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# Geotechnical Properties of Subsurface Soils in Warri, Western Niger Delta, Nigeria

**Avwenagha, Enivwenaye Oghenero[1], Akpokodje Enuvie G.[2] and Tse Akaha Celestine[3]**

## Abstract

Integrated surface electrical resistivity survey, borehole drilling and insitu testing by CPT were used to determine engineering geological properties of soils underlying Warri metropolis for the planning and design of civil engineering structures. Results revealed that three major sub-soil types underlie the area characterized by dry, swampy and marshy ground conditions. These soils occur in the dry plains and swampy areas, from top to bottom, as silty sand, clayey sand and sand. However in the marshy NPA area, only two soil layers occur: the top 6m thick organic clay layer overlying the sand layer. The geotechnical properties suggest that all the layers can support structural loads from civil structures, provided foundation design is preceded by adequate subsoil investigation to provide construction specific data.

**Keywords:** Geotechnical, lithology, foundation, electrical resistivity

## 1 Introduction

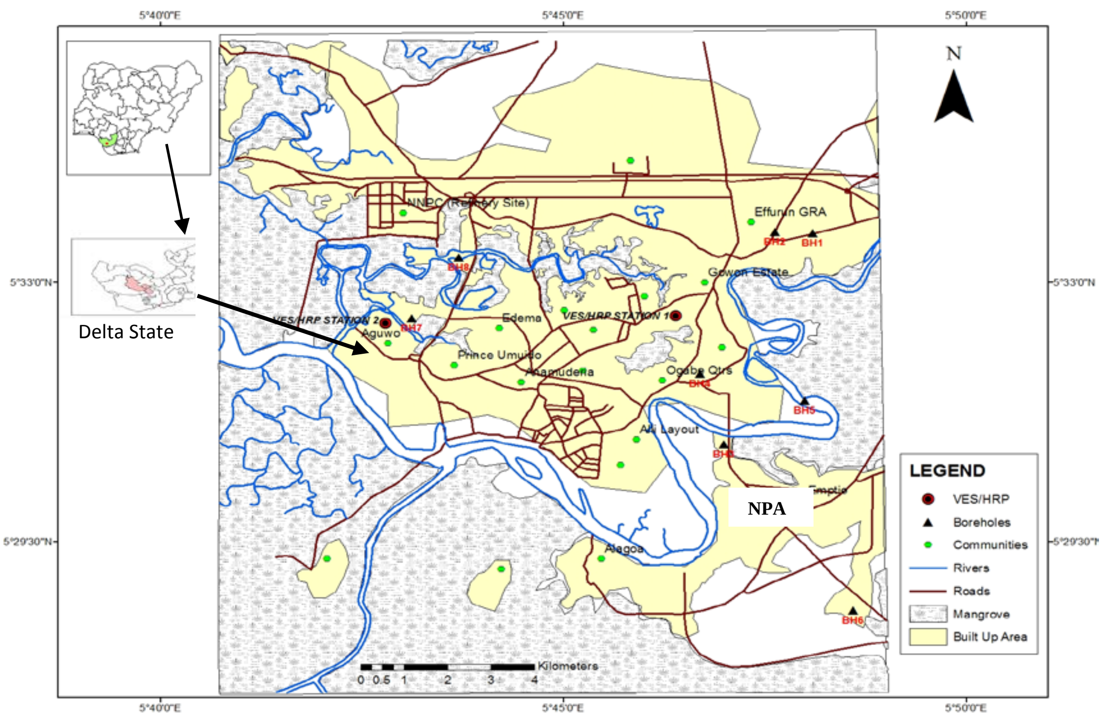
Warri is an important metropolis in Nigeria in the sense that other than Port Harcourt, it is the second town that serves as the centre of field logistics and operations of many companies in Nigeria engaged in exploration and production in the downstream sector of the oil industry in the western part of the Niger Delta. The western Niger Delta is the area that lies west of the Nun River and is geographically defined by Delta, Edo, and parts of Bayelsa States. This has resulted in the need for extensive infrastructural development to support these activities. Sub-soil geotechnical data are required for proper design and construction of civil engineering structures to prevent adverse environmental impact or structural failure. The geotechnical data of soils in the eastern Niger Delta made up of Rivers, Akwa Ibom and parts of Bayelsa State with Port Harcourt as the operating headquarters have been fairly well documented and published works are readily

[1] Department of Geology, University of Port Harcourt, Nigeria.
[2] Department of Geology, University of Port Harcourt, Nigeria.
[3] Corresponding author, Department of Geology, University of Port Harcourt, Nigeria.

available (Akpokodje 1989 [1], Abam and Okogbue 1997 [2], Teme 2002 [3], Tse 2006 [4], Onyebolise, and Akpokodje 2008 [5], Ugbe 2011 [6], Youdeowei and Nwankwoala 2011 [7], Tse and Akpokodje 2010 [8]) compared to paucity of data on the soils in western Niger Delta. Generally the delta area is a wetland characterized by swamps, marshes and bogs. From the engineering point of view, the soils in wetlands are generally low-bearing-capacity foundation materials with the voids saturated with water. Thus their major engineering problems include excess surface and groundwater, poor drainage, high compressibility, low bearing capacity and differential settlement, among others. Quaternary soils which are the foundation materials in the Niger Delta were deposited in a wide variety of environmental conditions with unique gemorphological features which have rendered them vertically and laterally heterogenous in form and anisotropic in engineering properties. This research is therefore to determine the geotechnical properties of sub-soils of Warri in order to provide basic data which would guide future development and construction in the area in view of the rapid vertical and lateral variation in the properties of the soils.

