

Determination of Elastic Constants and Seismic Velocity of Unconsolidated Layers around the Greater Port Harcourt City, Rivers State, Nigeria.

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ABSTRACT

A seismic survey using the seismic refraction method was carried out in area covering several small villages in Rivers State. The study area comprises of Elimgbu, Eneka, Etche, Igwuruta, and Omagwa. The aim of the study was to determine the elastic constants (shear and bulk modulus) of the unconsolidated layer and investigate the thickness and seismic velocities of the unconsolidated layer. The data was acquired using a 12 channel signal enhancement seismograph and geophones positioned at a regular interval of 5m along a single line. The data was further processed using computer software (Reflex 2D Quick) to pick the first arrival and Surfer 8 Software for contouring. A total of twelve (12) data points comprising of six (6) forward shooting and six (6) reversed shooting were occupied for this work.

Results revealed the dominance of two layered weathering structure. The weathering thickness ranges from 1m to 9m. Similarly, the seismic velocities for the forward shooting varies between 220 and 600m/s, while the seismic velocities for the reversed shooting ranges between 235 and 587m/s. The bulk modulus obtained goes from 25 to 240kN/m² while the shear modulus varies from 23 to 220kN/m². Geological interpretation of the results of the study area from the contour map and the time-distance plot revealed that the shear strength and the incompressibility of the soils in some of the locations like Omagwa I and Eneka was low. Hence there is need to replace the unconsolidated layer with soil of higher shear strength and incompressibility in order to avoid collapse of roads and other structures. The 3D surface plot topography revealed that Elimgbu and Omagwa II are on a higher elevation which is believed to be responsible for the high velocity values. The plot also revealed that there is a

gradual dipping as one moves from Elimgbu to Omagwa through Igwuruta.

(Keywords: greater Port Harcourt City, elastic constants, unconsolidated layers, seismic refraction)

INTRODUCTION

The recent pronouncement by Rivers State Government in 2008 to develop the Greater Port Harcourt City is expected to bring social, economic, industrial and infrastructural development and population increase in the area. This will place a greater demand on the land use and groundwater abstraction. Since the location of the study is a new area marked for development, there is need to increase the geological/ geophysical database of the area that will help in site development; hence, the need for this study. Greater Port Harcourt City is yet to be fully investigated geologically and geophysically; as such this study will contribute to the knowledge of the local geology.

The news of incessant collapse of buildings and other civil engineering structures in Nigeria have continued to come unabated. This avoidable and horrendous situation calls for a synergy among all professions connected with the building industry. The said synergy can only be possible when these professionals imbibe the law of comparative advantage: where each profession stops at where it knows best. In this way one profession can provide data which can be useful for other professions to carry on their work. It is this candid belief that encourages this attempt to provide geologic/geophysical data on the Greater Port Harcourt City. The project area lies within latitudes 04° 30' to 05° 30'N and longitudes 06° 00' to 07° 10'E covering Igwuruta, Eneka, Etche, Elimgbu and Omagwa towns (Figure 1).

