender element in compaction has been done. According to this research, a new method has been proposed which Gmax value was determined by using bender element within mould of laboratory compaction test [14]. This test was generally performed to decide the specifications of field compaction before construction [14]. The testing procedure was laid out for bender element test after compaction of soil in the mould and vertical load has been applied to stimulate the overburden expected at different depths of embankment. It concluded that the proposed testing method can be performed at different overburden pressure values to define shear modulus variation with different depth and it also acted as a tool for quality control of compaction in field.

As time goes by, an Omni-directional SH wave piezoelectric transducer (OSH-PT) was proposed which consist of a ring array of twelve face shear wave (d24) trapezoidal PZT element [15]. The proposed Omni-directional transducer can excite and receive pure SH wave over full 360 ° in plate- like structure. It claimed that each PZT element produced face-shear deformation under voltage [15]. In fact, the pure SH waves were excited and received in a selected frequency range where no unwanted wave modes such as lamb wave generated [15].

This paper present soil compaction testing using Piezoelectric Sensor where here the problem is to measure the soil compaction. From the reviewing process that have been done, the suitable technique to be used is using piezoelectric by differentiating the effect of frequency towards its shear wave velocities. Piezoelectric are used for quality assurance, process control, and for research and development in many industries. It was discovered in the 1880's by the Curie brothers, but only in the 1950's did manufacturers begin to use the piezoelectric effect in the industrial sensing application [16]. Since then, this measuring principle are chosen for majority of researcher in soil testing.

## 2.METHODOLOGY

The experiment for soil compaction testing was conducted by preparing two types of soil which is specimen A and B with different dense, where Specimen B is more compact than specimen A. Two piezoelectric sensor that act as transmitter and receiver was prepared using different wire connection.

### 2.1 Piezoelectric Transmitter

A simple bender element consists of two piezo ceramic layers and a metal shim which separates the ceramic piezo layers. In this project, shear waves were generated by a transmitter which used the bender element. An electrical pulse were sent to the transmitter to make it vibrated and caused a shear wave propagate in soil. It used a parallel type connection for piezoelectric transmitter as shown in Figure 1.

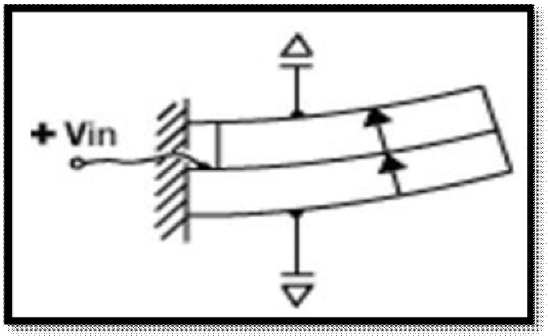

**Figure 1**: Parallel connected operation [9]

Parallel connected operation refers to the case where the supply voltage was applied to each layer individually. A two layer bending element wired for parallel operation requires three wires where one attached to each outside electrode and another one attached to the metal shim as illustrated in Figure 1[9]. For the same motion, a 2 layer element poled for parallel connected operation needs only half the voltage required for series connected operation [17].

### 2.2 Piezoelectric Receiver

On the other hand, receiver in this project also used a bender element. For piezoelectric receiver shown in Figure 2, a voltage applied to the surface of a combination of two piezoelectric materials causes one to expand while the other contracts, causing the entire element to bend. In this project, the series type connection were used as receiver sensor.

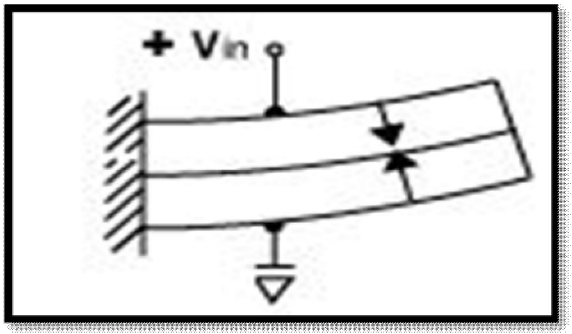

**Figure 2:** Series connected operation [9]

Series connected operation refers to the case where supply voltage was applied across all Piezo layers at once. The voltage on any individual layer is the supply voltage divided by the total number of layers. A 2-layer device wired for series operation used only two wires, one attached to each outside electrode which illustrated in Figure 2 [9].

