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RESEARCH ARTICLE

INVESTIGATION OF STABILITY OF ENGINEERING PROJECTS USING SEISMIC REFRACTION TECHNIQUE

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ABSTRACT

Seismic refraction survey was conducted at Ibiono Ibom Local government area of Akwa Ibom State, Nigeria, using 12 channels ES 3000S enhancement seismograph. This was done to evaluate and obtained information on depth and thickness of the shallow subsurface and characterized the bearing and engineering parameters on the bases of soil and rock competencies for stability of engineering works. The travel times of refracted waves measured were used to calculate P and S wave velocities employed in the evaluation of bearing strength and engineering parameters. The results revealed that seismic waves penetrated into three layers. The values of depth and thickness for upper layer ranged from 0.0 m to 4.5 m and 4.5 m, middle layer ranged from 5.0 m to 12.5 m and 7.5, lower layer ranged from 15.0 m to 25.2 m and 10.2 m. The bearing capacity parameters calculated were allowable bearing capacity and ultimate bearing capacity, engineering parameters: Concentration Index, Stress Ratio, Material Index and Density Gradient. The third layer reflected good competent soil and rock quality in the southeastern part of the study area, and was delineated as a better layer for engineering stability.

KEYWORDS

Allowable bearing capacity, Ultimate bearing capacity, engineering parameters, foundation.

1. INTRODUCTION

The shallow seismic refraction technique is considered one of the most reliable method for stability of engineering and foundation studies, geotechnical and environmental investigation, groundwater and hydrocarbon (Lankston, 1989; Bridle, 2006; Yilmaz et al., 2006). Shallow seismic refraction has been widely applied to resolve problems within the subsurface layers, from engineering vantage point, shallow seismic refraction has been used to study foundation properties, hydroelectric power plants, nuclear power plants and many other facilities.Information about the shallow subsurface structures is important for assessment of the stability of engineering project. Lack of adequate shallow subsurface information creates problems such as structure defect, transportation challenges due to road failures, destruction of properties and environmental hazards. On the other hand, shallow subsurface problems are also as a result of inadequate knowledge of the characteristic and behavior of residual soil and not putting the bearing capacity, elastic and engineering properties of the soil into consideration.

Shallow seismic refraction method calculates the time-depth plot intercept of refracted P and S wave velocities in order to find their velocities. P and S wave velocities calculated are the effective parameters for the determination of the bearing capacity and engineering parameters (Grant and west, 1965; Ulugergerli and Uyanik, 2007). The measured and calculated bearing capacity and engineering parameters relate with elastic parameters which include: young modulus, bulk modulus, shear modulus, Poisson ratio, oedometric modulus, compressibility and compliance. The bearing capacity calculated includes: allowable and ultimate bearing capacity which depends on the subgrade coefficient (Atat et al., 2013; Aka et al., 2018). The subgrade coefficient measures the pressure per unit area of the subsurface contact and settlement produced by the load application. Engineering parameters includes: concentration index, material index, density gradient and stress ratio respectively.

A foundation is the supporting base of a structure which forms the interface across which the loads are transmitted to the underlying soil. However, if the structural loads are transmitted to the subsurface soil, a shallow foundation is formed. Shallow foundations include; mat foundation and spread footing (Agoha et al., 2015; George et al., 2010a). The failure of the shallow foundation could be due to inadequate bearing capacity of the soil leading to shear failure or sliding of the foundation. Shear failures could be sudden and catastrophic or not continuous and not catastrophic. Sudden and catastrophic shear failures are accompanied by tilting of the footing associated with low compressibility and compliance soils which include dense sand or over consolidated clays. Non continuous and non-catastrophic shear failures are associated with some minor heaving at the ground level.

These shear failures may be local if the significant compression footing causes only a partial development of plastic equilibrium. Therefore, bearing capacity of the soil support the loads applied to the ground, which measures the maximum average contact pressure between the foundation and the soil. On the other hand, there are some precautions which must be

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taken into consideration when using shallow seismic refraction techniques such as profile length and source energy which limits the depth penetration of the seismic refraction method. However, a profile can only detect features at a depth of one fifth of the survey length and another significant limitation to the refraction method is the hidden layer problem.

