Evaluation of Geotechnical Parameters using Geophysical Data

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Abstract. The financial implications and the time required for carrying out a comprehensive geotechnical investigation to characterize a site can discourage prospective private residential building developers, especially where a large area of land is to be investigated for construction purposes. Also, most of the geotechnical test procedures utilized during site investigation only provide information on points tested in the subsurface. This research method suggests an approach of investigating the subsurface condition of a site in order to obtain key subsoil geotechnical properties necessary for foundation design for proposed engineering facilities. Seismic wave velocities generated from near surface refraction were combined with percussion drilling and cone penetration tests to obtain a comprehensive geotechnical investigation. From the results of the seismic refraction method, the bulk density of the soil, Young's modulus, bulk modulus, shear modulus and allowable bearing capacity of a competent layer that can bear structural load at the particular study site were determined. The most competent layer was found within the depth observed by geotechnical methods. In addition, regression equations were developed in order to directly obtain the bulk density of the soil, Young's modulus, bulk modulus, shear modulus and allowable bearing capacity from the primary wave velocities.

Keywords: *characterization; environment; geophysical; geotechnical; seismic.*

1 Introduction

The expenses and time required to carry out the geotechnical investigation of a proposed construction site can discourage the building developer, especially if the construction site is a large expanse of land. These challenges have made many private 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

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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 subsurface. Geophysical methods, on the other hand, can give volumetric measurement and produce images of the subsurface without physically disturbing the subsoil. Therefore, in order to cover a large expanse of land in the shortest possible time and at a highly reduced cost, geotechnical investigation could be conducted at certain central locations on the proposed site, while geophysical investigations would be conducted to cover up for the portion of the site not investigated by geotechnical methods. The results obtained from the geophysical investigation would be checked against the results of the geotechnical method, which would serve as the control for the entire subsurface characterization. According to Soupios, *et al.* [1], there is an increasing requirement for geophysical surveys conducted during geotechnical investigations so as to provide direct information about rock/soil quality and other geotechnical parameters that will be useful in correlating geophysical results with actual rock/soil properties.

Bery and Saad [2] together with Karaman and Kesimal [3] proved that it is possible to study the P-wave velocities of materials both in the laboratory and the field. The P-wave values obtained by Bery and Saad [2] were later compared with the engineering parameters of a site such as the SPT-N (blow count) values, rock quality, friction angle, velocity index, density and penetration strength. Empirical correlations were also found for selected parameters and the regression coefficients obtained showed a high degree of correlation. They concluded that their method could be used to estimate and predict the properties of the subsurface material in order to reduce the cost of subsurface investigation. Altindag [4], Kahraman [5] and Yagiz [6], on the other hand, studied the relationship between P-wave velocity and mechanical properties of sedimentary rocks. The latter used already acquired data and a simple regression analysis. All the data were later subjected to a multi-regression analysis and he went further to derive some empirical equations with high correlation coefficients that would be useful for rock engineers. Atat, *et al.* [7] carried out a study using seismic refraction techniques to determine the allowable bearing pressure of a site for construction purposes in the Eket area of Akwa Ibom State in Nigeria. They obtained both compressional and shear wave velocities, which were substituted into some equations from the literature to determine the elastic constants, allowable bearing capacity and the ultimate bearing capacity of the site. Their result revealed that the allowable bearing pressure increased with increase in shear modulus and shear wave velocity. The empirical relation between allowable bearing capacity and shear modulus also showed that the allowable bearing capacity increased with depth. Tezcan, *et al.*

[8] proposed an empirical formulation for the rapid determination of allowable bearing capacity of shallow foundations. The proposed expression consistently corroborated the results of the classical theory and it was proven to be rapid and reliable. It was indicated that once the shear and P-wave velocities were measured in situ by an appropriate geophysical survey, the allowable bearing capacity as well as the coefficient of subgrade reaction and many other elasticity parameters could be determined rapidly and reliably through a single-step operation for both soils and rock formations.

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 when access is difficult with geotechnical equipment (see Anderson and Croxton, [9], Fitzallen [10], Uyanik, [11], Nastaran, [12], Mohd, *et al.* [13]). Also, this method can easily detect changes in the subsurface characteristics as there are changes in the behaviors of a passing seismic wave as it passes through media of different characteristics, in order to determine zones of structural weakness in the basement and analyze the stability of the subsurface. Therefore, in this study, a combination of seismic refraction, cone penetration and percussion drilling tests was used to reduce the difficulties usually faced by geotechnical engineers and building developers in determining the geotechnical parameters of a site for construction purposes. Also, empirical correlation equations were developed by correlating P-wave velocity with other geotechnical parameters.

2 Geology and Location of the Study Area

The area under investigation is part of the geologically termed alluvium deposits of the southwestern Nigeria basin, which is an integral part of the Dahomey embayment (Figure 1). The superficial materials of the general area under investigation are silts, sands and clays with fibrous peat on the surface in some places. The Dahomey sedimentary basin extends from the eastern part of Ghana through Togo and Benin Republic to the western margin of the Niger Delta. The eastern half of the basin lies within Nigerian territory. The base of the basin consists of unfossilerous sandstones and gravels weathered from the underlying Precambrian basement. The vegetation of the study area has given way to fens and other water loving shrubs and herbs (Adegbola and Badmus [14]).