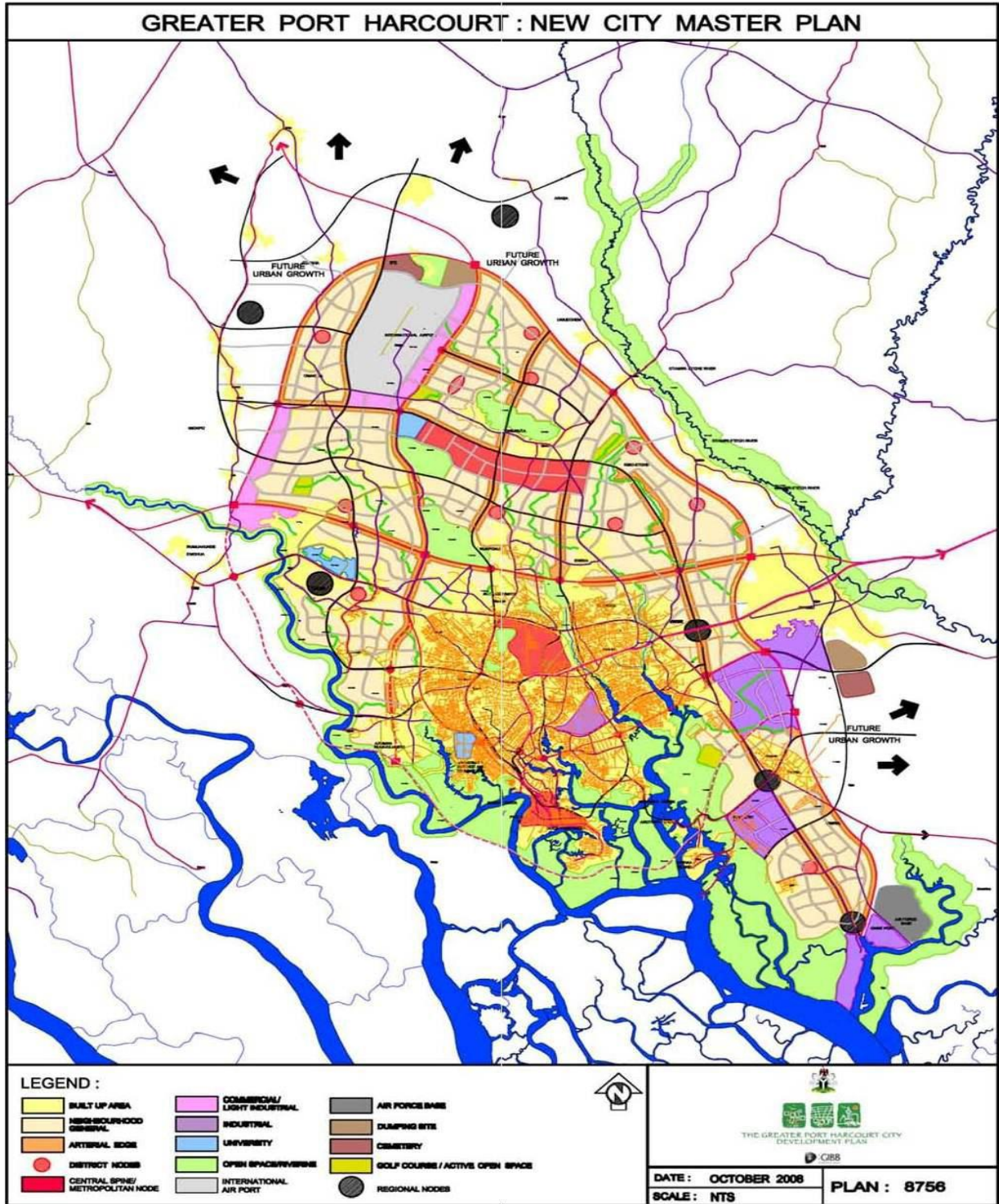


Figure 1: Location Map of the Study Area (Greater Port Harcourt City Development Authority).

The need to determine the thickness and velocity of the weathered layer, the shear and bulk moduli of the top soil and the enhancement of knowledge of the geology of the study area, using seismic refraction method, formed the basis of this research.

Seismic refraction method has been widely utilized by both geotechnical engineers and geologists involved in hydrogeological and site investigations. This stems from the fundamental simplicity of the method especially in the investigation of the depth and quality of rock layers for shallow engineering problems. In seismic refraction method, an elastic pulse or a more extended elastic vibration is generated at shallow depth, and the resulting motion of the ground at nearby points on the surface is detected by small geophones. Measurements of travel time of the pulse to geophones at various distances give the velocity of propagation of the pulse in the ground.

The ground is generally inhomogeneous in its elastic properties, and its velocity will therefore vary both vertically and laterally. To ensure that the relevant cross-over distances are well exceeded, refraction profiles typically need to be between 5 and 10 times as long as the proposed depth of investigation. The geophone spacing in a seismic refraction survey will depend on the depth of exploration and the subsurface details required. As a rule of thumb, the total spread length should be three to five times the maximum depth anticipated (Redpath, 1973). The interpretation method adopted here is the critical distance method. This method assumes that the subsurface layers are present with uniform velocity in each layer. It involves plotting the times of the first arrivals of the refracted waves against the distance from the shot point for each corresponding geophone.

The weathering layers often consist of two parts- a near surface low velocity (usually dehydrated) layer with velocities of about (152.4 - 914.4m/s), and a second intermediate velocity layer (usually water saturated) with a velocity greater than 914.4m/s but less than the velocity of the first consolidated layer (bedrock). Variations in thickness and velocity of layers are most pronounced near the surface because of the process of weathering which produces a layer of non-homogenous and unconsolidated materials at the Earth's surface. Seismic shooting within the low velocity layer results in low energy penetration

of the subsurface for a given source – energy level thus exciting a greater proportion of boundary waves (Parasnis, 1978).

A lot of seismic refraction and downhole / uphole survey works have been carried out in the Niger delta in the course of acquiring seismic reflection data for oil exploration. Independent research works have also been done by several people bothering on the use of seismic refraction survey to study the shallow part of the subsurface. Ananaba, et al. (1993) carried out a geophysical study of the gravel deposit in Ihiagwa, Owerri using both resistivity and seismic refraction surveys. They determined the velocity and depth of this unconsolidated formation and made conclusion on the effects of this layer economically.

Nwachukwu (2001) used uphole shooting technique to determine the weathering layer depth in some parts of Owerri, Southeastern Nigeria and discovered the weathering and sub weathered layers have a total average depth of 21.76m and average velocity of 547.3m/s respectively. A seismic refraction survey in the Calabar area showed seismic wave velocity of 700-800 m/s and 400-600 m/s respectively for the aquiferous and non aquiferous zones (Ugwu and Nwankwoala 2008). Ugwu (2010) used seismic refraction method to determine the depth to bedrock in Afikpo syncline of the Benue Trough Nigeria.

Other workers (Uko et al., 1992; Nwankwo et al., 2009) have utilized the refraction geophysical method in mapping the velocities and thicknesses of the low velocity layer in the area. Hence among the available geophysical methods the seismic refraction (forward and reverse shooting) method is particularly well suited for the investigation of the unconsolidated layer and quality of rocks for engineering problems (Hawkins 1969).

