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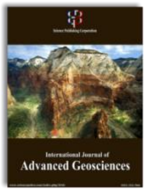

Characterization of the geological and geotechnical properties of soil using the surface wave approach

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Abstract

As part of the efforts to examine the elastic and engineering properties of the subsurface sequence at a proposed new power plant site in Edo State, a geophysical survey involving Multichannel Analysis of Surface Waves (MASW) was carried out. The MASW was adopted to determine the vertical and lateral variations in velocity beneath each seismic line. The MASW was carried out on two seismic lines each trending NE-SW. A geophone interval of 3 m was used, and the length of the seismic lines ranged from 60 – 90 m. The ES-3000 seismograph was used for the surface wave data acquisition and the Shear-Wave velocity structures of the area were obtained through the inversion of the acquired surface wave data. The one dimensional (1D) S-Wave velocity profiles along the lines were diagnostic of generally low velocity lithologies that suggest sand, clayey sand and sandy clay formations with relatively varying thicknesses. The subsurface layers delineated had shear-wave velocity values in the range of 63-400 m/s. They were classified using the NEHRP Seismic Site Classification, and all of them were in the range of stiff soil to soft clay soil. The bulk moduli (k) for these soils were in the range of 3.22-3.98 GPa. This depicts relatively low strength of the subsurface materials. The shear moduli (μ) values range from 7.15-7.43 MPa, which is indicative of low to moderate strength. The information provided in this study will aid the structural engineer or architect in foundation design of the proposed power plant. From the results of this study, it is concluded that although the subsurface layers are of relatively low strength, with the right intervention of the civil engineer, a suitable foundation can be designed for the gas plant.

Keywords:*Coastal Plain Sands;MASW;Soil Stability;Velocity Variations.*

1. Introduction

Civil Engineering structures are founded on or within the earth. One of the priority considerations in the design of the foundation of such structures, therefore, is the pre-construction investigation of the proposed site in order to ascertain the competence of the host earth material. The pre-construction investigation may involve direct mechanical boring, pitting, and trenching for subsurface sequence delineation, groundwater table mapping, soil sampling and geotechnical laboratory analysis. It may also involve non-invasive geophysical investigations.
The pre-construction investigation provides information on the subsurface lithologies and their thicknesses identifies the competent bedrock and determines depths to its upper interface, available geological structures, bedrock relief or configuration and the degree of competence of the foundation bedrock (Aina *et al*., 1996; Adewumi and Olorunfemi, 2005; and Idornigie *et al*., 2006) which is the purpose of this investigation.
In geotechnique, subsoil competence is evaluated through series of tests, which include compaction, triaxial, and consolidation tests. In geophysical prospecting, the Compressional (P) and Shear (S) wave velocities in earth materials can be used to evaluate subsoil competence through the determination of the bulk modulus (Sjqgren *et al*., 1979 and Dutta, 1984) as well as its shear modulus. A compact subsoil is characterized by reduced porosity and moisture content with the consequent increase in Shear wave and Compressional wave velocities.

Recent work has shown that surface wave observables possess sensitivity to density as well as shear wave velocity (Lin *et al*., 2012). Furthermore, other various wave types have found usage in geotechnical and geophysical mapping; for example direct waves map out the smooth velocity variations in cross well seismic tomography; wide angle refracted waves play a crucial role in full waveform inversion (Hole *et al*., 2005), and surface waves provide unmatched sensitivity to near-surface shear wave velocity structure. Surveys based on surface waves provide a low-cost, non-invasive means of probing the shallow subsurface using either active sources (Xia *et al*., 1999) or in passive mode using microtremors (Aki, 1957, 1965; Louie, 2001; Okada, 2003).
This investigation provides information on the subsurface sequence; the elastic and engineering properties estimated using empirical relations at the proposed gas power plant site. The following objectives were utilized: (a) acquire Rayleigh wave data using vertical component seismometers, (b) generate the 1-D S-Wave velocity structures of the subsurface, (c) estimate the bulk moduli of the subsurface sequence and thereby determine the strength of the sequence, (d) classify the subsurface sequence using the generated S-Wave velocity structures and estimated bulk moduli, proffer the necessary measures to be put in place for proper foundation design of the gas power plant.