The study area lies between latitude 06° 26' N and 06° 32' N and longitude 03° 35' E and 03° 45' E in the Lagos Island area of Lagos State[15]. The Nigeria coastal zone has a tropical climate with two seasons: a rainy season and a dry season. The rainy season is between April and November while the dry season is between December and March (Akintorinwa and Adesoji, [16]). The amount of annual rainfall varies between 2030 mm and 2540 mm (Obasi and Ikubuwaje, [17]).

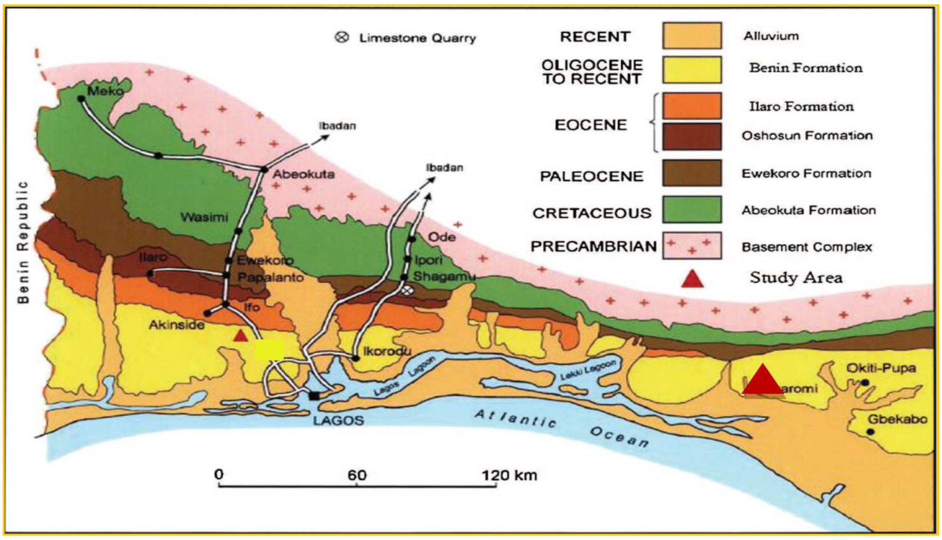

Figure 1 Geological map of Nigeria, showing the Nigerian part of the Dahomey basin (modified after Aizebeokhai and Oyeyemi [15]).

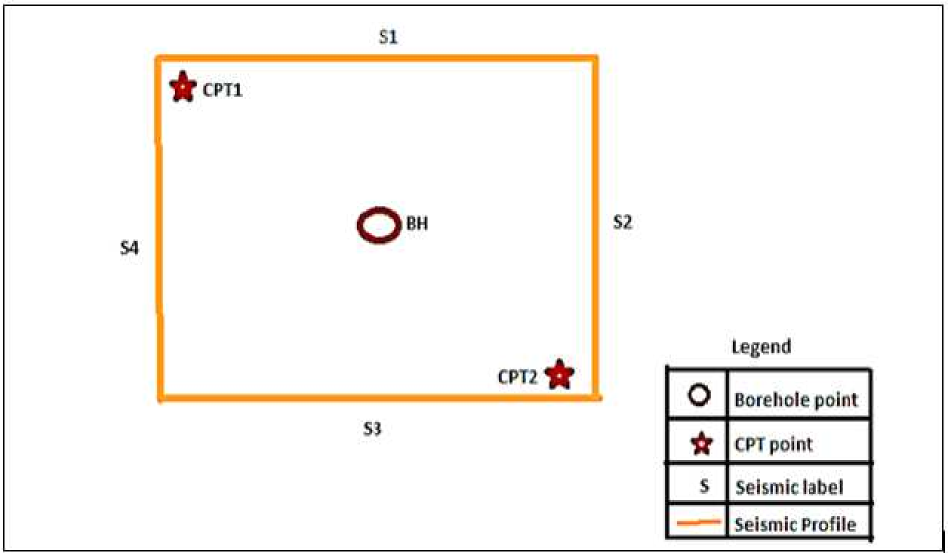

Figure 2 Base map of the study area.

3 Theory

Field surveys can readily provide both primary and shear wave velocities, V_P and V_S, measured in meters/seconds (m/s). These velocities can be used to determine the following engineering parameters: the Young modulus, the bulk modulus, the shear modulus and the Poisson ratio. These are used to measure the degree of stiffness of the subsurface material (Clayton, [18]). The three stiffness parameters are the Young modulus, the bulk modulus and the shear modulus. These elastic moduli are represented mathematically as expressed in Eqs. (1) to (6) below:

$$\nu = \frac{\left[\left(\frac{V_P}{V_S}\right)^2 - 2\right]}{\left\{2\left[\left(\frac{V_P}{V_S}\right)^2 - 1\right]\right\}} \tag{1}$$

$$E = \frac{\rho_b V_P^{\,2}\left(1-2\nu\right)\left(1+\nu\right)}{\left(1-\nu\right)} \tag{2}$$

$$E_c = \frac{(1-\nu)E}{(1+\nu)(1-2\nu)} \tag{3}$$

$$G = \frac{E}{\left[2\left(1+\nu\right)\right]} \tag{4}$$

$$B = \ell_b V_p^{\,2} = \frac{E}{3(1-2\nu)} \tag{5}$$

$$\rho_b = \frac{\gamma}{g} \tag{6}$$

where γ is the unit weight of the soil and g is the acceleration due to gravity, which is given by $9.8\, m/s^2$. The unit weight of the soil relates with P-wave velocity V_p is as shown in Eq. (7) below:

