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UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCE

GROUND STIFFNESS AND DEPTH TO BEDROCKINVESTIGATIONS USING MULTICHANNEL ANALYSIS OF SURFACE WAVES: A CASE STUDY AT A RECLAIMED LANDFILL SITE IN ACCRA.

BY

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MPHIL. APPLIED GEOPHYSICS

THIS THESIS IS SUBMITTED TO UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF M.PHIL APPLIED GEOPHYSICS DEGREE.

DECEMBER, 2021

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DECLARATION

I hereby declare that this thesis is the author's own study conducted on the mapped area except references to other people's work which have been duly cited. This thesis has not been submitted in whole or in parts for a degree either in this university or elsewhere.

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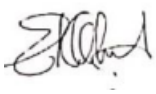

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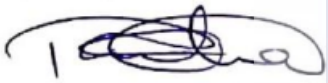

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ABSTRACT

This study was undertaken in Accra over an abandoned landfill site on which the authorities of Apenkwa Presbyterian Basic School desire to build a school facility. Obtaining information about the ground condition of the study site to support the intended architectural design is crucial. The main objective of this study is therefore, to investigate the ground stiffness and depth to bedrock of the study site using the Multichannel analysis of surface waves (MASW) technique. Acquiring subsurface information using the MASW procedure is grouped into three phases: acquiring data from the field, extracting the fundamental mode dispersion curve, and inversion of dispersion curve. The inversion of the dispersion curve provides a 1-dimensional (1D) velocity profile that is a representative of the subsurface where a geophone on the surface picked a response of the source energy generated. Several 1D velocity profiles that make up a traverse line were stacked to produce a 2-dimensional (2-D) Vs profile. From the processed field data, it was observed that, the surveyed site has a shear wave velocity (Vs) ranging between 340m/s and 1925m/s. The Vs velocity showed five distinct clear cutting wide ranges. The shear wave velocity at a depth of 30m (Vs30) gave a least value of 350m/s and a maximum value of 1400m/s. From this information, it was concluded that, the study site has at least five different stratigraphic layers at a maximum depth of 30m. The bedrock of the site is estimated to a depth of 25 m representing deep-seated bedrock. The Vs30 information obtained suggests that the site falls under category B and category C of the National Earthquake Hazards Reduction Program (NEHRP) Soil Profile Type Classifications.

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Acknowledgement

This work wouldn't have been a success without the efforts and tolerance of my supervisors. I sincerely express my gratitude to Dr. Armah who went through with me from the initial stage of selecting thesis topic, acquiring research instrumentation, field surveying to proofreading. He has supported this research work with sincere love and selflessness.

I also express my profound gratitude to Dr. Paulina Amponsah for taking her time through the proofreading and correcting every single mistake.

I thank the Head of Department of Earth Science Department for continuously reminding me of the time spent and the need to submit on time.

I also express my gratitude to Mr. Emmanuel Adusei-Poku who relentlessly tested several computer applications with and helping me choose the most practical one.

I also thank each and every one whose effort directly and or indirectly contributed to the success of this research work.

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LIST OF ABBREVIATIONsS

1D = one (1) dimension

2D = Two (2) dimension

BSSC = Building seismic safety council

IBC = International Building Code

MASW = Multichannel analysis of surface waves

NEHRP = National Earthquake Reduction Program

R-waves = Raleigh wave

SASW = Spectral analysis of surface waves

Vs = Shear wave velocity

Vs30 = Shear wave velocity at a depth of 30m

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CHAPTER ONE

INTRODUCTION

Foundation site investigation is increasingly attaining fame because it has become imperative in obtaining knowledge of the subsurface material before putting up any huge constructional design. Several geophysical methods can be used to determine the ground characteristics such as stiffness and density. Stiffness largely defines the characteristic of deformation of geologic materials (Sawangsuriy, 2012). Consideration of the stiffness properties of geologic materials as key parameter in engineered structures is thus crucial when designing and analyzing architectural projects under different environmental conditions and pressure loading.

1.1 Background of the study

Measuring accurately, the stiffness of geologic materials has gained amplified recommendation. The local displacement transducer procedure has been applied in the static triaxial test to quantify local axial strains (Goto et al,. 1991). By the use of the torsional shear devices and the resonant column the dynamic and the cyclic properties of geologic materials has been extensively examined (Drnevich, 1985, Saada, 1988).

Traditionally, the assessment of the stiffness of geologic materials makes use of displacement transducers or resonant column devices (Lo Presti et al., 2001). The seismic technique is largely recognised in estimating the shear velocity of the ground because the method is quick, economically affordable and environmentally friendly (Richart et al., 1970, Matthews et al., 2000, Santamarina et al., 2001, LoPresti et al., 2001).

By measuring accurately, the shear velocity with the appropriate techniques (e.g. MASW) and identifying the density of the media, it is feasible to determine the stiffness of geologic materials. Generally, shear velocity is the parameter for determining the shear modulus of geologic materials. Shear velocity quantification has been investigated extensively using resonant column tests (Hardin and Drnevich, 1972), shear plates (Lawrence, 1963, 1965) as well as bender elements (Shirley, 1978, Shirley and Hampton, 1978). Because the shear plate is bulky and needs a high voltage to excite it, it has limited it uses. (Ismail et al., 2005).

Among the geophysical methods, the seismic methods are preferred in assessing the stiffness of the ground and have several advantages including but not limited to;

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- Most seismic methods are relatively simple, fast and procedure does not disturb the ground.

- Under relatively similar conditions, the stiffness measured in the field and the stiffness measured in the laboratory show strong agreement. (Anderson and Woods, 1976), (Viggiani and Atkinson, 1995a), (Nazarian et al., 1999), and (Atkinson, 2000).

- In the small-strain region, loading frequency, strain rate and load repetition have no effect (Iwasaki et al., 1978, Ni, 1987, Bolton and Wilson, 1989, Tatsuoka and Shibuya, 1991, Jardine, 1992, Shibuya et al., 1992, 1995, Ishihara, 1996).

- Volumetric and shear strain are totally recoverable, and geologic materials do not stretch or shrink as a result of draining shear (Ishihara, 1996).

1.2 Problem Statement

Increasing population density and urbanization has led to high demand for new residential lands. This has resulted in the exploitation of abandoned dump sites/landfill being reclaimed and developed for residential purposes without necessarily paying attention to the capability of the reclaimed land to support the structures they put up.

There have been countless incidents of buildings collapsing due to ground subsidence all across the world. When structures are constructed on shaky ground or in karst systems, they run the risk of collapsing due to foundation failure caused by subsidence caused by intense fracturing of the subsurface materials.

In light of the aforementioned issue, this thesis seeks to investigate the ground competence and depth to subsurface layers of an Apenkwa reclaimed landfill site on which the Presbyterian basic school is situated, as well as the stiffness of the ground to support the authorities' intended high buildings.

1.3 Objectives of the research

The principal objective of this research was to determine the stiffness of the study area which is an important geotechnical/foundation investigation parameter. It also sought to interpret the result in terms of subsurface stratigraphic/topographic map and delineate bedrock-overburden contacts. Weathering zones within a rock/soil unit was imaged using the MASW data. The research utilized ideal MASW array arrangement to allow imaging to a depth of up to 30

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meters while maintaining good data quality. These goals were accomplished using the approaches described below.

- Acquiring active MASW data from the field
- Use the overtone images to estimate the superiority of acquired MASW data.
- Estimating dispersion curves and inversion of dispersion curves of acquired MASW data.
- Generate 2D shear wave velocities (Vs) profile from inversion of dispersion curves
- Estimate the distance to the top of bedrock from the surface using 2D Vs profile images
- Estimate subsurface layers using 2D Vs profile images.
- Estimate the stiffness of ground materials by analyzing shear wave velocities from 2D Vs profile images.

1.4 Study area

The study area is located within the Greater Accra region. The survey was carried out on a site at Apenkwa Presbyterian Basic School, a suburb of Accra. The surveyed site is bounded by the following coordinates; (5^0 36' 35"N, 0^0 13' 49"W), (5^0 36' 35"N, 0^0 13' 50"W), (5^0 36' 37"N, 0^0 13' 48"W) and (36' 37"N, 00 13' 50"W). The total surface area of the site is 2500 square meters (50m x 50m). Fig. 1.1 and Fig. 1.2 below is a Google map showing the surveyed locality and schematic representation of profile lines respectively.

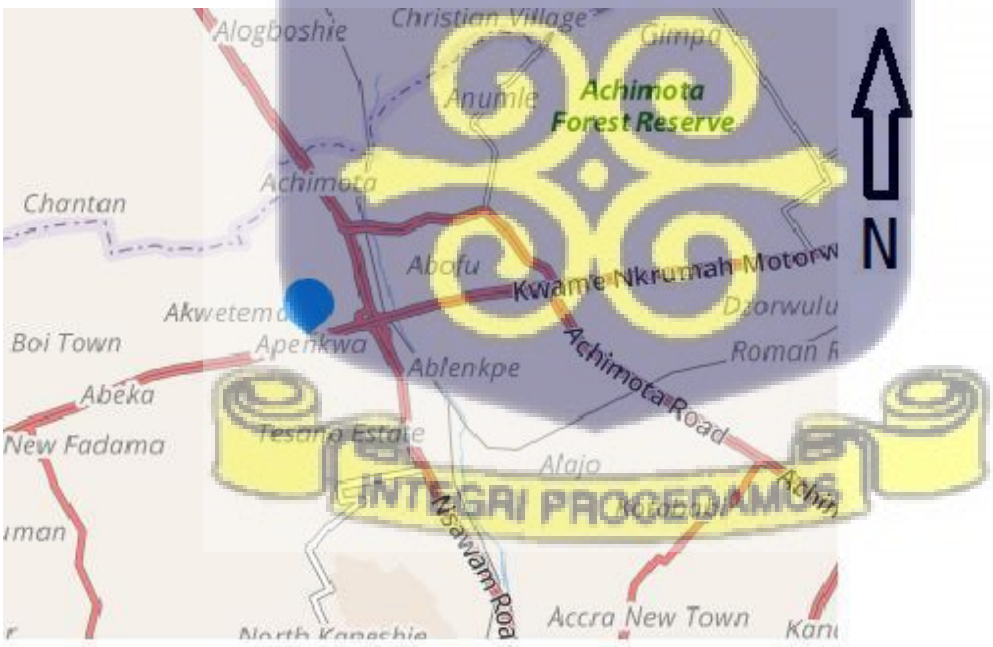

Fig. 1.1 A section of the map of Accra showing the study area: Google map

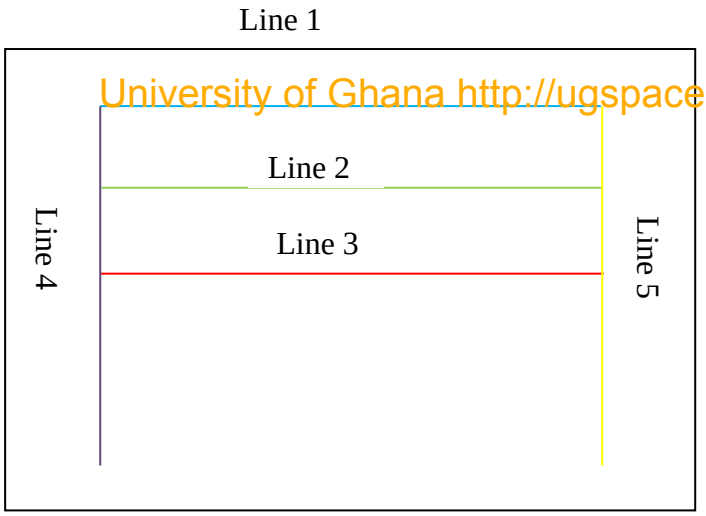

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Fig. 1.2: Schematic representation of profile lines. (Line 1, 2 and 3 were oriented east-west, line 4 and 5 were oriented south-north.

1.5 Regional Geology of Ghana

The geology of the country is part of the Precambrian Guinea Shield in West Africa. The main Precambrian rock units in the nation include the metamorphosed and folded Birimian, Tarkwanian, Dahomeyan Formation, Togo and Buem Formations. Birimian rocks consist of almost two-thirds of Ghana, with five volcanic belts which consistently are separated, trending northeast southwest. The basins between the volcanic belts are filled with sediments. The remaining one third comprise post-Birimian rocks namely the central part of Voltain, and the coastal sediments of recent deposit (Amedoful et al., 2008; Kesse., 1985). The regional geological map of Ghana is shown in fig 1.3 below.