2. Location, Geology and Hydrogeology

The study area (Figure 1) is located in Edo State, Nigeria. It lies within Latitudes 5^0 59’ 49’’ and 5^0 60’ 00’’ North of the Equator and Longitudes 5^0 53’ 53.5’’ and 5^0 53’ 54’’ East of the Greenwich Meridian.

The area is underlain by the Coastal Plain Sands or the Benin Formation (Figure 2). The sediments of the Coastal Plain, deposited during the Late Tertiary – Early Quaternary period (Jones and Hockey, 1964), consist of unconsolidated, coarse to medium-fine grained sands and clayey shale in places (Okosun, 1988). The sands are generally moderately sorted and poorly cemented. The Benin Formation is overlain by lateritic overburden or recent alluvial deposits. The Coastal Plain Sands to constitute the major shallow hydrogeologic units in the area. The lateritic earth overlying the sands, as well as the underlying impervious clay/shale member of the Agbada Formation, constitute protective configuration for the aquifer units. Also, the high annual rainfall and other favourable climatic and geologic factors guarantee adequate groundwater recharge in the area (Omosuyi *et al*., 2008).

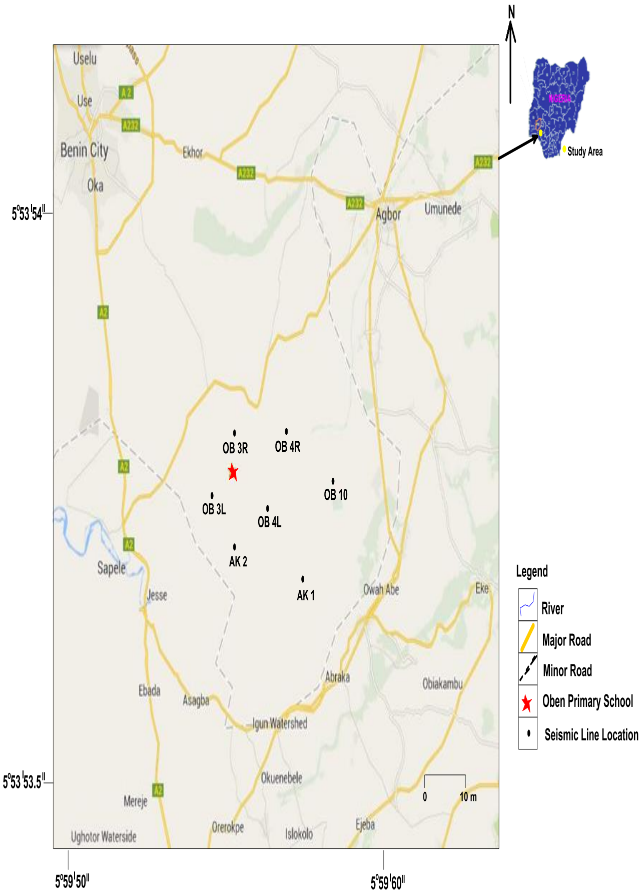

Fig. 1: Location and Data Acquisition Map of the Study Area (Modified from Google Maps).

3. Methodology

Two seismic lines were established at the site each trending in the NE-SW direction. The Surface Wave method was applied in this survey and utilized the Multichannel Analysis of Surface Waves technique. The MASW survey was adopted to determine the lateral and vertical ground velocity variations beneath each seismic line. The ES-3000 seismograph was used for the surface wave data acquisition along the two studied segments.

A geophone interval of 3 m was used, and the length of the seismic lines ranged from 60 – 90 m. The acquired surface-wave data were inverted using SeisImager SOFTWARE, and the interpretation results were presented as velocity profiles.

4. Results and Discussion

The S-Wave velocity models derived for the two wells are shown in Figures 3-6. A distinct gradual velocity variation with depth is observed in the shear wave velocity models.

