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GEOTECHNICAL PROPERTIES OF SOIL FOR CIVIL ENGINEERING CONSTRUCTIONS IN NYUENE, BONNY ISLAND, NIGERIA

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ABSTRACT

The geotechnical properties of soils for civil engineering constructions in Nyuene, Bonny Island were evaluated using seismic refraction survey. A 3-layer soil structure was delineated: topmost layer, 6.9 m thick; second layer, 17.1 m thick and consolidated bedrock layer extending to great depths. Results across these layers respectively reveal that V_p/V_s has averages of 1.29, 1.50 and 1.78 indicating fluid-saturated top layers; Poisson's ratio has averages of -0.72, 0.05 and 0.29; Shear modulus has averages of 2.10 x10^8 Nm^{-2}, 5.20 x10^8 Nm^{-2} and 8.09 x10^8 Nm^{-2}; Young's modulus has averages of 0.67 x10^8 Nm^{-2}, 10.80 x10^8 Nm^{-2} and 20.80 x10^8 Nm^{-2}; Bulk modulus has averages of 0.60 x10^8 Nm^{-2}, 4.62 x10^8 Nm^{-2} and 16.7 x10^8 Nm^{-2}. Furthermore, the ultimate bearing capacity averages at 464.5 kNm^{-2}, 764.6 kNm^{-2} and 995.8 kNm^{-2} respectively across the layers and the allowable bearing pressure averages at 116.1 kNm^{-2}, 191.2 kNm^{-2} and 248.9 kNm^{-2} respectively. The trend of the dynamic elastic parameters respectively indicates increase in compressive soil strength, increase in the capacity to withstand shear stress and increase in compaction. These values show that the consolidated layer can withstand more pressure and bear more load than the other layers. The properties of this layer fall within the standard criteria for civil engineering constructions. For the construction of high-rise buildings/skyscrapers and bridges in the study area, 24m of topsoil should be reinforced by piling. However, for other non-high-rise buildings/structures, about 7.0 m of topsoil should be excavated for proper siting of foundations due to the tidal flooding and land subsidence in Bonny Island and environs. This method should be combined with Cone Penetrometer Test at early stage of any construction work to properly determine the soil depth and geotechnical properties to locate foundations. This will forestall the problems of cracks in foundations and buildings collapse.

Keywords: Bonny Island, Seismic refraction, dynamic elastics parameters, engineering foundation properties.

INTRODUCTION

The crucial stage in the planning and construction of foundations for civil engineering structures such as high-rise buildings, dams, bridges, roads and so on requires accurate delineation of the geotechnical properties of the soil/rock. This is very indispensable in Bonny Island and its environs which have challenging terrain with 70 % of the total land area, 214.52 m^2 suffering from tidal flooding and land subsidence (NLNG, 2005). The Island is witnessing a rapid population growth due to the presence of oil and gas activities leading to an increase in civil engineering structures to accommodate industrial installations and the teeming population.

One of the conventional methods used for establishing the geotechnical properties of soils/rocks is the Cone Penetrometer Test (CPT). However, surface geophysical methods which involve taking measurements at or near the surface of the earth have also been employed to better investigate the geotechnical properties of the soil/rock underlying construction sites and determine the thickness of the overburden that may be excavated or reinforced prior to construction. Seismic refraction and uphole surveys are surface geophysical methods that have been used to study the bearing capacity of the foundation soils/rocks with elastic properties of the rock such as Poisson ratio (σ), Shear modulus (μ), Bulk modulus (k) and Lame's constant (λ) used to determine zones of weakness (Agha *et al*., 2006; Oladapo *et al*., 2008; Tezcan *et al*., 2009; Atat *et al*., 2013; Obianwu *et al*., 2015; Adewoyin *et al*., 2017).

Most soils/rocks are usually assumed to be very good foundation materials but their heterogeneous nature caused by the existence of faults, voids, cracks, fractures or joints filled with fluids or organic matter can reduce their bearing capacity. Consequently, it is appropriate to critically examine the *insitu* conditions of even the presumably strong consolidated soils/rocks when

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constructions of civil engineering structures are planned. This research determines the foundation soil/rock properties suitable for civil engineering constructions in Nyuene, Bonny Island, Nigeria. The thicknesses, elastic properties and bearing capacities of different soil/rock layers have been delineated using the seismic refraction method. This method has the advantage of producing results that are more stable, consistent and reliable when compared with those of the conventional methods which disturb the natural site conditions (Tezcan *et al*., 2009).