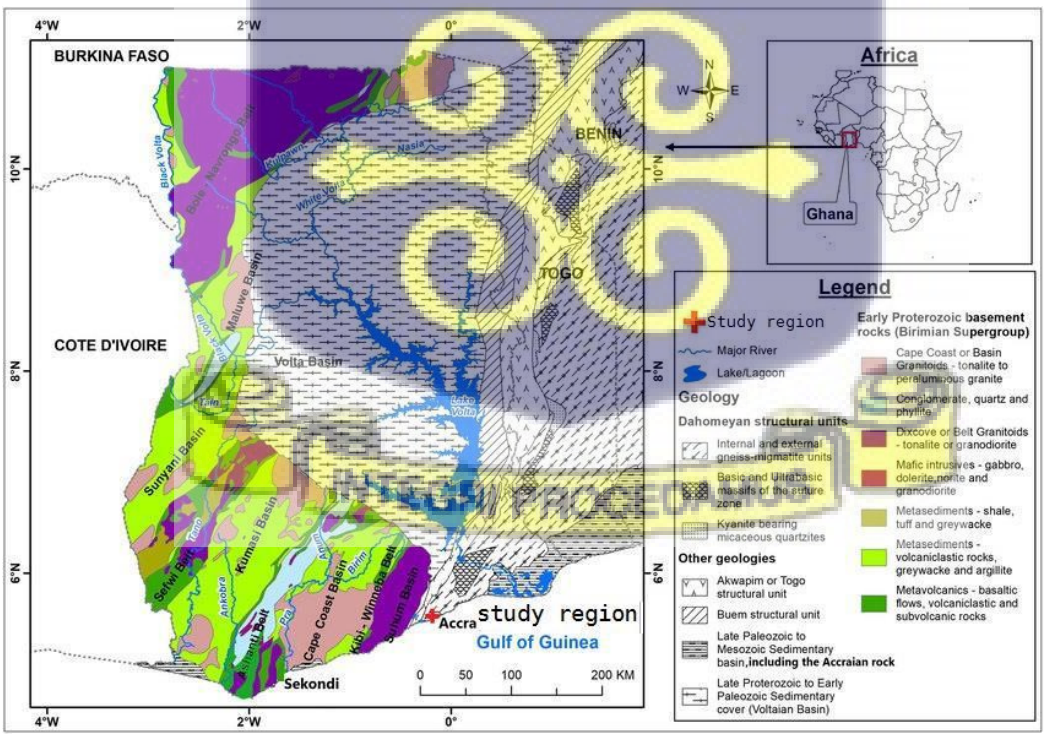

Fig 1.3: Regional geological map of Ghana. Source Geological survey Authority and modified by author.

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1.6 The Togo structural Unit.

The Togo unit represents cover rocks of the basement Dahomeyan gneisses. To the east lies the border between Togo and Dahomeyan. The Togo structural units are the rocks that make up the Akwapim range of hills, which run northeast from Accra's coast through Kpong, Anum, and into Togo. In the Togo structural unit, phyllites, schists, and quartzite are the most common rocks. Unaltered shale and sandstone are found in some areas. Many excavation sites throughout the Togo and the underlying Dahomeyan Formation have yielded phyllonite. The phyllites and quartzites on the Akwapim range are intercalated, foliated and tightly folded.

The Greater Accra Metropolitan Area is essentially made up of the West African Craton's Birimian rocks on the west and the Dahomeyide orogenic terranes on the east. The Birimian province and the Dahomeyide terranes are separated by a strong northeast-southwest tectonic border. The Dahomeyide belt (Akwapimian-Togo range) extends westward toward the West African Craton's eastern boundary. The oldest unit within the Dahomeyide is the Dahomeyan, which serves as the basement for the overlying rocks. The rocks here in this unit are metamorphosed Precambrian rocks. (Orthogneiss, Amphibolites Metamicro gabbro, Quartz schist and Schistose Marbles). Granitoid and biotite gneisses, mica schist, and heavily bedded quartzite intercalating with phyllites and sandstones are among the Togo Structural Units (Nortey et al., 2018).

The Accraian is made up mostly of Devonian shales and interbedded sandstones (Ayetey and Andoh, 1988). In low-lying places, the Accraian's interbedded sandstone and shale formations have often resulted in fine to coarse sands, which become silty to clayey when shales are interbedded. Sandy to gravel-like lateritic soils predominate in the highlands. Clays are formed by the shale units in this formation. In low-lying places, the Togo series forms fine to coarse sands, while on higher terrain, it grades into gravel-like laterites to extremely quarzitic cobbly, with the schist zones generating clayey to silty sands (Nortey et al 2018). Fig 1.4 below is the geological map of Accra plains

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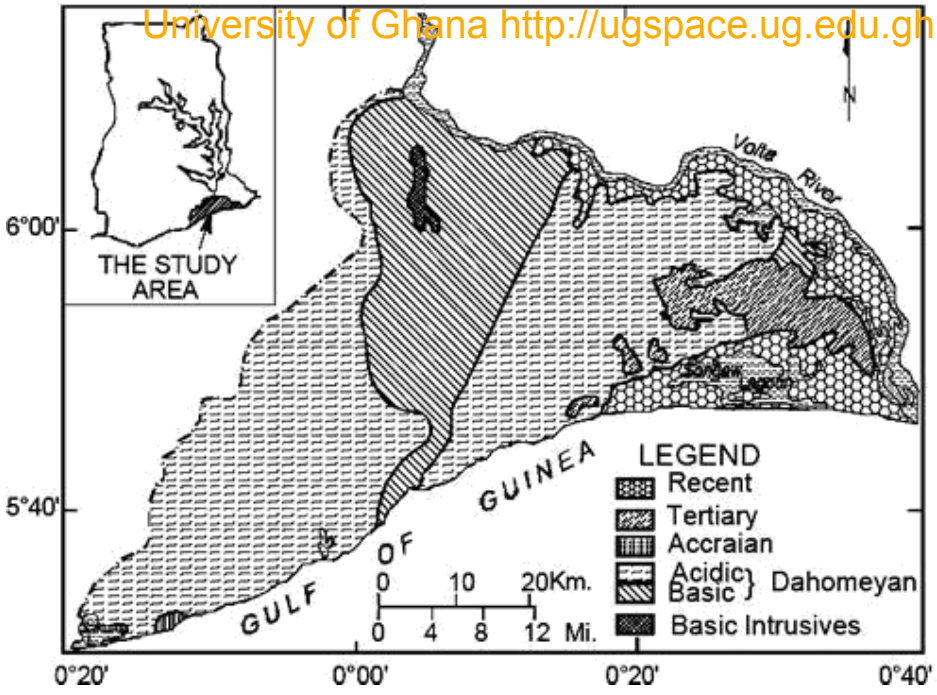

Fig. 1.4 Geological map of Accra Plains (source: Kortatsi, 2006)

1.7 Local Geology of Apenkwa area.

The study area is limited in in-situ out crops. The study area lies on a flat plane. The soil cover is gravelly lateritic. The observed boulders are quartzitic which are usually weathered. Excavations nearby expose quartzites. Where deep excavations are exposed, some plyllites are seen together with the quartzites.

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CHAPTER TWO

LITERATURE REVEIW

Various geophysical methods can be used to investigate the subsurface. In terms of the approaches to imaging of the subsurface, the investigation aim(s) and to a certain extent the location of the survey predetermines the choice of the geophysical method. The geophysical method used measures the attributes of the earth and reveals the nature of the ground from the properties by means of reverse and forward modeling.

2.1 Potential Wave propagation method for estimating the stiffness of the ground/geologic materials

Test	Standard	Test Principle
Soil Stiffness Gauge (SSG)	ASTM D 6758	Dynamic force produced in the device is applied via a ring-like shape foot at base (on the ground surface). Deflection is calculated by the use of velocity detectorsa. The stiffness of the near-surface material is then calculated as the ratio force applied to the detected deflection.
Bender Element	None	The shear wave velocity is estimated by measuring the shear wave propagation time and the distance between the piezoceramic bender sections. The equivalent shear stiffness is calculated using the shear wave velocity and mass density of the geologic materials. (Dyvik)
Resonant Column	ASTM D 4015	The resonant frequency is measured and connected to the shear wave velocity and shear stiffness.

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Pulse Transmission (Ultrasonic Pulse)	ASTM C 597	The elastic wave velocity is computed by monitoring the travel time of either compressional or shear wave arrivals as well as the distance between piezoelectric ultrasonic transducers. Geomaterial stiffness is calculated using an elastic theory.
Seismic Reflection	None	The travel time of seismic waves reflected from subsurface boundaries by means of the law of reflection is measured in order to estimate the elastic wave propagation velocity and the corresponding stiffness of geomaterial.
Seismic Refraction	ASTM D 5777	The elastic wave propagation velocity and the accompanying stiffness of geomaterial are obtained by measuring the travel duration of seismic refracted waves when they reach a stiffer material (higher shear wave velocity) in the subsurface interface following the law of refraction (Snell's law).
Spectral Analysis of SurfaceWaves (SASW)	None	Using the dispersion properties of surface waves and the natural phenomena that surface waves travelling at depths are proportionate to their wavelengths or frequencies, the stiffness of subsurface profiles is assessed as their velocity varies with

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		frequency.
Seismic Cross-Hole	ASTM D 4428	Wave propagation velocity (compressional or shear wave) measured in a linear array from one deep drilling to another nearby. The seismic wave is generated in a variety of methods, resulting in elastic waves propagating horizontally through the geomaterial and are detected by geophones situated in the opposite hole.
Seismic Down-Hole or Up-Hole	None	The vertical propagation of compressional and/or shear waves in a single borehole is seen. It is measured how long it takes compressional and/or shear waves to travel from the source to the receiver(s). The wave propagation velocity at any depth can be calculated by plotting transit time vs depth.
Multichannel Analysis of Surface wave	None	Surface (Rayleigh) wave velocity varied with frequency is measured by utilizing The dispersion characteristics of surface wave and the fact that surface waves propagate to depths that are proportional to their wavelengths or frequencies in order to determine the stiffness of subsurface profiles
Seismic Cone Penetration		The seismic penetration test is similar to the seismic down-hole test, except that no borehole is required. The shear wave velocity profile is obtained in the same way as the seismic down-hole test. The

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		receiver is housed within the cone.

Table 2.1 summarized wave propagation methods for determining the stiffness of the ground (Sawangsuriy, 2012)

2.2 Seismic Waves

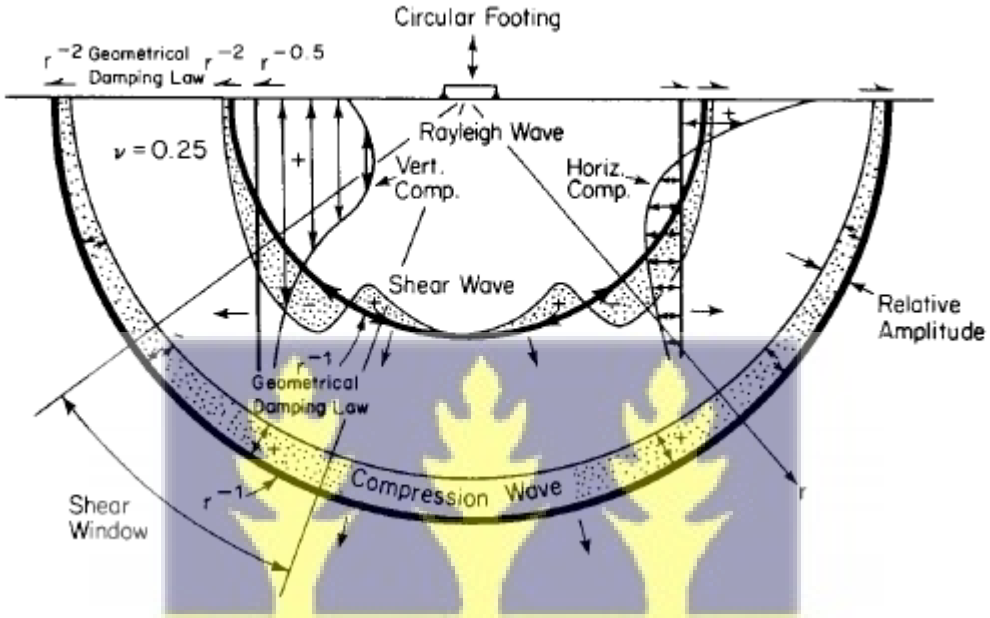

Fig. 2.1 Compressional, shear, and Rayleigh waves generated by a point load are disseminated in a homogeneous, isotropic, elastic half-space (Woods, 1968).

Waves that travel through the earth's interior or over the earth's surface are referred to as seismic waves. Generally, they are packs of strain energy that propagate outwards from a seismic point. Surface waves and body waves are the two main forms of seismic waves that propagate through the earth and along its surface (Aki and Richards, 2002; Evrett, 2013).

2.3 Body (or pressure) Waves. Compressed waves (longitudinal, primary, or dilatational) and S-waves (transverse, secondary, or shear-wave) are the two different forms of body waves known. The inherent energy of an elastic material allows body waves to propagate. S-waves are slower than P-waves. P-waves travel in the same way as sound waves do. They spread out and compress and expand the earth's materials as they travel (Aki and Richards, 1980). P-waves, unlike S-waves, may travel through both solid and liquid objects.

2.4 Surface Waves. Surface waves are created when overlapping P-waves (compressional body waves) and/or S-waves (oscillating body waves) travel predominantly alongside a

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material surface or along the boundary of unrelated materials (Kearey, Brooks and Hill, 2002). Surface waves cause particles to move in a vertical direction parallel to the wave's propagation path, with both a vertical and horizontal component. Rayleigh waves and Love waves are the two forms of surface waves that are most important for engineering reasons. They can reveal a considerable image of the subsurface through which they propagate depending on their modes of propagation, dispersion velocities, and the depth range of penetration of the related particle motion.