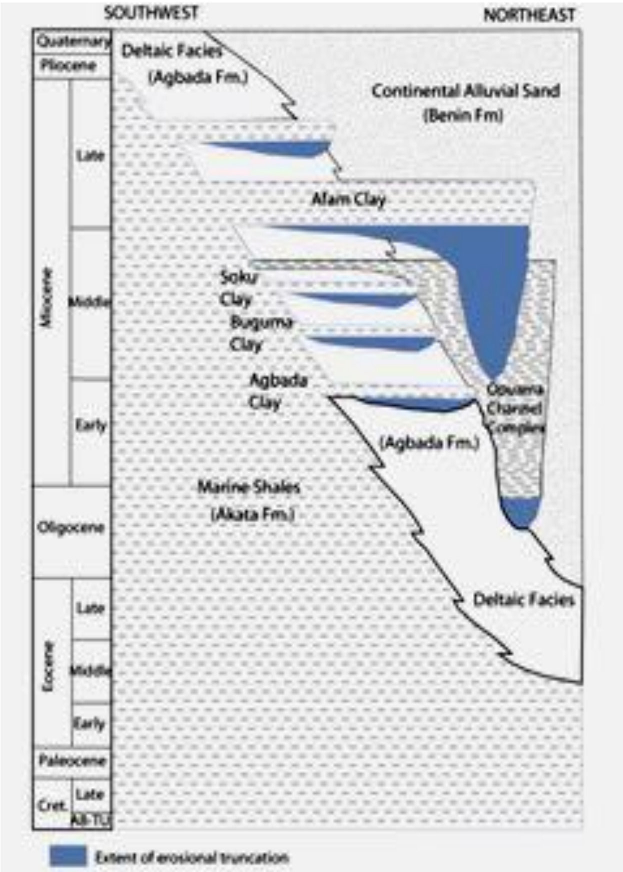

Fig. 2: Stratigraphic Column of the Three Formations of the Niger Delta (Modified From Shannon and Naylor (1989)).

