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CHARACTERIZATION OF NEAR SURFACE SOIL OF AN ENGINEERING SITE USING SEISMIC REFRACTION METHOD: A NIGER DELTA CASE STUDY.

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Abstract
Seismic refraction survey was utilized to describe soil structure on a construction site in Warri area due to its implications for engineering structures in a water saturated soil. The survey occupied two traverses, each covered a length of 96m. The layout consists of 24 geophones arranged at 4-meter intervals to provide good lateral resolution. The profiles revealed a 3-layered structure with compressional wave velocities (P-wave) and elastic constants that increased with depth. P-wave increased from 329.96m/s in the first layer to 874.3m/s in the third layer. Young's modulus increased from 122MPa in the first layer to 857.32MPa in the third layer. Likewise, shear modulus recorded an increment of 45.23MPa in the first layer to 317.53MPa in the third layer. Bulk modulus increased from 150.75MPa in the first layer to 1058.42MPa in the third layer. Poisson's ratio and density maintained 0.35 and 1800kg/m^3 respectively in the three layers because near surface soil of the area is composed of lateritic soil with high percentage of sand. The implication is that foundations for superstructures should get to the second or third layer at depth ≥ 15m beneath the surface where earth materials are stiffer for structural stability.

Keywords: Elastic constant; Near surface; Seismic; Stiffness.

Introduction

Soil properties play crucial roles in building foundations, road construction, underground storage tanks, and other engineering works that involve soil; its study cannot be overemphasized. There are serious consequences if there is no prior knowledge of the local soil properties and when such information are ignored before construction works are carried out due to the complexities of the subsurface and varied topography in some areas (Akinrinmade & Uko, 2014). This study stresses the importance and necessity of accurate soil characterization to lessen the risks of road failures, tilting of gigantic structures, foundation cracking, and structural defects prevalent in the region due to the structure of its soils. It can also be utilized as a proxy to describe the behavior of undersurface media in engineering and mining sites qualitatively (Eze at al., 2026). Seismic refraction, which is the use of acoustic wave to probe the subsurface offers a non-invasive, effective and efficient geophysical method to investigate the subsurface without disturbing the natural positions of soil particles as is the case for drilling or excavation of soils from their natural position; which can be expensive, time consuming and sparse samples are often taken in vast areas. These will result in missing vital hidden features of the subsurface and will lead to serious errors in interpretation (Ighere, 2024). The work done by Ighere (2024) near the area also revealed that the first two subsurface layers have low shear strength of 33.61 MPa and 72.99 MPa respectively, indicating poor bearing capacity, while the third layer had 244.4 MPa which is highly compressible and suitable for construction. Seismic refraction method is non-destructive to the user and the environment, gives wide coverage and it is relatively affordable. From the analysis of these elastic waves as they travel through different layers of soil and rock types, their velocities and arrival times can be known. The arrival times and velocities of these waves have direct link to the distance of earth materials beneath surface, how rigid, dense, and elastic the subsurface materials are, which will eventually reveal how they will respond when stress is applied upon them (Aka et al., 2018). Proper knowledge of soil properties helps engineers and environmental Scientists make informed decisions regarding land use and development (Nwankwo, 2018).

Niger delta is a sedimentary terrain environment, the area consists of fresh water swamp, coastal plain sands, mangrove swamps, and Sombreiro-Warri plains (Omo – Irabor and Oduyemi, 2006). The water table in the study area is close to the surface, approximately 4 to 5 m beneath the surface (Uchegbulam et al., 2022). These makes the top soil to be loose and wet almost throughout the year. The top soil also tends to be slippery under a load where there is intercalation of clay hence; a detailed knowledge of the near surface soil, about 1-30m depth is necessary for effective construction and other engineering works.

The Study Area

The study area is along Refinery Road in Warri area of Delta State, Southern Nigeria. Warri lies between latitudes 5°30′N and 5°35′N and longitudes 5°45′E and 5°50′E. The city has elevation of about 20 meters above sea level. The area is bounded by Uvwie and Udu Local Government Areas and can be accessed through the Warri–

Effurun Expressway and other adjoining road in the area. Geologically, Niger Delta region has three stratigraphic units, from top to bottom; Benin, Agbada and Akata formations. The area is a sedimentary terrain which lies on top of different types of quaternary deposits made up of topsoil, red laterite, clay, fine sand, medium sand and coarse sand in the form of pebbles. The map of the study area is shown in Figure 1.