GEOMORPHOLOGY AND GEOLOGY OF THE STUDY AREA

There is a good network of both tarred and motorable earth roads within the project area. The geology and geomorphology of the Niger delta have been described in details by various authors (Allen, 1965; Doust and Omatsola, 1990; Short and Stauble, 1967; Evamy et al., 1978). The formation of the present day Niger Delta

METHODOLOGY

Data for the forward and reversed shootings were acquired from the field using a 12 channel signal enhancement seismograph (Terraloc) that has combined features of speed, accuracy, and light weight, with visible CRT display and electro-sensitive plotter. This instrument automatically stores data for subsequent hard copy printouts. The data acquisition electronics allows selection of sample rates from 1/8 milliseconds to 4 milliseconds and also incorporates both high cut and low cut filters to provide cleaner signals and extended range. Other accessories include: 12 strings of 10Hz SM4 geophones, 16kg sledge hammer as the energy source, a 24-volt rechargeable battery, Personal computer and diskettes, strike plate and GPS. Each seismic refraction survey was conducted along a single straight line traverse.

The seismic spread cables, which have been fabricated with pre-measured shot point and geophone locations, were positioned along the single line of investigation. The geophones fitted with a spiked base to provide coupled ground contact were positioned at a regular interval of 5m along the line which makes the seismic spread to be 60m. The length of this spread determines the depth of penetration. The seismic spread was connected to the seismograph which records the signal arrivals from the energy source along the seismic spread, acquiring separate data for each geophone position.

Forward and Reversed shootings were adopted and this was done by placing the energy source (strike plate beside a trigger geophone) at 5m away from both ends of the geophone. A series of 3 shots from the energy source was used to generate a compressional seismic wave energy that propagates into the earth. At a certain incident angle (critical angle) the wave was refracted and traveled along the top of the second layer producing headwaves that were picked by the geophones. The detected signals were recorded on the multi-channel seismograph and later downloaded to a computer with a floppy disk for further analysis. This procedure was carried out in all the locations of the study area for both the forward and reversed shootings.

Data Processing and Interpretation

The first breaks of the seismic traces (Figure 3) were picked with the aid of a computer software program (Reflex 2D Quick) and the time-distance graph plotted. Similarly, the data collected using the ABEM Terraloc seismograph within a distance of 60m was further processed using the SURFER 8 software. A total of twelve (12) data points comprising six (6) forward shooting and six (6) reversed shooting survey points were used for this work. The geophones interval and arrival times for Etche Location are as shown in Table 2.

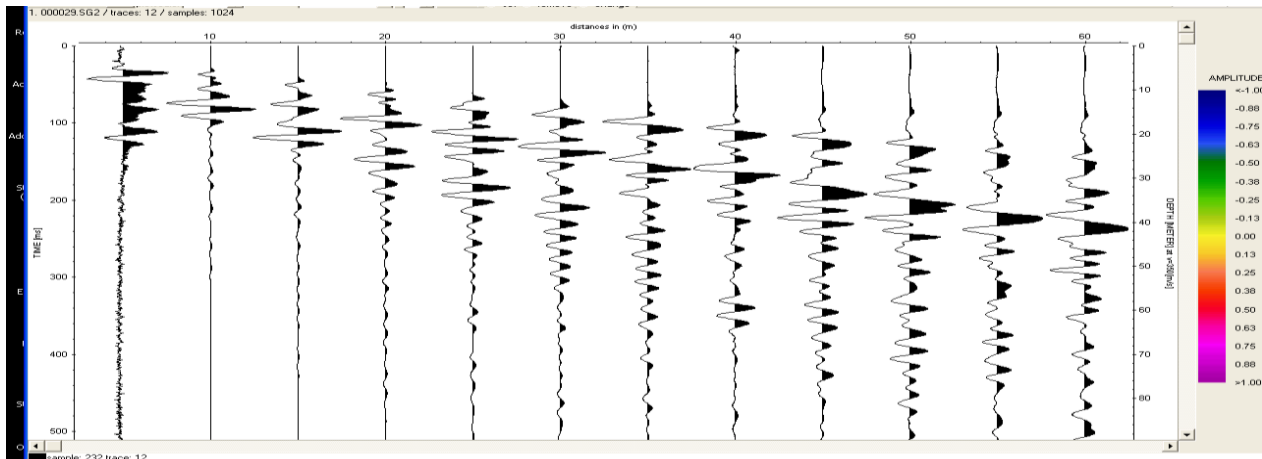
The wiggle traces and time – distance graph for the different first break plots are shown in Figures 3 and 4. The unconsolidated layer and its calculated values were derived using the critical distance method. This implies the use of the time-distance plot whereby the inverse slope of a line connecting points represents the same layer. Velocities for the overburden and refractor layers are calculated as distance travelled divided by time elapsed for each portion of the time-distance plot using crossover distance and intercept time.