$$\gamma = \gamma_o + 0.002V_p \tag{7}$$

γ_0 is the reference unit weight value in kN/m^3 for soil and rock types. The value of γ_0 is 16 for loose, sandy and clayey soil (Atat, *et al.* [7], Tezcan, *et al.* [8]). The relationship between shear wave and primary wave velocities is expressed in Eq.(8):

$$V_p \approx 1.7V_s \tag{8}$$

where E is the Young modulus (N/m^2), G is the shear modulus (N/m^2), B is the bulk modulus (N/m^2), ρ_b is the bulk density (kg/m^3) and ν is the Poisson ratio. The subgrade coefficient (K_s), ultimate bearing capacity (q_f) and the allowable bearing capacity (q_a) can be determined using the following equations respectively:

$$K_s = 4\gamma V_s \tag{9}$$

$$q_f = \frac{K_s}{40} \tag{10}$$

$$q_a = \frac{q_f}{n} \tag{11}$$

where n is the safety factor and n = 4 for soils. The results of Eqs. (9) to (11) further confirm the strength of the soil being considered for construction purposes.

4 Materials and Methods Applied

4.1 Seismic Refraction Method

Seismic refraction was carried out in the study area, using a 24-channel ABEM Terraloc Mark 6 seismograph. This method requires the use of a seismograph, a 12-volt DC battery, a roll of trigger cable, 2 seismic cable reels, a 15 kg sledge hammer, a metal base plate, 24 geophones of 14 Hertz frequency, a log book and measuring tapes. The geophones were connected to the 2 seismic cable reels, which are signal cables that were in turn connected to the seismograph. The seismograph was placed in the middle of the survey line on each traverse. The geophones were planted at an interval of 2 m from each other along the traverse so as to obtain quality data and a good depth of investigation. The trigger cable reel connects the sledgehammer to the equipment and each time it is triggered, by hitting the hammer on a base plate, the seismogram records a seismic event. The base plate is a thick, heavy iron metal plate hit with the sledgehammer for the measurements to be taken. The base plate was placed at a distance of 2m from the first geophone.

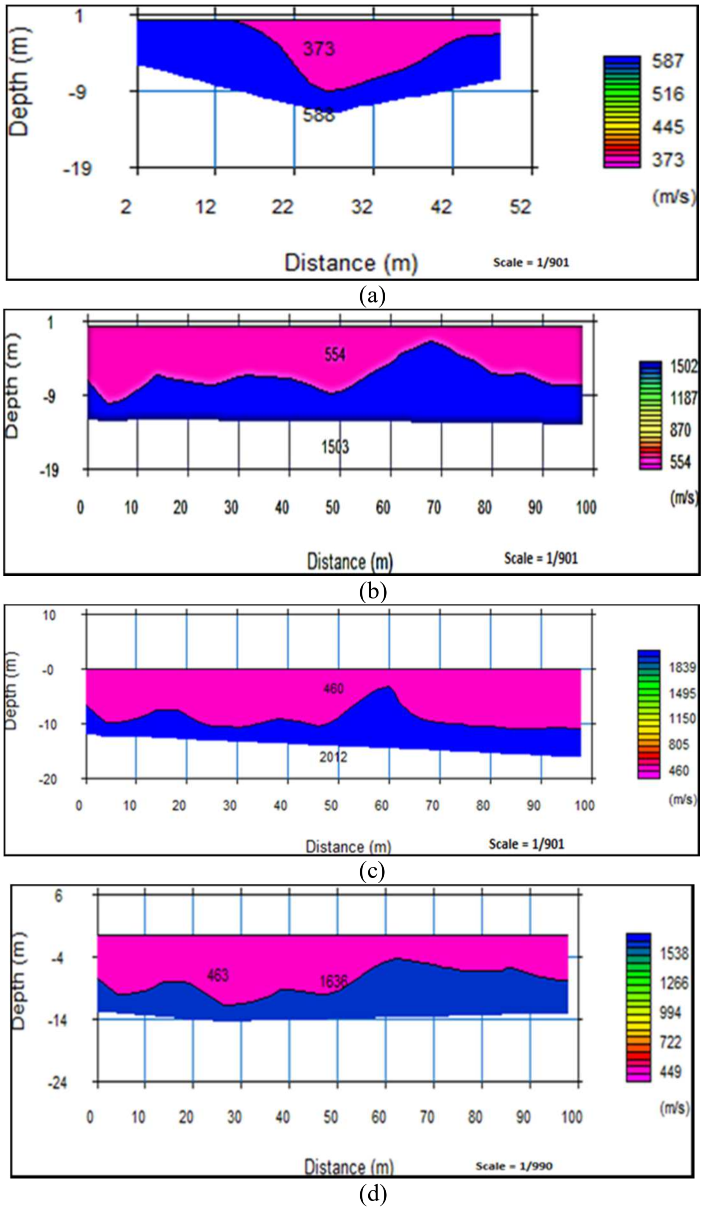

Figure 3 (a)-(d) 2D seismic refraction image of the study area, indicating the number of layers, P-wave velocity of each layer and depth of investigation.

Four (4) traverses were surveyed in the areas studied, as shown in Figure 2. Shots were taken at the following points on each traverse: offset distance, which was 2 m from the first geophone, between the 6th and 7th geophones, between the 12th and 13th geophones, between the 18th and 19th geophones and 2 m after the 24th geophones. These shot points are termed the offset, quarter spread, mid-spread, three-quarter spread and off-end respectively (Keary, *et al.* [19], Mohd, *et al.* [13]). The SeisImager software application was used to produce a 2D seismic image of the collected data (Figure 3).

