

Estimation of near-surface geotechnical parameters using seismic measurements at phase II site, Ahmadu Bello University Zaria, North-western Nigeria

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ABSTRACT: Determination of the dynamic geotechnical properties and seismic wave velocities serves as essential inputs for a foundation design cognizant of seismic site response and rock strength. This study evaluates competent zones for construction at Ahmadu Bello University Zaria, Phase II site. Four shallow seismic refraction profiles were carried out using the ABEM Terraloc Pro seismograph. Compressional (P) and shear (S) waves were acquired and the time-term technique, which is a combination of linear least squares and delay time analysis to invert the first arrivals for a velocity section and then to tomography section was adopted. These sections were correlated with a borehole report and a good matching was observed. The result shows that the area consists of three subsurface layers; an overburden with average thickness of about 10.5 m and P- and S-wave velocities (velocities) of about 550 m/s and 345 m/s respectively, the weathered basement with an average thickness of 12.5 m and velocities of 950 m/s and 550 m/s respectively, while the fresh basement was found at a depth of about 24 m with velocities of 1250 m/s and 680 m/s respectively. The Concentration Index, Material Index, Poisson's Ratio, and Stress Ratio were calculated to be in the range of 4.869 to 6.128, -0.032 to 0.312, 0.172 to 0.258, and 0.267 to 0.346 respectively in the study area. The seismic velocity values, engineering consolidation, and strength parameters showed that the subsurface soil/rock at the eastern parts of the study area is characterized by less competent soil/rock quality while the western parts are characterized by more competent soil/rock quality. Hence, the western and north-western parts are more preferable for the foundation of structures to be erected.

Keywords: Geotechnical, near-surface, P- and S-waves, seismic refraction, velocities.

INTRODUCTION

In the last few years, the application of geophysics in civil and environmental engineering has become a likely approach. Geophysical tools are implemented in a wide range of applications ranging from building ground investigations to the inspection of dams and dikes (Soupios et al., 2007), targeting toward the exploration of geological structures and the determination of the physical parameters of the rock formations.

The expenses and time required to carry out the

geotechnical investigation of a proposed building site can be discouraging to the building developer, especially if the construction site is large. These challenges have made many developers carry out various construction projects without undertaking a proper site investigation. One of the implications of this is its significant contribution to the incessant building collapse experienced in many developing countries. An effort to reduce the cost and reliably estimate the geotechnical parameters needed for

proper foundation design will bring a sigh of relief to geotechnical engineers and building developers. A combination of geophysical and geotechnical techniques to study the required geotechnical parameters needed for construction purposes has the potential to make this contribution. Typically, the results of geotechnical tests are for point measurements because of the inability of this technique to provide lateral information on the surface. Geophysical methods, on the other hand, can give volumetric measurements and produce an image of the subsurface without physically disturbing the soil.

The statistics of failure of structures such as buildings, roads, bridges, dams and even boreholes throughout the nation have increased geometrically (Akintorinwa and Adeusi, 2009). The need for the pre-foundation study has, therefore, become very imperative so as to prevent loss of lives and properties that always accompany such failure (Akintorinwa and Adeusi, 2009).

The increase in student population year in year out on the campuses of Ahmadu Bello University (A.B.U.) Zaria has led to more expansion work. One of such expansion is the A.B.U. Zaria Phase II. Though a Standard Penetration Test (SPT) was carried out prior to laying the foundation of some buildings, a seismic refraction survey is to be used to further compliment the results and also cover a wider range of the study area.

Seismic refraction is one of the geophysical techniques that offer a non-intrusive and non-destructive way of performing geotechnical properties measurement. Seismic refraction can be an attractive alternative to boring where access is difficult with geotechnical equipment (Anderson et al., 2008; Nastaran, 2012). Also, this method can easily detect changes in the subsurface characteristics as there are changes in the behavior of a passing seismic wave as it passes through the media of different characteristics, in order to determine zones of structural weaknesses in the basement and analyze the stability of the subsurface.

The main target of this paper is to investigate the geotechnical parameters in the Ahmadu Bello University Phase II site area, by applying the seismic refraction technique to prove its potential in providing accurate information to the civil engineer, and in saving time and costs. This sort of study is important to tie geophysical concepts with different engineering applications. The objectives of this research were to determine the depth, thickness and seismic velocities (P-waves and S-waves) of the subsurface layers. Also, empirical correlation equations were adopted in correlating the P-wave and S-wave velocity with other geotechnical parameters.

MATERIALS AND METHOD

Location and geology of the study area

The study area is situated in A.B.U. Zaria main campus

Samaru, Kaduna state, Nigeria which is bounded by latitude 11° 08' 32" N to 11° 07' 53" N and longitude 7° 37' 56" E to 7° 39' 00" E. It is occupying 9% area of Kubanni River Basin and positioned on the North-Western part of the basin as shown in Figure 1.