### 2.3 Design and Functional Test

In this experiment, function generator will send ±20V sine pulse of frequencies ranging around 3 kHz until 20 kHz to generate an input signal to the transmitter of bender element. An electrical pulse were sent to the transmitter to make it vibrated and caused a shear wave propagation in soil.

A receiver of bender element can feel the waves in the soil and convert the motion of that wave into electrical signals. After that, the digital oscilloscope will capture the output waveform of shear wave. Lastly, the result of the receiver's waveform will be analyses for interpreting the soil characteristics. Figure 3 shows the block diagram for the whole process of the experiment.

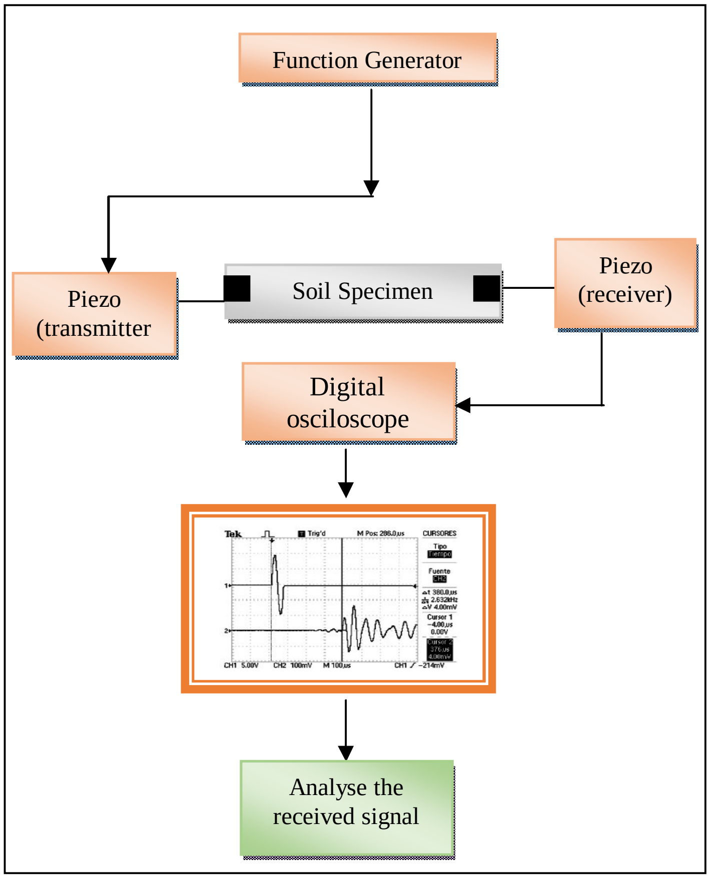

**Figure 3**: Block diagram of the conducted experiment

This phase is aim to implement the design with the actual experiment using soil. Polycarbonate container will be used for preparing the soil specimen. The arrangement for both transmitter and receiver with the soil sample are shown in Figure 4 for specimen A and Figure 5 for specimen B.