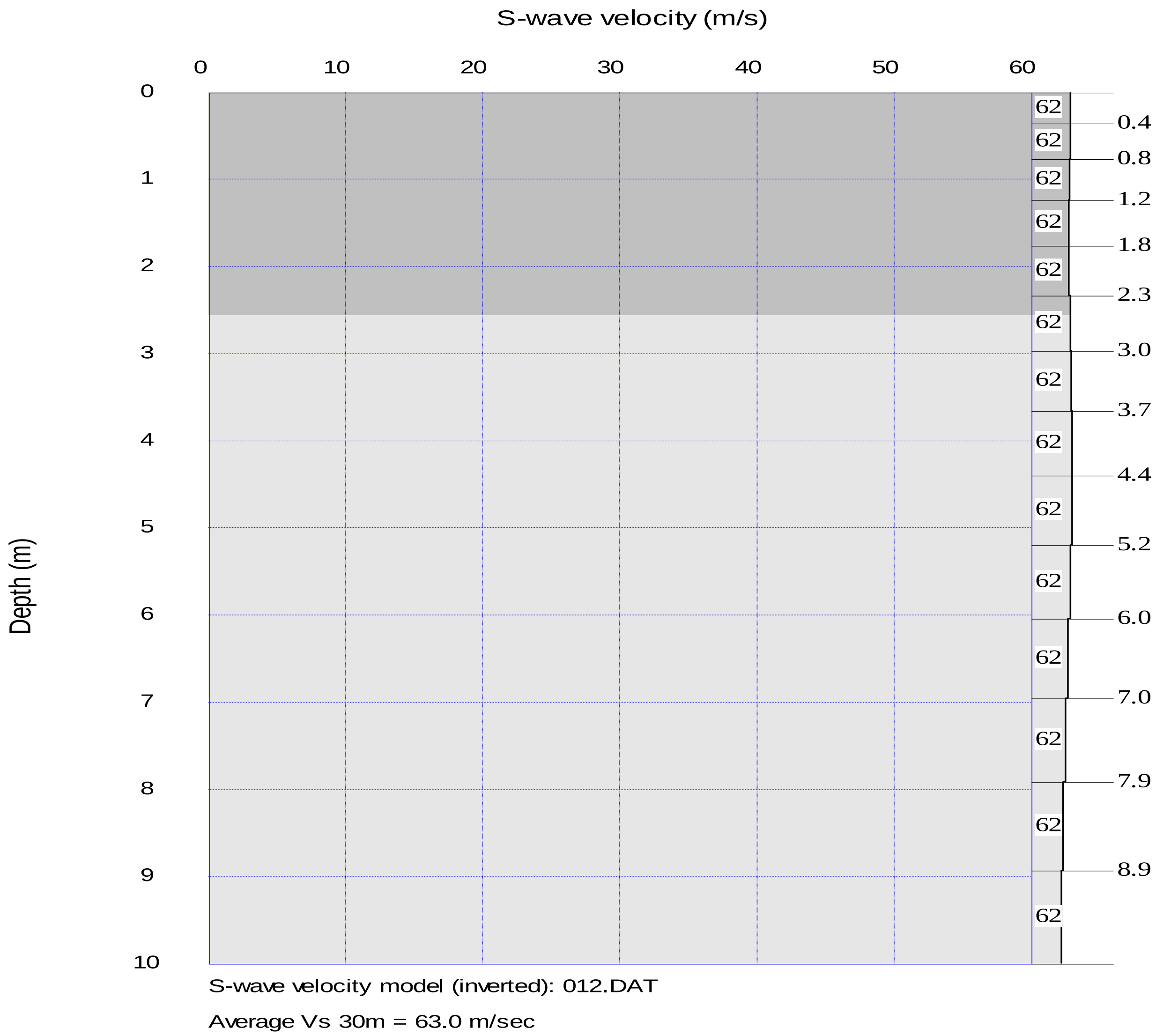

Fig. 3: S-Wave Velocity Curve for Well 1

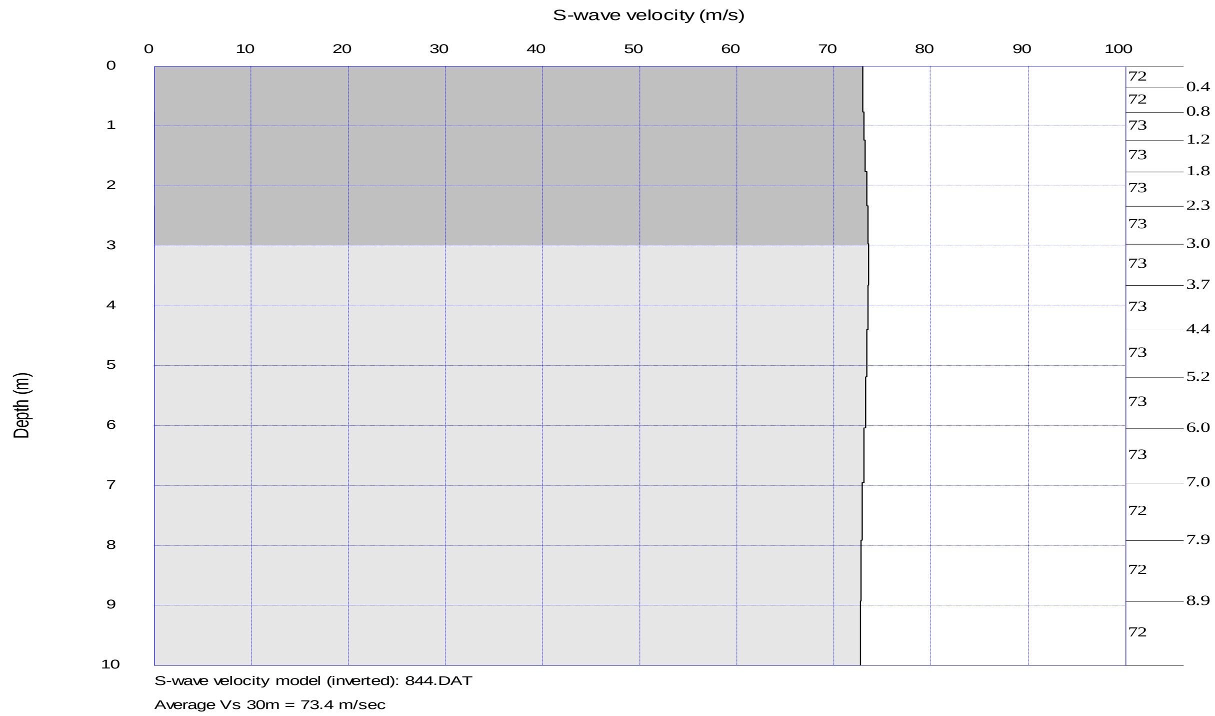