The study area is predominated by Biotite Gneiss (Figure 2) which is occasionally broken up eastwards by older granites (McCurry, 1970; Abubakar et al., 2019) and extends westward forming a gradational contact with Quartz-Mica Schist. The outcrops of this rock unit are found mainly at the stream valleys, of which they are intensively weathered. They are medium to coarse-grained and moderately to weakly foliated rocks. They are mostly composed of quartz, turbid oligoclase and accessory apatite (Truswell and Cope, 1963; Abubakar et al., 2019). The superficial deposits are the Quarternary deposits and Older Laterites which constitute the sporadically distributed Older and Younger Alluviums (Eigbefo, 1978; Abubakar et al., 2019). The Biotite Gneiss at the site has been weathered to lateritic soil. Some sections of this lateritic soil, measuring up to 3 m in thickness, are exposed around the study area.

Data acquisition and processing

To achieve a 2D seismic tomography of the study area, the ABEM Terraloc Pro seismograph was used to conduct four seismic profiles; two profiles each for P- and S-waves respectively. Each profile extends for a total length of 115 m. The inter-geophone spacing was 5 m and an offset of 5 m at both ends of the profile with a total of 24 (10Hz) vertical and horizontal geophones per profile respectively. The total record length (time) for both the P- and S-waves was 327.7 millisecond (ms) with a sampling interval of 20 μ s and the number of samples per trace was 16384.

For both P- and S-waves data acquisition, vertical and horizontal geophone is set as the receiver type respectively in the "layout geometry" settings in the seismograph. A total of seven shots (Figure 3) was taken including the two offsets; shot 1 (offset1) at -5 m, shot 2 at 0 m, shot 3 at 30 m, shot 4 at 60 m, shot 5 at 90 m, shot 6 at 115 m and shot 7 (offset2) at 120 m for both P- and S-waves profiles.

A sledgehammer weighing 7.26 kg (16 lbs) was used to generate both waves. For the P-waves, vertical geophones, a trigger geophone was arranged according to the layout geometry. A sophisticated round rubber-like plate (about 38 cm diameter and 6 cm thick) was used to receive the sledgehammer strikes. A total of 2 stacks were made per each P-wave shot location. The position and elevation of all the geophones and shot locations are noted and the data saved in the memory of the ABEM Terraloc Pro.

To generate the S-waves, the Kobayashi method was adopted along with horizontal geophones. In this method, a wooden plate (2 m x 0.5 m x 0.2 m) was held in firm