## 2 Geomorphology, Regional Geology and Hydrology

Warri is located in the western portion of the Niger Delta (Figure 1) some 40 kilometers away from the shores of the Atlantic Ocean. It lies on a flat to gently undulating area with slopes of about 0-4° and occupies a low-lying area which is drained by the tide influenced River Warri whose drainage pattern is dendritic with anostomising tributaries and creeks. As a result of fresh water-salt water mixture, a brackish environment is created at the banks of the river and associated creeks.



The general geology of the Niger Delta consists of various types of Quaternary deposits overlying the three major lithostratigraphic units. These are from bottom to top the Akata, Agbada and Benin Formations. The units have been extensively studied and described in literature, including the classic work of Short and Stauble (1967) [9]. The Akata Formation forms the basal unit of the Niger Delta stratigraphic sequence and consists of an open marine facies unit dominated by high-pressured carbonaceous shales. The formation ranges in age from Paleocene to Eocene in age and its thickness could exceed 1000 meters. It is overlain by the Agbada Formation consisting of a sequence of alternating deltaic sands and shales. It is Eocene to Oligocene in age and exceeds 3000meters in thickness. This formation is oil-reservoir of the Niger Delta Basin. The overlying Benin Formation is Oligocene to Pleistocene in age and consists predominantly of fresh water continental friable sands and gravel that are of excellent aquifer properties with occasional intercalation of shales. The thickness of the formation is variable but generally exceeds 2000 meters. Geologically Warri area is underlain by the Benin Formation which consists of sandy silt, brownish clayey/silty sand, and fine-medium/coarse grained unconsolidated sands. The formation generally does not exceed 120 meters in thickness and it is predominantly unconfined. The Benin Formation is overlain by various types of quaternary alluvial deposit comprising mainly of Recent deltaic sand, silt and clay of varying thickness. These alluvial deposits occur in five major geomorphic units namely: Active and abandoned coastal beaches, Salt water /Mangrove swamp, Fresh water swamp, Sombreiro-Warri Deltaic plain with abundant fresh water swamps and Dry flat land and plain overly the Benin Formation. Warri lies on the Sombreiro-Warri Deltaic plains where the sub-soils comprise distinct units or intercalations of sand, clay and some silt. The Benin Formation constitutes the regional aquifer in the Niger Delta. Knowledge of the groundwater conditions in the Niger Delta area is obtained from the work of Etu-Efeotor and Akpokodje (1990) [10] which delineated several irregular, lenticular and laterally discontinuous layers of clay aquitard that regionally subdivide the regional aquifers into five units. Except in most of the coastal beach islands, all the aquifers in the other geomorphic units are generally overlain by sandy/silty clay or clay at near the surface. However in the coastal beach islands, a thin surficial sand layer, 0.5-3m thick, directly overlie a relatively thick clay which in turn overlies the regional aquifer resulting in perched aquifers. In Warri area, the aquifers occur under semi confined and unconfined conditions. The water table is very close to the ground surface and varies from 0 to 4meters. The hydraulic conductivities of the sand vary from 3.82 x 10-$^{3}$ to 9.0 x $10^{-2}$cm/sec which indicates a potentially productive aquifer Offodile (1991) [11]. Specific capacities recorded from different areas within this formation vary from 6700lit/hr/m to 13,500lit/hr/m. Groundwater recharge is mainly by precipitation. The hydraulic conductivities of the sand vary from 3.82 x $10^{-3}$ to 9.0x$10^{-2}$cm/sec which indicates a potentially productive aquifer. Specific capacities recorded from different areas within this formation vary from 6700lit/hr/m to 13,500lit/hr/m. The water table is very close to the ground surface and varies from 0 to 4 meters but was encountered between 2.5 and 4m below the ground surface during this study.

## 3 Method of Study

Field investigations were undertaken by the integration of electrical resistivity and geotechnical surveys (Figure 2). Reconnaissance shows that the study area is characterized by marshy, swampy and dry land conditions. Hence field surveys were designed to capture the engineering properties of soils underlying the three distinct ground conditions. Electrical resistivity surveys consisted of both vertical electrical sounding (VES) and horizontal resistivity profiling (HP) conducted in both swampy and dry terrains using ABEM-SAS 300C terrameter. Schlumberger and Wenner electrode configurations were employed with maximum electrode spacing of 200 meters. The co-ordinates of each sounding station were established using a hand held GARMIN 12 model GPS. VES 1 was performed at Warri Industrial Business Park, Edjeba with point coordinates as N005° 32' 48.15'' E005° 46' 26.46'' while VES 2 with coordinates N005° 32'45.81'' E005° 43'33.61'' was located at Urhobo College Premises, Enerhen. Horizontal profiling was also conducted at these points The apparent resistivity measurements obtained were input into a computer modeling program “RESIST version 1.0” to produce geo-electric layers and 2D lateral resistivity profiles. Also, a geotechnical investigation involving the drilling of eight 20m deep boreholes (four boreholes each sited in the dry and swampy terrains), and three boreholes in the NPA area was performed. During drilling, soil samples were obtained at 1m interval to enable lithological description and laboratory testing programme consisting of determination of moisture content, particle size distribution, Atterberg limits, dry density and California bearing ratio (CBR) according to procedures described in the relevant sections of BS 1377 (1990) Offodile (1991) [12].