Because both the intercept time and the crossover distance are directly dependent upon the velocities of the two materials and the thickness of the top layer, they can be used to determine the depth to the top of the second layer. The depth of the weathered layer can be calculated using the critical distance method, and is given as:

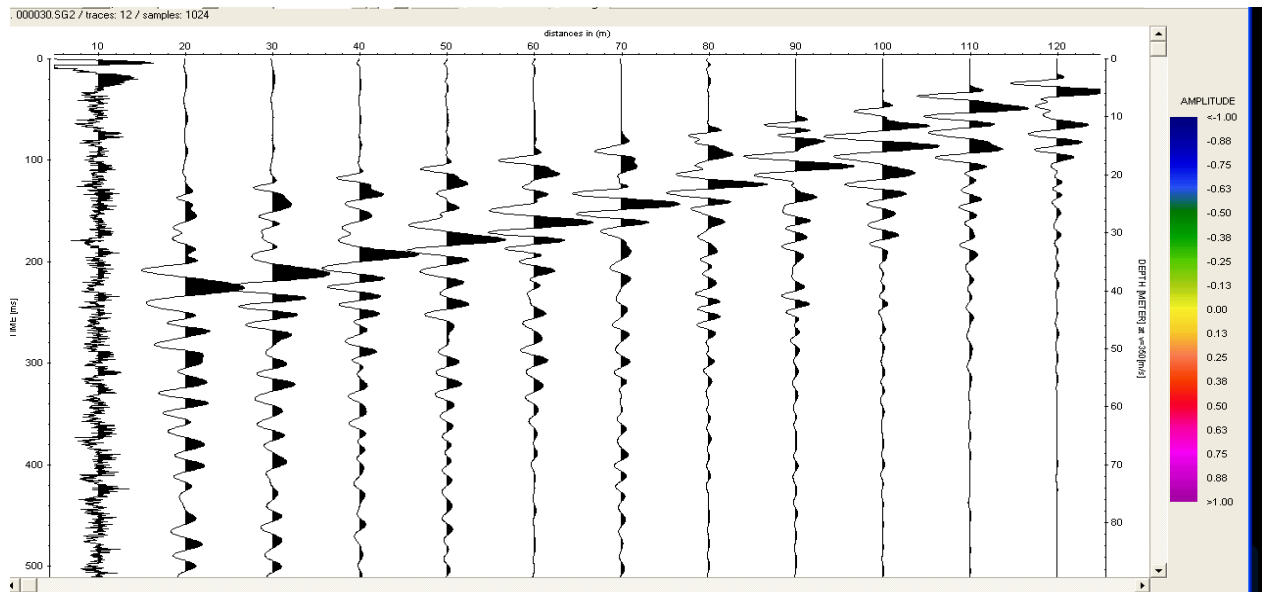
$$Z_1 = \frac{x_c}{2} \sqrt{\frac{v_2 - v_1}{v_2 + v_1}} \quad (1)$$

where Z_1 = Thickness of the weathered layer;
 X_c = Cross-over distance
 V_1 = Velocity of the weathered layer
 V_2 = Velocity of the sub-weathered layer

The elastic constants of the unconsolidated layer quantitatively describe the physical characteristics of the layer. The bulk modulus describes the compressibility of the layer and the shear modulus describes how difficult it is for a layer to be deformed. The bulk modulus and the shear modulus can be calculated from the Equations 2 and 3, respectively.



A



B

Figure 3: (A) Forward Wiggle Trace and (B) Reversed Wiggle Trace at Etche.

Table 2: Geophone Interval and Arrival Times for Etche Location (4°58'02.26"N and 7°01'51.56"E).

Distance (m)	Time (milliseconds)	
	Forward	Reverse
5	26.2	Ns
10	32.3	132.9
15	46.3	121.8
20	58.5	108
25	69	95.2
30	80.3	83.7
35	90	78
40	98.7	63.4
45	111	57.3
50	118.8	46.3
55	129.3	27.2
60	139.8	16.3