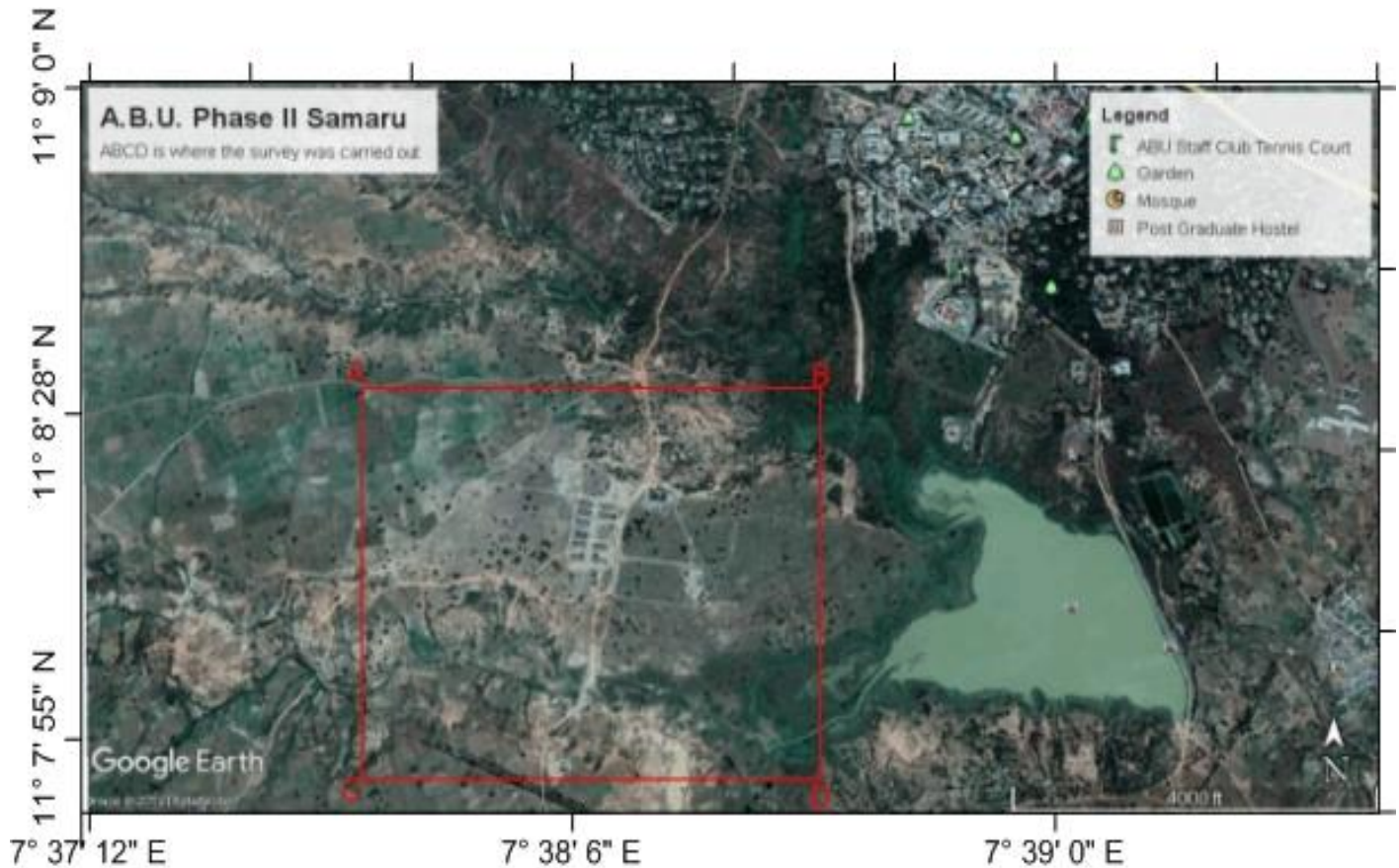


Figure 1. Google map showing the location of the study area (courtesy of Google earth).

contact with the earth surface by the weight of two heavy persons standing on it was used to receive the sledgehammer strike. The piece of wood was located such that its long side (2 m) was perpendicular and centered relative to the line of geophones (profile line). Two separate files were recorded (a) a right-side shot, where the sledgehammer was striking on the wood in a horizontal direction at its right side, and (b) a left-side shot, where the sledgehammer was striking on the wood in a horizontal direction at its left side. This was done in order to facilitate the identification of shear waves arrivals and suppressing the compressional (P) waves. S-waves' records are usually displayed in the same manner as P-waves. Similarly, the position and elevation of all the geophones and shot locations are noted and the data saved in the memory of the ABEM Terraloc Pro.

The data collected was processed using SeisImager 2D software developed by Geometrics Inc. The time-term technique which is a combination of linear least squares and delay time analysis to invert the first arrivals for a velocity section and then to tomography section. The two sets of data (right-side shot and left-side shot) gotten for the S-waves shots are subtracted from each other to get a good shear wave velocity before picking the first arrivals.

Boreholes are often used to correlate results obtained from geophysical surveys as these surveys are indirect. This is often done by correlating the tomography sections obtained in the area with the lithological information in the area. Boreholes which provide lithologic information, are necessary and reliable source of primary data and Seismic Refraction Tomography (SRT) interpretations provide secondary information. The 2D tomography results of the survey were correlated with the Borehole log (Table 1) taken about 3 km from the study area but of the same geological setting. The seismic velocities are used to calculate the elastic moduli and the engineering parameters using the relationships in Tables 2 and 3 respectively then compared with standard tables which are shown in Tables 4 and 5.

Geotechnical parameters

No construction material has more variable engineering and physical parameters than the ground soil. These parameters vary both laterally and vertically, and often the variations are strong (Bowels, 1982). Several parameters are calculated; the concentration index, the material index,