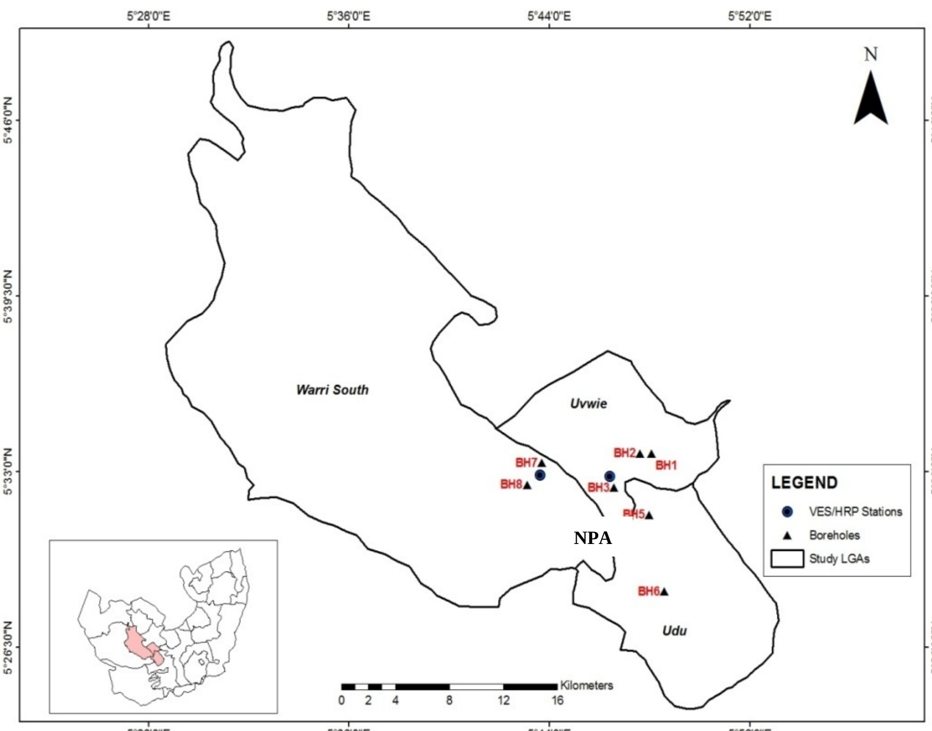



Figure 2: Field map of study area showing VES and borehole positions

In situ Cone penetration tests (CPT) to obtain the soil bearing capacity were conducted using a 2.5 ton CPT machine. The test involved advancing a $60^{\circ}$ steel cone with base area of $10cm^2$ into the ground with the view to ascertaining the resistance (stiffness) of the soil. This was achieved by securing a winch frame to the ground by means of anchors. These anchors provided the necessary power to push the cone into the ground at the rate of 2cm/sec and the resistance to penetration registered on a pressure gauge connected to the pressure capsule was recorded. In the end, series of cone resistance and sleeve friction readings were plotted against depth and the bearing capacities of sub-soil horizons calculated. The overall aim was to determine the engineering geological properties of sub-soils of Warri including the delineation of the various subsoil horizons, their lateral extents and engineering properties and the suitability of the sub-soils for use in road construction and as foundation materials.

# 4 Results and Discussions

## 4.1 Geolectric and lithological characteristics

The VES sounding curves obtained in the Urhobo College premises representing dry locations in the Enerhen axis (Figure 3a) and Warri industrial business park representing the swampy axis of Ejeba (Figure 3b) all show AQ type curves depicting six geo-electric layers whose characteristics are summarized in Tables 1 and 2 respectively. The sand in the swampy locations were found to exhibit higher resistivity values (1771Ωm) relative to those of the dry plains (1681Ωm) which implies the pore fluids of the former axis are less conductive than the latter. These geoelectric characteristics were used to erect a simplified geological model of Warri area as being underlain by three subsurface soil layers: top silty sand underlain by a second layer of clayey sand passing down into a massive sandy layer.

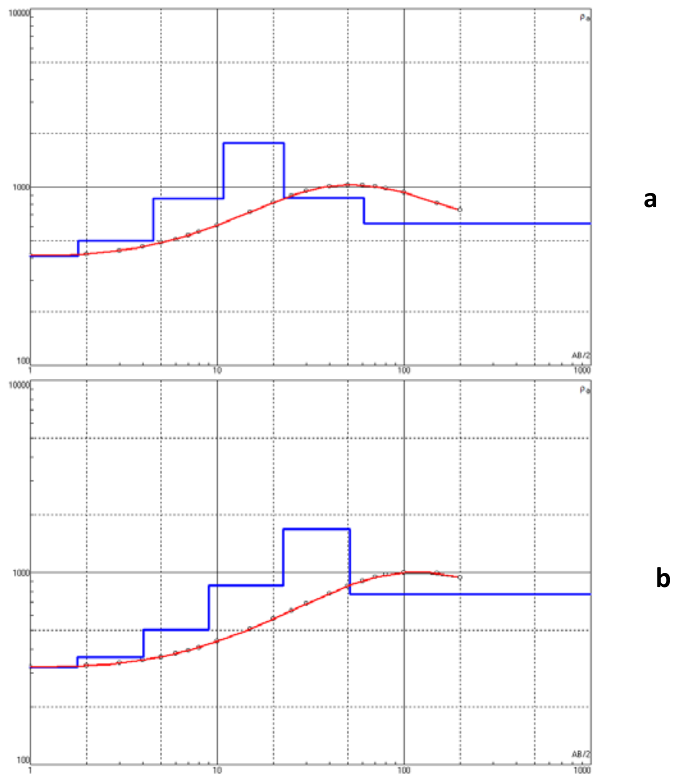



Figure 3: Typical sounding curve dry axis (a) and swampy axis (b)