This integrated approach is most preferable for the study since it provides a reliable means to solve the shallow subsurface problems by properly integrating the bearing strength and engineering properties of shallow subsurface that is suitable for sustaining engineering structures. Also, integrated approach gives reliable information that will help in decision making, minimize collapse of properties and fast track economic development in Ibiono Ibom Local Government, of Akwa Ibom State, Southern Nigeria. The objective of this study is to evaluate the depth and thickness of the shallow subsurface in order to characterize the bearing and engineering parameters of subsurface materials for stability of engineering works.

2. Location and Geology of The Study Area

The study location is Ibiono Ibom Local Government Area of AkwaIbom State, Nigeria. It is located within Latitudes 5.05⁰N - 5.15⁰N and Longitudes 7.46⁰N - 8.00⁰N. It is bounded in the North by Ini Local Government Area of Akwa Ibom State and Arochukwu Local Government Area of Abia State, in East by Itu, in the West by Ikono and South by Uyo Local Government Areas of Akwa Ibom State with a total area of 2761.76 square kilometer as shown in Figure 1. Ibiono Ibom is underlain by sedimentary formation of late tertiary and Holocene ages within the tropical rainforest belts of Nigeria. It is enriched with natural resources which include sand stones, granites, clay, laterite, forest resources and hydrocarbon (Akpan, 2012). The study area lies in the equatorial climatic region which experiences two seasons: wet and dry seasons between March to February and November to February (George et al., 2010b). The rivers, Stream and wetlands are potential resources that support aquatic lives like fishes, periwinkle, crayfish, shrimps and oyster respectively. The major occupations of the people in the area are education, fishing, farming and trading.

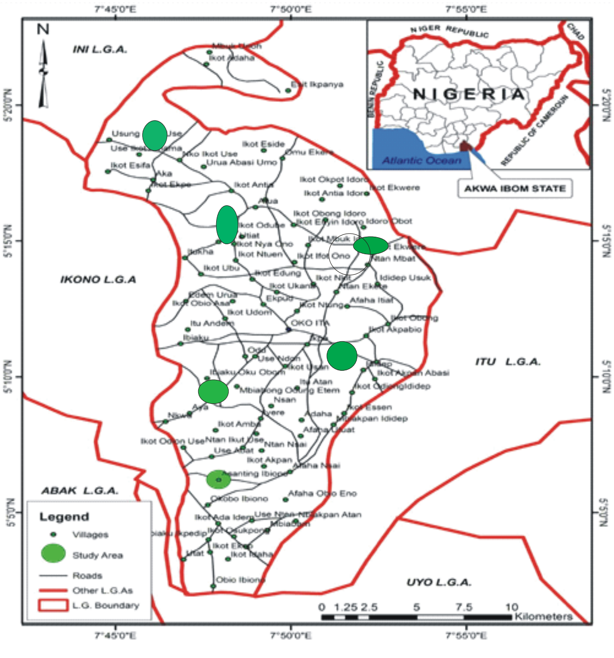

Figure 1: Map of IbionoIbom Showing the Study Area

2.1 Theoretical Foundation

In seismic refraction survey, once the refracted travel times of P and S waves are measured, their velocity can be calculated from the inverse slope of time – distance graph. However, the bearing capacity and engineering parameters can also be calculated. The bearing capacity is the capacity of the soil to support the loads applied to the ground which measures the maximum average contact pressure between the foundation and the soil. It is subdivided into two: the ultimate bearing capacity and allowable bearing capacity, the bearing capacity depends on the soil subgrade (George et al., 2010). Subgrade coefficient (K_s) measures the ratio of the pressure of the surface contact to the settlement produced by the load application as expressed in equation 1 and the unit weight of the soil in equation (2).

$$K_s = 4\gamma V_s \tag{1}$$

$$\gamma = \gamma_0 + 0.002V_p \tag{2}$$

γ_0 = 16 KN/m³ which is the average unit weight of loose soil, γ is the unit weight of the soil, V_s is the velocity of S wave and V_p is the velocity of P wave.