Each traverse showed two geological layers with the topmost layer being characterized by low P-wave velocities, which may be as a result of the loose and soft nature of the soil material. The second layer, on the other hand, is composed of a formation that is relatively stiffer because of a higher velocity observed, which may be due to saturation and compression of the geomaterial in the subsurface. The significant change noticed in the elastic properties of the two layers may be due to a change in the composition of the subsurface, uneven saturation and changes in the unit weight of the soil.

4.2 Geotechnical Methods

In this study, geotechnical investigations, including cone penetration and borehole tests, were carried out in the area of study. A borehole was dug and two (2) cone penetration tests were carried out. These were carried out to determine the in situ bulk properties of the subsurface material and to provide a control for this research. They were carried out to provide a good level of confidence for our results. The borehole was dug to a depth of 30 m with the use of shell and auger boring equipment. Ordinary disturbed samples were collected at changes of strata and as deemed fit for strata identification purposes through visual inspection and classification tests. The result of the borehole test was used to produce a log that contains information on the lithology and strength of the area of study (Figure 4).

Also, cone penetration tests were carried out using a Dutch cone penetrometer with a capacity of 2.5 tons. The apparatus consisted of a cylindrical probe of 1000 mm^2 cross sectional area and a conic head with an of apex angle 60°. The probe was forced down through the soil at a steady rate of about 20 mm/s by exerting pressure on the outer sounding tube (Hunt [20], Look [21]). The tests were terminated at depths where the machine anchors began to lift out of the ground. This method allows for the soil strength to be determined from the measured values of cone resistance and sleeve friction. The results of the cone penetration test are presented in the graph below (Figure 5).

5 Results and Discussion

In this study, geotechnical parameters, i.e. density, Young's modulus, bulk modulus, shear modulus, oedometric modulus, were obtained from the result of the primary and secondary wave velocities for each layer using Eqs.(1) to(8). These relationships also led to the determination of the ultimate bearing capacity and the allowable bearing capacity of the area of study. The results obtained are presented in Table 1. As mentioned before, two geologic layers were delineated with the SeisImager software application. The first geologic layer had a lower seismic wave velocity while the second layer had a higher seismic wave velocity. The bulk density of the first layer ranged between 1.7088 kg/m^3 and 1.7457 kg/m^3 with an average bulk density of 1.7286 kg/m^3. The bulk density of the second layer ranged between 1.7527 kg/m^3 and 2.0433 kg/m^3 with an average density of 1.9420 kg/m^3.

This result shows that the second layer is more compressed than the first layer. This may be as a result of the geologic formation of this layer, its level of saturation and the level of cementation of the geomaterial. It was also observed that the density of the subsurface increased in direct proportion with the seismic wave velocity and the two parameters increased with depth. The Young modulus of the first layer ranged between 0.2032 GPa and 4.5808 GPa, while in the second layer, the modulus ranges between 0.5181 GPa and 7.0719 GPa. The average Young moduli for the first and the second layers were 0.3354 GPa and 4.5048 GPa respectively. This also shows that the second layer has more strength than the first layer.

The oedometric modulus, which is a measure of the ease of deformation of subsurface geomaterial, ranged between 0.2377 GPa and 0.5358 GPa with an average layer modulus of 0.3922 GPa for the first layer. In the second layer, the modulus ranged between 0.6060 GPa and 8.2714 GPa with an average layer modulus of 5.2690 GPa. This result also shows that the first layer would deform more easily under shear stress than the second layer. The bulk modulus for the first layer ranged between 0.12806 GPa and 0.2886 GPa, while it ranged between 0.3264 GPa and 4.4553 GPa in the second layer. The average bulk moduli for the first and second layers were 0.2113 GPa and 2.8381 GPa respectively. This further confirmed the second geologic layer to be more competent than the first layer.

The shear modulus ranged between 0.0823 GPa and 0.1854 GPa with an average modulus of 0.1357 GPa in the first layer. On the other hand, the second layer had a shear modulus that ranged between 0.2097 GPa and 2.8621 GPa

with an average layer modulus of 1.8232 GPa. This result reveals that the second geologic layer is more competent than the first layer.

The ultimate bearing capacity and the allowable bearing pressure were also estimated, to buttress the results provided by the earlier discussed elastic moduli. The ultimate bearing capacity for the study area ranged between 0.3674 MPa and 0.5575 MPa, while it ranged between 0.5941 MPa and 2.3699 MPa in the second layer. The average ultimate bearing capacity was 0.4702 MPa and 1.7356 MPa in the first and second layers respectively. This further confirms the second layer to have more bearing capacity than the first layer. Also, the allowable bearing pressure for the study site ranged between 0.0919 MPa and 0.1394 MPa with an average of 0.1175 MPa in the first layer while it ranged between 0.1485 MPa and 0.5925 MPa with an average of 0.4339 MPa in the second layer. This result also shows that the second layer is more competent than the first layer. Furthermore, it shows that the depth to the most competent layer ranges between 7 m and 15.7 m. This result is in agreement with the results obtained from the borehole log and the cone penetration tests carried out in the area of study.

Table 1 Seismic wave velocities for each traverse and their geotechnical parameters.