Fig. 4: S-Wave Velocity Curve for Well 2

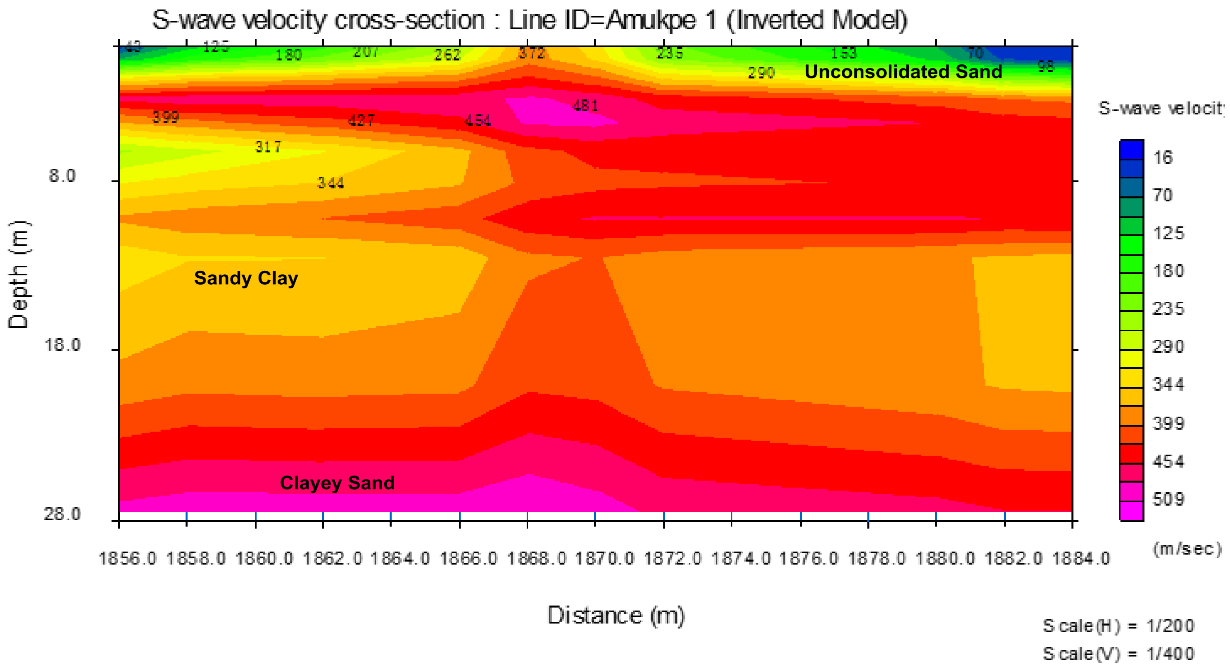

Fig. 5: Inverted S-Wave Velocity Model for Well 1.