Table 1: Geo–electric layers and lithologic description of soils in the dry area.

| **Number of layers** | **Apparent resistivity, ρa (Ωm)** | **Thickness (m)** | **Depth (m)** | **Lithologic description** |
|---|---|---|---|---|
| **1** | 321.80 | 1.78 | 1.78 | Very silty, sand |
| **2** | 363.20 | 2.25 | 4.03 | Silty sand |
| **3** | 504.70 | 4.98 | 9.01 | Fine sand |
| **4** | 855.70 | 13.53 | 22.56 | Medium sand |
| **5** | 1681.00 | 28.79 | 51.35 | Coarse sand |
| **6** | 771.30 | -------- | ----------- | Fine- medium sand |

Table 2: Geo electric layers and lithologic description of soils in the swampy area

| No. of layers | Apparent resistivity, ρa (Ωm) | Thickness (m) | Depth (m) | Lithologic description |
|---|---|---|---|---|
| **1** | 410.00 | 1.80 | 1.80 | Clayey coarse sand |
| **2** | 500.30 | 2.74 | 4.54 | Clayey sand |
| **3** | 863.20 | 8.07 | 10.81 | Medium sand |
| **4** | 1771.00 | 11.95 | 22.76 | Coarse sand |
| **5** | 870.70 | 27.22 | 49.88 | Fine to medium |
| **6** | 626.60 | --------- | ------ | |

The lateral distribution of the soil layers are elucidated by the 2-D resistivity profiles (Figure 4) The dry Enerhen axis (Figure 4a) exhibits resistivity anomalies indicative of silty sand (488-627Ωm) to medium sands (542-883Ωm) and coarse sand (1034 - 1171Ωm). These anomalies are randomly distributed and localized which implies that these sub-soils are laterally heterogenous in the dry terrain. In constrast, the resistivity profile for the swampy Edjeba axis (Figure 4b ) exhibit two main anomalies which are low and high resistivity values indicative of fine to medium sand (48 -803Ωm) and clayey/coarse sands (912-1771Ωm). These resistivity anomalies are extensive and evenly distributed which implies that the subsoil are laterally homogenous in contrast to those of dry Enerhen axis. The maximum lateral extents of the fine to medium sands and coarse sands in the dry area are about 70m and 60m respectively while the clayey/coarse sands and fine to medium sands in the swampy area have a stretch of about 80m and 160m respectively. In essence there is a rapid lateral variation this sub-soils in the dry Enerhen axis unlike the relatively homogenous sub-soils in the swampy axis of Edjeba. The three layer soil profiles delineated using electrical resistivity methods correspond to the results obtained from drilling, sampling and lithologic description and stratigraphic construction of subsurface soils in the eleven boreholes located across the study area (Figure 5).

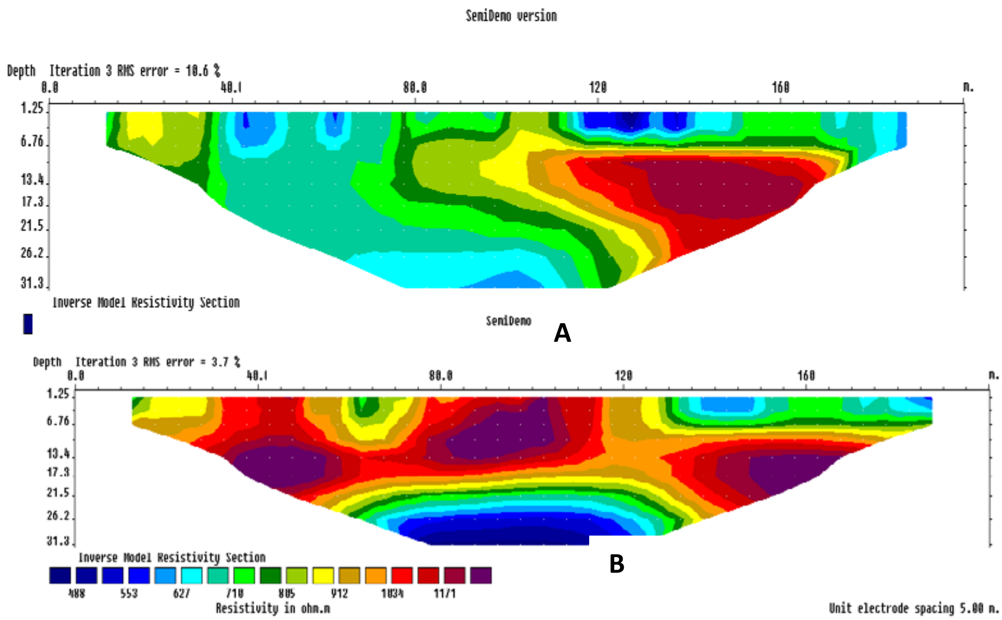



Figure 4: 2-d resistivity profile of dry area (A) and swampy area (B)

## 4.2 Engineering Properties.

The combined interpretation of results from borehole logging, visual examination of soil samples, laboratory testing and in-situ cone penetration testing clearly reveal that the sub-soil profile of the study area inferred from the electrical resistivity data was corroborated by soil data in eleven boreholes to consists of three layers. These layers from top to bottom are: silty sand (top soil), clayey/silty sand and sand (Fig. 5).