Si-de	V_p (m/s)	V_s (m/s)	ρ (Kg/m^3)	$Depth$ (m)	V	E (GPa)	E_c (GPa)	B (GPa)	G (GPa)	K_s $(MPas)$	q_f (MPa)	q_a (MPa)
S1	498	292.94	1.7343	7.6	0.2355	0.3677	0.4301	0.2317	0.1488	0.0199	0.4979	0.1245
	1961	1153.53	2.0329	15.7	0.2355	6.6837	7.8174	4.2108	2.7050	0.0919	2.2981	0.5745
S2	554	325.88	1.7457	8.7	0.2355	0.4581	0.5358	0.2886	0.1854	0.0223	0.5575	0.1394
	1503	884.12	1.9394	10.9	0.2354	3.7458	4.3811	2.3598	1.5160	0.0672	1.6804	0.4201
S3	460	270.59	1.7265	7.9	0.2354	0.3124	0.3653	0.1968	0.1264	0.0185	0.4578	0.1145
	2012	1183.53	2.0433	11.4	0.2354	7.0719	8.2714	4.4553	2.8621	0.0948	2.3699	0.5925
S4	373	219.41	1.7088	7.0	0.2355	0.2033	0.2377	0.1281	0.0823	0.0147	0.3674	0.0919
	588	345.88	1.7527	10.3	0.2355	0.5181	0.6060	0.3264	0.2097	0.0238	0.5941	0.1485

The result from the borehole log (Figure 4) revealed the geomaterial in the second layer to be sandy clay of firm to stiff consistency underlain by a medium dense sand material. The sand material is more geotechnically stable because it has high shear strength and low compressibility potential (Atat, *et al.* [7], Sarsby, [22]). The formation at this depth can be considered for engineering construction purposes. The result of the cone penetration tests confirmed that the geomaterial at that depth has stable geotechnical properties. Also, the cone penetration log showed a rise in the cone resistance values from a depth of 6.50 m in the log presented below (Figure 5).

		BOREHOLE LOG							
		Ground Water Level : Surface level							
Depth (m)	Samples	Soil Description	Symbol	Nspt 0	10	20	30	40	50
0	□	Soft dark brown organic PEAT.							
0.6									
0.75	□								
1.5	□								
2.25									
		Soft dark brown organic peaty CLAY							
3	□								
4.5	□								
5.25									
		Firm to stiff greyish/pinkish sandy CLAY							
6	□								
7.5	■								
7.75									
		Medium dense dark grey very silty SAND							
9	□					23			
9.75	□								
10.5	□					23			
12	□					26			
13.5	□					27			
15	□					26			
16.5	□								
18	□	Medium dense to dense grey silty SAND				25			
19.5	□						35		
20									
		Soft dark greyish organic CLAY							
24	□								
		Light greyish coarse SAND							
25.5	□								
		Very stiff dark organic CLAY							
27	□								
30	□								
		End of Borehole							
		KEYS:							
		□							
		■							

Figure 4 Result of the borehole log obtained from the area of study.

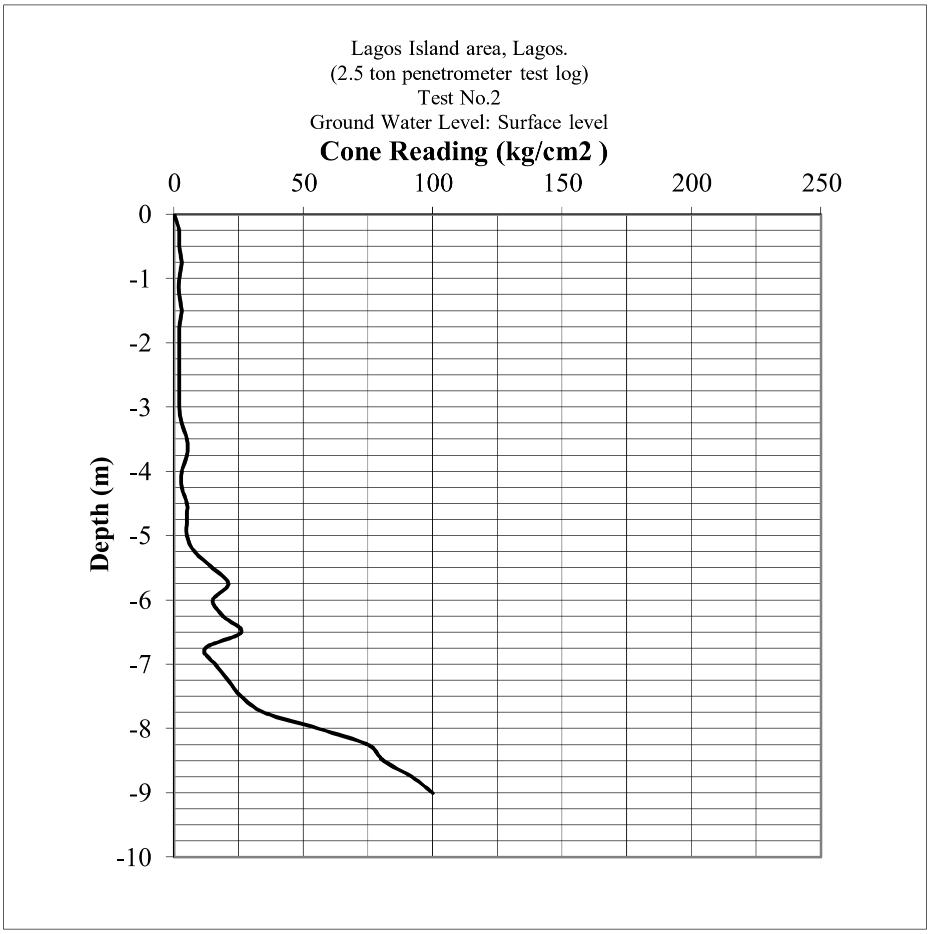

Figure 5 Cone penetration test result in Lagos Island area.