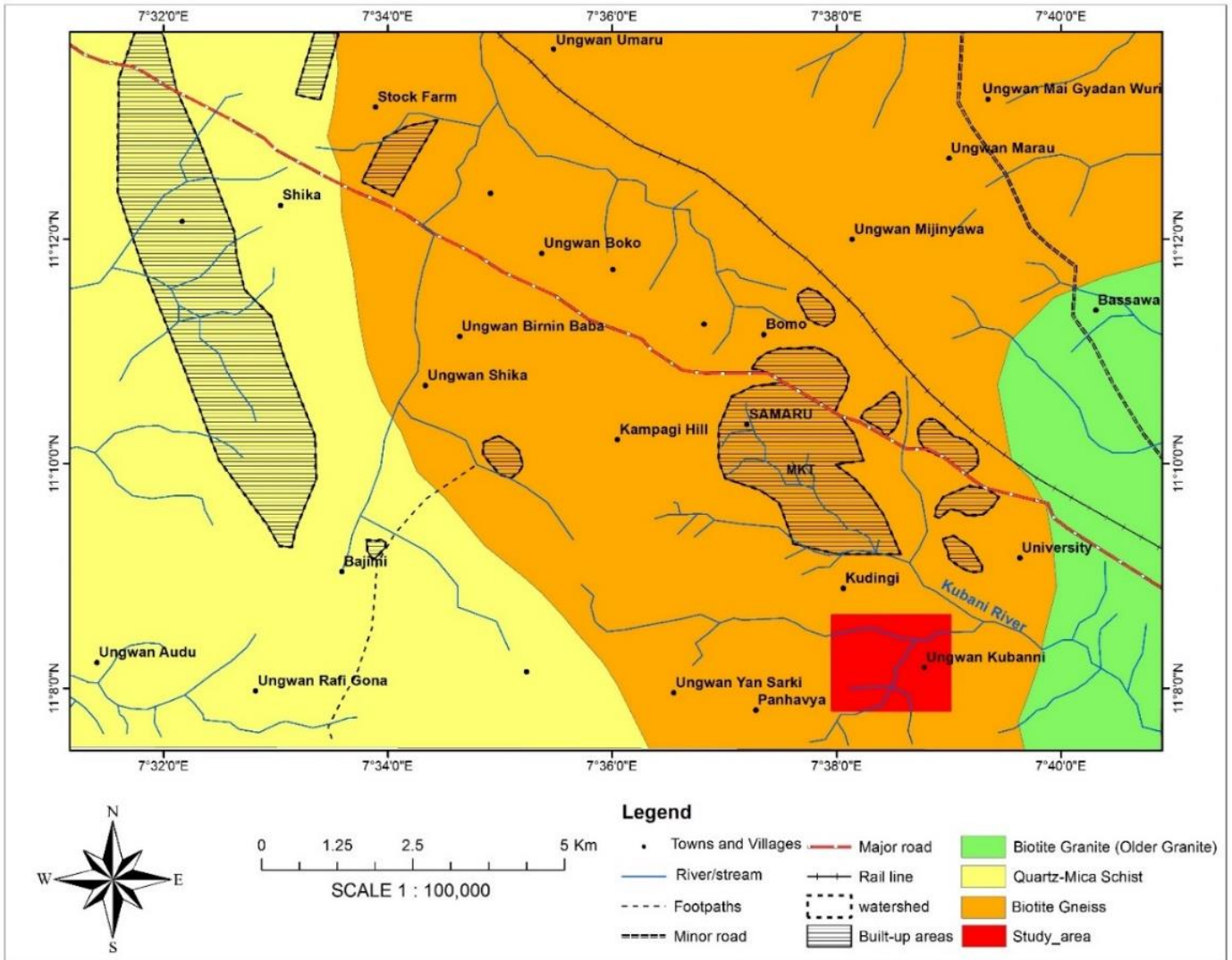


Figure 2. Geological map of the study area (Adapted from McCurry, 1970; Abubakar et al., 2019).

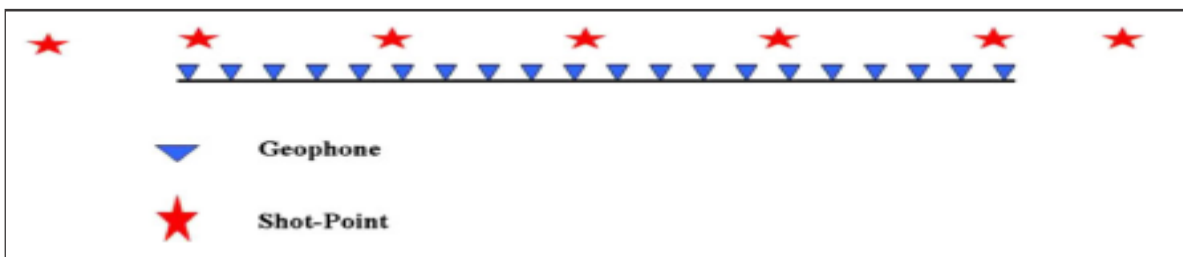


Figure 3. Profile layout of both P- and S-wave.

the Poisson's ratio and the stress ratio (Bowles, 1982). In order to evaluate the competence of the subsurface for construction, some of the shallow soil engineering parameters were calculated. Four parameters are calculated; the Concentration Index (Ci), the Material Index (V), the Density Gradient (D), and the Stress Ratio

(S). The integration of these four parameters is used to select the most appropriate site for construction.

To calculate these parameters the values of P-wave velocity (V_p), S-wave velocity (V_s), density (ρ), Poisson's Ratio (ν), Young's Modulus (E), Lamé's Constant (λ), and the Shear Modulus (μ) are required. Both P- and S-wave

Table 1. Lithology and Geologic section of borehole 1 – Akenzua Hostel (Hydro-Skill Ltd., 2006).

Depth (m)		Thickness (m)	Layer depth (m)	Interpreted lithology
From	To			
0.0	5.0	5.0	Overburden	Reddish-brown Topsoil
5.0	9.0	4.0	0.0 – 9.0	Reddish-brown Sandy soil
9.0	12.0	3.0	Weathered Basement 9.0 – 22.0	Grayish brown Sandy soil
12.0	17.0	5.0		Mottled clay
17.0	22.0	5.0		Coarse to medium-grained sand
22.0	27.0	5.0	Fresh Basement 22.0 – 27.0	Fractured Basement

Table 2. Equations of elastic moduli used. V_p and V_s are P-and S-waves velocities respectively.