Ultimate bearing capacity or ultimate failure (q_f) measures the intensity of bearing pressure at which the supporting ground is expected to fail in shear as expressed in equation (3).

$$q_f = \frac{K_S}{40} \tag{3}$$

Allowable bearing capacity (q_a) measures the bearing pressure that will cause acceptance settlement of the structure against instability due to shear failures as expressed in equation (4).

$$q_a = \frac{q_f}{n} \tag{4}$$

Where n = 4.0 for soil, which is the factor of safety.

Engineering parameters are generalized characteristics representing an engineering situation of the subsurface. No construction material has more variable engineering and physical parameters than the ground soil. These engineering parameters vary both laterally and vertically in order to evaluate the competence of the subsurface for construction (Bowles, 1982). These engineering parameters include: concentration index, material index, stress ratio and density gradient. Material Index (V_1) is derived based on the trade-off between a constraint and the free variable as a function of the material properties. Each combination of function, objective and constraint leads to a particular performance index defined by a material property or combination of material properties. It is expressed as shown in equation (5).

$$V_1 = \frac{3-(V_P/V_S)^2}{(V_P/V_S)^2-1} \tag{5}$$

Stress Ratio (S_1)given equation (6) is the ratio of the ultimate strength of the engineering material to the allowable stress. The relationship between the stress and strain that a particular material displays is given by the materials stress- strain curve. It is unique for each material to records the amount of deformation (strain) at distinct intervals of tensile or compressive loading (stress).

$$S_1 = 1-2(V_S/V_P)^2 \tag{6}$$

Also, Concentration Index (C_1) measures the concentration of the load and soil strength which describe the magnitude of the shear stress that a soil can sustain as a result of friction and interlocking of soil particle, cementation or bonding at particle contacts (equation 7).

$$C_1 = \frac{3-4\left(\frac{V_S^2}{V_P^2}\right)}{1-2\left(\frac{V_S^2}{V_P^2}\right)} \tag{7}$$

Density Gradient (D_1) is a spatial variation in the density of engineering material. The density of the engineering material varies with temperature and pressure. This variation is typically small for solids and liquids but much greater for gases. Moreover, increasing the pressure of an object decreases the volume of the object and increases its density. Increasing the temperature of a substance decreases the density by increasing its volume. In most of the engineering materials, heating the bottom to the top, due to the decrease in the density of the heated fluid causes it to rise relative to dense unheated material. It is expressed as in equation (8).

$$D_1 = \left[\left(\frac{3}{V_P^2}\right)-\left(\frac{4\mu}{E}-1\right)\right] \tag{8}$$

2.2 Data Acquisition

Shallow Seismic refraction survey was carried out using 12 channels ES 3000S enhancement seismograph. Each profile extends for a total length of 60m at 5m inter geophones spacing, shot to the Ist geophone spacing was 3m. The total record length of P waves was 715.09m/s with a sample interval of 0.5ms.While for S wave total recorded length was 1400m/s, sample interval was 7ms.A 10kg sledgehammer was used to generate the seismic P and S wave respectively. To generate P waves, a rectangular aluminum plate of (40 x 40 x 5) cm was used to receive the impact from the sledgehammer strikes. A total of 5 shots were recorded at each test location and 3 stacks were made per shot location. In S waves, 6 shots were recorded at each location and 3 stacks were made per shot location using 48Hz frequency geophones for P and S waves as expressed in Figures 2 and 3.