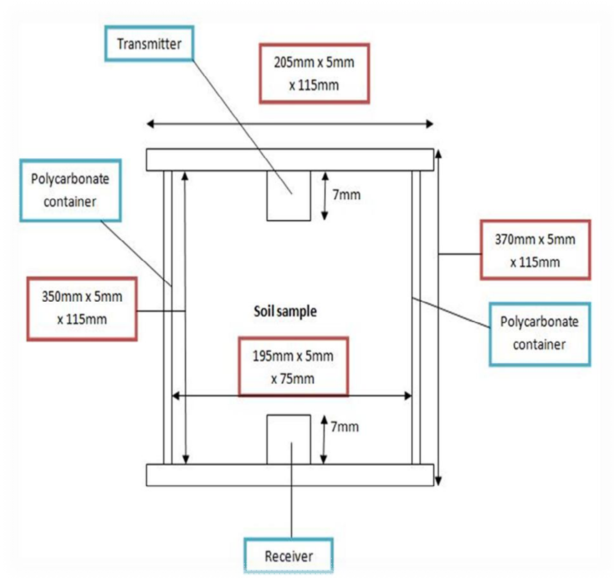

**Figure 4**: Details of the transmitter and receiver with the soil specimen A

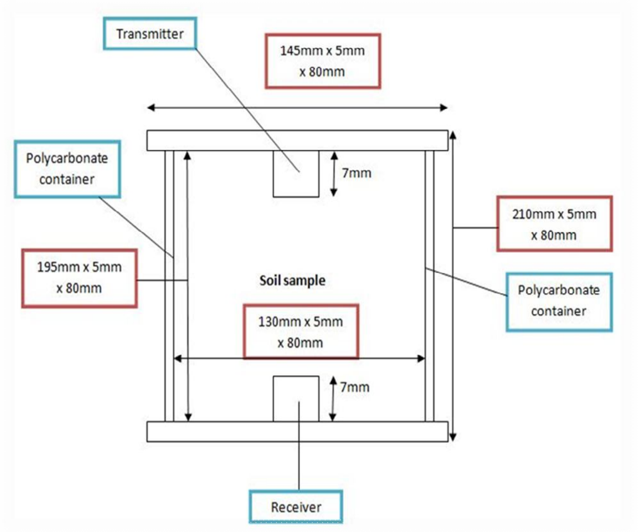

**Figure 5**: Details of the transmitter and receiver with the soil specimen B

## 2.4 Experimental Works

This section details the results of the experimental test which were used for performance evaluation in determining the compaction characteristics of soils. The tests were conducted on soft soil. Basic properties of soft soil with typical values used for all test were presented in Table 1 [18]. The soft soils used in this experiment were depicted in Figure 6.

**Table 1:** Basic range properties of soft soil

| **Properties** | **Values** |
|---|---|
| Poisson’s Ratio | 0.2-0.4 |
| Young’s Modulus, E | 30-320 MPa |
| Sand content % | 85-100 |
| Slit content % | 0-15 |
| Clay content % | 0-10 |

**Figure 6**: Soft soil

### 2.4.1 Test Specimen

This experiment was tested by using the same type of soil which is soft soil with different densities. The soil was left to dry out under the sunlight for a couples of day in order to reduce the humidity in the soil specimen. This action was necessary so that short circuit and damaging transmitter and receiver can be avoided as there is no water proofing protection. After the drying process, the soil has been weighted by using weighting scale to measure its mass as depicted in Figure 7.

**Figure 7**: Weighting process

Then process was repeated again with another specimen. This process has been done to obtain soil with measured their bulk density. In physics, objects with the different volume but same mass will have different density. Density can be obtained as

$$\rho = m/V \qquad (1)$$

Where

$\rho$ = bulk density of the soil specimen
m = the mass of the soil specimen
v = the volume of the soil specimen

The masses and densities of the soil specimen have been recorded in Table 2 where specimen A has smaller density compared with specimen B.

**Table 2**: Mass and density of the soil specimen

| **Specimen** | **Volume($m^3$)** | **Density ($kg/m^3$)** |
|---|---|---|
| **A** | 0.005118 | 566.54 |
| **B** | 0.002028 | 1429.98 |

The tests were carried out by placing the transmitter and receiver inside the soil specimen. The distance between the tips of the transmitter and receiver in this test was 350mm for specimen A and 195mm for specimen B as shown in Figure 8.

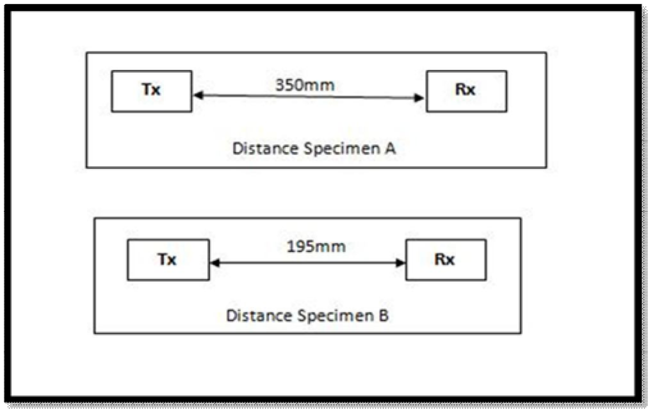

**Figure 8**: Distance between transmitter and receiver in the soil specimen

In this test, function generator excited the pulses and were sent to the transmitter with peak-to-peak amplitude voltage of 20V and tested with different input frequency such as 3 kHz, 5 kHz, 7 kHz, 10 kHz, 15 kHz and 20 kHz. The continuous shear waves would travel through the soil specimen and received by the receiver at the other end.