Elastic Modulus	Used Equation	Reference
Poisson's Ratio	$\sigma = \frac{1}{2} \left(1 - \left\{ \frac{1}{\left(\left(\frac{V_p}{V_s} \right)^2 - 1\right)} \right\} \right)$	Adams (1951), Salem (1990), Khalil, <i>et al.</i> , (2008)
Young's Modulus	$E = \rho \left[\frac{3V_p^2 - 4V_s^2}{\left(\left(\frac{V_p}{V_s} \right)^2 - 1\right)} \right]$	Adams (1951), Khalil <i>et al.</i> , (2008)
Lame's constants	$\lambda = \frac{\sigma E}{(1 + \sigma)(1 - 2\sigma)}$	King and Olhoeft (1966), Toksoz <i>et al.</i> , (1976), Khalil <i>et al.</i> , (2008)
Density	$\rho = [0.3 V_p^{0.25}]$	Gardner <i>et al.</i> , (1974), Araffa <i>et al.</i> , (2014)
Shear Modulus	$\mu = \frac{E}{2(1 + \sigma)}$	King and Olhoeft (1966), Toksoz <i>et al.</i> , (1976), Khalil <i>et al.</i> , (2008)

Table 3. Soil description with respect to Poisson's ratio and Material Index, after Birch (1966), Gassman (1973), Tatham (1982), Sheriff and Geldart (1986).

Soil Description Parameter	Incompetent to slightly competent	Fairly to moderately competent	Competent materials	Very high competent materials
Poisson's Ratio (σ)	0.41 – 0.49	0.35 – 0.27	0.25 – 0.16	0.12 – 0.03
Material Index (ν)	(-0.5) – (-1)	(-0.5) – (0.0)	0.0 – 0.5	> 0.5

velocities are obtained from the acquired seismic refraction profiles. The elastic moduli values are calculated from the equations listed in Table 2.

Poisson's ratio

Poisson's ratio (σ) is the ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force. In other words, Poisson's ratio is the lateral contraction per unit breadth divided by the longitudinal extension per unit length, with dimensionless units. Tensile deformation is considered positive and compressive deformation is considered negative.

By this definition, Poisson's ratio contains a minus sign so that normal materials have a positive ratio. Virtually all common materials become narrower in cross-section

when they are stretched. The reason for this, in the continuum view, is that most materials resist a change in volume (determined by the bulk modulus, (K) more than they resist a change in shape (determined by the shear modulus, μ).

In the structural view, the reason for the usual positive Poisson ratio is that interatomic bonds realign with deformation. If α is expected to be the ratio of the squared shear- and longitudinal-wave velocities, then:

$$\alpha = (V_s/V_p)^2 = V_s^2/V_p^2 \tag{1}$$

Thus, Poisson's ratio (σ) may be expressed as:

$$\sigma = \frac{1 - 2\alpha}{2 - 2\alpha} \tag{2}$$

Table 4. Ranges of Concentration Index and Stress Ratio correspondent to soil competent degree, after Abd El-Rahman (1989).

Soil engineering parameters	Weak (Incompetent)		Fair (Fairly Competent)		Good (Competent)
	Very soft	Soft	Fairly compacted	Moderate compacted	Compacted
	Concentration Index (C_i)	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0	5.0 – 5.5
Stress Ratio (S_i)	0.70 - 0.61	0.61 – 0.52	0.52 – 0.43	0.43 – 0.34	0.34 – 0.25

Table 5. Ranges of Concentration Index and Stress Ratio correspondent to soil competent degree, after Abd El-Rahman (1989).

Soil engineering parameters	Weak (Incompetent)		Fair (Fairly Competent)		Good (Competent)
	Very soft	Soft	Fairly compacted	Moderate compacted	Compacted
	Concentration Index (C_i)	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0	5.0 – 5.5
Stress Ratio (S_i)	0.70 - 0.61	0.61 – 0.52	0.52 – 0.43	0.43 – 0.34	0.34 – 0.25

Table 3 shows the soil description with respect to Poisson's ratio and material index.

Concentration Index

The Concentration Index is an engineering parameter indicating the degree of material concentration or impaction (competence) for foundation and other civil engineering purposes. It depends mainly on the elastic moduli of the materials and the depth–pressure distribution.

Therefore, "C" is a material-dependent factor. Bowles (1982) formulated the Concentration Index in terms of Poisson's Ratio (s) as;

$$C_i = \frac{1 + \sigma}{\sigma} \quad 3$$

Where σ is Poisson's ratio as previously defined in equation (2). The competence index may be expressed in terms of the velocity squared ratio according to the following form:

$$C_i = \frac{(3 - 4\alpha)}{(1 - 2\alpha)} \quad 4$$

where α is expected to be the ratio of the squared shear- and longitudinal-wave velocities.

Table 4 shows the ranges of Concentration Index and Stress Ratio correspondent to soil competent degree.

Material Index

The material index from the engineering viewpoint defines the material quality for foundation purposes. According to

Abd El-Rahman (1989), this expression addresses the degree of competence based on their elastic moduli. Thus, this index has relations to the material composition, the degree of consolidation, fracturing, jointing, and the presence or absence of fluids in pore space, which affect the medium of the materials and the wave velocities in consequence. Abd El-Rahman (1989) derive the Material Index from the ratio between Lamé's Constants (λ) and the Rigidity Modulus (μ) or in terms of Poisson's Ratio (σ) as follows:

$$V = \frac{\mu - \lambda}{\mu + \lambda} = (1 + 4\sigma) \quad 5$$

The material index consequently has values between +1 and -1 (Table 4).