Rayleigh waves represent waves that travel laterally over a free surface, such as the ground/surface-air interface, and whose penetration depth is determined by the wave's wavelength. Love waves develop whenever a delicate stratum sits on top of a firmer layer, causing particulates to flow horizontally and transversely in the direction of wave propagation (Parasnis, 1997). Love waves are rarely discovered in seismic surveys that use only vertical sources and receivers because their particle movement is always lateral (Xia et al., 1997).

The Rayleigh wave that propagates on or near the Earth's surface and is defined by its low frequency, very high amplitude and low velocity is called Ground Roll (Park et al., 1999; Xia et al., 1999). Physical properties of layers at deeper depth are picked by longer wavelengths. On the contrary, physical properties of the surface layers are sensed by waves of shorter wavelengths. In general, waves of longer wavelengths have faster phase velocities. In this connection therefore, each individual wavelength might have a distinct phase velocity for a specific mode of surface wave, resulting in seismic signal dispersion (Xia et al., 1999).

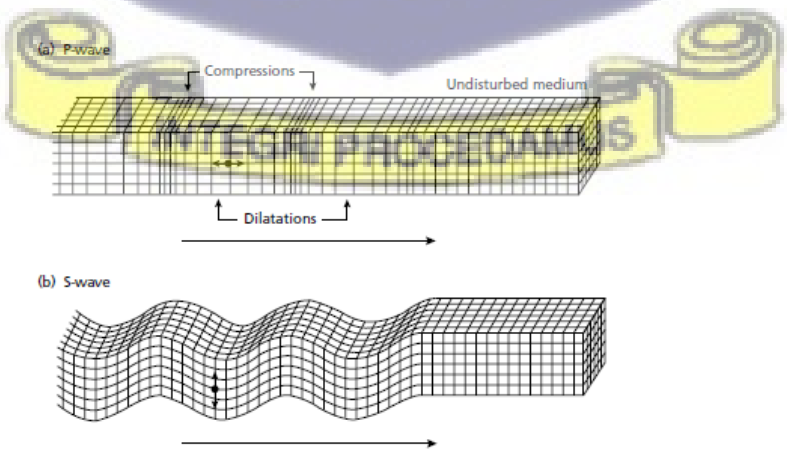

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Fig. 2.2. Particle motions associated with a Rayleigh wave. Rayleigh waves are a result of interfering P- and S- waves and this is illustrated here with particles undergoing dilation and compression associated with P-waves, and oscillations associated with S-waves

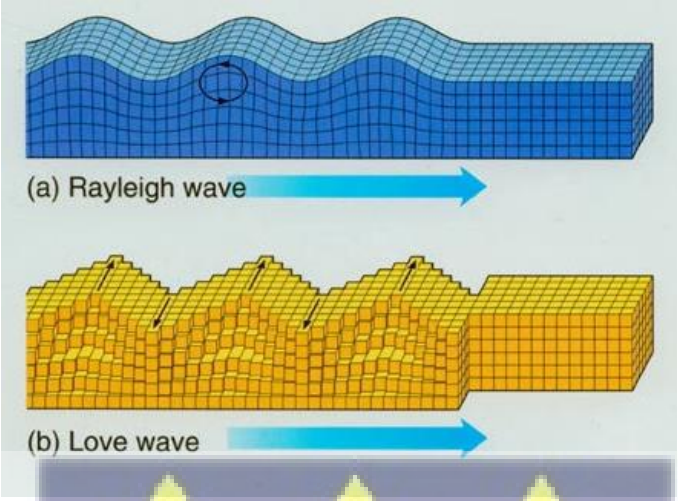

Figure 2.3 (a) Rayleigh wave motion. (b) Love wave motion

(http://thinkgeogeek.blogspot.com).

2.5 Surface wave analysis method

In general, there are two effective approaches for creating near-surface shear wave velocity (Vs) profiles that exploit Rayleigh-wave dispersion property. These are Spectral Analysis of Surface Waves (SASW) and Multi-Channel Analysis of Surface Waves (MASW) (Park et al., 1996a; 1997a). The dispersive nature of surface waves when propagating through a heterogeneous stratified medium is the principle behind surface wave analysis methods. The practicality to produce, generate and detect Rayleigh waves has made it an easy tool in surface wave analysis method. (Socco et al., 2010). It is well known that, velocities of Rayleigh waves increase with depth. The relation below links frequency (f/Hz), Rayleigh wave phase velocity (c/ms^{-1}), and wavelength (λ/m).

$$\lambda = \frac{c}{f} \qquad (1)$$

In a layered medium, the average stiffness and density of the soil layers through which a Rayleigh wave component propagates determine its phase velocity (Everett, 2013). The phase velocity of individual wave component is only controlled by the layer's material through which it propagates. In the diagram below, the phase velocities of wave components (1), (2) and (3) are affected by the properties of topmost layer (L1), middle layer (L2) and bottom layer (L3) respectively.

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The way these three processes are carried out varies amongst surface wave analysis methodologies. The primary difference between the SASW and MASW approach is how surface wave records are gathered and how data is processed.

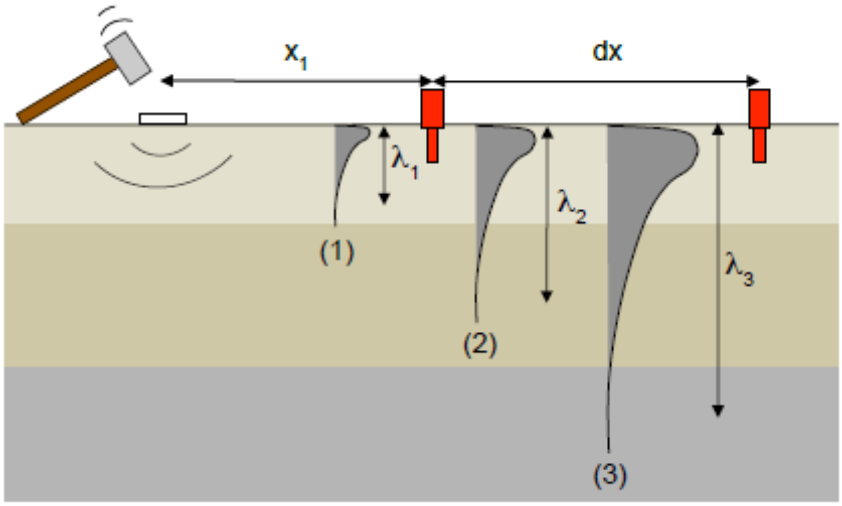

Fig. 2.4 Different wavelengths of Raleigh waves propagating through a stratified medium. Different frequencies reveal properties of geologic material at diverse depths. (ElínÁstaÓlafsdóttir, 2016)

2.6 Spectral analysis of surface waves (SASW)

The early 1980s saw the introduction of the Spectral Analysis of Surface Waves (SASW) approach (Park et al., 1999). Surface waves are generated by an impulsive source in the SASW approach, and geophones detect them. Field survey is conducted by using a pair of geophones (fig. 2.4), thus the test must be repeated with a variety of field configurations (varying source and receiver spacing) to cover various depths of study. The test is repeated in the other end to account for any internal phase changes caused by receivers and instruments (Nazarian et al., 1983). The need for multiple tests is also necessary in order to reduce the impact of random noise (Park, Miller and Xia, 1997). The geophones are either evenly spaced on the test site's surface or in a symmetrical line-up with varied spacing. Multiple measurements are taken at a particular location using various types of impulsive sources (such as a sledgehammer) and altering the distance between the impact load point and the first receiver in the geophone line-up.

This is necessary in order to stimulate waves of various frequencies. In ideal conditions, surface waves with an impact load that can be handled by manpower, such as a sledgehammer, can produce a reliable estimate of the shear wave velocity profile down to around 20m depth (Bessason and Erlingsson, 2011;, Kramer, 1996).

Using a spectrum analyzer, the data collected is evaluated to calculate the dispersion curve based on cross-spectral phase and coherence (Stokoe et al., 1994).

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Because numerous experiments with varied field setups are required, the procedure is time consuming and labor intensive. As a result, the full procedure takes many hours to complete. Furthermore, because just two geophones are utilized, all possible negative effects cannot be discovered and dealt with in a timely and effective manner, which may result in mistakes in the results. The acquired data may be contaminated by P waves (refracted, direct, air waves, and reflected P-waves) as well as higher-frequency waves (higher modes), reflected, and non-planar surface waves. As a result, the quality of the data is compromised. This affects the data processing phases and eventually faults the findings.

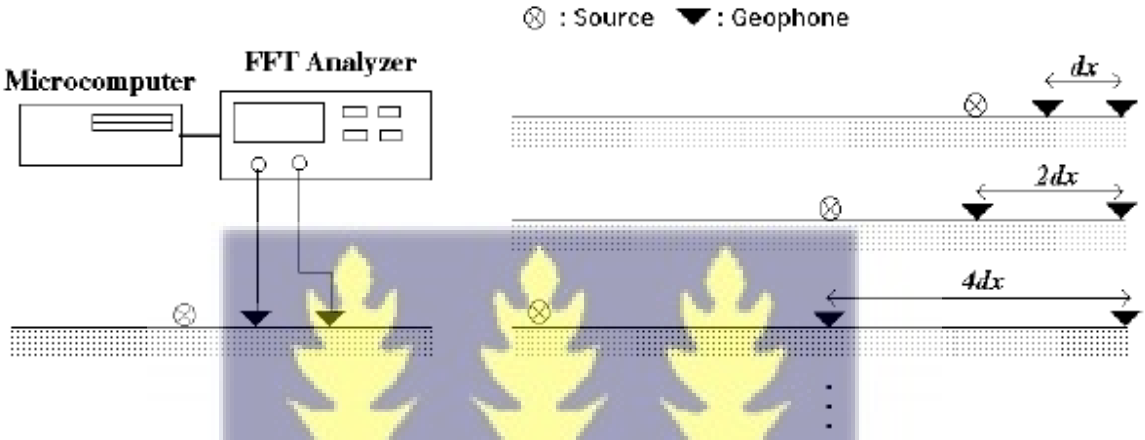

Fig. 2.5: schematic diagram of Spectral analysis of Surface Waves (SASW) After Park, Miller and Xia 1997

2.7 Multichannel Analysis of Surface Waves technique

In the early 1999, the Multichannel Analysis of Surface Waves (MASW) method was introduced into the geotechnical and geophysical environment. However, it was preceded by other similar methods example Spectral analysis of Surface Waves (SASW) as indicated above (Park and Brohammer, 2003; Yuan, 2011, Park et al., 1999). Similar to the SASW, but the differences lie in how the surface wave records are acquired and how the data processing is performed.

The MASW technique determines the ground's shear wave velocity profiles with depth by analyzing surface waves. With the MASW, the near surface of the earth shear-wave velocity (Vs) is measured 1-D, 2-D, and 3-D for the purpose of geotechnical, geological and geophysical work. (Park, Miller et al. 1999). It can investigate the subsurface to a depth range of 30 and 50 meters (Park, Miller et al. 1999). MASW is fast, and the method of data acquisition does not disturb the test site. Also, the MASW method provides information down to greater depth than SASW (Park et al. 1999).

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Multiple geophones (at least twelve) connected to a multiple seismograph are utilized in the MASW approach. The receivers are planted with equal spacing. Because the fundamental field setup is very similar to that for body-wave surveying (Park et al., 1996c), the surface-wave survey may be undertaken as a by-product of body-wave surveying, making 100% of recorded seismic energy useable.

At Kansas Geological Survey, two types of MASW are employed: Vibroseis method of multi-channel analysis of surface waves (MASWV) (Park et al., 1996c) and impulsive source multi-channel analysis of surface waves (MASWI) (Xia et al., 1997). The source and data processing technique used to construct the dispersion curve differ for each type. MASWV makes use of a sweeping source, comparable to Vibroseis, whereas MASWI uses an impulsive source, such as a sledge hammer. MASWV uses a time-domain method (Park et al., 1996), whiles MASWI uses frequency-domain method (Xia et al., 1997).

The use of Rayleigh waves to characterize the shear wave velocity profiles with depth of the near-surface has been the primary focus of MASW (Socco et al., 2010). The MASW approach considers R-waves on a multi-channel record because R-waves dominate the energy imparted in a seismic survey (Park et al., 1999; Park and Brohammer, 2003; Ivanov et al., 2005; Duffy, 2008 ;). Being dispersed by frequency, the R-wave phase velocity is linked to a variety of soil properties, most notably the shear wave velocity. Regarding this, the shear wave velocity profile at the test site is obtained by inverting the experimental dispersion curve. Xia et al., (1999)

MASW deduces the shear-wave velocity (Vs) profile of the subsurface of the site under study after it has analyzed the propagation of seismic surface waves generated by a source. Shear-wave velocity (Vs) is an elastic constant that is linked to shear and Young's moduli. Vs used to estimate load-bearing capacity because it is directly related to ground stiffness (Kramer, 1996).