Experiments were repeated with different input frequency, f for each density of the soil specimen. The received signals that resulted from this experiment had smaller amplitude compared with the transmitted signal. This smaller amplitude was due to the low density of the soil specimens used in this experiment.

From the received signal, the shear wave velocity can be obtained by measure the travel time and the distance between the tips of the transmitter and receiver as

$$Vs = L/t \qquad (2)$$

Where

Vs = shear wave velocity
L = distance between the tips of the transmitter and receiver
t = travel time

The shear wave arrival time determination method used in this experiment was first arrival method where it is the most commonly used method of shear wave arrival time determination. Travel time taken at the waveform was illustrated in Figure 9.

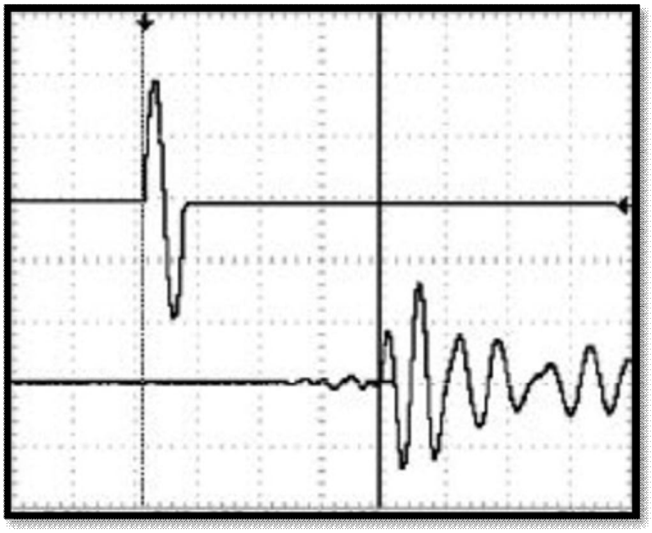

**Figure 9**: Travel time

Besides that, shear wave velocity also can be obtained by using different formula which is

$$V_s = f\lambda \qquad (3)$$

Where

f = frequency received when the transmitter was excited

λ = wavelength of the signal

The travel time was measured and the shear wave velocities obtained in this experiment were tabulated in Table 3 and 4.

## 3 RESULT AND DISCUSSION

Based on the results represented in Table 3, the wavelengths in this experiment were ranged between 1mm – 6mm for soil specimen A. Based on the results represented in Table 4, the wavelengths in this experiment were ranged between 1mm – 3mm for soil specimen B.

**Table 3**: Shear wave velocity for Soil Specimen A

| **Soil Specimen A** | | | |
|---|---|---|---|
| **Frequency, *f*** **(kHz)** | **Travel time, t** **(ms)** | **Wavelength, λ** **(mm)** | **Shear wave velocity, Vs** **(m/s)** |
| 3 | 0.0220 | 5.30 | 15.9 |
| 5 | 0.0128 | 5.46 | 27.3 |
| 7 | 0.0420 | 1.19 | 8.3 |
| 10 | 0.0110 | 3.18 | 31.8 |
| 15 | 0.0060 | 3.89 | 58.3 |
| 20 | 0.0088 | 1.99 | 39.8 |

**Table 4**: Shear wave velocity for Soil Specimen B

| **Soil Specimen B** | | | |
|---|---|---|---|
| **Frequency, *f*** **(kHz)** | **Travel time, t** **(ms)** | **Wavelength, λ** **(mm)** | **Shear wave velocity, Vs** **(m/s)** |
| 3 | 0.0260 | 2.50 | 7.5 |
| 5 | 0.0144 | 2.71 | 13.54 |
| 7 | 0.0130 | 2.14 | 15.00 |
| 10 | 0.0092 | 2.12 | 21.19 |
| 15 | 0.0106 | 1.54 | 18.39 |
| 20 | 0.0068 | 1.43 | 28.67 |