6 Evaluation of Geotechnical Parameters from Seismic Data

This study was also aimed at obtaining model equations from the correlations of the primary wave velocities and the different geotechnical parameters studied. This was to obtain direct relationships between the P-wave velocity and the geotechnical parameters. These equations can be used for a speedy evaluation and inexpensive estimation of the various geotechnical parameters. The graphs of the geotechnical parameters were plotted against the primary wave velocities. The regression equations and their coefficient of determination were obtained. The graph of density against the P-wave velocity (Figure 6) gave the empirical equation below. The empirical correlation equation is defined in Eq. (12).

$$\rho = 6 \times 10^{-11} V_p^{\,2} + 0.0002 V_p + 1.6328 \tag{12}$$

The coefficient of determination is 1. This also shows the polynomial relationship between the density of the subsurface and the primary wave velocity. Also, the graph of the Young modulus against the primary wave velocity was plotted (Figure 7). The empirical correlation equation was obtained in Eq. (13):

$$E = 2 \times 10^{-6} V_p^{\,2} - 0.0009 V_p + 0.3082 \tag{13}$$

The coefficient of determination was obtained to be 1. This implies that the higher the primary wave velocity of the geomaterial, the higher the level of its competence. The graph of the bulk modulus against the primary wave velocity was also plotted (Figure 8). The empirical correlation equation and the coefficient of determination were obtained. The empirical correlation equation was obtained in Eq. (14):

$$B = 1 \times 10^{-6} V_p^{\,2} - 0.0006 V_p + 0.1942 \tag{14}$$

while the coefficient of determination is 1. This shows the polynomial relationship between the bulk modulus and the primary wave velocity in the area of study. This simply implies that the higher the primary wave velocity, the higher the strength of the geomaterial that is being tested. The shear modulus was also plotted against the primary wave velocity, as shown in Figure 9. Both the empirical correlation equation and the coefficient of determination were obtained. The empirical correlation equation is defined in Eq. (15):

$$G = 9 \times 10^{-7} V_p^{\,2} - 0.0004 V_p + 0.1247 \tag{15}$$

The coefficient of determination obtained is 1. This confirmed the polynomial relationship between the shear modulus and the primary wave velocity. This implies that the higher the value of the primary wave velocity, the more confidence we can have in the fitness for construction purposes of the subsurface being studied. The oedometric modulus was also plotted against the primary wave velocity (Figure 10); the empirical correlation equation is given as in Eq. (16):

$$E_c = 2 \times 10^{-6} V_p^{\,2} - 0.001 V_p + 0.3606 \tag{16}$$

The coefficient of determination is 1. The graph of unlimited bearing capacity was plotted against the primary wave velocity (Figure 11); the correlation equation is given as in Eq. (17):

$$q_f = 1\times10^{-7}V_p^{\,2} + 0.0009V_p - 8\times10^{-5} \tag{17}$$

The correlation equation derived from the graph of allowable bearing capacity versus the primary wave velocity (Figure 12) is given in Eq. (18):

$$q_a = 3\times10^{-8}V_p^{\,2} + 0.0002V_p - 6x10^{-5} \tag{18}$$

The coefficient of determination is 1.

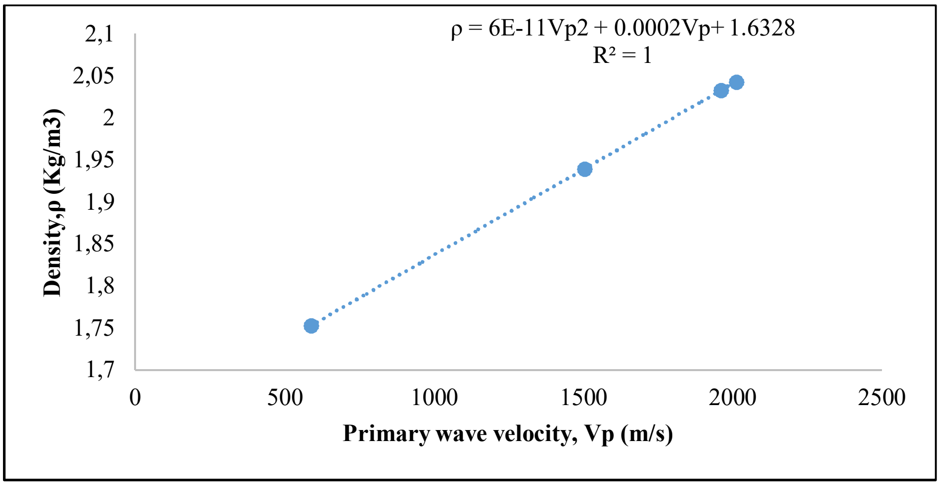

Figure 6 Graph of density (kg/m^3) against primary wave velocity (m/s).