The MASW method has been used successfully to investigate various types of geotechnical and geophysical projects over the last several years. These projects comprise delineating 2D bedrock surface and shear properties of overlying materials mapping karst systems (Miller et al., 1999), analysing the distribution of Poisson's ratio (Ivanov et al., 2000), generating Vs profiles (Xia et al., 2000), voids mapping (Park, 1998a), seismic assessment of pavement and asphalts (Ryden et al., 2001; Park et al., 2001a; 2001b) among others.

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MASW makes use of energy that would normally be deemed noise in traditional reflection surveys (Park et al., 1999), as well as multi recording channel and processing techniques that have been widely employed in reflection seismic surveys for oil exploration for decades (Park and Brohammer, 2003).

The method entails analyzing the phase velocity dispersion of surface waves traveling horizontally along the ground surface. Shear wave velocity data is commonly displayed in a depth only (1D) and or depth and lateral surface (2D) layout. One of the most common applications of surface wave dispersive qualities is the construction of a Vs analyzing planar, fundamental-mode Rayleigh waves. The MASW reveals essential characteristics used to evaluate the stiffness of the near-surface which is an important attribute in civil engineering and geotechnical investigations (Park et al., 1999).

Field testing of the stiffness of the ground (using the MASW seismic survey method) has the plus over the laboratory testing because the soil is analyzed in situ. Moreover, field tests measure the response of a large volume of soil, so there is a reduced risk of the investigated soil not being illustrative of the full tested location. On the premise of a layered earth model, surface wave analysis methods need the generation and usage of (Rayleigh and/or Love) waves to infer the shear wave velocity profile of the test site as a function of depth. The square of a single earth layer's specific shear wave velocity, assuming a constant mass density, will determine the stiffness of that layer (Kramer, 1996).

2.8 MASW Data Acquisition.

Active source MASW surveys, in which data collection is triggered by an impact; passive source MASW surveys, in which data is collected over longer periods of time with no energy triggered from a source (Park and Miller, 2006); and in walkaway active source MASW surveys, between two and four shot records are "stitched" into complex records, whiles either the receiver or source is kept stationary. These are the three common types of MASW based on how the MASW data is acquired (Gibbens, 2014). Two approaches toward performing a passive MASW survey exist, depending on the receiver configuration: the passive distant MASW (Park et al., 2005Park et al., 2004) put receivers arranged in a two-dimensional array,

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while the passive roadside MASW receiver array in a one-dimensional (Park and Miller, 2008) configuration.

The word "walkaway" refers to a survey in which the source points and the receivers are arranged in such a way that, either the shot points are placed at a very far offsets and the receivers stay fixed or the receivers are put at very a far offsets and the source of energy location remains constant. If the geophones spread remains stationary and the source location moves a step forward to the nearest geophone in the line, it forms the fixed-receiver walkaway surveys (FRW), (Vincent et al., 2006). This study makes use of the active method of the MASW data capturing procedure.

In an active MASW survey, low-frequency geophones (4.5 Hz), vertically polarized, are set up at proper equal intervals on the test site surface. Donohue and Forristal, 2013; Lin and Chang (2004), employed at least 24geophones with a consistent space between adjacent geophones. The study was tuned for specific geological and site conditions.

Each geophone has its own recording station (Park et al., 1997), and the entire configuration is linked to an operating seismograph and a field laptop capable of recording and storing the data for processing.

A surface wave is created at one end of the array, and the geophones, as a function of time, record the ensuing wave motion. A shotgun, a 20-25 kg sledgehammer, an impact device, or explosives can used as the impact source, depending on the aims and objectives of the investigation and the specific site factors. The networked geophones detect the arrival of a surface wave, which is recorded by a seismograph, with each geophone's output displayed as a separate trace.

The proper setting of data gathering parameters, the complete distance of the receiver line, source offset (the distance from the source to the nearest geophone), and the space between adjacent receivers are all essential field factors that contribute to the success of surface waves survey. Because the geophones capture vertical motions only, it's critical to bury them upright. Generalized Field arrangement for active MASW is shown in figure 2.5 below.

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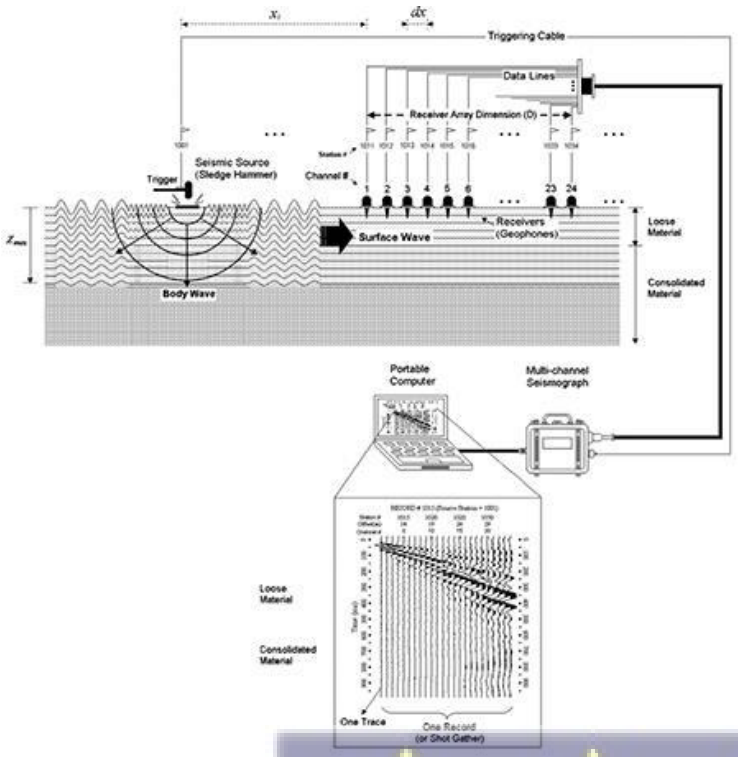

Fig. 2.6 (Modified from Park et al., 2002). Generalized Field arrangement for active MASW. Important field configuration is shown above on the diagram; D = the receiver linelength, dx = receiver spacing, and X_1= the source offset.

As shown in Figure 2.5 above, geophones are put up on the surface of the test location. The propagation of a wave is recorded after it is created. The investigation's maximum depth (Zmax) varies depending on the location, the geophones' natural frequency (f), and the type of seismic source employed. The longest Rayleigh wavelength observed during data gathering (λmax) determines the maximum research depth. The widely used empirical criterion is as follows (Park and Carnevale, 2010):

$$\mathbf{Z_{max} = 0.5\lambda_{max}} \qquad (2)$$

2.9 Geophone spacing, length and offset.

The full length of the spread of the geophones defines the maximum wavelength of the Rayleigh wave; (D). Therefore, the length of the receiver array is related to the maximum investigation depth (Z_{max}). According to Park and Carnevale (2010),

$$\mathbf{\lambda_{max} \approx D} \qquad (3)$$

If a lengthier Rayleigh wavelength than that shown in equation 3 above is applied, it may result in less accurate results. Latest studies have shown that, despite variable imprecision, it will remain within 5% during the interval;

$$\mathbf{D_{max} = 2Z_{max}} \qquad (4)$$

due to the uncertainties (noise) that are persistently incorporated in the data capturing (Park

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and Carnevale, 2010). It's ideal to avoid using an extreme wider receiver spread (Park et al., 1999). The end of an extremely wider geophone spread usually experience decreased noise when surface waves are generated by the common seismic sources (including relatively powerful sledgehammers) leaving signal from most far away geophone useless.

$$\lambda_{max} = 0.5D \quad (5)$$

(Park et al., 1999; Xia et al., 2009) is the maximum wavelength of R-waves that can be investigated.

The chance that the receiver/geophone will sense partially generated surface waves (near field effect) is eliminated when the source offset is chosen correctly. Table 2.2 below illustrates data acquisition parameters for active MASW survey.

Data acquisition parameters

++*Values listed here are by no means definitive and required. There can always be a tolerance of, at least, ±20% to the most recommended values.*

[1]maximum depth to be investigated, [2]weight of hammer in pounds, [3]natural frequency of geophone, [4]approximate total length of receiver spread ($D \approx mZ_{max}$ with $1 \le m \le 3$), [5]distance between source and the closest receiver ($X_1 \approx \kappa D$ with $0.2 \le \kappa \le 1.0$), [6]distance in receiver spacing (dx) that the source (S) and receiver (R) setup moves after acquiring data at one location, [7]degree of lateral resolution being sought, [8]recording parameters for seismograph, [9]sampling interval in milliseconds (ms), [10]total recording time in seconds (sec), [11]number of stacking data in seismograph's memory before being saved under different conditions of calm (C), noisy (N), and very noisy (VN) environment, respectively, [12]acquisition filter (e.g., low-cut, high-cut, etc.), *24-channel acquisition system.

Data Acquisition Parameters++ for Active MASW Survey (in meters)

**Most Recommended Values

Depth (Z_{max})[1] (m)	Source (S)[2] (lb)	Receiver (R)[3] (Hz)	Receiver Spread (RS) (m)				SR Move[6] (dx)			Recording[8]				
			Length[4] (D)	Source Offset[5] (X_1)	Receiver Spacing (dx)		Lateral Resolution[7]			dt[9] (ms)	T[10] (sec)	Vertical Stack[11]		
					24-ch*	48-ch	High	Medium	Low			C	N	VN
≤ 1.0	≤ 1	4.5–100	1–3	0.2–3.0	0.05–0.1	0.02–0.05	1–2	2–4	4–12	0.5–1.0	0.5–1.0	1–3	3–5	5–10
	(1)**	(40)	(2.0)	(0.4)	(0.1)	(0.05)	(1)	(2)	(4)	(0.5)	(0.5)	(3)	(5)	(10)
1–5	1–5	4.5–40	1–15	0.2–15	0.05–0.6	0.02–0.3	1–2	2–4	4–12	0.5–1.0	0.5–1.0	1–3	3–5	5–10
	(5)	(10)	(10)	(2)	(0.5)	(0.25)	(1)	(2)	(4)	(0.5)	(0.5)	(3)	(5)	(10)
5–10	5–10	≤ 10	5–30	1–30	0.2–1.2	0.1–0.6	1–2	2–4	4–12	0.5–1.0	0.5–1.0	1–3	3–5	5–10
	(10)	(4.5)	(20)	(4)	(1.0)	(0.5)	(1)	(2)	(4)	(0.5)	(1.0)	(3)	(5)	(10)
10–20	≥ 10	≤ 10	10–60	2–60	0.4–2.5	0.2–1.2	1–2	2–4	4–12	0.5–1.0	1.0–2.0	1–3	3–5	5–10
	(20)	(4.5)	(30)	(10)	(1.5)	(1.0)	(1)	(2)	(4)	(0.5)	(1.0)	(3)	(5)	(10)
20–30	≥ 10	≤ 4.5	20–90	4–90	0.8–3.8	0.4–1.9	1–2	2–4	4–12	0.5–1.0	1.0–2.0	1–3	3–5	5–10
	(20)	(4.5)	(50)	(10)	(2.0)	(1.5)	(1)	(2)	(4)	(1.0)	(1.0)	(3)	(5)	(10)
30–50	≥ 10 (20)	≤ 4.5	30–150	6–150	1.2–6.0	0.6–3.0	1–2	2–4	4–12	0.5–1.0	1.0–3.0	1–3	3–5	5–10
	or passive	(4.5)	(70)	(15)	(3.0)	(2.0)	(1)	(2)	(4)	(1.0)	(1.0)	(3)	(5)	(10)
> 50	≥ 10 (20)	≤ 4.5	> 50	> 10	> 2.0	> 1.0	1–2	2–4	4–12	0.5–1.0	≥ 1.0	1–3	3–5	5–10
	or passive	(4.5)	(150)	(30)	(6.0)	(4.0)	(1)	(2)	(4)	(1.0)	(2.0)	(3)	(5)	(10)

Table 2.2 Data acquisition parameters for active MASW survey. Park et al. (2005)

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CHAPTER THREE

METHODOLOGY

The MASW approach takes advantage of the frequency-dependent features of a certain form of seismic surface wave (fundamental-mode Rayleigh waves) that move horizontally from the impact site to the receiver spread. Shear wave velocity data is provided in any of the following; 1D (Vs in vertical/depth profile), 2D (Vs depth profile and lateral distant/cross-section), and 3-D (interpolation between densely dispersed 1-D profiles) formats.

3.1 Pre field studies

This study used the conventional geological/geophysical field surveying method. Desk studies provided the local and regional geology of the study site.

The main field work involves the acquisition of the MASW data. As stated above, there are 3 common types of MASW survey this study adopted the active source MASW, source of energy is generated from a source with an impact device.

3.2 Main field

Field measurement materials and equipment

Seismogram (Smartseis TM)

24 (4.5 Hz), Low frequency geophones

Sledge hammer (10.5 kiogram)

Metal plate

Computer with seismic program (Geostru Easy MASW software)

3.3 Data acquisition

Twenty four (24) Low frequency (4.5 Hz), vertically polarized geophones were lined up (vertically as geophones record vertical motion) in a 50m stretch on the test site's surface in an equally (2m) spaced line. Three profile lines were stretched first in the east-west direction and then two in the north-south direction, yielding a total of five profile lines.