LOCATION, PHYSIOGRAPHY AND GEOLOGY OF THE STUDY AREA

The study area is Nyuene, a coastal community located off Bonny River Terminal (BRT) lying at the eastern part of Bonny Island approximately 40 km South of Port Harcourt, Nigeria. Bonny Island lies between $4^{\circ}52'$N to $5^{\circ}02'$N and longitudes $6^{\circ}56'$E to $7^{\circ}04'$E within the Beach ridges onshore geomorphic sub-environment of the Niger Delta (Fig. 1). The Island has a relatively flat topography on an elevation of 3.05 atmospheric mean sea level (NLNG, 2005).

Bonny Island is situated in the rain forest vegetation region. Its river banks and tributaries are made up of brackish mangrove forest vegetation. The Island is traversed by several creeks that divide it into mainly the northern and southern parts. The greater northern half up to the east of Bonny Town, next to the Opobo Channel is mainly mangroves, and lies just above sea level. The southern part lies higher and contains typically freshwater swamp forests, in some places mixed with mangrove, open swamp, dry land rainforest or dune slacks (EAU, 1992).

According to Amadi *et al*. (2012), the area geologically comprises Pleistocene to Recent sediments deposited by fluvial and shallow continental shelf hydrodynamic processes. The area is characterized by beaches, mangroves, swamps and barrier sands. It is underlain by the Coastal Plain Sands which is predominantly sandy with a few intercalations of silt beds. The substrata of the island consist mainly of fine sands, down to about 10 m with occasional clay layers. The lithofacies include the delta tip, mainly evenly laminated fine to medium grained sand.