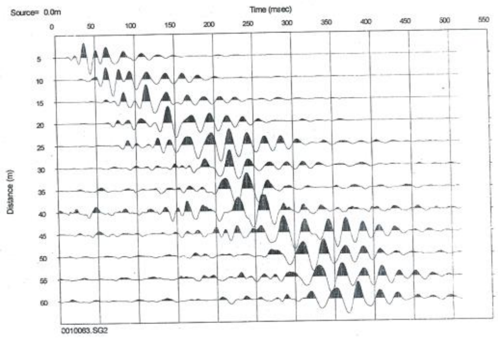

Figure 2: Forward Shot Gathers for Waves at Single Shot Point

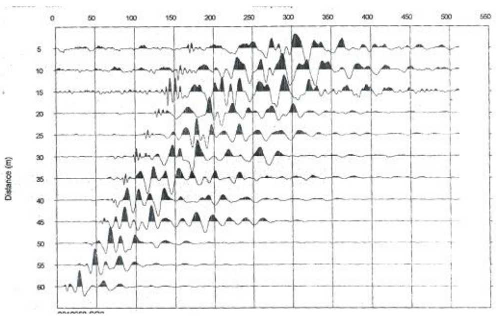

Figure 3: Reverse Shot Gathers for Waves at Single Shot Point

2.3 Data Processing, Interpretation and Result

The acquired shallow seismic refraction data were processed and interpreted using Seisimager software packages of Pickwin and IXrefrax. The first stage involved accurate picking of the first breaks from the seismic signal by using Pickwin software for every shot taken to obtain the time-distance of P and S curves. The curves were constructed based on the profile distance, geophone spacing, source location and first arrival time respectively. The second stage involved the calculation of the P and S wave velocities from the inverse slope of time-distance curves, calculation of bearing and engineering parameters from equation 1 to 8, and plotting of the graphs using IX-Refrax software (Figures 4 to 7). The third stage involved the modeling of 2D/3D subsurface bearing and engineering parameters as shown in Figures 8 to 11.

The results depict three layer formations which includes: upper, middle and lower layers. The upper layer has low seismic velocities with V_p ranging from 209.80 m/s to 578.80 m/s, V_s ranged from 205.43 m/s to 492.02 m/s, depth and thickness both ranged from 0.00 m to 4.5 m corresponding to recent superficial deposits. The middle layer has fairly low seismic velocities ranging from 650 m/s to 1500 m/s for V_p , 625 m/s to 1460 m/s for V_s and depth and thickness ranging from 5.0 m to 12.5 m and 7.5 m respectively, corresponding to river terraces and clays formation. The lower layer has good competent and compacted seismic velocities which ranged from 1730 m/s to 2450 m/s for V_p, 1525 m/s to 2230 m/s for V_s and depth and thickness ranging from 15.0 m to 25.20 m and 10.20 m respectively, corresponding to sandstone, marlstone and mudstone lithofacies respectively. The bearing capacity and engineering parameters for the stability of engineering can be summarized as follows:

Allowable bearing capacity (q_a) ranged from (0.84 to 2.11) x 10^5 N/m^2 and ultimate bearing capacity (q_f) range from (3.37 to 8.44) x 10^5 N/m^2 for the upper layer characterized by relative low allowable capacity, which indicates incompetent soil and rock quality. (0.87 to 2.17) x 10^5 N/m^2 and (3.50 to 8.70) x 10^5 N/m^2 for middle layer characterized by fair to moderate competent soil and rock quality. (1.15 to 2.57) x 10^5 N/m^2 and (4.61 to 10.31) x 10^5 N/m^2 for lower layer characterized by high bearing capacity which indicates good competent and compacted soil and rock quality as shown in Tables 1 and 2. The engineering parameters which includes: Concentration Index (Ci), Stress Ratio (Si), Material Index (Vi) and Density Gradient (Di).

Table 1: Ranges of the Calculated Bearing and Engineering Parameters of the Layers

Vp(m/s)	Vs(m/s)	D(m)	Th(m)	q_a x 10^5 (N/m^2)	q_f x 10^5 (N/m^2)	C_I	S_I	V_I	D_I
First Layer									
209.80	205.43	0.00	5.00	0.96	3.85	0.13	-0.92	0.84	-0.92
578.80	492.0	5.00		2.61	8.90	0.91	0.04	5.81	3.15
Second Layer									
650.00	625.00	6.00	8.00	1.37	4.32	0.90	0.91	0.60	-0.85
1500	1460.00	13.00		3.70	10.21	1.8	2.18	4.7	4.43
Third Layer									
1730	1525	13.50	11.50	2.18	6.10	0.60	1.37	1.02	-1.00
2450	2230	25.00		4.57	12.32	2.70	3.70	8.13	5.28

Table 2: Characterization of the Calculated Bearing and Engineering Parameters of the Bedrock Layers