### 4.2.1 Layer 1

The top layer consist of light to dark grey, loose to medium dense, silty sand containing insignificant proportions of fines. Its average thickness is 0.5m. However, this layer is absent in the marshy NPA location and its place is occupied by 1.5m thick backfill material consisting of fine to medium sand with root materials. It occurs in boreholes 9 and 10 but is absent in BH 11. Generally, it does not possess enough thickness for any meaningful foundation consideration.

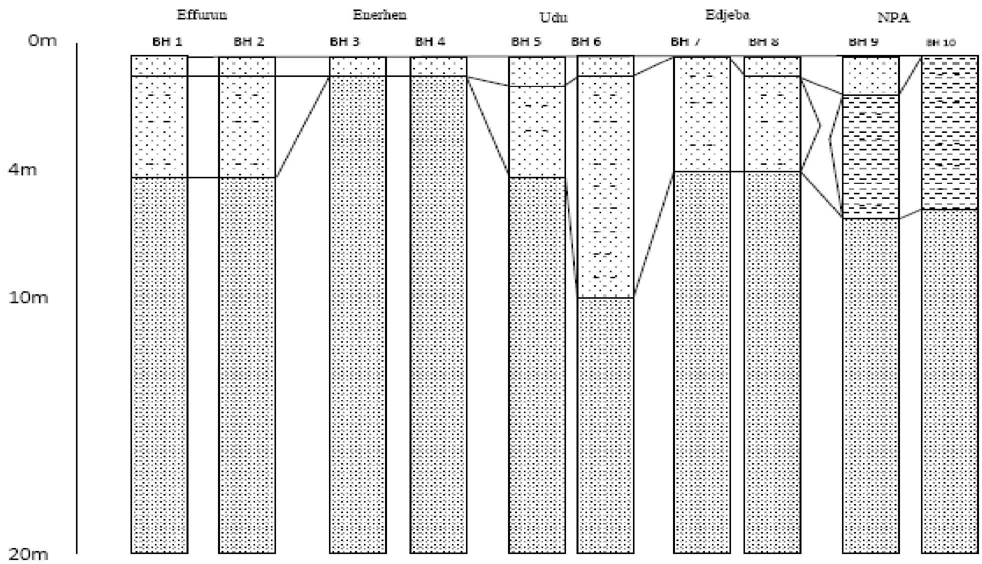



Figure 5: Lithological correlation of boreholes in study area

### 4.2.2 Layer II

The second layer consist of the mainly brownish, medium stiff to stiff, clayey. However in the dry plains represented by the Enerhen axis ($BH_3$ and $BH_4$) it occurs as a 4m thick dark brown, loose silty sand. In Effurun, Udu and Ejeba axes ($BH_1$, $BH_2$ and $BH_5$-$BH_8$ respectively) the sand becomes clayey, ranging in thickness from 4 to 10m. The variation in thicknesses may be due to more rapid deposition of fines in the swamp terrains of Udu and Edjeba areas when the surrounding Warri River overflows its bank during the wet season unlike the dry terrains of Effurun and Enerhen. The engineering properties of the layer in the dry and swampy locations are summarized in Table 3. The fines content range from 17 to 41% and liquid limit values fall between 25 and 37 %. The liquid limit values imply predominantly low compressibility according to BS 5930 (1999) [13]. The values of the natural water content, which gives an indication of likely volume change, fall between 9 and 14%, with an average value of 11%. These values indicate that the volume changes as well as the swelling and shrinkage normally associated with clayey soils will also be relatively lower. Most of the soil plot above the A-line on the Casagrande plasticity chart (low-medium plasticity clays), except soil samples in NPA which plot below the line to confirm their organic nature. In the marshy NPA area, the second layer is an approximately 7m thick soft to firm, dark grey organic clay, overlain by 1.5m thick sand, probably the backfill material in layer l. This is thought to be the natural soil type that occurs from the ground surface to a depth of 6m in borehole 1 located in an unimpacted area, but which has been excavated and backfilled in the locations where boreholes 10 and 11 were sited.