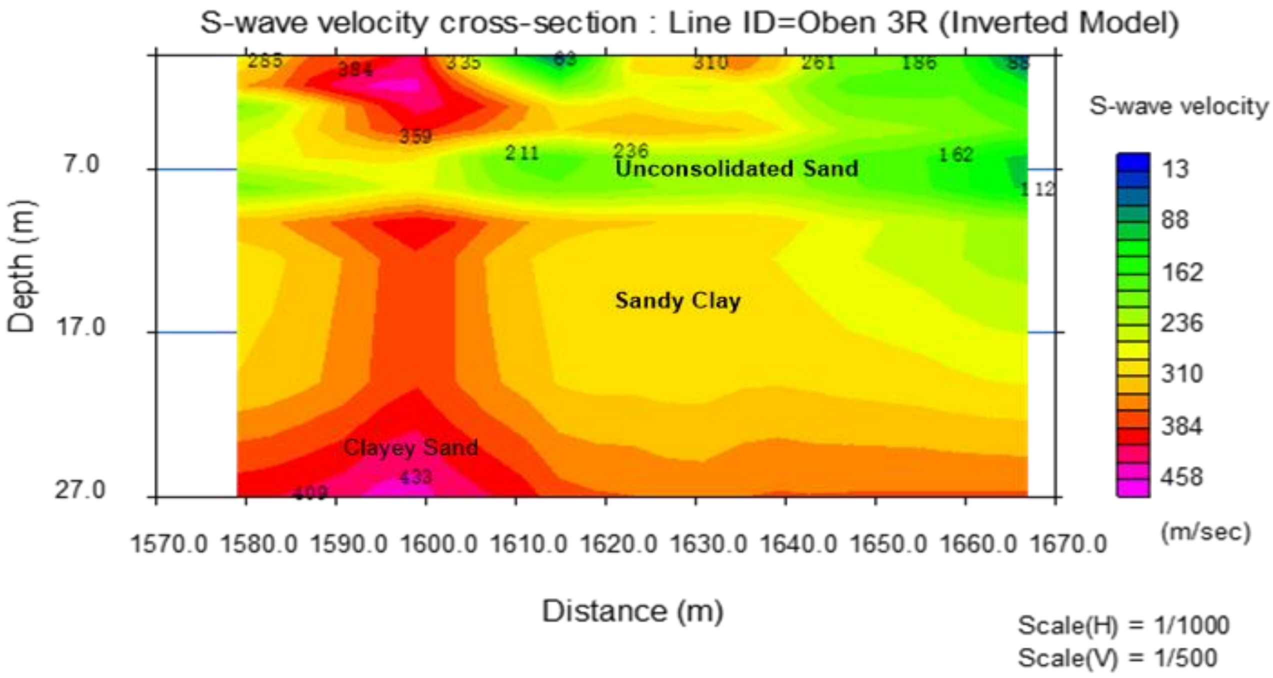

Fig.6: Inverted S-Wave Velocity Model for Well 2.

For the upper 10 m of the wells studied; this is the area of concern for engineering construction.

The average shear-wave velocity in Well 1 is 63 m/s and 73.4 m/s in Well 2.

These 2D S-Wave velocity models suggest that the upper 10 m of the wells are characterized by unconsolidated sand, sandy clay and clayey sand.

The derived elastic and physical properties of the formations encountered in the two wells investigated in this study are shown in Tables 1-2. The computation of the V_s, V_p, ρ, V_s^2, V_p^2, $4/3\ V_s^2$, μ, $\left[V_P^2 - \frac{4}{3}V_S^2\right]$ and bulk moduli K for the wells were carried out in order to understand the elastic, physical, insitu and engineering properties of the formations encountered in the wells studied.

The NEHRP seismic site classification (Table 3) which is based on shear-wave velocity can be used to classify the soils.

Using the site classification technique in Table 3, it is observed that Well 1 falls within site class E, Well 2 falls within site class E. The soil types in class D and E are generally classified as stiff soil to soft clay soil.

Generally, it is evident that the subsurface formations in the area investigated are characterized with low to moderate bulk moduli (K) values and shear moduli (μ) values in the range of 3.2-3.9 GPa and 7.15-7.43 MPa respectively. These values suggest low shear strength for the subsurface formations for the depth range investigated.

Before construction of the Gas Plant, it is appropriate to subject the soils to ground improvement such as chemical injection, vibratory compaction and vacuum preloading methods in order to stabilize the soils.

The soil types found in the wells were classified using the NEHRP seismic site classification that is based on shear-wave velocities only (Table 3).

Table 1: Table of Elastic and Physical Properties for Well 1.

Layer	V_s (m/s)	V_p (m/s)	ρ (g/cm^3)	ρ (kg/m^3)	μ (MPa)	V_p^2 (m^2/s^2)	V_s^2 (m^2/s^2)	{4/3(V_s^2)} (m^2/s^2)	{(V_p^2)-4/3(V_s^2)} (m^2/s^2)	K (GPa)
1	65.191	1362.188	1.74203	1742.03	7.4034	1855554.813	4249.896	5666.528	1849888.285	3.2225
2	65.077	1362.236	1.74203	1742.03	7.3776	1855686.554	4235.069	5646.758	1850039.796	3.2228
3	65.191	1362.362	1.74203	1742.03	7.4034	1856030.839	4249.896	5666.528	1850364.311	3.2233
4	65.303	1362.487	1.74203	1742.03	7.4289	1856369.826	4264.523	5686.030	1850683.796	3.2239
5	65.348	1362.537	1.74203	1742.03	7.4392	1856507.591	4270.473	5693.965	1850813.627	3.2241
6	65.309	1362.494	1.74203	1742.03	7.4304	1856389.480	4265.371	5687.162	1850702.318	3.2239
7	65.198	1362.370	1.74203	1742.03	7.4050	1856052.395	4250.826	5667.768	1850384.627	3.2234
8	65.036	1362.191	1.74203	1742.03	7.3684	1855564.143	4229.802	5639.736	1849924.407	3.2226
9	64.848	1361.982	1.74203	1742.03	7.3257	1854993.696	4205.295	5607.060	1849386.636	3.2216
10	64.652	1361.764	1.74203	1742.03	7.2815	1854401.244	4179.921	5573.228	1848828.017	3.2207
11	64.465	1361.557	1.74203	1742.03	7.2395	1853837.380	4155.837	5541.116	1848296.264	3.2197
12	64.301	1361.375	1.74203	1742.03	7.2028	1853342.366	4134.746	5512.994	1847829.372	3.2189
13	64.171	1361.230	1.74203	1742.03	7.1736	1852947.835	4117.975	5490.633	1847457.202	3.2183
14	64.082	1361.132	1.74203	1742.03	7.1537	1852679.063	4106.566	5475.422	1847203.642	3.2178
15	65.484	1362.688	1.74203	1742.03	7.4702	1856918.304	4288.235	5717.647	1851200.657	3.2248