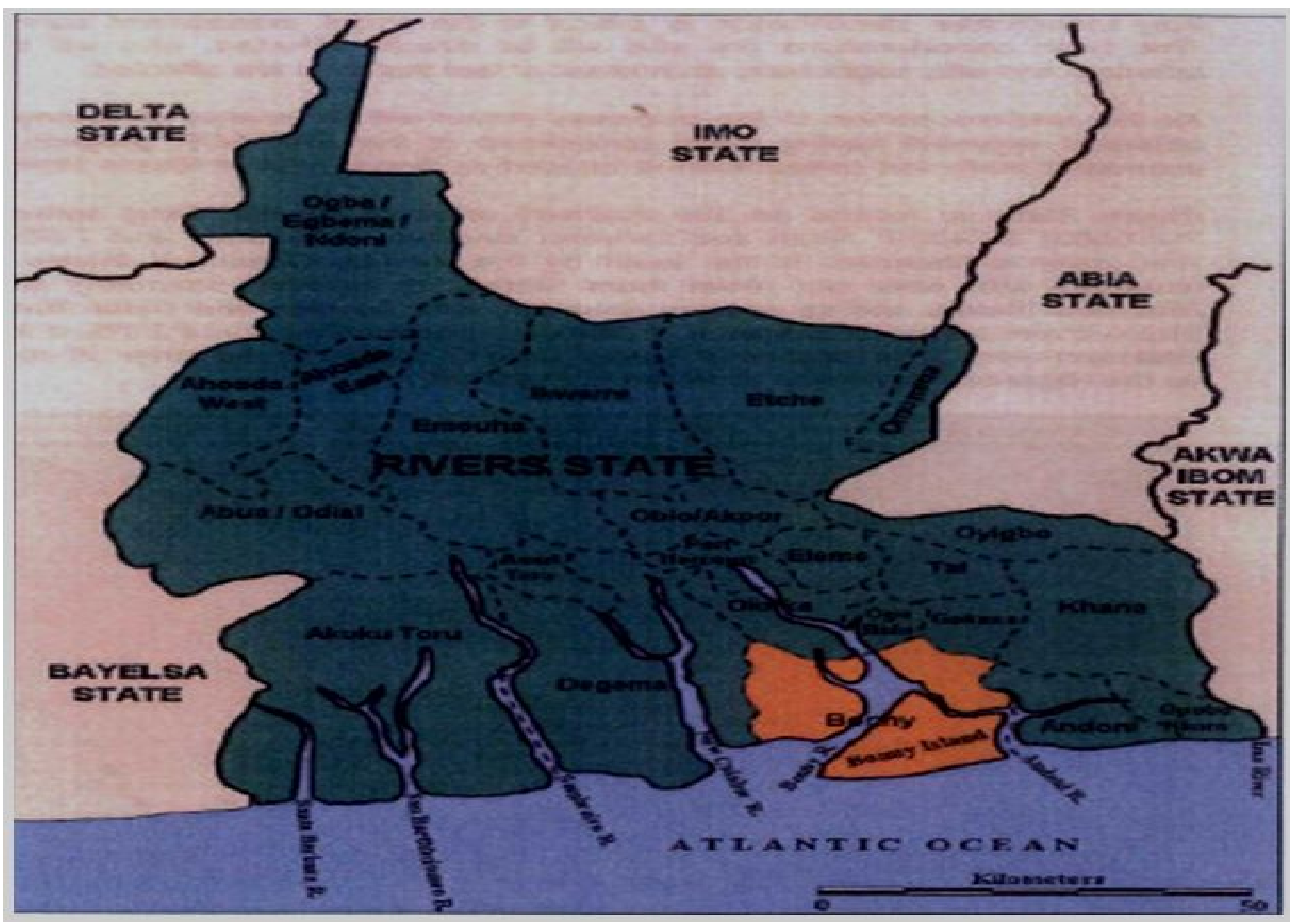

Fig. 1. Map of the Niger Delta showing Bonny Island.

MATERIALS AND METHODS

Methodology

Field Layout and Data Acquisition

Seismic refraction survey was conducted by generating seismic waves and recording the traveltimes of the Compressional and Shear waves at each measurement point in the survey area. A Nimbus model ES-1210F multi-channel signal enhancement seismograph with a 0.5 kg dynamite buried at a depth of 5.0 m at offset of 10.0 m was used for the survey. A total of 14 shots with shot hole diameter of 4.75 inches were taken covering an area of about 4.0 km^2 during the seismic survey in Nyuene. Measurements in 7 different receiver lines using offsets of 10.0 m in-between 12 geophones were employed giving a total spread length of 120 m. The layout and acquisition geometry is shown in Figure 2.

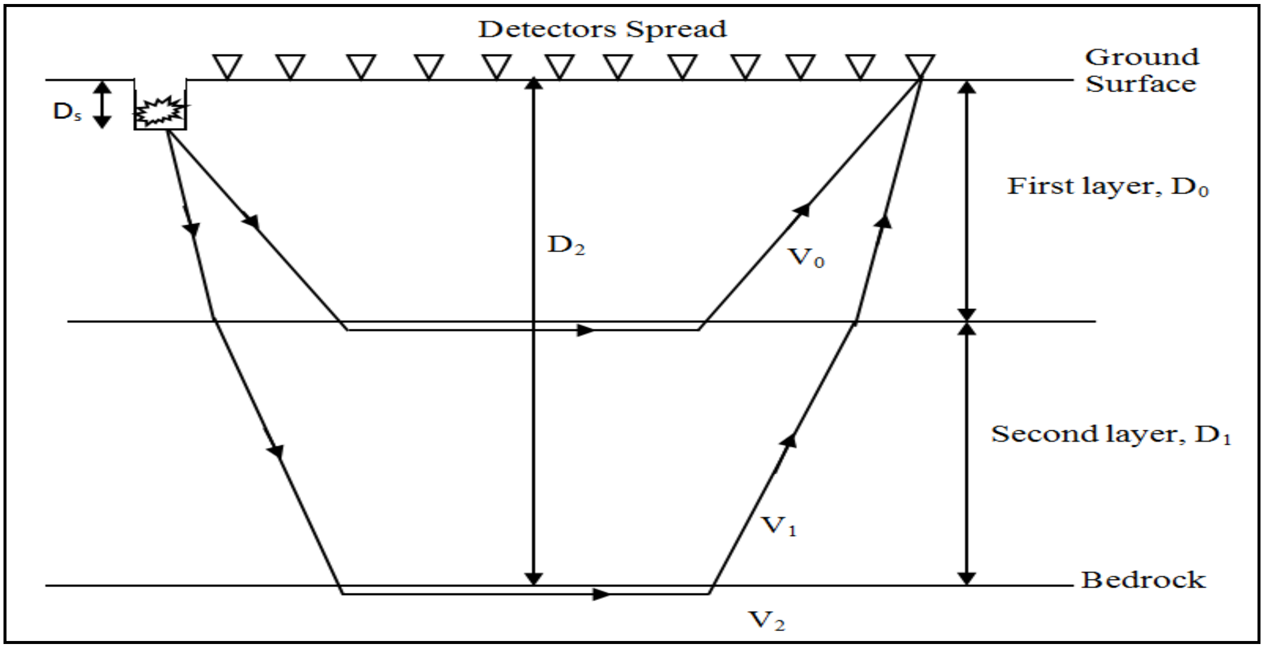

Fig. 2. Seismic Refraction Acquisition Geometry.