Table 3: Engineering properties of Layer II in the dry and swampy areas .

| Borehole No. | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
|---|---|---|---|---|---|---|---|---|
| Location | PTI Road behind First Bank | PTI Road by Agofure Park | Urhobo College | Jefia Estate Enerhen | Udu area (SEDCO) | Ujevwu | Ejeba (Warri Industrial Business Park) | Ejeba by Chevron |
| Coordinates | N05$^0$33΄40” E005$^0$47΄ 37” | N05$^0$33΄41” E003$^0$47΄ 37” | N05$^0$31΄53” E005$^0$46΄ 41” | N05$^0$31΄43” E005$^0$46΄ 52” | N05$^0$31΄23” E005$^0$47΄ 37” | N05$^0$27΄49” E005$^0$48΄ 38” | N05$^0$32΄39” E005$^0$43΄ 23” | N05$^0$33΄08” E005$^0$43΄ 48” |
| Water table | 3.5m | 4m | 4m | 3.5m | 3m | 2.5m | 3m | |
| Depth (m) | 0-4 | 0-4 | 0 -4 | 0 - 4 | 0 - 4 | 0-10 | 0-4 | 0 -4 |
| %w | 9.33 | 7.44 | 12.25 | 10.20 | 8.70 | 14.05 | 11.30 | 12.50 |
| % sand | 65.17 | 68.80 | 80.52 | 82.65 | 74.17 | 58.36 | 67.64 | 69.55 |
| % fines | 34.83 | 31.20 | 19.48 | 17.35 | 25.83 | 41.64 | 32.36 | 30.45 |
| % Liquid limit | 29.30 | 30.20 | NP | NP | 25.00 | 37.4 | 24.90 | 28.70 |
| % Plastic limit | 19.9 | 20.40 | NP | NP | 19.19 | 25.30 | 18.50 | 21.40 |
| Plasticity index | 9.40 | 9.80 | NP | NP | 5.80 | 12.10 | 6.40 | 7.30 |
| % OMC | 12.50 | 12.10 | 10.08 | 10.02 | 10.20 | 13.80 | 10.20 | 10.04 |
| MDD (g/cm$^3$) | 1.945 | 1.960 | 1.962 | 2.071 | 2.058 | 1.935 | 2.044 | 2.068 |
| CBR (%) | 15.60 | 21.50 | 18.20 | 17.70 | 26.10 | 14.50 | 10.10 | 19.20 |
| Classification Scheme USC | CL | CL | SM | SM | CL | CL | CL | CL |
| Classification Scheme AASHO | A2-4 | A2-4 | A3 | A3 | A2-4 | A6 | A2-4 | A2-4 |

OMC = Optimum Moisture Content (%) MDD = Maximum Dry density CBR = California Bearing Ratio

All the three bored sites in NPA are underlain by this clay whose consistency ranges from very soft to soft to firm. The engineering properties are summarized in Table 4. The organic content ranges from 6 to 19%. The occurrence of this thick clay layer as the top soil in NPA area is a deviation from the pattern of occurrence of a thin top sandy clay layer that underlies soils in the swampy and dry plains locations immediately beneath the ground surface.

Table 4: Engineering properties of the soil layers in the marshy NPA area.

| Layer/lithology | Layer 2: **Clay** | | | Layer 3: **Sand** | | |
|---|---|---|---|---|---|---|
| Description | Soft to firm, dark grey organic CLAY, overlain by 1.5m thick sand, probably sandfill. | | | Fine to medium to coarse SAND | | |
| Parameter | Min | Max. | Average | Min | Max. | Average |
| Depth below ground surface (m) | 0 | 9 | - | 6 | 20 | - |
| Average thickness (m) | | | 7.5 | | | 14 |
| % fines (<0.074mm) | | | | 0 | 4 | 2 |
| % Sand | | | | 96 | 100 | 98 |
| Plastic limit | 13 | 69 | 24 | | | |
| Plasticity Index | 25 | 150 | 54 | | | |
| Specific Gravity | 2.62 | 2.64 | 2.64 | 2.66 | 2.67 | 2.65 |
| Bulk Density (mg/m$^2$) | 1.2 | 1.0 | 1.76 | 1.86 | 2.01 | 1.87 |
| $D_{10}$ (mm) | | | | | | |
| $D_{60}$ (mm) | | | | | | |
| Uniformity Coefficient, CU | | | | 2 | 6 | 4 |
| Undrained cohesion (kN/m$^2$) | 14 | 18 | 45 | | | |
| Angle of internal friction | 2$^{\circ}$ | 3$^{\circ}$ | 3$^{\circ}$ | | | |
| MDD (kg/m$^3$) | 1845 | 1955 | 1950 | | | |
| OMC (%) | 10 | 11 | 11 | | | |
| SPT N-value | | | | 5 | 10 | 8 |
| USC Classification | CL | CH | CH | SP | SW | SP |

MDD = Maximum Dry density OMC = Optimum Moisture Content (%)

For pavement considerations, the granular soil classify as A-2 and A-3 type materials while the silty-clayey material has characteristics of A-6 soils based on the American Association of State Highway and Transport Officials (AASHTO) classification scheme. The granular soils may therefore be rated as good to excellent sub-grade materials for road construction except the silty-clayey material ofof borehole 6 which classifies as an A-6 material implying poor pavement quality. This is similar to results obtained by Olobaniyi *et al* (2005) [14], who investigated the geotechnical properties of lateritic soils in Osubi area on the outskirts of Warri and produced data to show that the soils belong to the A-2-4 and A-2-6 category of the AASHTO classification scheme implying that these soils will be suitable for use as sub-base and base material, after appropriate stabilization. The range of CPT values and allowable bearing capacities of the layer are 0.9 to 2Mpa and 86 to 225kpa respectively. Based on these results the layer would be a suitable foundation material for medium sized civil engineering structures. The OMC and MDD values of the soils range from 10 to 13% and 1.935-2.072 g/cm$^3$ respectively. The compaction characteristics of clayey soils in the western Niger Delta have been shown to be dependent on their percentage content of fines (Akpokodje 1986 [16] &1987 [18], Ugbe 2011[6]). Soils with the highest percentage of fines (Udu axis, BH6) had the highest OMC but lowest MDD which indicates that increase in fines implies greater porosity and requires more water for soil compactions. This in effect, reduces density and consequently lowers the MDD. Also, the soaked California Bearing Ratio (CBR) values range from 10.6 to 26.1%. A comparison of these CBR values with Nigerian standards (Federal Ministry of Works, 1997) [15] also confirms that the soil could be used as a sub-grade material but unsuitable for use as sub-base and base material in road pavement construction since the CBR values are less than 30% and 80% respectively. This suggests that pavement failure will occur under heavy load under this condition. Thus soil stabilization would be needed to improve their engineering properties and hence remedy these deficiencies. Such stabilization methods are mainly mechanical and chemical stabilization as suggested by Akpokodje (1986) [16] and Omotosho and Eze-Uzomaka (2008) [17].