### 3.1 Calculating The Small-Strain Shear Modulus

The small-strain shear modulus, Gmax value was used to interpret the soil stress conditions. Therefore, the shear wave velocity and Gmax value were measured and has been used as parameters for soil compaction testing in this project. The Gmax value can be determined by measuring the shear wave velocity of the shear wave propagation through the soil specimen. From the data presented in Table 3 and 4, the Gmax value can be calculated using equation (4).

$$G_{max} = \rho V_s^2 \qquad (4)$$

Where

Gmax = small strain shear modulus

ρ = bulk density of the soil specimen

Vs = shear wave velocity

The small strain shear modulus obtained in these experiments was tabulated in Table 5 and 6.

**Table 5**: G*max* value obtained for Soil Specimen A

| **Soil Specimen A** | | |
|---|---|---|
| **Frequency, *f*** **(kHz)** | **Shear wave velocity, Vs** **(m/s)** | **G*max* value** **(MPa)** |
| **3** | 15.9 | 0.143 |
| **5** | 27.3 | 0.422 |
| **7** | 8.3 | 0.039 |
| **10** | 31.8 | 0.573 |
| **15** | 58.3 | 1.926 |
| **20** | 39.8 | 0.897 |

**Table 6:** G*max* value obtained for Soil Specimen B

| Soil Specimen B | | |
|---|---|---|
| **Frequency, *f* (kHz)** | **Shear wave velocity, Vs (m/s)** | **G*max* value (MPa)** |
| **3** | 7.5 | 0.080 |
| **5** | 13.54 | 0.262 |
| **7** | 15.00 | 0.322 |
| **10** | 21.19 | 0.642 |
| **15** | 18.39 | 0.484 |
| **20** | 28.67 | 1.175 |

The frequency of input signal was adjusted with different value to assess its effect on shear wave velocity in each of soil specimen. The results for this study can be found in Figure 10 and Figure 11.

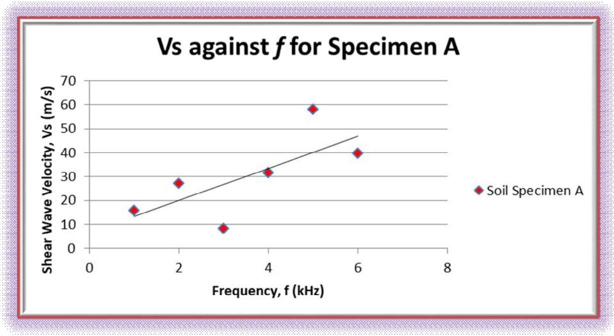

**Figure 10**: Shear wave velocities at various input frequency for soil specimen A

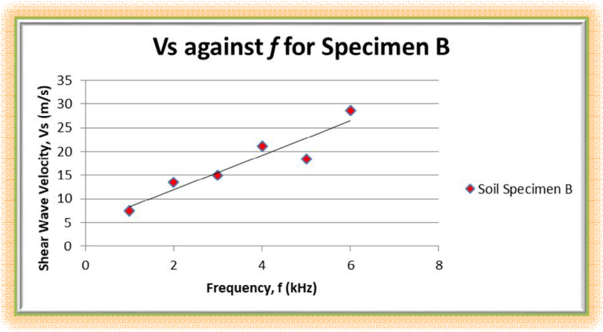

**Figure 11**: Shear wave velocities at various input frequency for soil specimen B

Referring to Figure 10 and Figure 11, it can be concluded that the shear wave velocity was directly proportional to the input frequency. The shear wave velocity increase as the frequency increases. The effect of the frequency on the shear wave velocity was confirmed. However, according to graph illustrated in Figure 11, it can be seen that the linearity of the shear wave velocities plots improves at lower frequencies. It shows better linearity compared to graph in Figure 10. In sands, this effect is one of particular interest because the high soil permeability increases as the frequency dependency of shear wave velocity.

Travel time of the shear wave between the transmitter and the receiver was one of the important parameter to be determined in this experiment which used to calculate the shear wave velocity. The travel time were measured in this experiment by using first arrival method. The method depends on a visual determination of the first major positive departure of the received signal from zero amplitude.