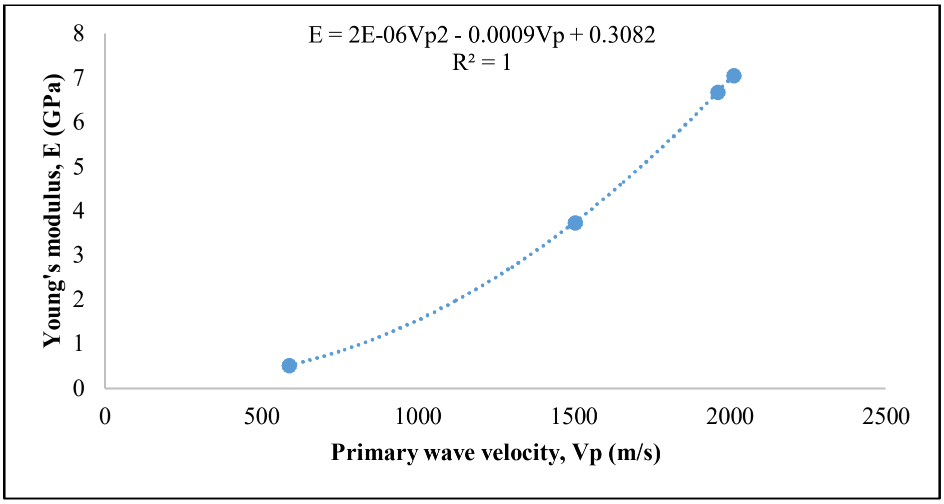

Figure 7 Graph of Young's modulus (GPa) against primary wave velocity (m/s).

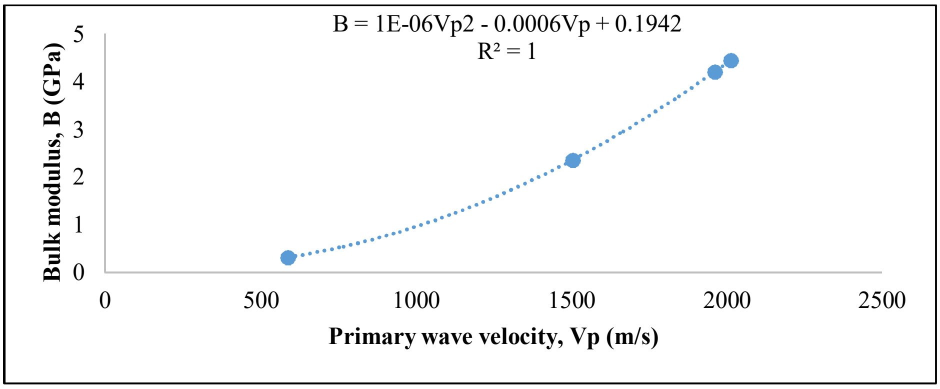

Figure 8 Graph of bulk modulus (*GPa*) against primary wave velocity (m/s).

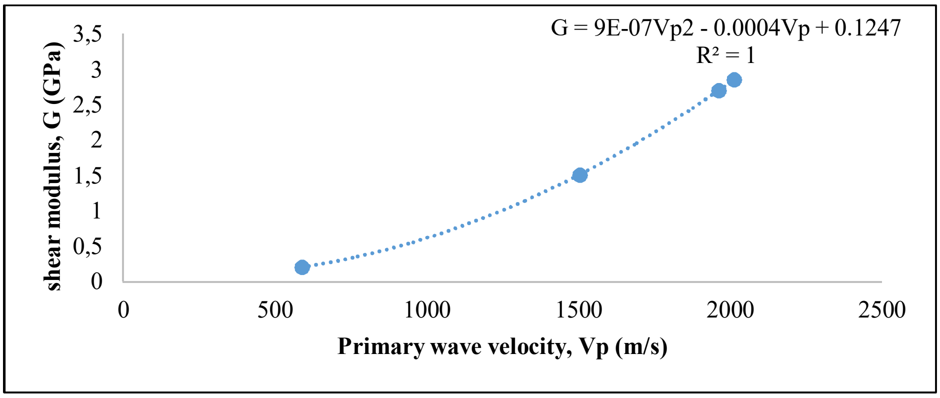

Figure 9 Graph of shear modulus (*GPa*) against primary wave velocity (m/s).

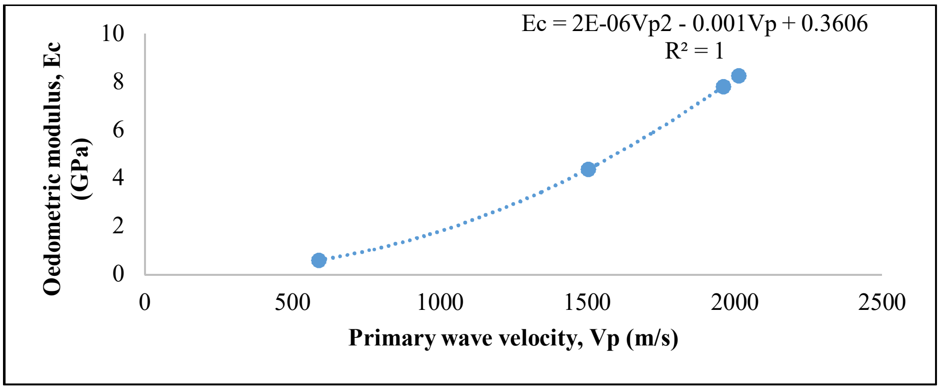

Figure 10 Graph of Oedometric modulus (*GPa*) against primary wave velocity (m/s).