Data Processing

The acquired data were processed by auto-picking the first-breaks from the recorded traces. The travel times for each shot were digitized from each monitor record for both compressional and shear waves respectively. The seismic travel time data for the various receiver lines (RL) 01 to 07 for both types of waves are presented in Table 1.

Table 1. Seismic Traveltime Data for the Survey Area.

TRACE NO.	OFFSET (m)	TRAVELTIMES (*ms*) FOR COMPRESSIONAL WAVES, T_c AND SHEAR WAVES, T_s													
		RL 01		RL 02		RL 03		RL 04		RL 05		RL 06		RL 07	
		T_c	T_s	T_c	T_s	T_c	T_s	T_c	T_s	T_c	T_s	T_c	T_s	T_c	T_s
1	10.0	28.2	38.4	28.0	38.4	27.0	39.0	27.0	40.2	28.0	38.4	30.0	39.1	28.0	40.2
2	20.0	50.6	66.2	48.8	66.0	51.2	68.0	52.2	69.4	50.6	68.2	52.0	68.0	48.0	69.4
3	30.0	60.8	86.0	60.5	86.0	58.8	88.0	58.6	86.0	60.8	88.0	62.0	86.2	60.0	84.8
4	40.0	80.8	110.2	82.0	108.6	80.6	110.0	80.6	112.0	80.8	110.2	82.0	110.0	82.0	112.0
5	50.0	90.8	124.4	88.5	124.8	89.4	126.0	88.8	122.8	90.8	122.8	92.0	124.6	88.3	124.4
6	60.0	100.6	140.0	96.8	140.2	98.4	140.0	98.4	138.9	100.6	140.3	100.0	140.0	96.0	141.9
7	70.0	110.6	164.8	104.8	164.6	108.6	164.4	106.6	165.0	110.6	164.8	110.0	164.2	110.0	165.0
8	80.0	120.5	184.6	120.0	184.8	118.6	184.8	120.5	184.8	120.5	184.6	120.0	184.6	120.0	184.8
9	90.0	130.8	218.2	128.2	220.0	132.0	220.0	130.0	218.2	130.8	220.2	130.0	218.4	130.0	218.4
10	100.0	140.6	228.5	136.8	228.8	140.2	228.8	142.0	228.4	140.4	226.8	140.0	226.8	140.0	228.8
11	110.0	150.5	246.0	148.4	246.2	150.4	246.0	150.2	246.2	150.2	246.2	150.0	246.2	150.0	246.4
12	120.0	170.6	254.0	166.8	254.4	172.8	254.6	170.6	255.0	170.2	256.0	170.0	256.2	170.0	256.2

Data Analysis/Interpretation

These travel times, T_c (*ms*) for the compressional waves and T_s (*ms*) for the shear waves are plotted against geophone offsets, X (m). The corresponding typical traveltime-offset curves for the data in Table 1 are shown in Figure 3 and 4.