It can be seen that travel time of the shear wave was indirect proportional to the input frequency as depicted in Figure 12 and Figure 13. Comparing Figure 12 and Figure 13, specimen B shows better linearity than specimen A. It can be concluded that the travel time become shorter as the frequency increases.

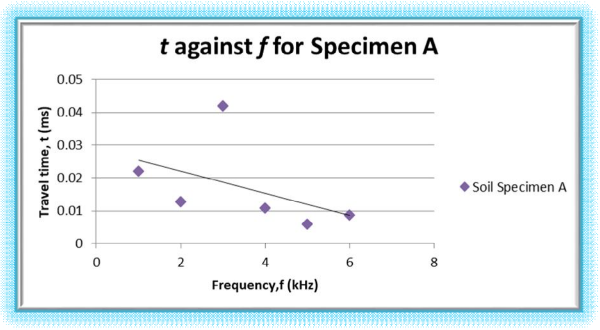

**Figure 12**: Travel time at various input frequency for specimen A

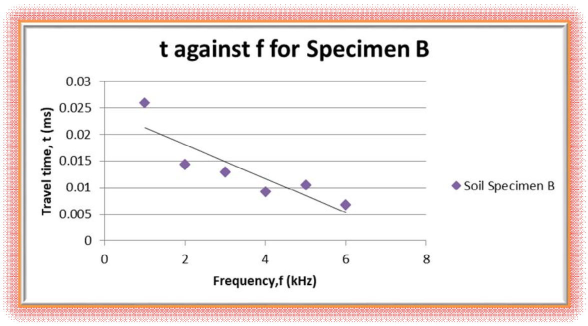

**Figure 13**: Travel time at various input frequency for specimen B

Comparison of Gmax values calculated from this experiment using different density with different shear wave velocity at varies input frequency were illustrated in Figure 14.

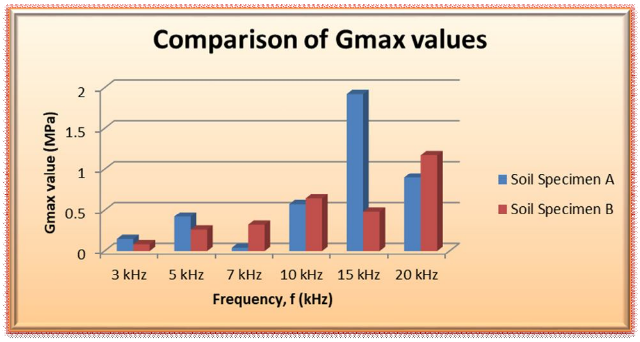

**Figure 14**: Comparison of Gmax values between shear wave velocities

Based on result obtained in this experiment, a clear difference in the small-strain shear modulus, Gmax values for the tested soil specimen was observed. In general, the input frequencies affect the small-strain shear modulus as it increases along with the increases frequency as shown in Figure 14.

## 5. CONCLUSION

This paper presents soil compaction testing using piezoelectric sensor. The piezoelectric sensor successfully determining the shear wave velocity in solids using simple, reliable and cost effective sensor. The shear wave velocity was directly proportional to the input frequency. The shear wave velocity also could produce the small shear strain modulus, Gmax values. The travel time by using first arrival method also become the output of the experiment where the more compact the soil, it shows better linearity of the travel time.

## ACKNOWLEDGMENT

The authors would like to thank the Universiti Tun Hussein Onn Malaysia, and Ministry of Higher Education (MOHE) for supporting this research. This work is supported by the Fundamental Research Grant Scheme (FRGS) vot number K074.

