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Engineering Geology of the Niger Delta

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Abstract

The Niger delta, an area of roughly 30,000km^2, is experiencing physical development challenges due to poor soil conditions, a situation which has escalated project cost and as a consequence impeded development. This study has characterized the geomorphic sub-environments of the Niger Delta using geotechnical and geophysical indicators to define basic parameters for economical and preliminary front end engineering design. The geomorphic sub-environments, each with its distinctive mode of formation and geologic history exhibited characteristic geotechnical and geophysical properties. This study explores the variations in topography, groundwater level and geo-resistivity of the shallow horizon (0-10m) as well as geotechnical properties and their variation across the Niger delta region. Both geophysical and geotechnical field testing were mostly at 1km interval and along linear traverses stretching some 178km in the west and 190km in the east. The geotechnical properties investigated included undrained strength (derived from triaxial tests, CPT, Vane shear and Pocket penetrometer), natural moisture content, unit weight, and Atterberg limits. In general terms, the topography shows a gradual decent towards the coastal limit of the Coastal plain sediments, where it meets the Mangrove swamp sediments. The lower Niger flood plain sub-environment is distinctively lower in elevation compared to the coastal plain sand but higher than both the Mangrove swamp and Beach ridge. Results show that the geotechnical properties are a reflection of the geomorphic sub-environment. The water table is season dependent and varies across the Niger delta from 0m at the coast to 10m at the northern end. Apparent resistivity also varies across the geomorphic units with the largest values recorded in the Coastal plain sands. The mangrove swamp, apart from exhibiting the lowest apparent

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resistivity values shows a distinctive increase with depth between the 0-3m and that of 0-10m depth profiles because of the highly heterogeneous composition within this soil horizon in this area. Undrained strength values derived from CPT, Triaxial, vane shear and pocket penetrometer, all similarly showed characteristic variations across the geomorphic units, with the mangrove soils as the weakest (0-20kPa) with a high probability of sudden increase in firmness or soil progression to sandy units between 3m and 10m. The increase in undrained strength with depth between 0-10m, in the other geomorphic units on the other was attributed largely to normal consolidation with overburden pressure playing a leading role. Results of consolidation settlement analysis show the mangrove swamp as the most compressible with settlements of up to 180mm, followed by flood plain sediments and then the coastal plain sands in the more elevated areas for an incremental vertical load of 30kPa. Similarities in the patterns of spatial variability in geotechnical properties across the geomorphic units in both eastern and western segments of the Niger delta have been determined.

Keywords: Geotechnical properties, Apparent Resistivity, Geomorphic units, CPT, Niger delta

1 Introduction

The Niger delta is characterized by a network of rivers and creeks which drain the hinterland, transporting both water and sediments to the Atlantic Ocean. This process has created an extensive sedimentary region, roughly 30,000km^2 in area and populated by about 35 million inhabitants. The area is also rich in hydrocarbon resources, accounting for over 90% of Nigeria's GDP. The difficulty of physical infrastructural development was foretold by the British colonial government (Willink Minorities Commission Report (1957-58), who also advised the setting up of a special development commission, culminating in the creation of NDDC.

Some have ascribed the challenge of development to poor soil conditions, a situation which has escalated project cost and as a consequence impeded development (NDES 1995). Others feel and rightly so, that it has more to do with understanding the interplay of the geomorphology, geology and the engineering behavior of the soils in the region. The slow physical development of the Niger delta region has been a major reason for youth restiveness, with its ramified impacts on crude oil production levels, security, employment, etc. This study investigates the relationship between geomorphic units and the geotechnical behavior of soils, and goes further to determine trends in the geotechnical properties across the Niger Delta region.

Sediments originating from the vast catchment area and geologically complex hinterland (Fig. 1) are dispersed through the delta by rivers, tidal, wave, and ocean currents, forming the Late Quaternary Niger delta in the Gulf of Guinea.