Table 2: Table of Elastic and Physical Properties for Well 2.

Layer	V_s (m/s)	V_p (m/s)	ρ (g/cm^3)	ρ (kg/m^3)	μ (MPa)	V_s^2 (m^2/s^2)	{4/3(V_s^2)} (m^2/s^2)	{(V_p^2)-4/3(V_s^2)} (m^2/s^2)	K (GPa)
1	76.706	1375.144	1.74621	1746.21	7.40361891022	5883.925	7845.233	1883177	3.2884
2	76.742	1375.184	1.74621	1746.21	7.37781891131	5889.403	7852.537	1883279	3.2886
3	76.837	1375.290	1.74621	1746.21	7.40381891422	5904.046	7872.062	1883550	3.2890
4	76.979	1375.448	1.74621	1746.21	7.42941891856	5925.884	7901.179	1883955	3.2897
5	77.136	1375.621	1.74621	1746.21	7.43891892334	5950.017	7933.356	1884401	3.2905
6	77.273	1375.774	1.74621	1746.21	7.43071892753	5971.194	7961.592	1884791	3.2912
7	77.366	1375.877	1.74621	1746.21	7.40541893037	5985.564	7980.751	1885056	3.2917
8	77.404	1375.919	1.74621	1746.21	7.36851893153	5991.436	7988.581	1885164	3.2918
9	77.389	1375.903	1.74621	1746.21	7.32601893109	5989.210	7985.614	1885123	3.2918
10	77.336	1375.843	1.74621	1746.21	7.28131892944	5980.862	7974.482	1884969	3.2915
11	77.261	1375.760	1.74621	1746.21	7.23891892716	5969.322	7959.096	1884757	3.2911
12	77.187	1375.678	1.74621	1746.21	7.20291892491	5957.929	7943.906	1884547	3.2908
13	77.136	1375.621	1.74621	1746.21	7.17381892334	5950.041	7933.388	1884401	3.2905
14	77.129	1375.613	1.74621	1746.21	7.15381892312	5948.885	7931.846	1884380	3.2905
15	77.481	1376.005	1.74621	1746.21	7.47031893389	6003.432	8004.576	1885385	3.2922

Table 3:NEHRP Seismic Site Classification Based on Shear-Wave Velocity (V_s) Ranges.

Site Class	S-Wave Velocity (V_s)(ft/s)	S-Wave Velocity(V_s)(m/s)
A (Hard rock)	>5000	>1500
B (Rock)	2500 - 5000	760 - 1500
C (Very dense soil and soft rock)	1200 - 2500	360 - 760
D (Stiff Soil)	600 - 1200	180 - 360
E (Soft Clay Soil)	<600	<180
F (Soils requiring additional response)	<600 and meeting some additional conditions	<180 and meeting some requirements

5. Conclusions

In this study, a geophysical investigation of the competence of subsurface layers in the area around a proposed new power plant site in Edo State has been carried out. The results from the geophysical survey conducted to investigate the strength of these layers reveal that these sites have relatively low bulk moduli in the range of 3-4 GPa, while the shear modulus (μ) values range from 7.15-7.43 MPa These values are indicative of low to moderate strength for the subsurface strata underlying the area. The shear-wave velocities obtainable from this survey depicts that of soft clay soil.

Although the degree of competence is low, the clayey sand and sandy clay layers can be grouted (ground improvement technique) by pumping cement at very high pressures into the formations thereby making the site suitable for the installation of the power plant. Also a pile foundation (and in this case a frictional pile) can be used to anchor the plant to the competent rock.

Arising from the results and conclusions of this study, it should be noted that the method used for this survey is by no means exhaustive. The Microtremor Array Measurement (MAM) technique can also be used alongside the MASW to have a better control of depth to competent soil or rock.

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