Seismic waves (both P-wave and S-wave) were actively generated at one end of the receiver line-up (off-set) by an impulsive seismic source (striking the sledge hammer on the metal plate). The arrival of a seismic wave is detected by a series of geophones and recorded on a seismograph, with each geophone's output displayed as a single trace. Schematic representation of MASW data acquisition is shown in figure 3.1

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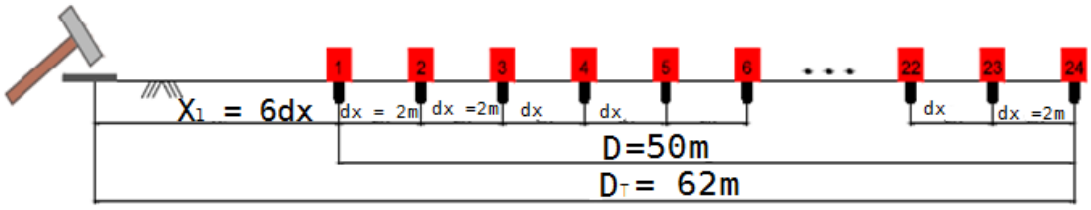

Fig. 3.1 MASW data acquisition. Schematic representation of MASW measurement profile used on the field. N = 24 geophones spread with equal spacing (dx). The source offset is x_1(near offset). The length of the receiver spread is D and the total length of the measurement profile (from impulse source to last geophone) is D_T (far offset)

3.4 Impact Source and offset

The field set up shown above in fig 3.1 was employed for perfect data acquisition. Seismic waves are generated when the seismic source is hit. The seismic waves created travel a distance X_1 from the source point to the first geophone, as told by (Richart et al., 1970; Gucunski and Woods, 1991; Stokoe et al., 1994). This proposal will ensure that the R-waves' planer properties become obvious, making them unfriendly to all other forms of acoustic waves, as well as preventing the near field effect (the chance that the receiver/geophone will sense partially generated surface waves). Figure 3.2 illustrates wave propagation of Raleigh's wave.

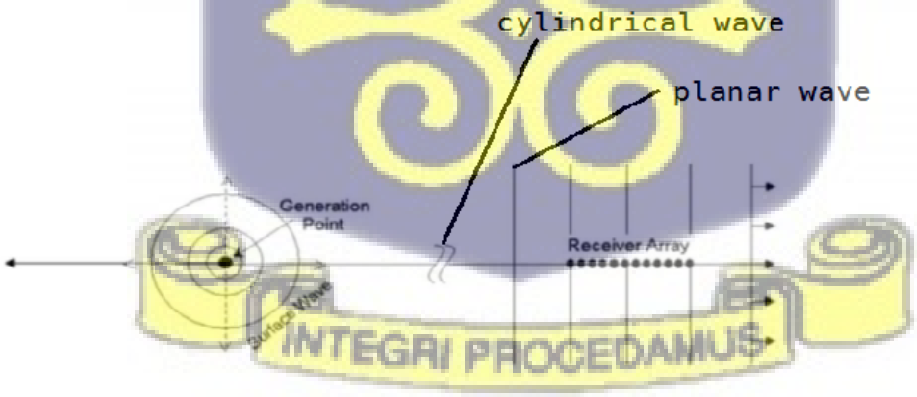

Fig 3.2 Wave propagation of Raleigh's wave. Close to the shot point the wave front is cylindrical, farther away it adopt planar wave front. (Park and Miller, 2006)

In this study, the impact source to the first geophone (near offset, X_1) is set to 12m (that is 6dx. (dx – the geophone spacing) is set to 2m. The length of the profile line is 50m and the

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total spread from the first shot source to the last geophone (far offset) is 62m as shown in fig 3.1 above.

Data was collected from the field using a (SmartSeis ST System) – a 24-channel seismograph. It was twenty four (24) 4.5 Hz geophones planted vertically. Impact was made on a 300mm X 300mm steel plate using a sledge hammer as the source of energy. Gathered shots on the seismograph were saved in a database file. A delay interval of 1 second was placed on the seismograph to ensure that only after 1 second will initial complete amplitude occur. Also, a sweep of 1Hz - 60Hz was used to help achieve maximum depth of penetration. For dispersion curve analysis, signal traces felt by the geophones were digitally saved in the form of SEGY data. At each shot location, three shorts were stacked with the aim of getting the average of the traces sensed by the geophone (shot gathers). The average signal traces cancel any disagreement around the exact energy conveyed in the test sample felt by the receivers

3.5 Receiver Spacing.

Receiver spacing (dx) controls the minimal inquiry depth (Z_{min}), and the minimum wavelength reachable and that can be investigated is proportional to the minimum geophone distance (dx) (Alsulaimani, 2017). This way, the minimum depth is dependent on the geophone spacing. In surface wave analysis technique, the following formula is used to estimate the depth of study (e.g., Stokoe, 1994, Park &Carnevale, 2010).

$$\mathbf{X_1 \geq Z_{min}}$$

$$\mathbf{Z_{max} = 0.5\lambda_{max}}$$

X_1 is the near offset (distance from impact source to first geophone) λ_{max} is the maximum Rayleigh wavelength. Only when the near-offset (X_1) exceeds half of the maximum desired wavelength (λ_{max}) is the Rayleigh wave expected to be planar. So longer wavelength waves must travel a further distance to become planar, necessitating a larger distance between short point and the first geophone of the profile line for deeper research (Richart et al., 1970; Park et al., 1999; Duffy, 2008; Yuan, 2011).

The complete length of the receiver spread (D) has a direct proportion correlation connection with the longest wavelength (λmax) that can be investigated. The receiver spread (D) must be same to or greater than maximum expected depth of investigation (Zmax) in most cases. If the profile line is made far too long, most active source generated surface waves become weak (attenuated) under noise level at the far end of profile line, as a results signals (Far-offset effect) become contaminated by high frequency (short wavelength) components of the

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surface wave (Bullen, 1963) or P-waves (Rix and Leipski,1991;Stokoe et al., 1994). For the optimal data collection, D is commonly set between 50 and 100 meters and the geophone spacing (dx) must be at least $\mathbf{dx \geq 0.5\lambda_{min}}$(Park et al., 1999, Yuan, 2011):

Table 3.1 Best field measurement parameters for MASW surveys.

Receiver (Hz)	Max. Depth [z_{max}] (m)	Minimum Offset [x_1] (m)	Maximum Offset (m)	Receiver Spacing [dx] (m)
4.5	50	10	100	1
10	30	10	100	1
40	15	10	100	1

3.5 Post field studies (MASW data processing and interpretation)

The post field studies involve extracting dispersion curve and inversion of the acquired time series or shot records and final interpretation. Preprocessing, dispersion analysis, and modeling are the three stages of surface-wave data processing. Preprocessing consists of transforming the data format. Most field data is captured in the .dat format. Such data should be converted to .sg2 or .sgy. Standardizing the geometry parameters, and eliminating bad signals all form part of the preprocessing stage.

The dispersion curve analysis stage involves picking the fundamental mode dispersion curve of Raleigh's waves (Wilson, Chapman, & Li, 2009

3.6 Extraction of dispersion curve

Signal traces are converted to dispersion spectrum for the purpose of picking the energy peaks on the dispersion spectrum (Taipodia et al., 2020). One pick is one dispersion point on the dispersion spectrum. The connected picks of maximum energy on the dispersion spectrum form the dispersion curve. Dispersion analysis is intended to derive Rayleigh wave dispersion curves from surface wave data. The generation of a dispersion curve is a critical step producing a reliable shear wave velocity profile. (Park et al., 1999).

Different phase velocities at different frequencies exist in a Raleigh's wave. The phase velocities represent theoretically, different propagating mode of Raleigh's wave. The fundamental-mode (M0), of Rayleigh waves has the least velocity among the other modes. The 1st higher mode (M1), the 2nd higher mode (M2) has velocities of **(M1<M2)**.

Points of dispersion located within the maximum energy with the least velocity in the dispersion spectrum form a dispersion curve.

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Removing noise from the ground roll data improves the accuracy of the dispersion curve (Park et al., 1999). The shot records were processed with computer programs (EasyMASW) to derive the dispersion spectrum and dispersion curve. A shot record is shown in figure 3.3.

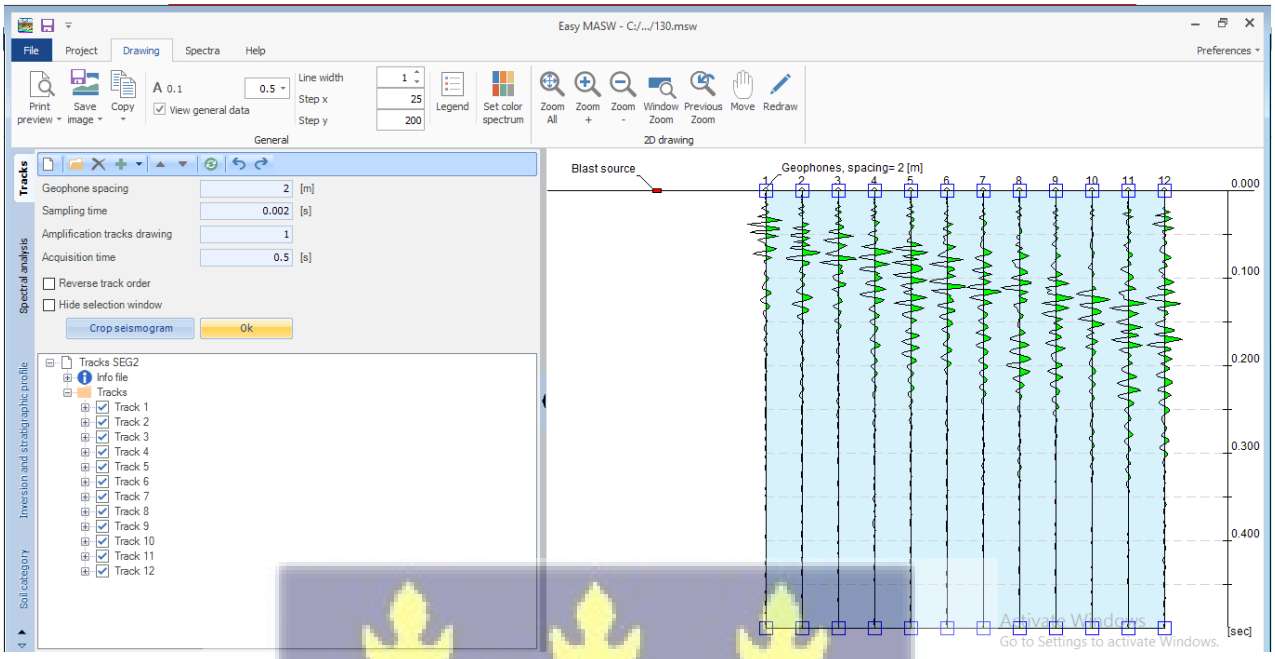

Fig 3.3 EasyMASW(from Geostru) window displaying trace shot record.

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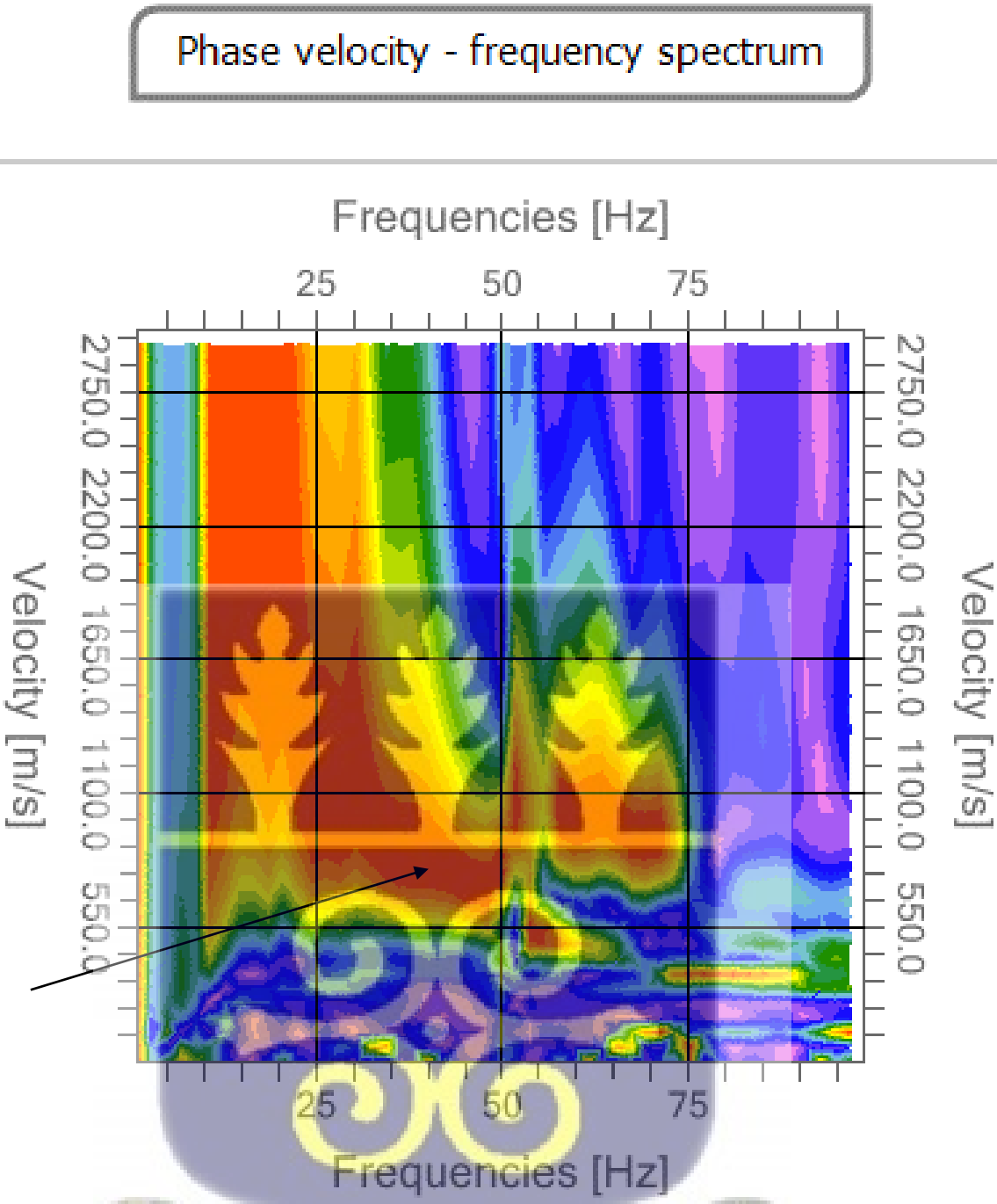