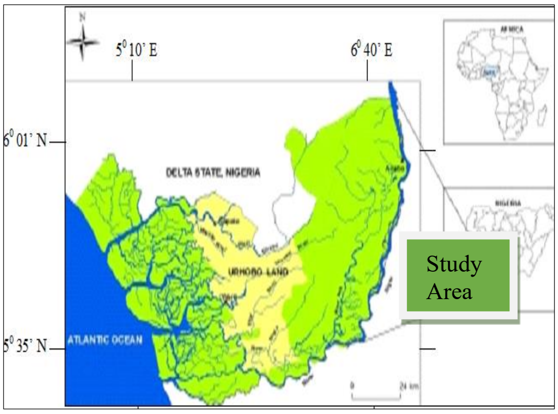

Figure 1: Map of Delta State, Nigeria showing the study Area

(After Odemerho and Ejemeyovwi, 2007)

Theoretical Framework

Refraction survey utilizes the fact that body waves (Primary-P and Secondary-S waves) travel with different velocities in different rocks. P-waves, or compressional waves, are longitudinal, while S-waves propagate with particle motion perpendicular to the direction of wave propagation. Seismic refraction is concerned with first arrivals, the P-wave being faster than the S-waves is used. Moreover, the S-wave cannot propagate through liquids as it terminates on the encounter of a liquid or gaseous medium. Velocities of seismic waves depends on elastic moduli and densities of media.

When seismic energy strikes a boundary between two velocities at a critical angle, a head wave is set up which travels along the interface at the higher of the two velocities. The energy from the head wave is propagated to the surface as a seismic refraction (Lowrie, 2007).

The velocity of P-wave, V_p is given by

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \qquad (1)$$

Where,

k = bulk modulus

μ =shear modulus

ρ = density

Depth to a refractor (bedrock) is given by

$$Z = \frac{x_c}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}} \qquad (2)$$

or

$$Z = \frac{t_0 v_2 v_1}{2\sqrt{(v_2 - v_1)}} \qquad (3)$$

where

Z = depth to a refraction

xc = critical distance

t0 = intercept time

v1 = velocity of first layer

v2 = velocity of second layer

Materials and Method

The refraction survey was designed to describe near-surface soil properties along two traverses, each 96 meters in length. The layout consists of 24 geophones arranged at 4-meter intervals to provide good lateral resolution.

Data Acquisition

Seismic refraction data were acquired using a 24-channel PASI GEA seismograph with 24 geophones spaced at 4 meters, yielding a total spread of 96 meters.

Shots were taken at three different source locations (near-end 0m, mid-point 48m, and far-end 96 m) along each traverse to obtain multiple ray paths through the subsurface layers.

Data Processing

Acquired data were exported from the seismograph to GEOSTRU software for processing and interpretation. The first step involved identifying and picking the first arrival times of seismic waves from each seismic trace. The travel times were then plotted against the corresponding source-to-receiver distances to produce time–distance graphs (T–X plots).

From the slopes of the linear segments on the T–X plots, the seismic velocities of the subsurface layers were determined. The intercept-time method was used to calculate the depths to refracting layers beneath each traverse. The velocities and depths obtained were used to interpret the subsurface structures based on the revealed geology.

Results

The results are presented as tables, graphs, and figures. The Generalized Reciprocal Method (GRM) was employed in analyzing seismic sections. Tables 1 and 2 are shot 1 travel time and interpretation with GRM, respectively. Figures 2 and 3 show the travel-time curves for the 3 layers and the subsurface velocity map, respectively, for traverse 1.

Table 1: Traverse 1 shot 1 travel times.

Geophone position [m]	Time [ms]
0.0	5.7208
4.0	18.5926
8.0	30.0342
12.0	40.0456
16.0	50.0570
20.0	61.4986
24.0	71.5100
28.0	81.5214
32.0	91.5328
36.0	102.9744
40.0	112.9858
44.0	124.4274
48.0	135.8690
52.0	148.7408
56.0	153.0313
60.0	157.3219
64.0	161.6125
68.0	167.3333
72.0	171.6239
76.0	175.9145
80.0	180.2051
84.0	185.9259
88.0	185.9259
92.0	190.2165

Table 2: Interpretation with the method G.R.M. (Transverse 1)