### 4.2.3 Layer III

The bottom layer consist predominantly of loose to medium dense to dense , fine to medium grained sand whose thicknesses within the explored depths range from 14 to 16meters. The full thickness of this horizon could not be determined because the boreholes did not penetrate its whole depth. The results of grain size analysis (Table 5) shows that the layer contains 88 to 99% sands and 0.35-12% fines with occasionally, gravel-sized materials.

In NPA, the percentage of the fines fraction range from 1 to 4%. The high density of the sand is demonstrated by the SPT N- values of 16 of 24. The coefficient of uniformity values ranging from 2 to 6 are indicative of poorly graded (SP) and well graded (SW) based on the Unified soil classification scheme. The range of CPT values of 1.7 to 7.5Mpa which gave allowable bearing capacity of 179.1-744.2 kPa implies that this layer will constitutes a sound foundation substratum for medium to heavy civil engineering structures using pile foundation. A typical CPT profile is shown in Figure 6.

Results of this study shows that there is similarity in soil stratification in Warri area. However the engineering properties of the soils show marked variation. The natural moisture contents and plasticity of the soils are influenced by the clay and organic content, season and drainage conditions. All these have directly proportional relationship. Thus the moisture content is higher in the wet season and in flooded areas.

Table 5: Particle size distribution characteristics of Sand Layer III

| Bore hole Number. | Depth of sample (m) | D10 (mm) | D50 (mm) | D60 (mm) | Cu = d60/d10 | USC | %fines | %sand |
|---|---|---|---|---|---|---|---|---|
| 1. | 4.00-6.00 | 0.09 | 0.31 | 0.41 | 4.50 | SP | 9.26 | 90.74 |
| | 6..00-9.00 | 0.09 | 0.30 | 0.33 | 3.52 | SP | 8.44 | 91.56 |
| | 9.00-11.00 | 0.09 | 0.23 | 0.24 | 2.70 | SP | 6.31 | 93.69 |
| | 11.00-12.00 | 0.15 | 0.79 | 0.89 | 5.90 | SW | 0.82 | 99.18 |
| | 12.00-15.00 | 0.13 | 0.33 | 0.34 | 2.60 | SP | 1.02 | 98.98 |
| | 15.00-18.00 | 0.20 | 0.56 | 0.59 | 3.00 | SP | 0.52 | 99.48 |
| 2. | 4.00-6.00 | 0.09 | 0.37 | 0.39 | 4.22 | SP | 0.43 | 99.57 |
| | 6.00-9.00 | 0.09 | 0.28 | 0.30 | 3.30 | SP | 4.12 | 95.88 |
| | 9.00-12.00 | 0.16 | 0.39 | 0.40 | 2.50 | SP | 2.19 | 97.81 |
| | 12.00-15.00 | 0.13 | 0.29 | 0.30 | 2.35 | SP | 0.825 | 99.18 |
| | 15.00-18.00 | 0.19 | 0.51 | 0.52 | 2.70 | SP | 0.64 | 99.36 |
| | 18.00-20.00 | 0.19 | 0.51 | 0.53 | 2.82 | SP | 0.70 | 99.30 |
| 3. | 4.00-6.00 | 0.16 | 0.18 | 0.19 | 1.18 | SP | 12.10 | 88.00 |
| | 6.00-9.00 | 0.11 | 0.31 | 0.34 | 3.00 | SP | 3.18 | 96.82 |
| | 9.00-12.00 | 0.16 | 0.28 | 0.30 | 1.82 | SP | 2.50 | 97.46 |
| | 12.00-13.00 | 0.30 | 0.60 | 0.75 | 2.48 | SP | 0.83 | 99.17 |
| | 13-15.00 | 0.30 | 1.40 | 1.50 | 5.00 | SW | 0.75 | 99.25 |
| | 15-18.00 | 0.18 | 0.80 | 0.90 | 5.00 | SW | 0.70 | 99.30 |
| . | 4.00-6.00 | 0.17 | 0.18 | 0.19 | 1.16 | SP | 0.28 | 97.11 |
| | 9.00-12.00 | 0.18 | 0.37 | 0.39 | 2.20 | SP | 0.35 | 99.65 |
| | 12.00-13.00 | 0.33 | 0.60 | 0.89 | 2.70 | SP | 5.34 | 94.66 |
| | 13.00-15.00 | 0.38 | 1.80 | 1.99 | 5.24 | SW | 0.67 | 99.35 |
| | 15.00-18.00 | 0.17 | 0.70 | 0.85 | 5.00 | SW | 0.72 | 99.28 |
| 5. | 4.00-5.00 | 0.13 | 0.37 | 0.39 | 3.00 | SP | 3.50 | 96.50 |
| | 5.00-10.00 | 0.10 | 0.31 | 0.32 | 3.20 | SP | 2.83 | 97.17 |
| | 10.00-15.00 | 0.11 | 0.26 | 0.28 | 2.50 | SP | 2.03 | 97.97 |
| | 15.00-18.00 | 0.20 | 0.80 | 1.00 | 15.0 | SW | 4.00 | 96.00 |
| 6. | 10-18.00 | 0.13 | 0.18 | 0.19 | 1.50 | SP | 4.33 | 95.67 |
| 7. | 4.00-5.00 | 0.12 | 0.19 | 0.20 | 1.60 | SP | 1.83 | 98.17 |
| | 5.00-6.00 | 0.16 | 0.42 | 0.43 | 2.70 | SP | 1.50 | 98.50 |
| | 6.00-7.00 | 0.11 | 0.30 | 0.32 | 3.00 | SP | 0.55 | 99.45 |
| | 7.00-18.00 | 0.18 | 0.50 | 0.51 | 2.91 | SP | 2.33 | 97.67 |
| 8. | 4.00-5.00 | 0.08 | 0.18 | 0.19 | 2.58 | - | 1.80 | 98.20 |
| | 5.00-6.00 | 0.11 | 0.33 | 0.34 | 3.21 | SP | 2.00 | 98.00 |
| | 6.00-8.00 | 0.08 | 0.22 | 0.23 | 2.90 | SP | 2.57 | 97.23 |
| | 8.00-18.00 | 0.20 | 0.48 | 0.50 | 2.50 | SP | 1.89 | 98.11 |