Fig 3.4 Example of dispersion spectrum (from shot point 113 of line one) in the processing software (EasyMASW). The arrow is pointing to the fundamental mode (M0)

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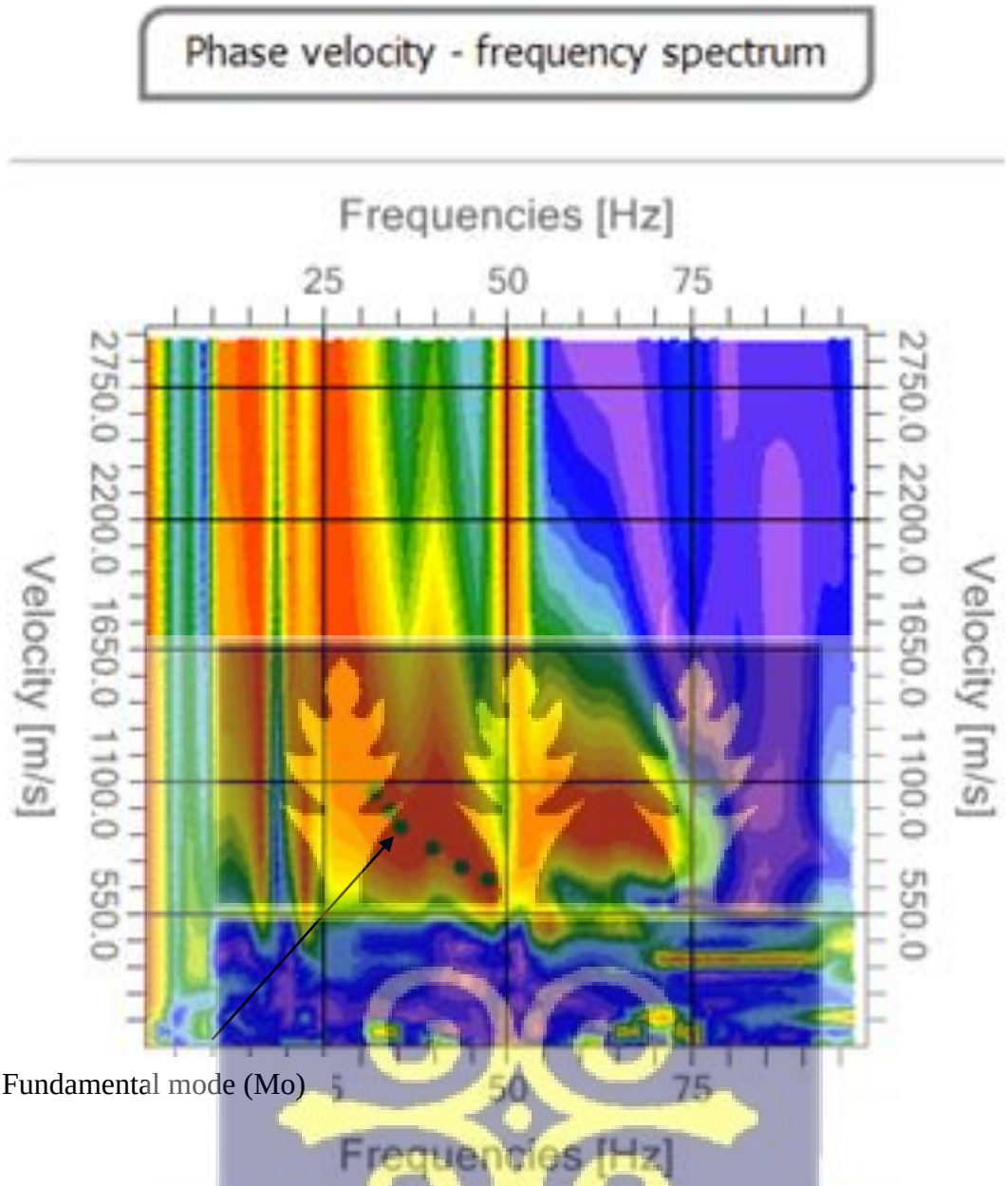

Fig 3.5. Dispersion curve (dotted curve) of 113 on traverse line 1

3.7 Inversion

Shear-wave velocity models (example shown in fig. 3.6) are obtained from the forward modeling of the dispersion curve. Iterative inversions are run on the models to deduce the best estimate of the shear wave velocity profile. The inversion process uses a least-square approach (Xia et al., 1999) to come to a best estimate of S-wave velocity with depth (Park et al., 1999). The S-wave velocities are achieved when a Rayleigh-wave dispersion curve is inverted to fit a layer model with default values of layer thickness, P-wave velocity, Poisson's ratio and density. When the inversion is well done, the theoretical curve matches or coincide the experimental curve with the least possible root mean square (R.M.S) error usually below

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10%. At this point, the result of the inversion can be said to be a correct or a true representation of the ground beneath the spread and it is taken as the best practical model of the ground materials at that point. Inverted dispersion curves generate 1D (depth – velocity) profile. Several 1D profiles are stacked to produce a 2D Shear wave velocity profile (Duffy, 2008).

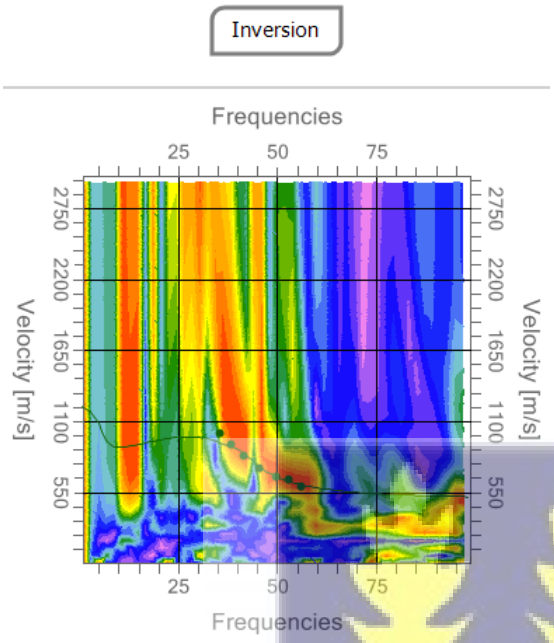

Fig 3.6 Inverted dispersion curve (from shot point 123 of traverse line 2) the green curve is the theoretical curve that coincide with the experimental curve- the green dotted curve.

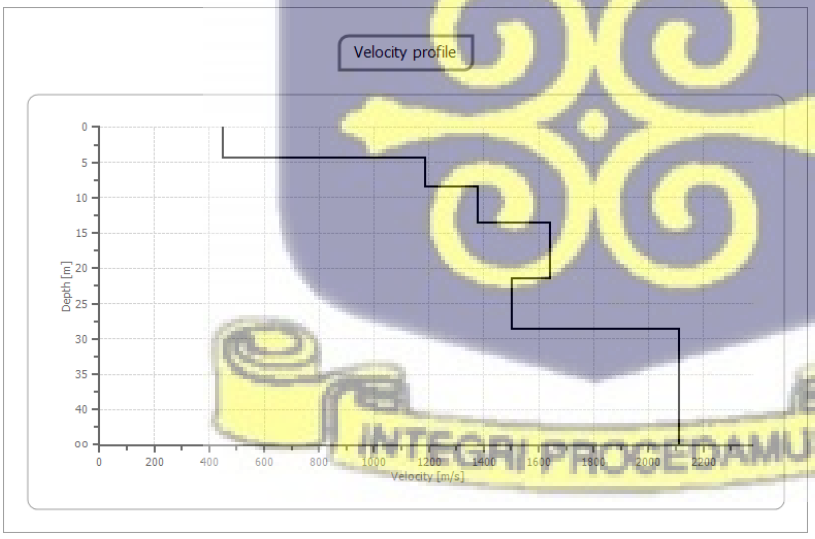

Fig 3.7 1D S-wave velocity profile of shot point 123 of line 2 obtained from the inversion of the dispersion curve.

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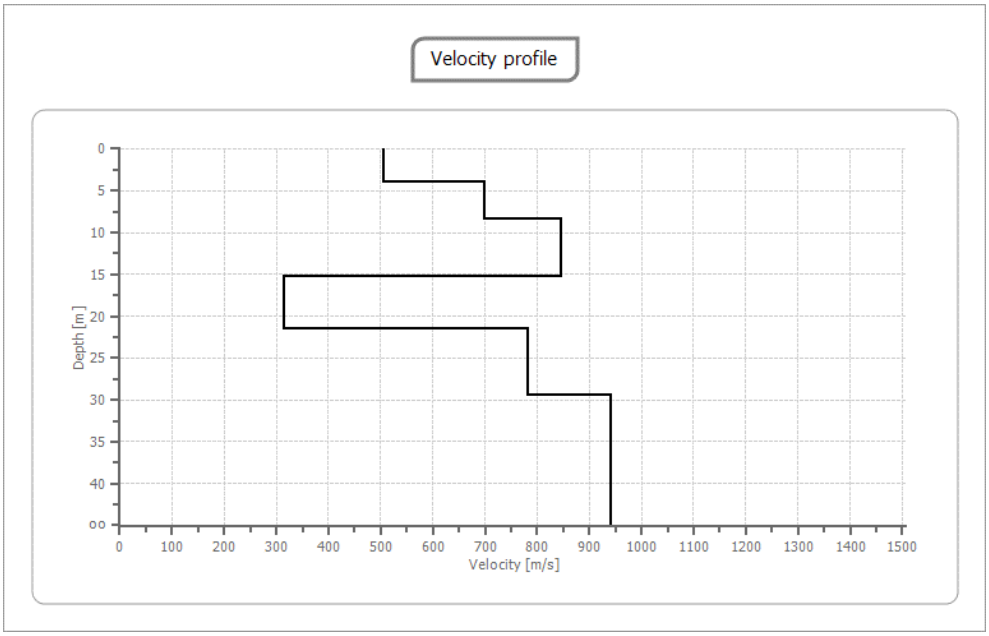

Fig 3.8 1D velocity profile of shot point 130 on traverse line 2.

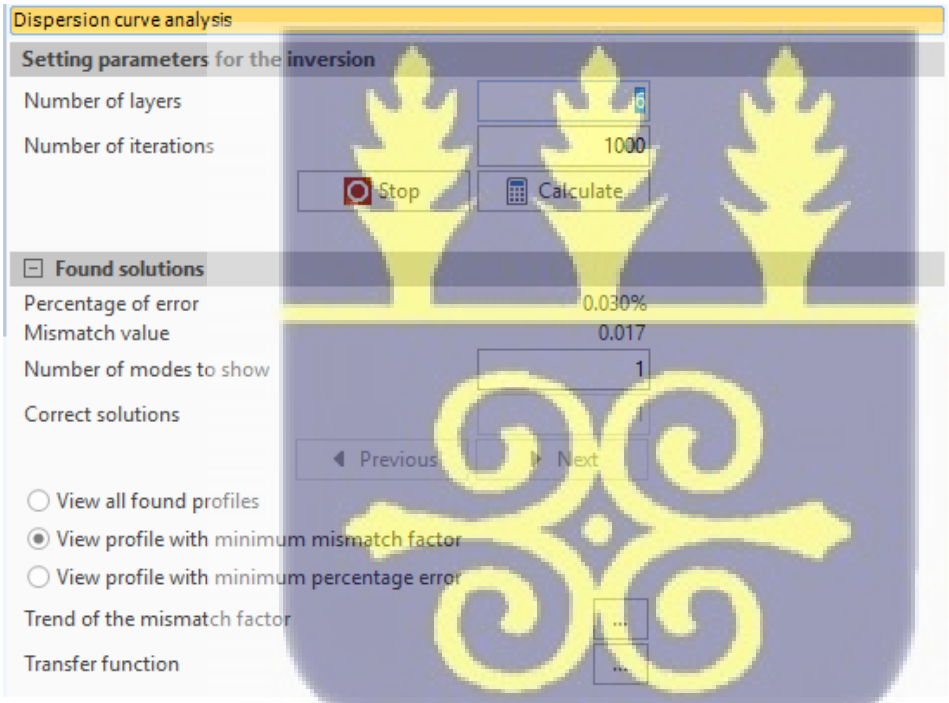

Fig 3.9. Dispersion curve analysis window showing setting parameter for the inversion.