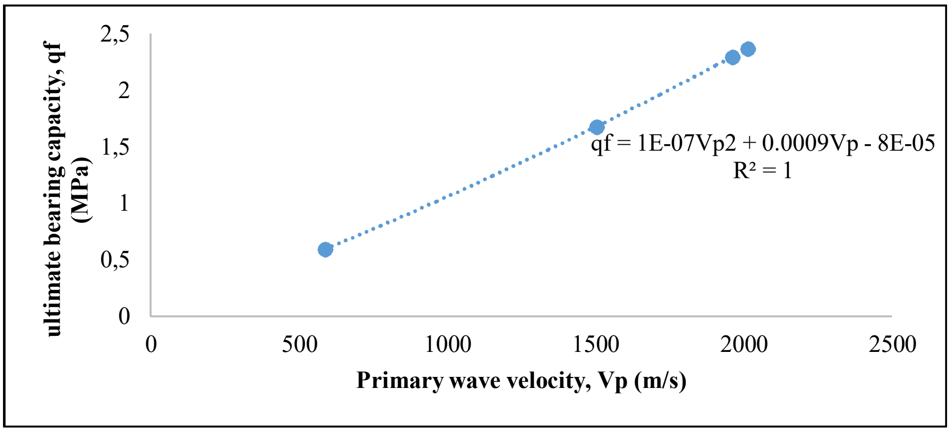

Figure 11 Graph of ultimate bearing capacity (*MPa*) against primary wave velocity (m/s).

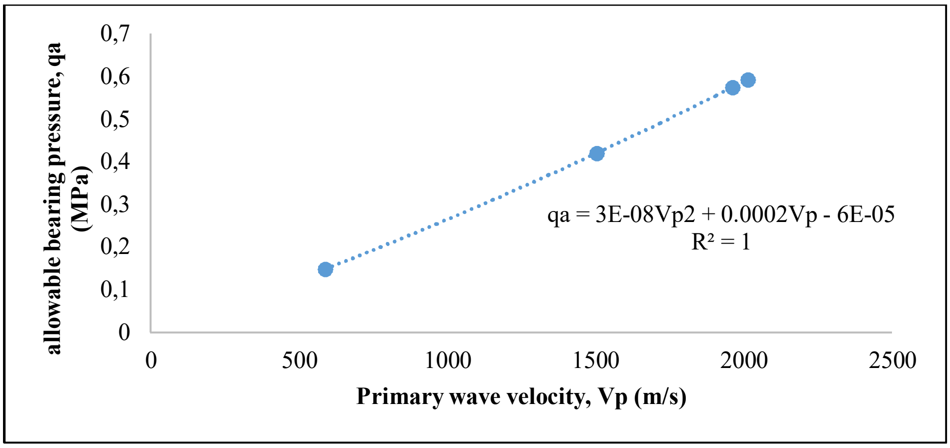

Figure 12 Graph of allowable bearing pressure (*MPa*) against primary wave velocity (m/s).

Figures 6 to12 are the graphs of density against primary wave velocity, Young's modulus against primary wave velocity, bulk modulus against primary wave velocity, shear modulus against primary wave velocity, oedometric modulus against primary wave velocity, ultimate bearing capacity and allowable bearing pressure against primary wave velocity. The results of the regression analysis showed good correlations between the properties tested in all cases. This shows that we can estimate the engineering parameters of the subsurface from the primary wave velocity data acquired (Bery and Saad [2]). The results obtained in the present study correlated well with the results of Altindag [4], Bery and Saad [2] and Atat, *et al.* [7].

The small variations observed in the correlation coefficient could be a result of the difference in geological formation, the types of curve fitting approximation engaged and the geotechnical parameters of interest could also be a factor. This is because curve-fitting approximations with the highest correlation coefficient were selected in each study. Also, the geotechnical parameters of interest varied in the various studies. For instance, in Altindag [4] the study was conducted on sedimentary rock samples and power curve fitting was observed to give the highest correlation coefficient. The correlation coefficient differs from the present study by a factor of 0.23, which could be as a result of the type of geomaterial and the geotechnical parameters studied. The correlation coefficient obtained in Bery and Saad [2] differs from the present study by 0.0685. This variation could be as a result of the geotechnical parameters studied and the linear curve fitting approximations used. In the present study, the geological formation is alluvium and the geotechnical parameters of interest also differ from the previous study. Polynomial curve fitting of order two was used because it was found to give the highest correlation coefficient.

7 Conclusion

A geophysical survey was carried out using a seismic refraction method and some geotechnical information was obtained from the study site. The seismic refraction results revealed two geologic layers with the second layer being more competent. The geotechnical results also confirmed the result obtained by the seismic refraction method. There is a correlation between the depths of competence delineated by the two methods.

This study also revealed that the P-wave velocities can be used to determine the geotechnical parameters of a site that can be used to easily characterize its subsurface condition. Also, the empirical equations obtained can be used to evaluate and predict the geotechnical parameters of the site studied. There was a good correlation between the results of the present and previous studies.

The results obtained are applicable to any area with a similar geological formation as the current study area, but a similar procedure may be applicable in other areas as well. This method has the potential to reduce the cost of geotechnical investigations. This approach will help to reduce the cost of geotechnical investigations and also protect the environment from destruction caused by the invasive nature of geotechnical equipment.

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