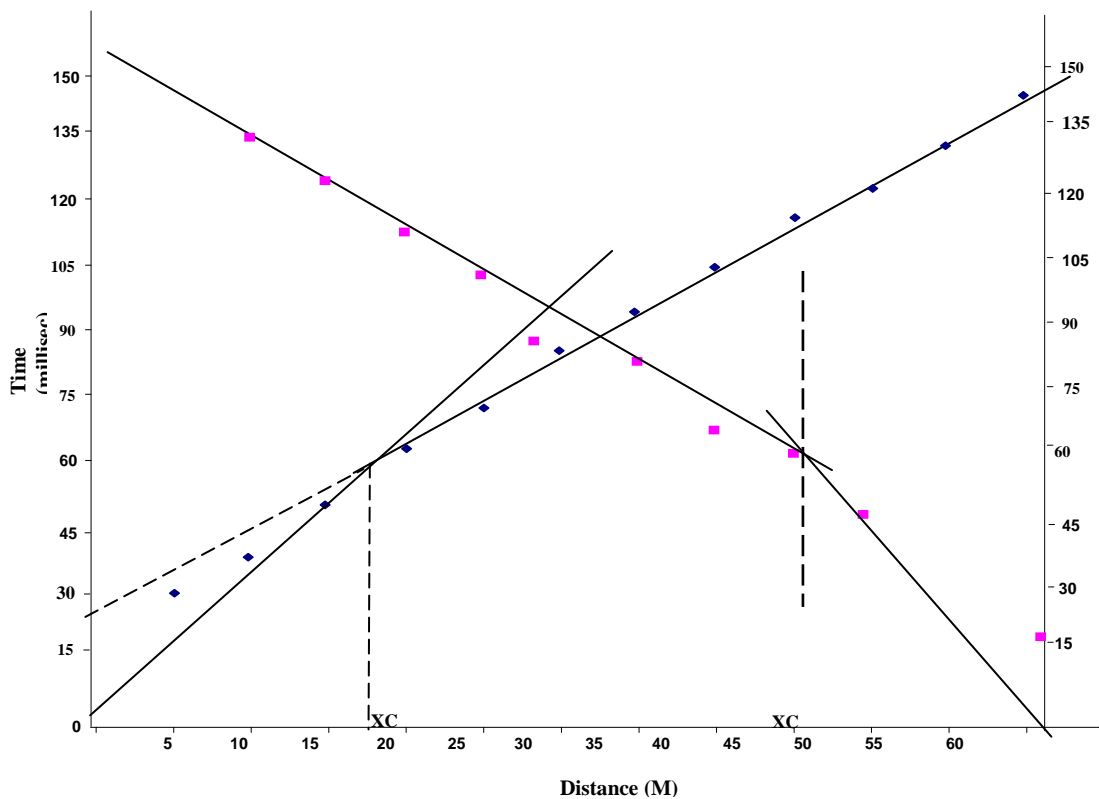


Figure 4: Time-Distance Plot for Etche Location.

$$V_p = \frac{\sqrt{\frac{4}{3}\mu + K}}{\rho} \quad (2)$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (3)$$

where, V_p = Compressional velocity
 V_s = Shear velocity, μ = Bulk modulus
 K = Shear modulus, ρ = density

The velocities of the layers are given by:

$$\text{Velocity} = \frac{\Delta d}{\Delta t} \quad (4)$$

where Δd = change in distance and Δt = change in time:

$$\text{But, slope} = \frac{\Delta t}{\Delta d}$$

$$\therefore \text{Velocity} = \frac{1}{\text{slope}} \quad (5)$$

Taken V_1 = velocity of the first layer and V_2 = velocity of the second layer.

The thickness, $Z(m)$, of the top layer is calculated using Equation 1.

The angle of dip can be calculated using Equation 6.

$$\theta = \frac{1}{2} \left(\sin^{-1} \frac{V_1}{V_U} - \sin^{-1} \frac{V_1}{V_D} \right) \quad (6)$$

where θ = angle of dip

Since the velocities at the various locations are between 200-600 m/s, the layers are all unsaturated sand. In unsaturated sand the ratio of V_p to V_s always gives a constant value.

$$\frac{V_p}{V_s} = 1.5 \quad (7)$$

(Murphy et al., 1991)

According to Gardners et al. (1974), the compressional velocity can be used to estimate the density of the unconsolidated layer using Equation 8:

$$\rho = 0.31(V_p)^{3/4} \quad (8)$$

Using Equation (3), the density of the unconsolidated layers is calculated (Table 3).

Table 3: Densities of Topsoil in all the Survey Locations.

Location	Density (g/cm ³)	
	ρ_1	ρ_2
Elimgbu	1.35	1.5
Eneka	1.22	1.34
Etche	1.32	1.46
Igwuruta	1.28	1.48
Omagwa I	1.19	1.4
Omagwa II	1.32	1.53

ANALYSIS OF RESULTS

The summary of results of the seismic refraction surveys in the six (6) locations that made up the Greater Port Harcourt City are as presented on Table 4.

The thickness of the weathered layer for both forward and reversed, are presented as contour maps (Figures 5 and 6) while the 3-D surface plot of the topography of the area is shown in Figure 7. The weathering and sub-weathering velocity profile for the forward shooting of the study area reveal that the velocities increase in the NE direction as one moves from Eneka towards Etche and SE direction from Eneka towards Elimgbu. The weathering velocity for the forward shooting ranges from 220 to 364.9 m/s and the sub-weathering velocity varies from 348 to 600 m/s. The weathering velocity V_1 and the sub-weathering V_2 for the reversed shooting of the area also indicate an increase in the NW direction as one move towards Omagwa from Eneka and SE direction towards Elimgbu. The weathering velocity varies from 235 – 355m/s while the sub-weathering velocity ranges from 380 – 587.5 m/s.

The weathering thickness t_1 of the unconsolidated layer for the forward shooting in the study area reveals a decrease in the WE direction as one

moves from Omagwa I towards Etche region (Figures 5 and 6). The weathering thickness varies from 5.46 -3.92m. The weathered layer thickness is lower in the areas comprising of Igwuruta, Etche Omagwa I and Omagwa II. There is also a decrease in weathering thickness as one moves from Omagwa II towards Igwuruta region. The thickness on this axis ranges from 3.5 – 1.04m.