All 1D S-wave velocity profile inversions used in this study, density and Poisson ratio are kept at 1800 kg/cm^3 and 0.2 respectively.

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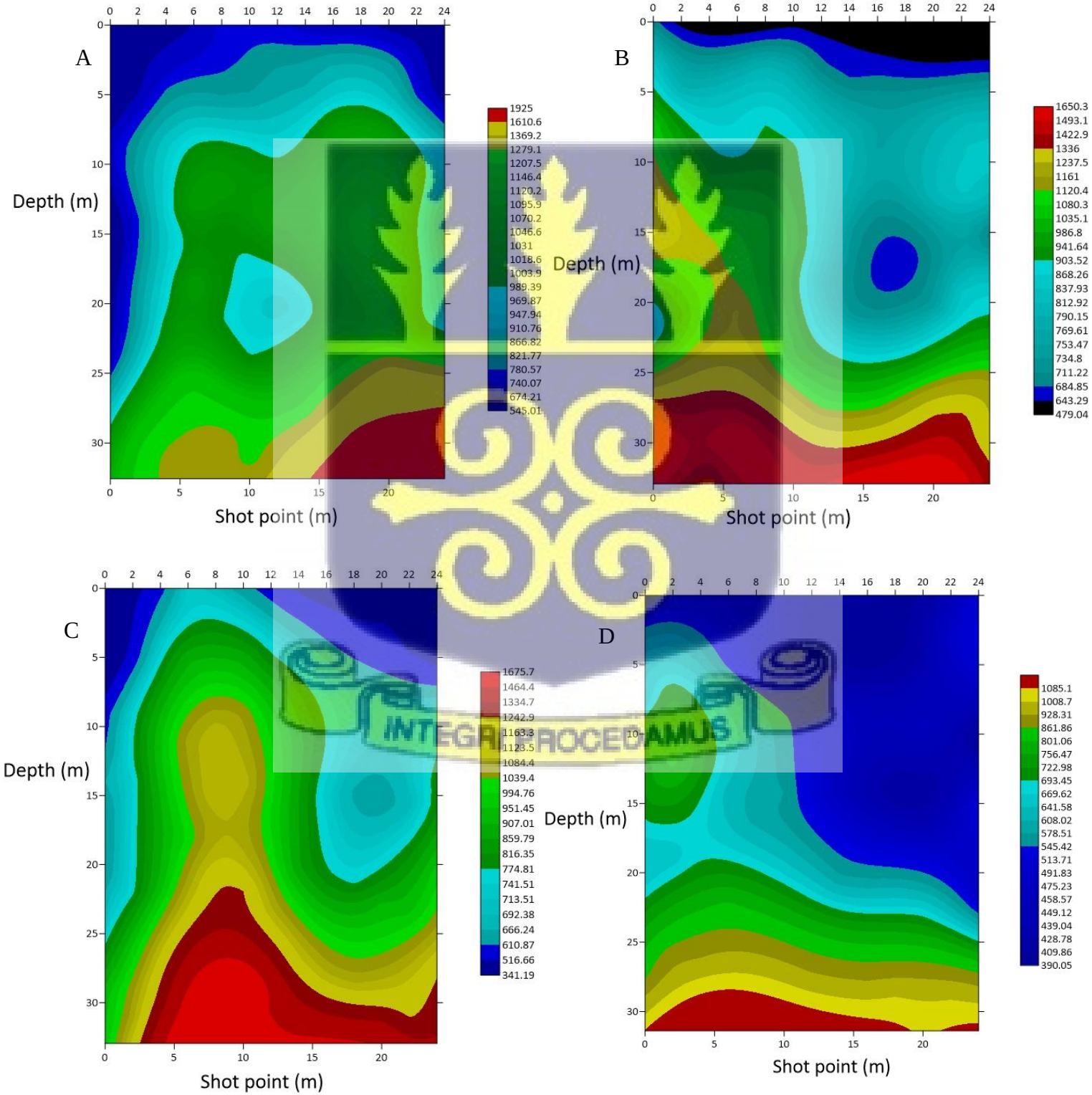
CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The 2D Vs cross section shown in figure 4.1 is as a result of interpolated 1D Vs velocity profiles (for example shown in fig. 3.7 and 3.8). The 2D Vs cross sections reveal the shear velocity of the subsurface materials with depth. In all the five profile lines, the maximum depth of investigation exceeded 30m and Vs shows consistent increase with depth. The Vs range with depth is indicated in the figure 4.1 below.



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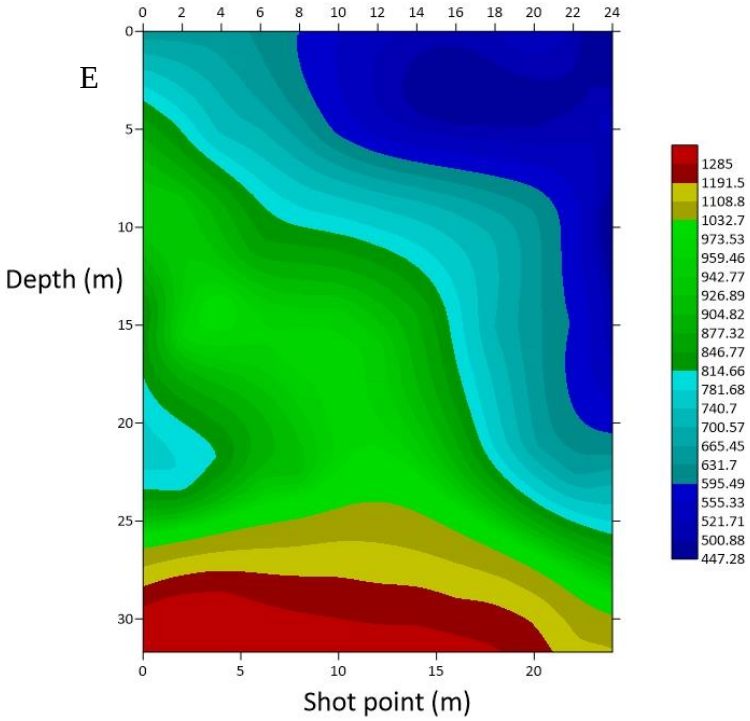

Fig 4.1 2D velocity profiles from the inversion of the dispersion curves (A) 2D Vs profile of line 1, (B) 2D Vs profile of line 2 (C) 2D Vs profile of line 3, (D) 2D Vs profile of line 4 and (E) 2D Vs profile of line 5.

4.2 Discussions

Maximum depth of investigation reached a little beyond 30 m for all five traverse lines. The 2D velocity profile of the five lines characteristically show a five layered model except line two that shows additional low velocity topmost layer. The layered subsurface materials is overlying a high Vs velocity bedrock which is seated deep at a depth beyond twenty-five meters deep although it was encountered around twenty two (22 m) meters on line 3. Line two and three shows shallower topmost layer whiles line 1, 4 and 5 have topmost layers that go deep a depth of 25 m at the beginning and the end of the line and transient into the immediate underlying layer. Line 4 and 5 were shot in the opposite direction. (South-north for line 4 and north – south for line 5). It is observed from the 2D Vs profile of the said lines (Line 4) that as the distance increases from X_1 (distance 0) to the last shot point (26m further fromX_1) the topmost layer increases in depth and appears shallower in the reverse direction (as in 2D profile of line 5). Line 1 shows a deeper depth of the topmost layer for the initial offset distance (0-4m) and maintained a steady thickness to 26m further away (last shot point).

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Vs velocity generally, increases from the topmost layer to the bottom bedrock. Generally, low Vs values characterize the residual soil derived from the subsurface parent rocks. In the Togo formation, the lateritic cover and quartzitic gravely may usually cover the near surface and the surface. The consistent increase in Vs (small margin increase) within the same layer with depth may be associated with compaction of the grains of soil/rock. The occasional velocity inversions in a rock unit as observed in line 1 and line 2 suggest fracturing, voids and or weathering or the inclusion of lower velocity material into the higher velocity soil/rock

Lateral change in rock unit/lithology is not clearly shown in this study except line 3 and line 5 that show the immediate layer beneath the topsoil as part of the topsoil.

The deep seated bedrock has shown consistent Vs velocity within the study site as shown in all the five spread lines. The bedrock may not be shallow. The shallowest part of the bedrock as shown in the line 3 is still within a depth range beyond 22 m. The bed rock may not be weathered or heavily fractured as there in little or no velocity inversion within the bedrock but shows consistent downward small range increase in shear velocity as shown in line 2, line 3 and line 5.

At least five layers of distinct Vs range can be resolved from the derived 2D-Vs profile. Topmost layer of mainly well compacted soil has Vs range between 350 m/s to 550 m/s. Soil/rock underlying the topmost layer ranges in Vs between (550-750)m/s. The third layer ranges in Vs values of (750-900) m/s. Layer 4 ranges in Vs velocity between (900-1100) m/s. The above listed layers all overly a deep seated rock that range in Vs between (1200-1900) m/s.

The entire study site shows competent rocks both vertically and laterally. The 2D Vs profile shows consistent lateral and vertical increase in Vs velocity. Although they may be occasional velocity inversion, the general Vs trend falls within competent/stiff soil or rock.

Scatter diagram of Vs30 (Shear velocity at 30m depth) shows that the study site ranges the least Vs30 value between 388 m/s and 760 m/s for the east-west oriented profile lines (line 1, 2 and 3) and highest Vs30 velocity range between 760 m/s 1400 m/s. The north – south oriented spread lines (line 4 and 5) however, show Vs30 range values between 440 m/s and 760 m/s

The scatter plots of Vs30 Vs lateral offset is shown below.

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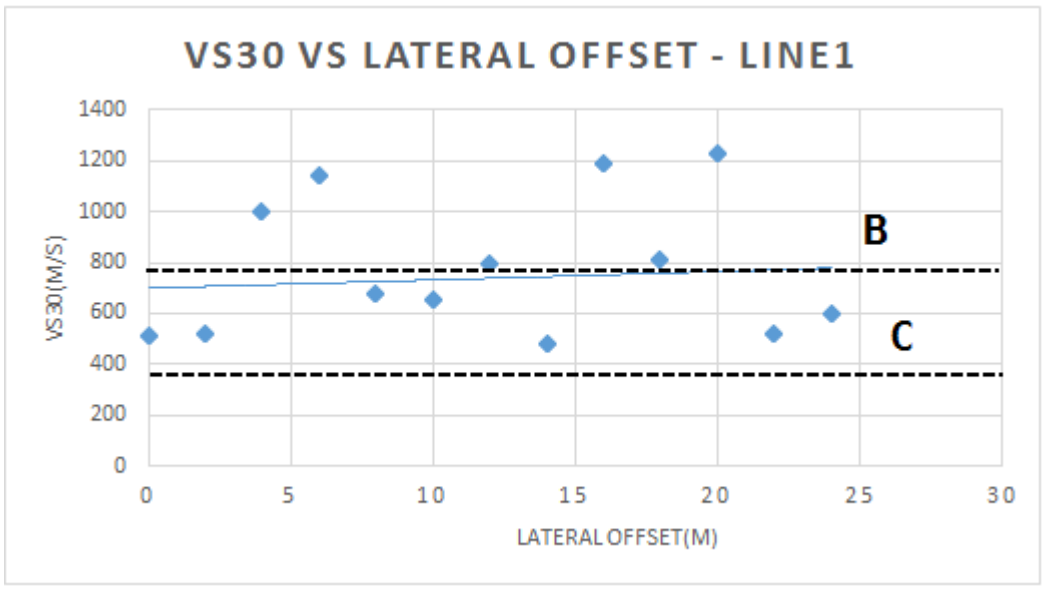
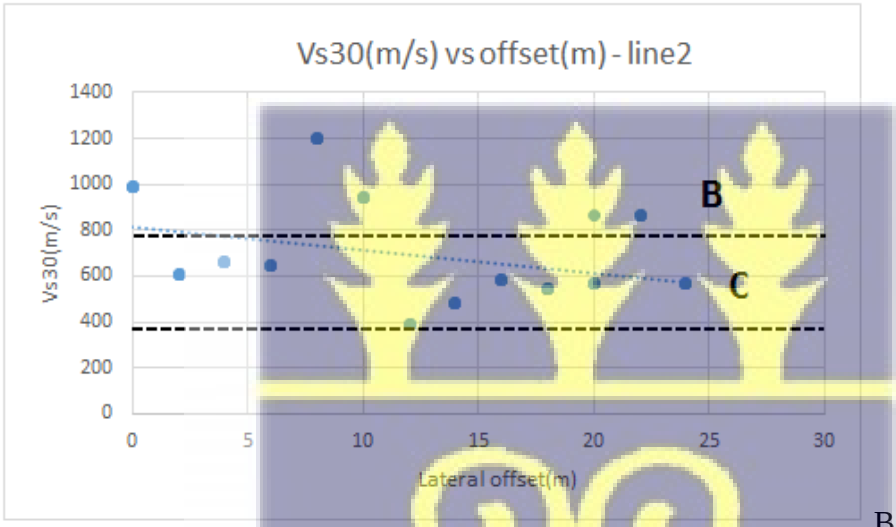
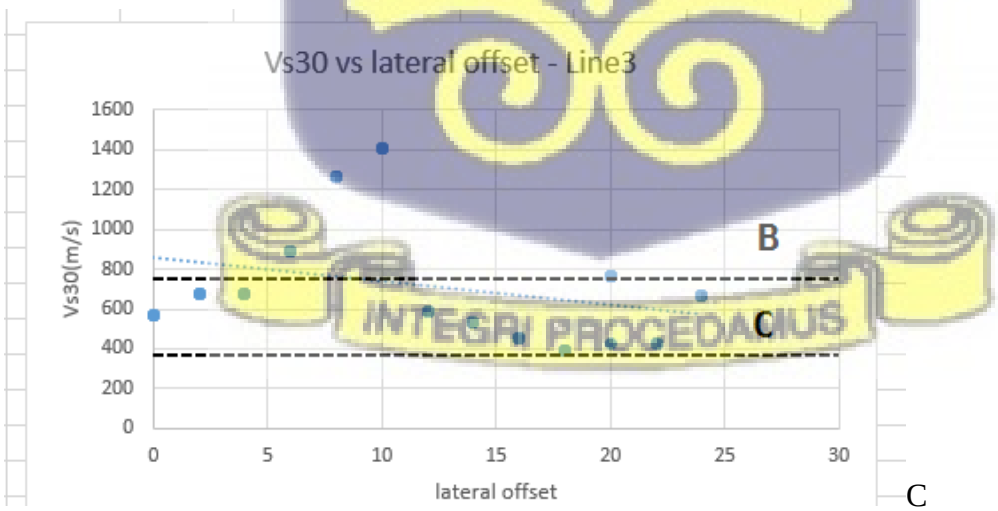