Stress Ratio

Stress ratio generally forms under high fluid pressure will have a low differential pressure and therefore abnormally low seismic velocities. The propagation velocity of seismic waves is proportional to the differential pressure between sedimentary overburden and the pore-filling fluids. According to Cordier (1985), these formations are termed sub-compacted or over-pressured zones. Such formations occur frequently in recent unconsolidated sedimentary series. For this reason, Bowles (1982) pointed out that there is a relationship between Poisson's Ratio (s) and Stress Ratio (S) for normally consolidated soils. This relationship was given by Bowles (1982) and Thomson (1982) as:

$$S_i = \frac{\sigma}{1 - \sigma} \quad 6$$

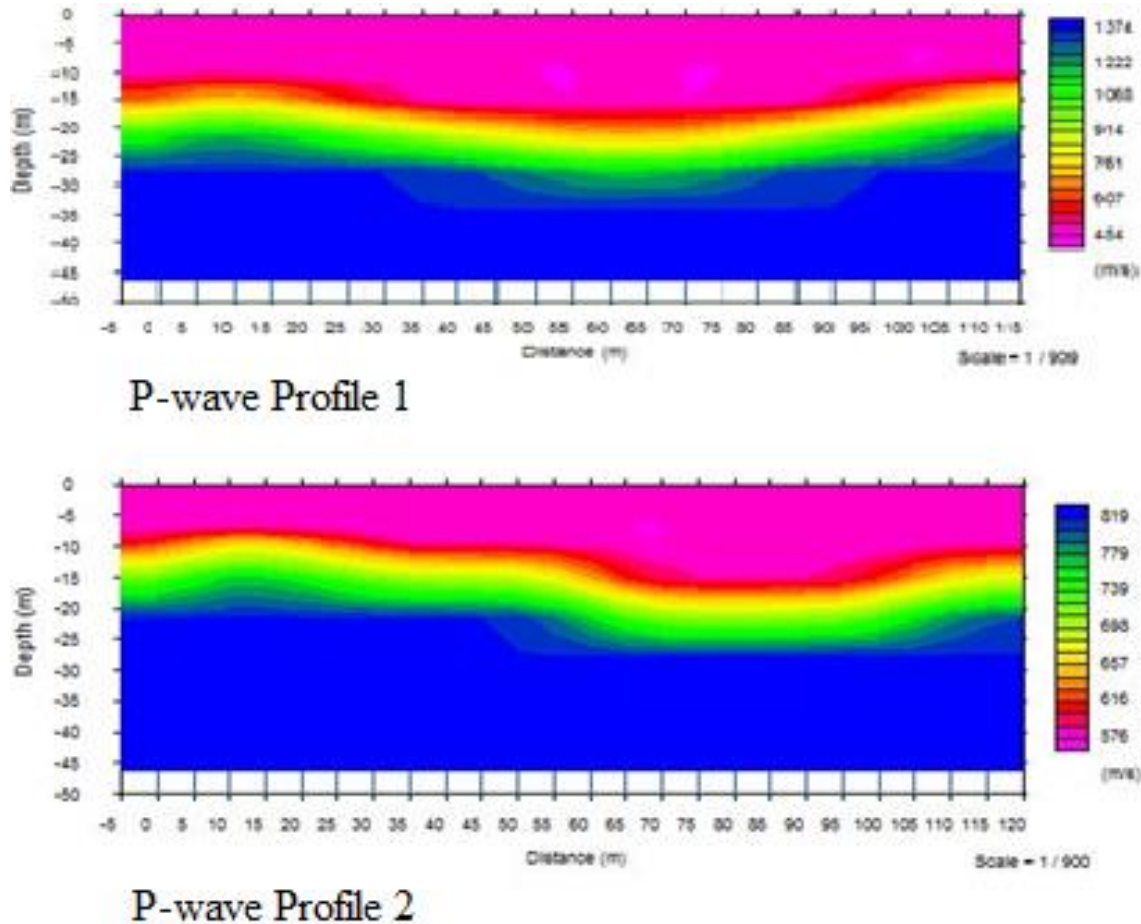


Figure 4. Tomography section of profiles 1 and 2 of the P-waves.

From several general observations about (S_i), Bowles (1982) pointed out that S_i tends to be higher for finer soils than for coarser soils, that S_i will be larger for loose cohesionless soils, that S_i tends to decrease with an increase in overburden pressure, and that S_i will be larger when the soil is over-consolidated. Abd El-Rahman (1991) pointed out a relationship between Poisson's Ratio, S_i and wave velocities as:

$$S_i = \left[1 - 2 \left(\frac{v_s^2}{v_p^2} \right) \right] = (C_i - 2)^{-1} \quad 7$$

RESULTS AND DISCUSSION

Seismic refraction tomography has shown the lithology of the study area as associated with the velocity of each layer. These results correlate with the borehole log of the area, which was used as control.