	Layer n. 1	Layer n. 2	Layer n. 3
G= 22.0 [m]	14.9	44.3	--
G= 26.0 [m]	16.2	46.2	--
G= 30.0 [m]	17.6	48.8	--
G= 34.0 [m]	18.5	48.1	--
G= 38.0 [m]	19.5	47.4	--
G= 42.0 [m]	20.4	42.1	--
G= 46.0 [m]	20.7	39.0	--
G= 50.0 [m]	20.4	36.0	--
G= 54.0 [m]	18.6	30.8	--
G= 58.0 [m]	16.6	25.4	--
G= 62.0 [m]	14.3	21.0	--
G= 66.0 [m]	12.7	17.9	--
G= 70.0 [m]	11.9	15.6	--
Velocity [m/sec]	357.5	1271.9	868.2
Description			

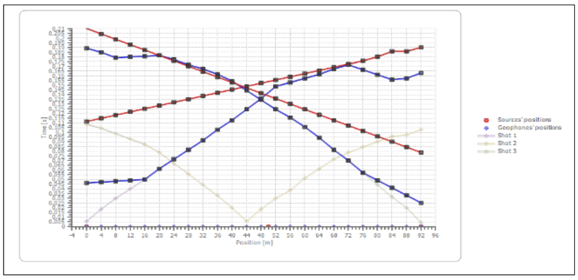

Figure 2: Traverse 1 travel time curves of the 3 shots for the 3 layers

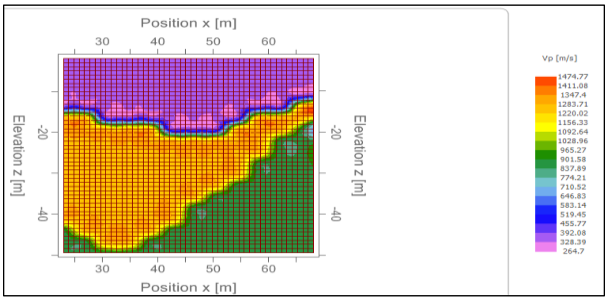

Figure 3: Velocity map of the subsurface (Traverse 1)

Profile 2 Results

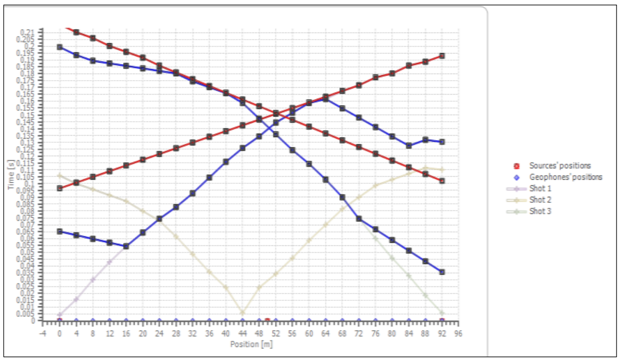

Figure 4: Traverse 2 travel time curves for the 3 shots.

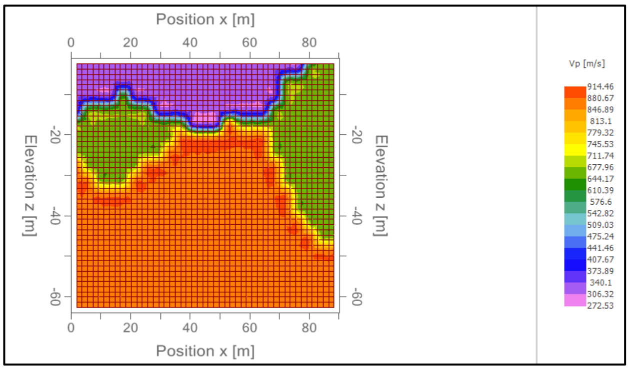

Figure 5: Velocity map of the subsurface (Traverse 2)

Figures 4 and 5 are travel time curves and velocity map of the three layers respectively.

The Summary of the results showing velocities of layers in traverses1 and 2, elastic constants of layers in traverses 1 and elastic constants of layers in Traverses 2 are shown in Tables 3, 4 and 5 respectively. The lithostratigraphy of borehole from the area used an aid in the interpretation is shown in Figure 6.

Table 3: Summary of results showing velocities of layers in Traverses1 and 2

Traverse 1:		
Layer	**V_P(m/s)**	**V_s(m/s)**
1	357.5	171.75
2	1271.9	611.01
3	868.2	471.05
Traverse 2		
Layer	**V_P(m/s)**	**V_s(m/s)**
1	330.0	158.5
2	663.4	318.7
3	874.3	420.0

Table 4: Summary of Elastic Constants of layers in Traverses 1.