The bulk modulus for the weathered layer reveals an increase in the SE direction going from Omagwa I towards Elimgbu, with a range 2.04 to 79.89kN/m² in the top layer. That of the sub-weathered layer increases in the NW direction from Eneka towards Omagwa II and in SE direction from Eneka towards Elimgbu. The shear modulus of the weathered layer shows an increase in the SE direction from Omagwa I towards Elimgbu. The shear modulus varies from 23 – 74kN/m². The shear modulus for the sub-weathered layer increases in the SE direction as one moves from Eneka towards Elimgbu and in the NE direction from Eneka towards Omagwa II . The shear modulus varies from 23 – 220kN/m².

The 3D surface plot (Figure 7) of the study area shows that Elimgbu and Omagwa II are on a higher elevation. Etche is slightly horizontal while Omagwa I is on a low lying area (Figure 7).

Table 4: Summary of the Results.

Location	Forward		Reverse		Forward	Reverse	Angle of dip (θ)	Top Layer	Bottom Layer	Top layer	Bottom Layer
	velocity V_1 (m/s)	velocity V_2 (m/s)	velocity V_1 (m/s)	velocity V_2 (m/s)	Thickness (m)	Thickness (m)		Bulk modulus (kN/m ²)	Bulk modulus (kN/m ²)	Shear modulus (kN/m ²)	Shear modulus (kN/ m ²)
Elimgbu	364.9	600	318.6	506	4.9	2.38	1°	79.89	240	73.23	220
Eneka	242.8	348	235.7	380	6.2	9.56	1°	31.56	72.12	29.30	66.11
Etche	252.2	488.9	352.38	555.5	3.92	3.5	1°	2.04	155.06	56.87	142.21
Igwuruta	292.9	522.2	333.3	506.3	5.46	2.26	0.5°	8.80	79.37	44.73	164.4
Omagwa 1	220	420	316	587.5	5.31	6.57	0.48°	5.59	109.76	23.46	100.6
Omagwa 2	333.3	592.5	354.8	547.6	5.15	2.31	0.09°	65.17	238.71	59.74	218.78

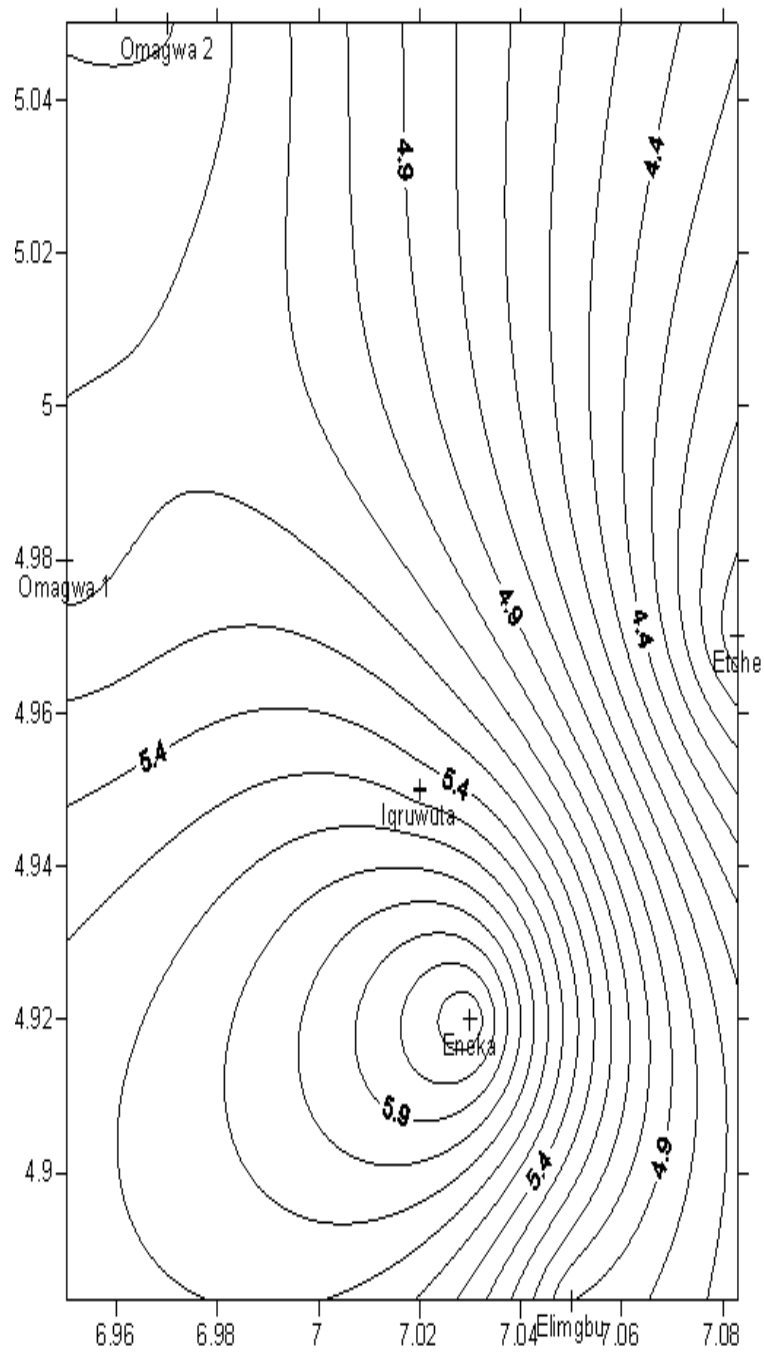


Figure 5: Weathering Thickness (t_1) for Forward Shooting in the Study Area in Meters.