According to previous studies (Khalil et al., 2008; Almalki et al., 2011) conducted in Northeast Gulf of Suez and Northwest of Riyadh respectively, near-surface seismic refraction survey in conjunction with engineering

geotechnical parameters were used to characterize and ascertain the competency of soil for engineering construction by comparing the results obtain with standard range of values for these parameters. This was used as a guide inferring the foundation in this study.

As compared with Obihan and Lawal (2014) results on tomography sections, both the P- and S-waves profiles presented in Figures 4 and 5 are all characterized by similar features of slight undulating subsurface and consist of about five lithological sections which are indicated as colours (pink, red, yellow, green and blue) with respect to velocity contrast.

Profile 1 of the P-waves (Figure 4) runs along the east-west direction in the study area. The first section (pink colour) is having an average thickness of about 14 m with a velocity range of 450 to 550 m/s. The second section (red colour) is having an average thickness of about 2.5 m with a velocity range of 550 to 700 m/s. The third section (yellow colour) is having an average thickness of about 3 m with a velocity range of 700 to 900 m/s. The fourth section is greenish in colour with an average thickness of 6 m with a velocity range of 900 to 1250 m/s and finally, the fifth section which is blue in colour with a velocity range

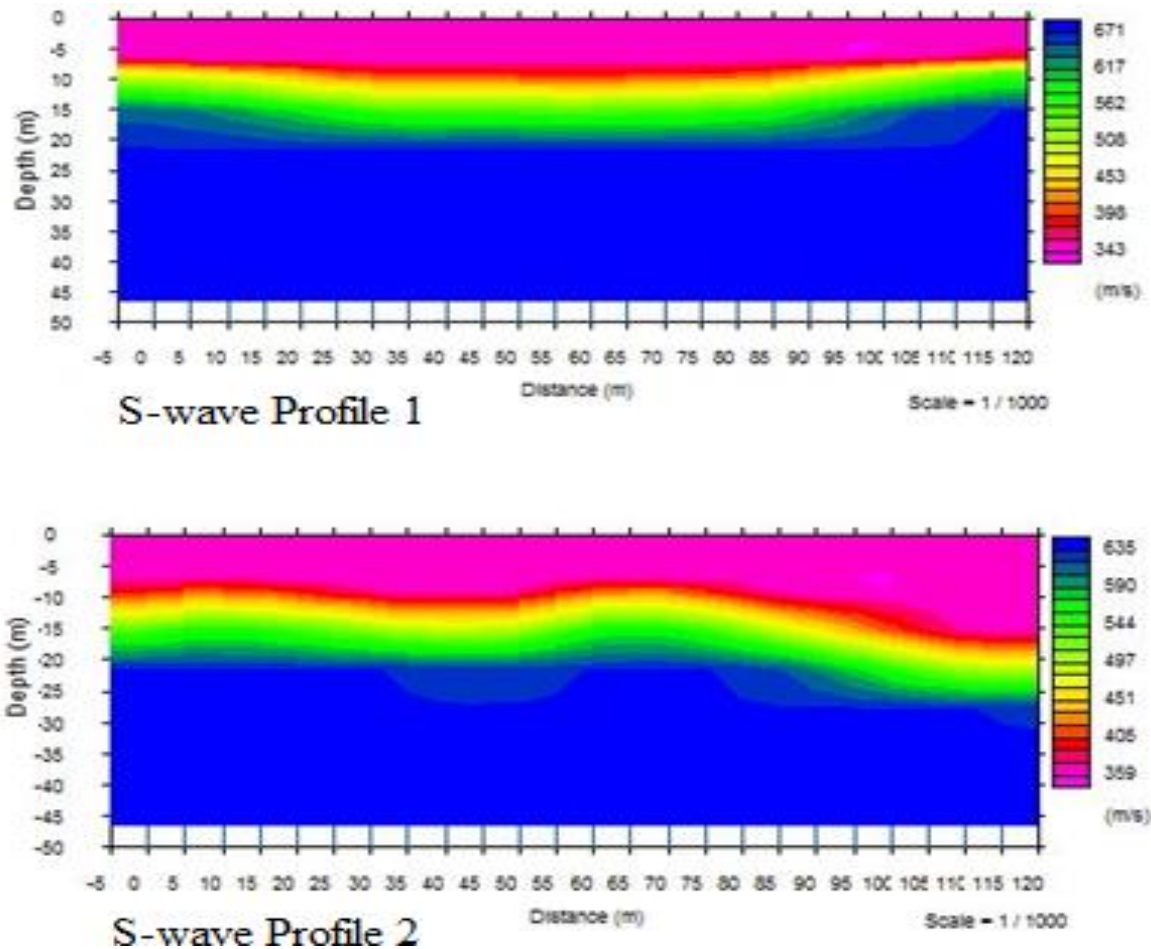


Figure 5. Tomography section of profiles 1 and 2 of the S-waves.

of 1250 to 1375 m/s at an average depth of about 22.5 m. Profile 2 of the P-waves runs along the north-south direction on the study area. This tomography section also reveals a slight undulating subsurface with also five lithological sections. The first section (pink colour) is having a velocity range of 500 to 600 m/s with an average thickness of 17.5 m. The second is red in colour with a velocity range of 600 to 700 m/s with an average thickness of 3 m. The third section is yellowish in colour having a velocity range of 700 to 850 m/s with an average thickness of 3 m too. The fourth section (green colour) is having a velocity range of 850 to 1250 m/s with an average thickness of 8 m. The final section (blue colour) is having a velocity range of 1250 to 1350 m/s with an average depth of about 29.5 m.