	Layer 1	Layer 2	Layer 3
Traverse 1			
Poisson's ratio	0.35	0.35	0.35
Density [kg/m³]	1800.00	1800.00	1800.00
Vp [m/s]	357.52	1271.91	868.17
Vs [m/s]	171.75	611.01	417.05
G0 [MPa]	53.09	671.99	313.08
Ed [Mpa]	230.08	2911.98	1356.69
M0 [MPa]	176.98	2239.98	1043.60
Ey [Mpa]	143.36	1814.39	845.32

Table 5: Summary of Elastic Constants of layers in Traverses 2.

	Layer 1	Layer 2	Layer 3
Traverse 2			
Poisson's ratio	0.35	0.35	0.35
Density [kg/m³]	1800.00	1800.00	1800.00
Vp [m/s]	329.96	663.37	874.31
Vs [m/s]	158.51	318.67	420.00
G0 [MPa]	45.23	182.79	317.53
Ed [Mpa]	195.98	792.11	1375.95
M0 [MPa]	150.75	609.31	1058.42
Ey [Mpa]	122.11	493.54	857.32

G0: Shear modulus;
Ed: Oedometric modulus;
M0: Bulk modulus;
Ey: Young's modulus;

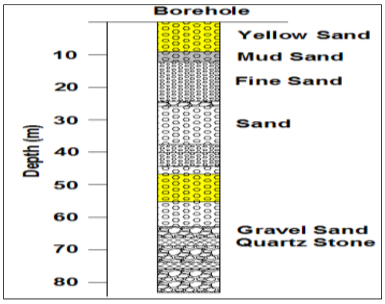

Figure 6: Litho-stratigraphy of Warri.

Interpretation of seismic sections

The two profiles reveal a three-layered subsurface structure, with compressional seismic wave velocity Vp and elastic constants increasing with depth (Tables 3 and 4). The increase in compressional wave velocities and elastic constants of earth materials with depth indicates greater consolidation beneath the surface. These can be explained by the fact that compressional waves travel faster in compact soil than in loose soil. It equally suggests progressive improvement in soil stiffness and bearing capacity. The progressive increase in the velocity of the body waves with depth confirms greater compactness of the soil materials at the near-surface of the investigation.

Interpretation of elastic constants derived from seismic section

Poisson's ratio and density of earth materials maintain constant values of 0.35 and 1800 kg/m3, respectively, in the three layers. These can be attributed to the predominantly soil structure in the area, which is basically fine-grained to coarse sands at the near surface. Poisson's ratio ranges from 0.05 to 0.02 for most non-indurated elastic sedimentary rocks, depending on porosity and weathering. It further confirms the litho-stratigraphy data of the area (Figure 6). The knowledge of Poisson's ratio prior to the construction of structures that rest on ground is vital, because it gives the strain rate of materials when stress is applied. Young's modulus and shear modulus increase with depth; this is a result of more compaction as depth increases since the materials become stiffer with an increase in depth. Topsoil tends to be loose as a result of exposure to weather changes near the surface, while materials buried deep in the subsurface are more compact. The implication is that for the foundation of gigantic structures to be firm and stable, they must get to the depth where there is compaction of sand materials, which is in the range of 15 – 20m beneath the surface. The oedometric modulus increases with depth, as expected, because it tends to increase with stress. The overburden adds stress to the materials beneath the surface, so the value generally increases with depth. The bulk modulus of elasticity also increases with depth because of the stiffer material beneath the surface.

Conclusion

The seismic refraction results shows that compressional wave velocity increases with depth due to the increase in the stiffness of earth materials as depth increases. Elastic constants like Poisson's ratio and density maintained constant value in the three layers, while Young's and bulk moduli increased with depth. Oedometric modulus also increased with depth. The revealed seismic velocities and elastic constants values near the surface are in agreement with the litho-stratigraphy of the area. The soil of the area is saturated with water and so proper geophysical description of soil is necessary before any construction work can be carried out.

Recommendation

It is recommended that foundation for gigantic structures get to second or third layers beneath the surface where there are stiffer earth materials for stability. Since seismic refraction is vulnerable to environmental noise and challenging site conditions, and its interpretations become ambiguous in complex geological formations hence the need to complement it with geotechnical investigation for a holistic site characterization in such complex geological features.

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