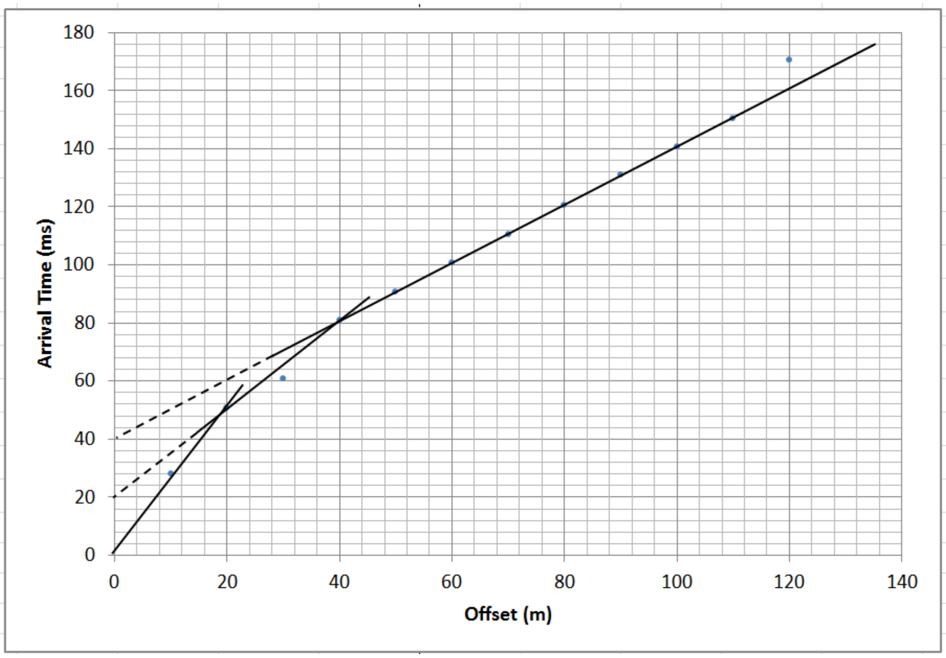

Fig. 3. Typical Traveltime-Offset Curve for the Compressional Waves.

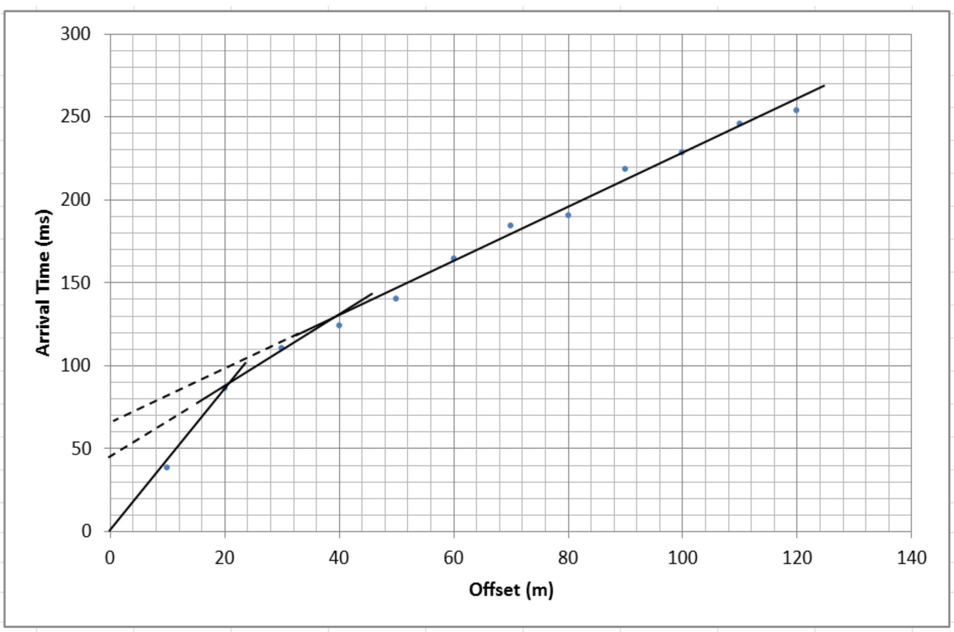

Fig. 4. Typical Traveltime-Offset Curve for the Shear Waves.

Intercept Times, T_c and T_s

Table 2 shows the intercept times, T_c and T_s deduced respectively from the curves on Figures 3 and 4 among others for the compressional and shear waves.

Table 2. Intercept Times from the Plotted Data.

S. No.	INTERCEPT TIMES (*ms*) FOR COMPRESSIONAL WAVES, T_{i_c} AND SHEAR WAVES, T_{i_s}													
	RL 01		RL 02		RL 03		RL 04		RL 05		RL 06		RL 07	
	T_{i_c}	T_{i_s}	T_{i_c}	T_{i_s}	T_{i_c}	T_{i_s}	T_{i_c}	T_{i_s}	T_{i_c}	T_{i_s}	T_{i_c}	T_{i_s}	T_{i_c}	T_{i_s}
1	20	46	14	22	22	28	24	28	22	28	24	25	18	26
2	40	68	36	36	34	38	38	40	42	46	42	40	43	40

Computation of Layer Velocities

The curves generated were used to compute the velocities of these waves as follows:

Slopes were calculated by: $$Slope = \frac{\Delta T}{\Delta X} \text{ (s/m)} \quad (1)$$