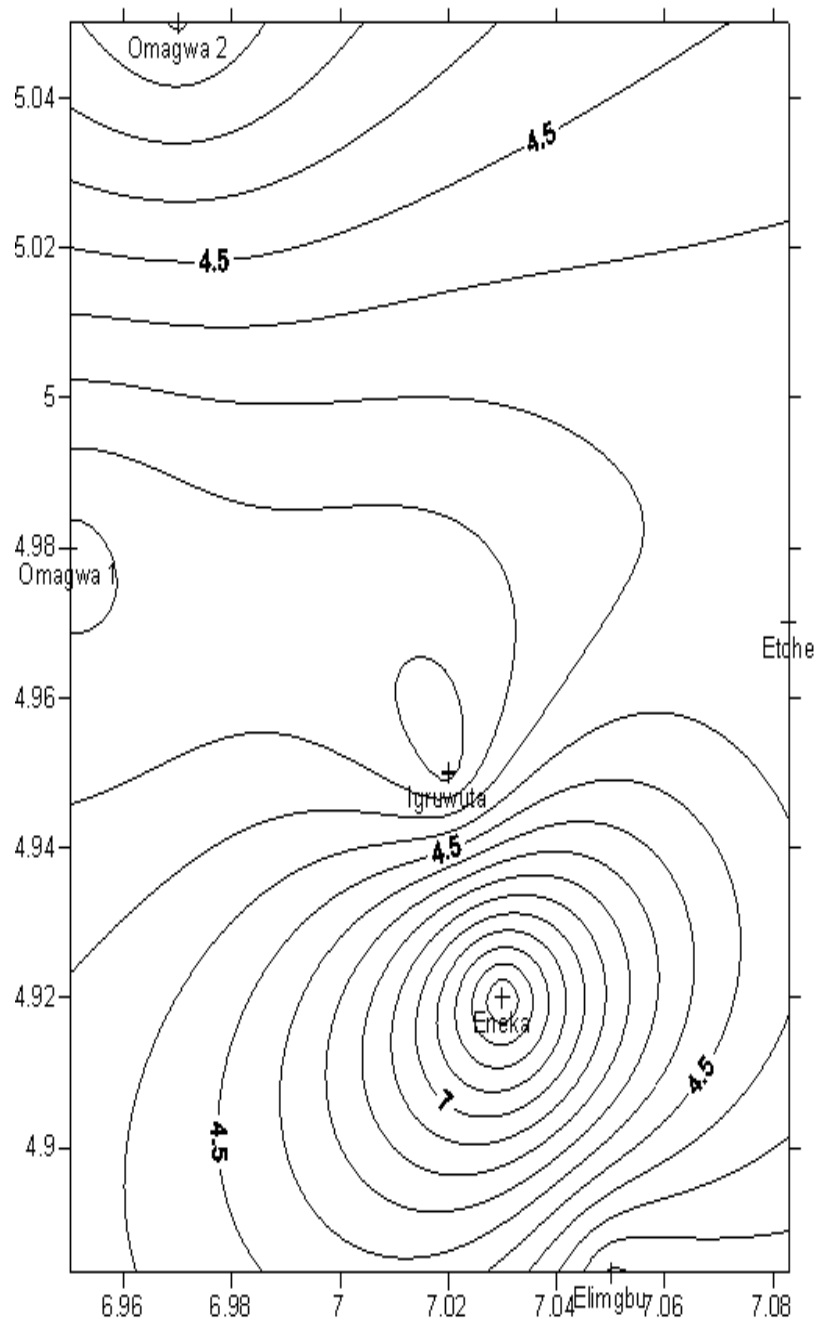


Figure 6: Weathering Thickness (t_1) for Reverse Shooting in the Study Area in Meters.