D10 = Effective Particle Size D50 = Mean Particle Size CU = Coefficient of Uniformity USCS = Unified Soil Classification

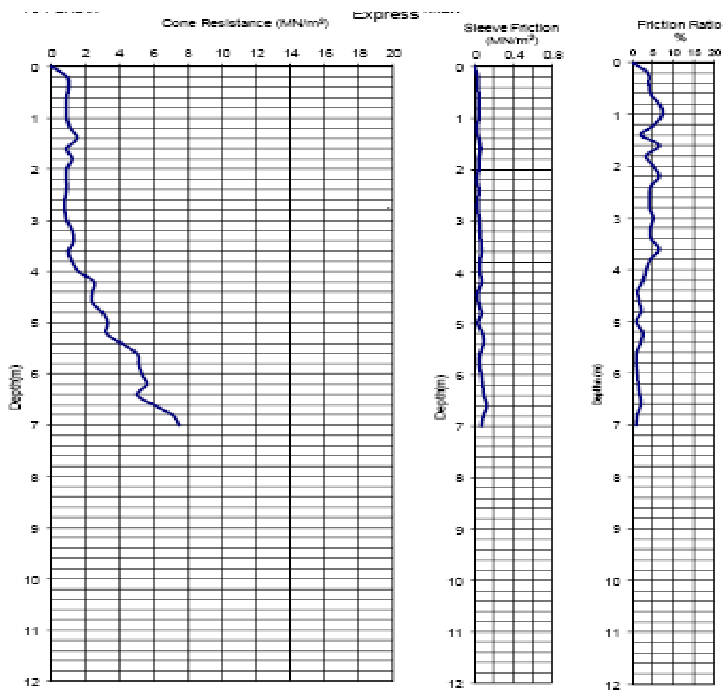



Figure 6: Typical CPT profile

The strength characteristics of the soils were evaluated in terms of triaxial test and insitu CPT test results. In line with expectations, the clayey soils have low to medium shear strengths and can therefore support load from light to medium structures without shear failure. For example the combination of relatively very low angle of internal friction ($2^{\circ}$-$3^{\circ}$) and cohesion (14-45kN/$m^2$) in NPA area portends low shear strength implying that piling may be imperative for medium to heavy structures to be founded in the dense sandy substratum underlying the sandy clay. This is in agreement with results obtained by other researchers on the soils in the Niger Delta (Akpokodje 1986 [16] & 1987 [18], Abam and Okogbue, 1997 [2], Ugbe, 2011 [6] ). Thus for proper planning, design, construction, maintenance and safety of civil engineering works, adequate and specific geological information is needed in view of the anisotropic engineering properties of soils in Warri area.

## 5 Conclusion

Integrated geophysical and geotechnical investigations in Warri area revealed three main sub-soil layers which are from top to bottom: greyish silty sand, brownish clayey/silty sand and sand. Analysis of foundation potentials using CPT results result revealed that the top soil has very low potentials while the underlying clayey /silty sand layer may be suitable substrata for light-small and medium civil engineering structures respectively. The deeper sand layer constitutes the best foundation substratum for medium to heavy structures owing to their high bearing capacities. The implication of the AASHO soil classification scheme is that the clayey/silty sand layers are suitable subgrade material for road construction but unsuitable for use as sub-base and base course material in pavement construction unless after appropriate stabilization. Results of this study constitute useful preliminary information and data required for future planning and infrastructural development in Warri area.

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