Velocities were computed by:

$$V = \frac{1}{slope} = \frac{\Delta X}{\Delta T} \text{(m/s)} \quad (2)$$

Where: ΔT = change in traveltime, ΔX = change in geophone offset

Determination of Thicknesses of Layers

The thicknesses and velocities of the various layers were determined by following the relation established by Knox, 1967 & Dobrin, 1976 for a 2-weathered layer case:

$$D_0 = \frac{T_1}{2}\left[\frac{V_1 V_0}{\sqrt{(V_1^2 - V_0^2)}}\right] + \frac{D_s}{2} \quad (3)$$

$$D_1 = \left[T_2 - \frac{2D_0\sqrt{(V_2^2 - V_0^2)}}{V_2 V_0}\right]\left[\frac{V_2 V_1}{2\sqrt{(V_2^2 - V_1^2)}}\right] \quad (4)$$

$$D_2 = D_0 + D_1 \quad (5)$$

Where: T_1 and T_2 = respective intercept times (ms) on the distance-time graph; V_0, V_1 and V_2 = velocity (ms^{-1}) of the first layer, second layer and the bedrock respectively; D_s = Depth of source (m)'; D_0 = Thickness (m) of the first layer; D_1 = Thickness (m) of the second layer; D_2 = Total Thickness (m) of the layers.

Computation of Dynamic Elastic Properties of Soils/Rocks

The elastic properties of soils are calculated from the following established relations (Sheriff and Geldart, 1983):

$$\text{Poisson's Ratio, } \sigma = \frac{0.5V_p^2 - V_s^2}{V_p^2 - V_s^2} \quad (6)$$

V_p and V_s are velocities of compressional and shear waves respectively

$$\text{Shear Modulus, } \mu = \rho V_s^2$$ (ρ is taken as 2650 kgm^{-3} for sedimentary soils) (7)

$$\text{Young's Modulus, } E = 2\mu(1+\sigma) \quad (8)$$

$$\text{Bulk Modulus, } K = \frac{E}{3(1-2\sigma)} = \frac{2\rho(1+\sigma)}{3(1-2\sigma)} \quad (9)$$

$$\text{Lame's Constant, } \lambda = \frac{E\sigma}{(\sigma+1)(1-2\sigma)} \quad (10)$$

Computation of Foundation Properties of Soils/Rocks

The foundation properties of soils/rocks were computed using the following established empirical engineering relations:

$$\text{Unit Mass Density, } \gamma = \gamma_0 + 0.002V_p \quad (kNm^{-3})$$

(Tezcan *et al.,* 2009) (11)

γ_0 is the reference unit weight value = 16 for loose, sandy and clayey soils (Terzaghi and Peck, 1967).

$$\text{Subgrade Coefficient, } k_s = 4\gamma V_s \quad (Nm^{-2}s^{-1})$$

(Bowles, 1982) (12)

$$\text{Ultimate Bearing Capacity, } q_f = \frac{k_s}{40} \quad (kNm^{-2})$$

(Bowles, 1982) (13)

$$\text{Allowable Bearing Pressure, } q_a = \frac{q_f}{n} \quad (kNm^{-2}) \quad (14)$$

Where n is the safety factor. For soils, n = 4.0 (Tezcan *et al.,* 2009)

RESULTS AND DISCUSSION

A summary of the results for the soil/rock properties necessary for geotechnical application in this study area is shown in Table 3.

Table 3. Summary of Soil/Rock Properties for Foundations in Nyuene, Bonny Island.