## REFERENCES

1. M. Alexander. **Waves and Their Properties**. Wiley-Interscience. 2009. (2): 77.
2. V. Sudha, S. Mohan, R.M. Mohan. **A High performance on extemporize yield of horticulture crops with predictions based water and soil properties using multivariate analytics and machine learning algorithms**. *International Journal of Advanced Trends in Computer Science and Engineering*, vol 8, no 4, pp. 1706-1710, 2019. https://doi.org/10.30534/ijatcse/2019/98842019
3. R.C. Mamat, A. Kasa, S.F.M. Razali. **Performance prediction of road embankment on soft soil stabilized with prefabricated vertical drains using numerical method**. *International Journal of Advanced Trends in Computer Science and Engineering*, vol 8, no 4, pp. 1601-1608, 2019. https://doi.org/10.30534/ijatcse/2019/85842019
4. Y. Wang, X. Li, B. Zheng. **Experimental study on mechanical properties of clay soil under compression by ultrasonic test.** *European Journal of Environmental and Civil Engineering***,** vol. 22, no. 6, pp. 666-685, 2018. https://doi.org/10.1080/19648189.2016.1217791
5. P.S Laxmi, K. Reiko. **Disk Shaped Piezo-ceramics Transducer for P and S Wave Measurement in Laboratory Soil Specimen**. *Soils and Foundations*, vol. 25, no. 4, pp. 510-524, 2013. https://doi.org/10.1016/j.sandf.2013.06.004
6. C.M. Chan. **On The Interpretation of Shear Wave Velocity from Bender Element Tests**. *Acta Technica Corviniensis - Bulletin of Engineering*, vol. 5, no. 1, pp.29-34, 2012.
7. M.F Nawaz, G. Bourrie, F. Trolard. **A review of Soil Compaction Impact and Modelling**. *Agronomy for Sustainable Development*, vol. 33, no. 2, pp. 291-309, 2013. https://doi.org/10.1007/s13593-011-0071-8
8. E. Ovando-Shelly, M. Guzman-Flores, C. Valle-Molina, **Laboratory Measurement of Compression and Shear Wave Velocities of Mexico City Clay with Piezoelectric Crystals**, in *Proc. 15th World Conference on Earthquake Engineering*, Lisbon Portugal, 2012.
9. K. Piriyakul, **Application of Piezoelectric Film to Measure the Shear Wave Velocity**. *Applied Mechanics and Materials*, vol. 418, pp. 161-164, 2013. https://doi.org/10.4028/www.scientific.net/AMM.418.161
10. M., Irfan, T. Uchimura. **Measuring Shear and Compression Wave Velocities in Laboratory Triaxial Tests Using Disk Shaped Composite P/S Piezoelectric Transducer**, i*n Proc. IACGE* 2013, pp. 414–421. https://doi.org/10.1061/9780784413128.049
11. Z. Hah, A. Partin, K. J. Parker. **Shear Wave Speed and Dispersion Measurements Using Crawling Wave Chirps**. *Ultrasonic Imaging*, vol. 36, no. 4, pp. 277-290, 2014. https://doi.org/10.1177/0161734614527581
12. A. R McNeese, K. M. Lee, M. S. Ballard, T. G. Muir, P. S Wilson, R. D. Costley. **Investigation of Piezoelectric Bimorph Bender Transducers to Generate and Receive Shear Waves,** *in Proc. Meetings on Acoustics*,Indianapolis, Indiana.2014, vol. 22, no. 1. https://doi.org/10.1121/2.0000036
13. J. J. R. Raj, S. M. K., Rahman, S. Anand. **An Embedded System for Elasticity Measurement Using Ultrasound Waves**, *in Proc.DIGNATE.* 2014, pp.38-43.
14. A. Prashant, H. Kotak, P. R. Jadhav. **Estimation of Small-Strain Shear Modulus of Embankment Soils Before Construction Using Bender Elements in Compaction Test**, *Indian Geotechnical Journal*, pp.1-10, 2016.

https://doi.org/10.1007/s40098-016-0191-9

15. H. C. Miao, Q. Huan, Q. Z. Wang, F. Li. **An Omni-directional Shear Horizontal Wave Transducer Based on Ring Array of Face-Shear (d24) Piezoelectric Ceramics**, 2016, pp. 1–15.
16. A. Manbachi,, R.S.C. Cobbold. **Development and Application of Piezoelectric Materials for Ultrasound Generation and Detection**. *Ultrasound*, vol 19, no. 4, pp. 187–196, 2011 https://doi.org/10.1258/ult.2011.011027
17. R.O. Deniz. **Bender Element of Shear and Compressional Wave Velocities in Large Sand Specimens**. M.S theses, North-eastern Univ., 2008.
18. T. Qiu, P.J Fox. **Effective Soil Density for Propagation of Small Strain Shear Waves in Saturated Soil,** *Journal of Geotechnical and Geo-environment Engineering*, vol. 134, no. 2, pp. 1815-1819, 2008. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:12(1815)