Parameters	Weak Incompetent		Fair Fairly Competent		Good Competent
	Very Soft	Soft	Fairly competent	Moderate competent	Compacted
Allowable Capacity (q_a) x 10^5 (N/m^2)	0.96 - 1.79	1.79 – 2.61	1.37 – 2.54	2.54– 3.70	2.18 - 4.57
Ultimate Capacity (q_f) x 10^5 (N/m^2)	3.85 – 6.38	6.38 – 8.90	4.32– 7.27.	7.27– 10.21	6.10 - 12.32
Concentration Index (C_I)	0.13 – 0.52	0.52 – 0.91	0.90 – 1.35	1.35 – 1.80	1.30 – 6.25
Stress Ratio (S_I)	-0.92 – 0.02	0.02 – 0.04	0.91 – 1.51	1.51 – 2.18	1.15 – 2.57
Material Index (V_I)	0.84 – 3.7	3.7 – 5.81	0.60 – 4.1	4.1 – 7.0	4.61 - 10.31
Density Gradient(D_1)	-0.92 – 1.6	1.6 – 3.15	-0.85 – 2.65	2.65 – 4.43	2.60 - 11.70

In the first layer: Concentration Index (Ci) values ranged from 0.13 to 0.91, Stress Ratio (Si) ranged from -0.92 to 0.04, Material Index (Vi) ranged from 0.84 to 5.81 and Density Gradient (Di) ranged -0.92 – 3.15, reflected weak incompetent soil and rock quality in the Northeastern part.

In second layer: Concentration Index (Ci) values ranged from 0.90 to 1.8, Stress Ratio (Si) ranged from 0.91 to 2.18, Material Index (Vi) ranged from 0.60 to 4.7 and Density Gradient (Di) ranged –0.85 – 4.43, reflected fairly competent soil and rock quality within the central part of the area.

In third layer: Concentration Index (Ci) values ranged from 1.30 to 6.25, Stress Ratio (Si) ranged from 1.15 to 2.57, Material Index (Vi) ranged from 4.61 to 10.31 and Density Gradient (Di) ranged 2.60 – 11.70, reflecting good competent soil and rock quality within the southeastern part of the study area.