The S-waves profiles (1 and 2) (Figure 5) are aligned along the same direction with that of the P-waves profiles, this is done in order to get uniformity of P- and S-waves velocities for calculations of engineering parameters. The first S-waves profile is also characterized by five lithological sections. The first section which is pink in colour is having a velocity range of 300 to 350 m/s with an average thickness of 7 m. The second is red in colour with

a velocity range of 350 to 400 m/s with an average thickness of 2 m. The third section is yellowish in colour having a velocity range of 400 to 480 m/s with an average thickness of 2.5 m. The fourth section (green colour) is having a velocity range of 480 to 620 m/s with an average thickness of 6 m. The final section (blue colour) is having a velocity range of 620 to 700 m/s with an average depth of about 16 m. The second is characterized also of five lithological sections and undulating too. The first section which is pink in colour is having a velocity range of 300 to 380 m/s with an average thickness of 8 to 15 m at the edges of the profile. The second is red in colour with a velocity range of 380 to 420 m/s with an average thickness of 2.5 m. The third section is yellowish in colour having a velocity range of 420 to 450 m/s with an average thickness of 3 m. The fourth section (green colour) is having a velocity range of 450 to 600 m/s with an average thickness of 6 m. The final section (blue colour) is having a velocity range of 600 to 650 m/s with an average depth of about 20 to 26 m at the edges.

The average P- and S-waves velocities of the first layer in all profiles are considered for the calculations of elastic moduli because no foundation depth exceeds 2 m which

Table 6. Results of calculated elastic moduli and velocities (V_p and V_s).

Profile	V_p (m/s)	V_s (m/s)	ρ (gm/cc)	σ	E (MPa)	λ (MPa)	μ (MPa)
P1	545	343	1.4495	0.172	0.39975	0.0894	0.1705
P2	629	359	1.5024	0.258	0.48734	0.2065	0.1937

Table 7. Results of the estimated geotechnical parameters.

Profile	Concentration Index (C_i)	Material Index (v)	Stress Ratio (S_i)
P1	6.128	0.312	0.278
P2	4.869	-0.032	0.346

the first layer depth is beyond in all cases of the tomography sections. Table 2 shows the list of equations used to calculate the elastic moduli. Table 3 shows the list of equations used to compute the engineering parameters. Table 6 shows the results of calculated elastic moduli and velocities (V_p and V_s) and Table 7 shows the results of the estimated geotechnical parameters. In the study area, the calculated Concentration Index (C_i) for the first layer reveals values ranging from 4.869 to 6.128 (Table 7) which according to Abd El-Rahman (1989), reflects good competent soil (compacted soil), the Material Index (v) values ranging from -0.032 to 0.312, which reflects a moderate/competent soil, and also, the Stress Ratio (S_i) with values ranging between 0.267 to 0.346, which, according to Abd El-Rahman (1991), reflects good competent soil. The Poisson's Ratio (σ), ranges from 0.172 (profile 1) to 0.258 (profile 2) which is characterized by relative low Poisson's Ratio, which indicates a competent soil (Salem, 1990).

These calculated results when compared with Tables 4 and 5 show some variation which is of importance to the civil engineers. Generally, properties of the location of profile 1 show competent earth materials than profile 2 which the concentration index, material index, stress ratio, and Poisson's ration shows lesser competency (fairly/moderately competent).

Conclusion

A seismic refraction survey was successfully carried out at A.B.U. Zaria, Phase II site, North-western Nigeria with the aim of checking the suitability of the study area for the foundation of buildings. For that purpose, both compressional (P) and shear (S) wave velocities were determined and interpreted using the tomography technique to give us a 2-D velocity model. These models show that the area consists of three layers; an overburden with average thickness of about 10.5 m and P- and S-wave velocities of about 550 m/s and 345 m/s respectively, the weathered basement with an average thickness of 12.5 m and velocities of 950 m/s for P wave and 550 m/s for S-wave respectively, while the fresh basement was found at

a depth of about 24 m with velocities of 1250 m/s for P-wave and 680 m/s for S-wave respectively. A number of shallow soil engineering parameters such as Concentration Index, Material Index, and Stress Ratio were calculated to be in the range of 4.869 to 6.128, -0.032 to 0.312, and 0.267 to 0.346 respectively to assess the subsurface from geophysical and engineering perspective. Integration between different engineering elastic, consolidation, and strength parameters indicates a high competent soil in the western and north-western parts while the eastern parts indicate lesser competency. This could be attributed to the proximity of the Kubanni river basin to the area, erosion, and level of excavation and embankment noticed during the survey. Hence, the western and north-western parts are more preferable for the foundation of structures to be erected.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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