Soil/Rock Properties	**Receiver Lines**							**Average Values**
	RL 01	**RL 02**	**RL 03**	**RL 04**	**RL 05**	**RL 06**	**RL 07**	
V_p (ms^{-1})	333.3	333.3	375	333.3	375	333.3	400	
V_s (ms^{-1})	240	300	285.7	300	280	300	240	
V_p/V_s	1.39	1.11	1.31	1.11	1.34	1.11	1.67	**1.29**
1st Layer Depth, D_0 (m)	6.35	5.34	7.66	7.02	7.26	7.12	7.33	**6.87**
σ	-0.04	-1.63	-0.19	-1.63	-0.13	-1.63	0.22	**-0.72**
μ(x10^8) Nm^{-2}	1.53	2.39	2.16	2.39	2.08	2.39	1.53	**2.10**
E(x10^8) Nm^{-2}	2.94	-3.00	3.50	-3.00	3.62	-3.00	3.72	**0.67**
K(x10^8) Nm^{-2}	0.91	-0.23	0.84	-0.23	0.96	-0.23	2.2	**0.60**
λ(x10^8) Nm^{-2}	-0.11	-1.80	-0.60	-1.80	-0.43	-1.80	1.19	**-0.77**
γ (kNm^{-3})	16.67	16.67	16.75	16.67	16.75	16.67	16.80	**16.71**
k_s(x10^8) Nm^{-2}s^{-1}	0.1600	0.2000	0.1914	0.2000	0.1876	0.2000	0.1613	**0.1858**
q_f (kNm^{-2})	400.1	500.1	478.6	500.1	469	500.1	403.2	**464.5**
q_a (kNm^{-2})	100	125	119.6	125	117.3	125	100.8	**116.1**
V_p (ms^{-1})	666.7	583.3	625	714.3	750	666.7	600	
V_s (ms^{-1})	400	400	400	480	480	450	480	
V_p/V_s	1.67	1.46	1.56	1.49	1.56	1.48	1.25	**1.50**
2nd Layer Depth, D_1 (m)	17.89	12.93	13.61	19.39	21.13	18.79	16.13	**17.12**
σ	0.22	0.06	0.15	0.09	0.15	0.08	-0.39	**0.05**
μ(x10^8) Nm^{-2}	4.24	4.24	4.24	6.11	6.11	5.37	6.11	**5.20**
E(x10^8) Nm^{-2}	10.30	8.96	9.78	13.3	14.1	11.6	7.46	**10.80**
K(x10^8) Nm^{-2}	6.10	3.36	4.70	5.38	6.77	4.62	1.40	**4.62**
λ(x10^8) Nm^{-2}	3.29	0.54	1.87	1.31	2.70	1.05	-2.7	**1.15**
γ (kNm^{-3})	17.33	17.17	17.25	17.43	17.50	17.33	17.20	**17.32**
k_s(x10^8) Nm^{-2}s^{-1}	0.2773	0.2747	0.2760	0.3347	0.3360	0.3119	0.3302	**0.3058**
q_f (kNm^{-2})	693.2	686.8	690	836.6	840	779.9	825.6	**764.6**
q_a (kNm^{-2})	173.3	171.7	172.5	209.2	210	195	206.4	**191.2**
V_p (ms^{-1})	1000	1000	1000	1000	1125	1000	1000	
V_s (ms^{-1})	600	533.3	533.3	571.4	560	533.3	533.3	
V_p/V_s	1.67	1.88	1.88	1.75	1.34	1.88	1.88	**1.78**
Consolidated Layer Depth	**Layer extends to great subsurface depths**							
σ	0.22	0.30	0.30	0.26	0.34	0.30	0.30	**0.29**
μ(x10^8) Nm^{-2}	9.54	7.54	7.54	8.65	8.31	7.54	7.54	**8.09**
E(x10^8) Nm^{-2}	23.3	19.6	19.6	21.8	22.2	19.6	19.6	**20.80**
K(x10^8) Nm^{-2}	13.8	16.4	16.4	15.0	22.5	16.4	16.4	**16.70**
λ(x10^8) Nm^{-2}	7.43	11.4	11.4	9.2	16.9	11.4	11.4	**11.30**
γ (kNm^{-3})	18.00	18.00	18.00	18.00	18.25	18.00	18.00	**18.04**
k_s(x10^8) Nm^{-2}s^{-1}	0.4320	0.3840	0.3840	0.4114	0.4088	0.3840	0.3840	**0.3983**
q_f (kNm^{-2})	1080	959.9	959.9	1028.5	1022	959.9	959.9	**995.8**
q_a (kNm^{-2})	270	240	240	257.1	255.5	240	240	**248.9**

With the seismic refraction surveys, three lithologic soil layers were delineated in the study area: topmost-weathered layer, sub-weathered layer and the consolidated layer. The topmost-weathered layer, at an average depth of 6.9 m, is made up of soils with pore spaces that are fluid-saturated which accounts for the low V_s values observed while the sub-weathered layer, at an average depth of 17 m, is made up of soils with saturated fine sand/clay. The soil materials in the third layer are compacted and consolidated and extend to great depth in the subsurface.