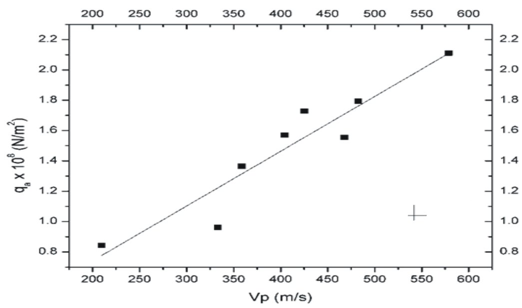

Figure 4: A plot of $q_a \times 10^8\ N/m^2$ against V_p (m/s) for Layer 1

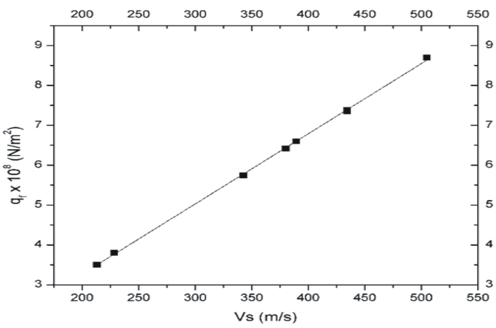

Figure 5: A plot of q_fx10⁵ (N/m²) against v_s (m/s) for layer 1

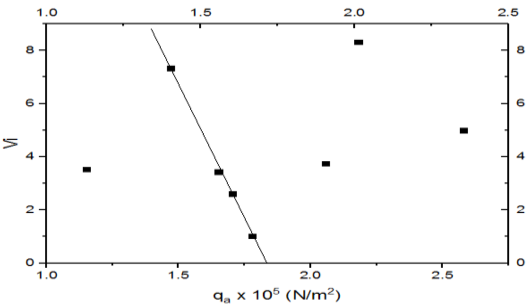

Figure 6: A plot of V_1against $q_a \times 10^8\ (N/m^2)$ for layer 2

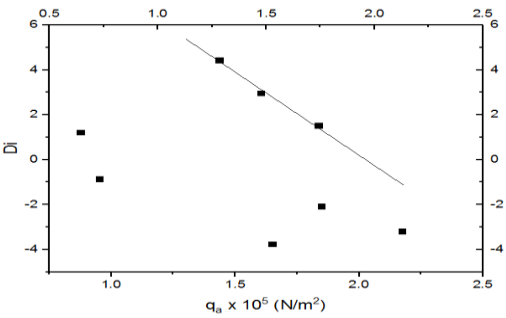

Figure 7: A plot of D_1 against $\mu \times 10^8\ (N/m^2)$ for layer 3

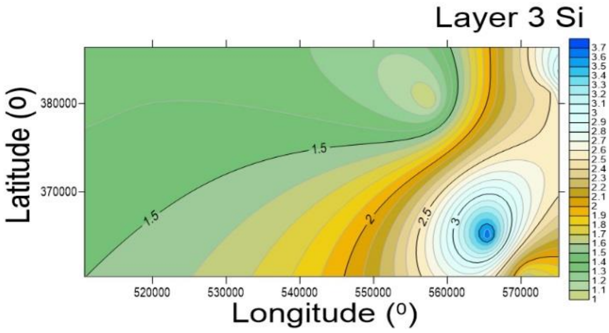

Figure 8: 2-D Contour Map Showing the Distribution of S_i in layer 3

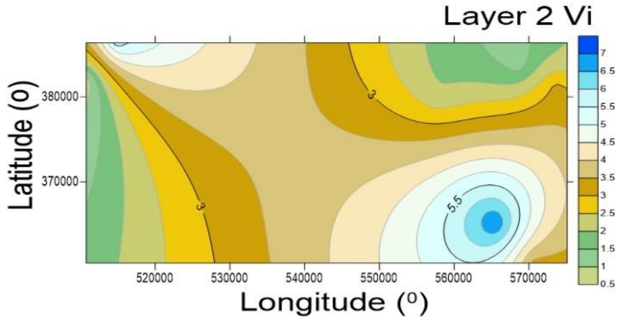

Figure 9: 2-D Contour Map Showing the Distribution of V_i in layer 2

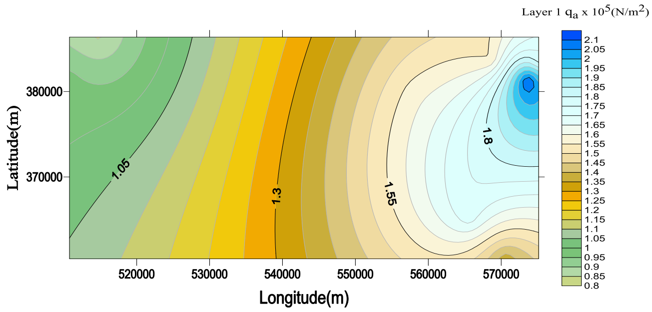

Figure 10: 2-D Contour Map Showing the Distribution of $q_a \times 10^5$ (N/m^2) in layer 1

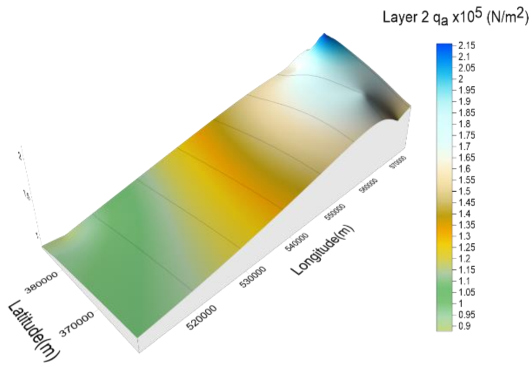

Figure 11: 3-D Contour Map Showing the Modeling of qa x 105(N/m2) in layer 2

3. Discussion

The area of study was divided into three-layer zones due to the bearing capacity and engineering parameters result obtained. That is, upper zone, middle zone and lower zone layers. The upper layer zone was characterized by incompetent soil and rock quality. V_P and V_S range from 209.80 m/s to 578.80 m/s and 205.43 m/s to 492.02 m/s respectively. Allowable and ultimate bearing capacity ranged from (0.96 to 2.61) × 10^5 N/m^2 and (3.85 to 8.90) × 10^5 N/m^2, the engineering parameters which include: concentration index, material index, stress ratio and density gradient range from 0.13 – 0.91, 0.84 – 5.81, -0.92 – 0.04 and - 0.92 – 3.15 respectively. The values of the depth and thickness of the bedrock both range from 0.0 to 4.5 m. The middle layer was characterized by fairly competent soil and rock quality, V_P and V_S range from 650.00 m/s to 1500 m/s and 625.00 m/s to 1460.00 m/s respectively. Allowable bearing capacity range from $(1.37 \text{ to } 3.70) \times 10^5 \ \mathrm{N}/m^2$ and the ultimate bearing capacity ranged from $(4.32 \text{ to } 10.21) \times 10^5 \ \mathrm{N}/m^2$.