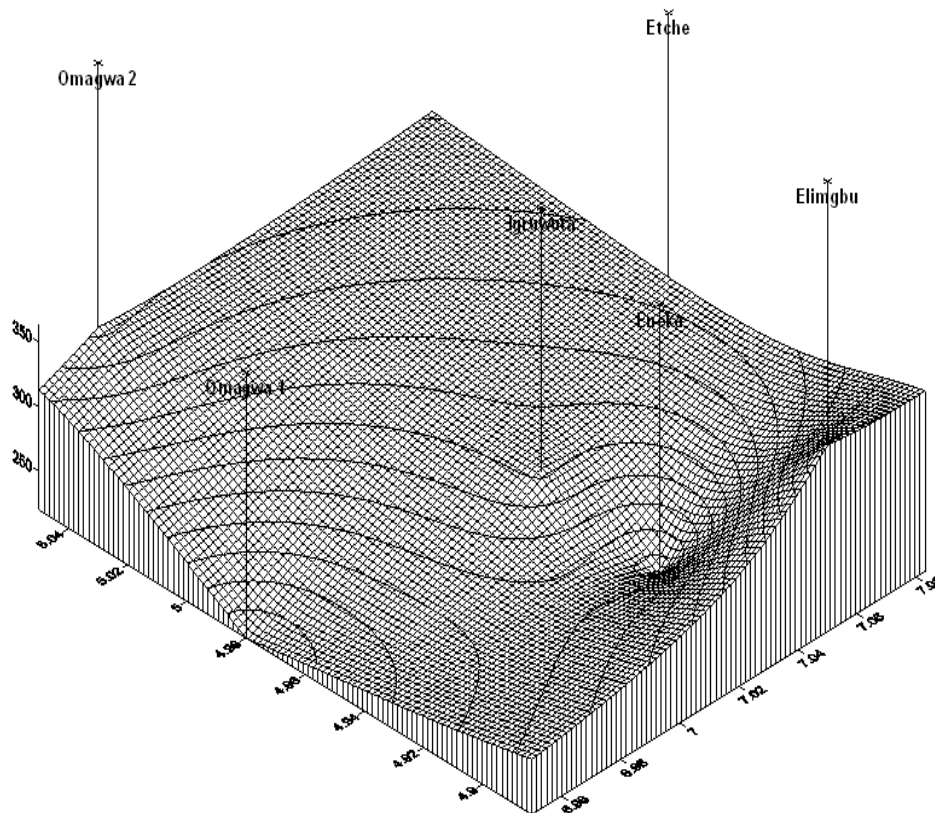


Figure 7: 3-D Surface Plot of the Topography in the Study Area.

DISCUSSION OF RESULTS

Results from the forward and reversed shooting in the project area reveal that the place is dominated by two (2) layer velocity model. Weathering thickness ranges from 1m to 9m while weathering velocities range from 220m/s to 600m/s. There seems to be a substantial variation in the thicknesses of the first layer with elevation. This proves that elevation has a strong effect on seismic velocities and subsequently on the thicknesses of subsurface layers. However, there are no consistent and significant variations in seismic velocities with lithology. This could be because velocity is a function of the degree of compaction rather than lithologic changes.

The weathering velocity contour maps (Figures 5 and 6) indicate that velocity variation in Elimbu ranges from 350m/s to 360m/s while at Omagwa I location, the seismic velocity varies from 220m/s – 240m/s. Since seismic velocity increases with

increase in compaction, this suggests that the topsoil at Elimbu location is more compacted compared to that at Omagwa I. Also, this result suggests that the acoustic impedance of that area is high since acoustic impedance is a function of velocity and density. The velocity at Omagwa II and Elimbu locations varies from 580m/s – 590m/s while at Eneka, the velocity ranges from 350m/s – 410m/s. As seismic velocity decreases with increase in porosity, it suggests that the porosity of the topsoil at Eneka location is high compared to the topsoil at Elimbu and Omagwa II locations.

The bulk modulus of the first layer at Omagwa I and Eneka locations ranges to a very low value of 25 to 32kN/m². This low value suggests that the compressibility of the first layer is high (can be easily compressed) and there is need to strengthen this layer before commencing any huge civil engineering project to avoid failure. The study results show that the bulk modulus for

the second layer at Omagwa II and Elimgbu has the highest incompressibility when compared to other locations; with values ranging from 238 – 240kN/m².

The result obtained from the shear modulus of the first layer indicates that the shear strength of the topsoil increases from Omagwa I to Eneka location, while the shear strength of the second layer decreases from Omagwa I to Eneka. In addition, the shear moduli of the first and second layers indicate a linear increase of the shear strength with depth and bulk modulus. This suggests that porosity and compaction influence the bulk and shear modulus of the first and second layers.

It is easily observed from figure 7 that Omagwa II and Elimgbu are on a higher elevation which is believed to be responsible for the relatively higher weathering layer velocity in those locations. There is also a gradual dip in the first layer from Elimgbu to Omagwa through the Igwuruta area. The topography of Etche region is slightly dipping. The high porosity of the unconsolidated layer results in low seismic velocity and explains why seismic wave velocities are markedly attenuated in some areas. In many areas weathering depth represents the groundwater table (Telford, 1976).

CONCLUSION

This work has successfully applied the forward and reversed shooting technique of seismic refraction survey method in providing subsurface information over large areas at reasonable cost thereby narrowing down the number of required drill sites. The top of the unconsolidated layer was delineated while the contour maps of the seismic models were created to show the area of high and low acoustic impedance. The 3D surface plot of the study area revealed the topography of the location. It can be inferred from the study that the shear strength and the incompressibility of the unconsolidated layer in parts of the study area is very low, hence, the need to strengthen the soil in the area before embarking on construction of engineering structures.

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SUGGESTED CITATION

Ugwu, S.A. and C.N. Nwankwo. 2013. "Determination of Elastic Constants and Seismic Velocity of Unconsolidated Layers around the Greater Port Harcourt City, Rivers State, Nigeria". *Pacific Journal of Science and Technology*. 14(2):551-564.