The computation of the dynamic elastic properties of soils/rocks was dependent on V_p/V_s which is considered as a lithology discriminator and the variation in its values across the study area indicates a high degree of anisotropy (Essien and Akpankpo, 2013). V_p/V_s is observed to increase with depth across the layers. The ratio in the topmost layer ranged from 1.11 to 1.67 with an average value of 1.29 while in the second layer it ranged from 1.25 to 1.67 with an average value of 1.50. Within the consolidated layer, it ranged from 1.34 to 1.88 with an average value of 1.78.

Poisson's ratio, σ ranges from -1.63 to 0.22 with an average of -0.72 for the topmost layer; -0.39 to 0.22 with an average of 0.05 for the second layer and 0.22 to 0.39 with an average of 0.29 for the consolidated layer. Poisson's ratio is observed to be highly variable increasing with depth of the layers with the negative values indicating high fluid saturations in the topmost layer. This increase in σ indicates increase in the compressive strength of the soil with depth. Shear modulus ranges from 1.53 to 2.39 $x10^8$ Nm^{-2} with an average of 2.10 $x10^8$ Nm^{-2} for the topmost layer; 4.24 to 6.11 $x10^8$ Nm^{-2} with an average of 5.20 $x10^8$ Nm^{-2} for the second layer and 7.54 to 9.54 $x10^8$ Nm^{-2} with an average of 8.09 $x10^8$ Nm^{-2} for the consolidated layer. Young's modulus ranges from -3.0 to 3.72 $x10^8$ Nm^{-2} with an average of 0.67 $x10^8$ Nm^{-2} for the topmost layer; 7.46 to 14.1 $x10^8$ Nm^{-2} with an average of 10.80 $x10^8$ Nm^{-2} for the second layer and 19.6 to 23.3 $x10^8$ Nm^{-2} with an average of 20.80 $x10^8$ Nm^{-2} for the consolidated layer. Bulk modulus ranges from -0.23 to 2.2 $x10^8$ Nm^{-2} with an average of 0.60 $x10^8$ Nm^{-2} for the topmost layer; 1.40 to 6.77$x10^8$ Nm^{-2} with an average of 4.62 $x10^8$ Nm^{-2} for the second layer and 13.8 to 22.5$x10^8$ Nm^{-2} with an average of 16.7 $x10^8$ Nm^{-2} for the consolidated layer.

Furthermore, the results reveal that the ultimate bearing capacity, q_f in the study area ranges from 400.1 to 500.1 kNm^{-2} with an average of 464.5 kNm^{-2} for the topmost layer and from 686.8 to 840.0 kNm^{-2} with an average of 764.6 kNm^{-2} for the second layer. The ultimate bearing capacity for the consolidated layer ranges from 959.9 to 1080 kNm^{-2} with an average of 995.8 kNm^{-2}. The allowable bearing pressure, q_a that the soil can withstand ranges from 100 to 125 kNm^{-2} with an average of 116.1 kNm^{-2} for the topmost layer and from 171.7 to 210 kNm^{-2} with an average of 191.2 kNm^{-2} for the second layer. The bearing pressure for the consolidated layer ranges from 240 to 270 kNm^{-2} with an average of 248.9 kNm^{-2}.

CONCLUSION AND RECOMMENDATION

The ranges of V_p/V_s values in the study area indicate that the topmost layer is fluid-saturated while the second and the consolidated layers are made up of sandstones (Pickett, 1963). The elastic parameters are all observed to increase with depth with their highest values in the third consolidated layer. The trend of Poisson's ratio, Shear modulus, Bulk modulus and Young's respectively indicate increase in compressive soil strength, increased capacity to withstand shear stress and increased compaction. According to Sjorgren and Berg (1979), the best area for siting foundation should have a Poisson ratio of about 0.33 and from this study, the third consolidated layers falls within this range.

The values of ultimate bearing capacity and allowable bearing pressure computed for the study area also justify that the third consolidated layer can withstand more pressure and bear more load than the other layers.

It is hereby recommended that for the construction of high-rise buildings/skyscrapers in the study area, the topsoil depth of about 24 m should be reinforced by piling. However, for other non-high-rise buildings/ structures, a topsoil depth of about 7.0 m should be excavated for proper siting of foundations giving to the challenging terrain of Bonny Island and environs with tidal flooding and subsidence.

Geophysical techniques of seismic refraction should be combined with the conventional geotechnical method of Cone Penetrometer Test at early stage of any construction work to properly determine the depth and soil property type to locate foundations. This will forestall the problems of cracks in foundations and buildings collapse leading to lose of lives, properties and money.

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