A



B



C

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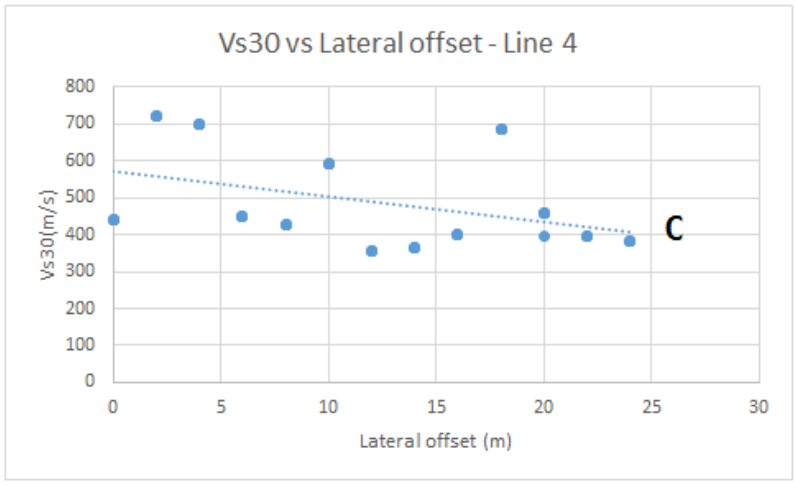
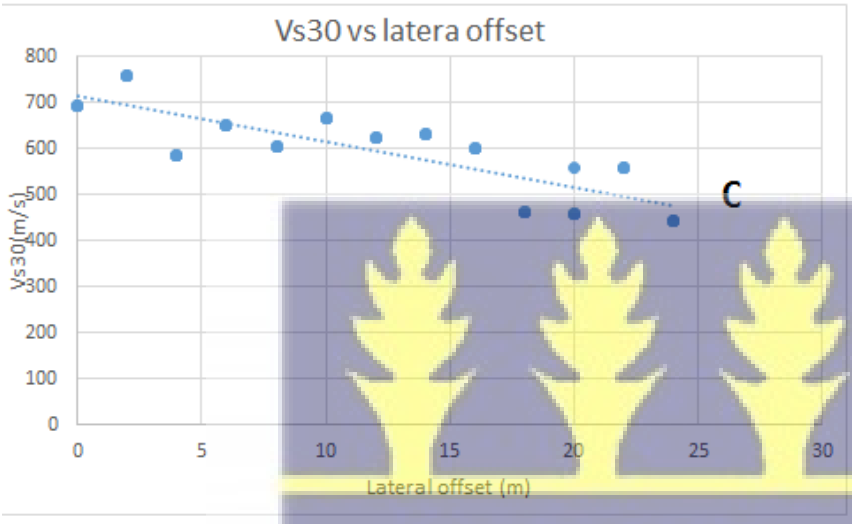


D



E

Figure 4.2 Scatter plot of Vs30(m/s) against lateral offset (m).

Table 4.1 (National Earthquake Hazards Reduction Program) NEHRP Soil Profile Type Classifications

Soil Profile Type	Average Shear-Wave Velocity to 30-m depth ($\bar{V}_{s30}$)
A	Vs_{30} > 1500 m/s, hard rock
B	760 m/s <Vs_{30} ≤ 1500 m/s, rock
C	360 m/s <Vs_{30} ≤ 760 m/s, very dense soil and soft rock
D	180 m/s < Vs_{30}≤ 360 m/s, stiff soil
E	Vs_{30}< 180 m/s soft clay and susceptible to liquefaction

From the shear wave velocity ranges proposed by the National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001) for 30m depth of soil deposits (see the table

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above), two (2) common velocity zones, B and C, conforming to rock and very dense soil/soft rock respectively can be inferred for line 1, 2 and 3. Refer to the scatter plot shown above. Line 4 and 5 correspond to category C of very dense soil and soft rock.

Although the bedrock is deep seated in the study site (beyond 22m deep) the general Vs30 mapping shows Vs30 value of at least 360m/s within the study site.

4.1 2D shear wave velocity profile Interpretation.

On the shear wave velocity model, low velocity zones can evidently be shown. The low velocity zones can be inferred as sinkholes, voids, fractured bedrock, or naturally in-filled collapsed features. The 2D shear wave velocity profile (2D Vs-profile) can be interpreted to delineate soil/overburden-bedrock contact and also delineates stratigraphic boundaries by displaying a boundary of appreciable velocity (Vs) rise (e.g., from 300m/s to 1000m/s). 2D Vs-profile has also shown vertical variants of soil/rock stiffness by way of presenting Vs velocity range with depth (e.g., 100 m/s - 300 m/s). Such small margin of boundary range of Vs regularly shows a steady change in velocity over a certain depth range rather than a sharp-defined interface.

4.2 Stiffness of the rocks/soil at the surveyed site

Shear wave velocity (Vs) measurement is needed for determining the stiffness qualities of near-surface geologic materials. The shear strength of geologic material increases as its shear wave velocity increases. The maximum shear modulus of soil/rock can be determined by the relation;

Shear Modulus (G_{max}) **= density (ρ) *$(Vs)^2$** **(6)**

i.e. density times the square of shear velocity. (Teccan and Ozdemir, 2012)

and maximum Young modulus (E_{max}) is

$$\mathbf{E_{max} = 2(1 + v)G_{max} = 2(1 + v)\,\rho Vs^2} \quad \mathbf{(7)}$$

Using this relation, the shear modulus of the surveyed site can be calculated using Vs from the inversion of dispersion curve. It is inferred that, the shear modulus of the surveyed increases with depth as Vs increases except in rock units or layers where small velocity inversions exist and thus the cohesion and interlocking of grain particle increases with depth in the study site.

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4.3 Load bearing capacity of the study site.

Each soil/rock class has its own strength and therefore has unique bearing capacity. The strength of the rocks/soils at the study site locally can easily be computed using the relation expressed above in equation (6)

Tezcan, Ozdemir and Keceli (2009) proposed that, the allowable bearing capacity q_a is calculated using the relation

$$q_a = 0.1 \ \gamma \ V_s / n = q_f / n \quad \textbf{(8)}$$

Where γ unit weight of soil/rock

n is safety factor

Vs is shear wave velocity

$$q_f = 0.1 \ \gamma \ V_s \quad \textbf{(9)}$$

q_f is ultimate bearing capacity

The safety factor n, is estimated as

$$n = 1.4 \ \ (for \ V_s \geq 4\ 000\ m/sec), \quad n = 4.0 \ \ (for \ V_s \leq \ 750\ m/sec)$$

Tezcan, Ozdemir and Keceli (2009)

From the above relations, if the safety factor n, and unit weight γ are constants, then Vs is the varying parameter that varies the bearing capacity of the study site. With the lateritic to gravely top cover of the study site and the least Vs of 341.19m/s and highest Vs of 1925m/s the least and the highest allowable and ultimate load bearing capacity can be estimated using equation **(8)** and **(9)** above assuming a unit of 18KN/m^3 (for the lateritic) top cover and safety factor n =4.

The least allowable bearing capacity (q_a) = 0.1 x 18 x 341.19/4 = 153.53KN/m^2.

The highest q_a = 0.1 x 18 x 1925/4 = 866.25KN/m^3.

The least ultimate bearing capacity (q_f) is 0.1 x 18 x 341.19 = 614 KN/m^3.

The highest ultimate bearing capacity (q_f) is 0.1 x 18 x 1925 = 3465 KN/m^3.

These values are suggesting that, the study site has firm grounds and can support shallow foundation of at least four (4) storeys. (https://theconstructor.org/geotechnical/foundation-selection-criteria/6971/). Since these values only used the soil geotechnical parameters of the topmost layer (the top lateritic layer), and the Vs values increases with depth, it can be deduced that the load bearing capacity of the study site increases with depth and thus can support foundation.

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4.4 Feasibility of huge construction on the study site.

From the simplified calculations of the load bearing capacity of the study area, it suggest that, the study has firm grounds and support foundation of huge architectural design. The shear strength of the soil/rocks of the study area consistently increases with depth. Although there are occasional instances of Vs inversions, it still falls within the acceptable range of shear strength values and load bearing capacity threshold to support shallow foundation. The base rock is estimated to sit at a depth of 22m-25m with firm soil/rock overlying it. This can support huge foundations.

4.5 Effect of landfill site on building facilities.

Building on an abandoned landfill sites has several negative effects. There is usually the problem of gas production (methane), attack on building materials by corrosive leachates and subsidence as a result of liquefaction. It is therefore very necessary to consider the negative impact on building on landfill sites before raising the foundation for the architectural design. Permeable gravels layers of gravels can be installed to create a pathway for the escape of gases and piped out at or beyond roof levels. Loose waste can also be moved away from where the building will be constructed so that the building can be put on firm ground, and where possible, deep foundation can be employed when building on an abandoned landfill site.

4.6 Possible uses of the study area/site

The study area is placed under soil type B and C of NEHRP soil profile classification. The ground is considered firm having dense soil and soft rocks sitting of a hard less fractured or jointed bedrock at a depth of about 22-25m. Such a site can be used for residential and or commercial purposes. The authorities of Apenkwa Presbyterian Basic School intend to build a school facility on this site. Based on the least load bearing capacity calculated for the site, they can at least build a four storey on the site and even more depending on how they strengthen the ground, the depth of the foundation and the height of the intended structure and also putting the occupancy into consideration.

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CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

The objective of this study was to determine the ground stiffness of a reclaimed landfill site using the MASW seismic technique. It also sought to interpret the results in terms of subsurface stratigraphic/topographic map and delineate depth to bedrock-overburden contacts. Weathering zones within a rock/soil unit was also investigated using the velocity inversion in the 2D Vs velocity profile.

From the observed results, the following conclusions can be drawn

- The surveyed site is made of competent soil/rocks overlying solid bedrock to a depth of about 25m.
- There about 5 distinct stratigraphic units with clear cutting Vs velocities.
- Velocity inversions in a rock unit may be interpreted as weathered zones, or voids or joints within that unit.
- On the basis of the Vs30 data, the surveyed site falls within category B and C of the National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001)

Shear wave velocity is thus an important soil parameter demonstrating a group of geotechnical soil parameters varying from shear and compressive strength, void ratio, load bearing capacity, soil cohesion etc.

5.1 Recommendation

This study is a preliminary study and further studies will be needed using integrated geophysical methods to ascertain the ground conditions of the surveyed site to investigate foundation potentials of the site. Methods such drilling, seismic cone penetration test and other potential wave propagation methods as stated in chapter two could be used to confirm the ground stiffness and depth to bedrock to acquire a reliable ground information of the site.

Raising a huge architectural foundation beyond four storey will require that due investigations including drilling and deep excavations is conducted to reveal to the subsurface materials. Factors such as the occupancy population should be taken into consideration before the foundation is raised.

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