The concentration index, material index, stress ratio and density gradient of the middle layer ranged from 0.90 – 1.80, 0.91 – 2.18, 0.60 – 7.0 and -0.85 – 4.43 respectively. The depth of the bedrock ranged from 5.0 to 12.5 m while its thickness ranged from 5.0 to 7.5 m. The lower (third layer) layer which is characterized by good competent soil and rock quality, the V_P ranged from 1730.00 m/s to 2450 m/s while V_S ranged from 1525.00 m/s to 2230.00 m/s. The allowable and ultimate bearing capacity the third layer ranged from $(2.18 \text{ to } 4.57) \times 10^5 \ \mathrm{N}/m^2$ and $(6.10 \text{ to } 12.32) \times 10^5 \ \mathrm{N}/m^2$ respectively. The engineering parameters (concentration index, material index, stress ratio and density gradient) calculated give values ranging from 1.30 – 6.25 for concentration index, 1.15 – 2.57 for material index, 4.61 – 10.31 for stress ratio and 2.60 – 11.70 for density gradient. The depth and thickness of the bedrock in this layer ranged from 13.0 to 25.2 m and 12.2 m respectively. No construction material has more variable engineering and physical parameters than the ground's soil. In order to evaluate the competence of the subsurface for construction, engineering parameters were integrated with bearing capacity.

The dependence of the engineering parameters with bearing capacity has been desirable through the various plots of the three layers; 1, 2 and 3 as shown in Figures 4 to 7. The slope of the plots shows a linear relationship between the plotted parameters which vary both laterally, vertically and often the variations are strong. The 2-D contour map in Figures 8 and 9 shows a continuous increment in the Stress ratio and material index in the south-east trend in layers 3 and 2 respectively. The contour map (Figure 10) shows the variation of the allowable bearing capacity which increases towards the eastern part of the study area in layer 1. This trend shows low allowable bearing and engineering parameters regions which is associated with zone that has weak and fair incompetent soil, rock quality and highly drained with water while high bearing and engineering regions reflected good competent soil, rock quality and unsaturated with water. However, in 3-D contour map (Figure 11), the region of high values of allowable bearing in the layer 2 conforms to the location noticed in layer 1.

These results demonstrate uniform consolidation trends from low to high values of engineering and bearing capacity with depth in layers 1 to 3. This conformity reveals the uniqueness of the method used in integrating the shallow subsurface structures. Compare the results of engineering and bearing parameters of upper, middle and lower layers with the standard geologic and engineering equivalence for engineering stability. The engineering and bearing parameters of lower layer indicates good competent soil and rock quality, therefore, the lower layer is recommended as the most eligible layer for stability engineering works for construction purposes.

4. Conclusion

Seismic refraction technique is a reliable geophysical technique for subsurface investigation. The refracted arrival time of P and S waves were measured and their velocities along with bearing capacity and engineering parameters were calculated. The result of the interpreted data reveals the variation of thickness across the three layers delineated. The bearing capacities estimated were allowable and ultimate; the allowable bearing capacity is one of the important parameters used in deciding the engineering foundations. The ability of the foundation to carry a load depends on the bearing capacity. The bearing capacity depends on the shear wave velocity, the values of the bearing capacity increases with high values of shear wave velocity. The shallow engineering parameters (concentration index, material index, stress ratio and density gradient) were also calculated to assess the subsurface bedrock. These parameters were contoured and the resulting maps show their variations across the study area and the plots show the relationships between the calculated parameters. The integration of the bearing capacity and engineering parameters indicate that the lower layer (third layer) has a good competent soil and rock quality. Therefore, the lower layer is recommended as the most appropriate layer for engineering and foundation stability.

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