Fig.1: Catchment area of the Niger delta

According to Allen (1965), Delta growth began during the Late Wisconsin lowstand of the sea when the rivers entrenched the continental shelf to reach mouths above submarine canyons at the shelf edge. The three major lithostratigraphic units in the Niger Delta underlying the superficial soils (Short and Stauble 1967) are from bottom to top the Akata, Agbada and Benin Formations. 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 Akata Formation is overlain by the Agbada Formation which consists of a sequence of alternating deltaic sands and shales. The principal interest in this formation is its hydrocarbon potential. 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 Benin Formation is overlain by various types of quaternary alluvial deposits comprising mainly of Recent deltaic sand, silt and clay of varying thickness, and spatially distributed as shown in Fig. 2.

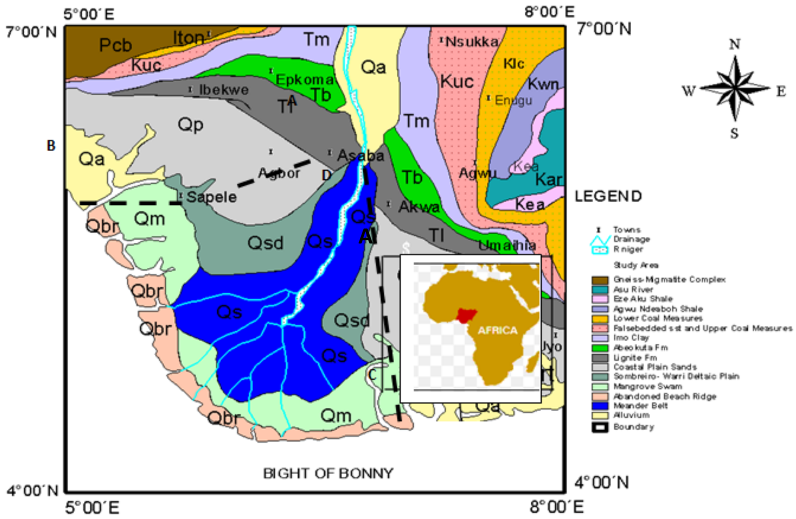


Fig.2: Distribution of Quaternary sediments in the Niger delta (NGSA-1978)

Allen (1965) identified the oldest stratigraphic unit of the Late Quaternary deltaic pile as the strand plain sand (Older Sands) representing a marine transgression into the hinterland. Later, in the Holocene, when sea-level became relatively stable, regressive advance across the sands of concentrically arranged delta environments gave rise to the Younger Suite, the uppermost stratigraphic formation in the deltaic lens. Lithofacies of this suite grade upward from open shelf clays, through pro-delta slope layered clays, silts, and sands, to well-bedded sands formed on the delta-front platform, river mouth bars, and beaches. Behind beach ridge/ barrier islands fringing the visible part of the delta occur tidal mangrove swamps in which organic-rich sands and silts are being deposited.

The Quaternary sediments which are the structural foundation materials in the Niger Delta were deposited in a wide variety of hydrologic conditions resulting in unique geomorphologic units (Fig. 3) which have rendered them both vertically and laterally heterogeneous in form and engineering properties. On the basis of similarity in geotechnical, geological and geomorphological characteristics, Akpokodje (1987) recognized four major superficial soil groups. Using purely geomorphic criteria as described by Allen (1965), six major geomorphic units can be identified, namely: Beaches and Barrier Islands, Mangrove swamp forests, Coastal plain sands, Warri-Sombreiro Deltaic plain, Lower Niger Flood plain and Niger flood zone.

From the engineering point of view, the Quaternary soils in the wetlands are generally described as low-bearing-capacity foundation materials (Avwenagha *et al* 2014). Thus their major engineering problems include low bearing capacity and differential settlement, vulnerability to flooding with high groundwater level resulting in water influx problems, poor drainage, high compressibility among others.

This paper therefore explores the geotechnical properties of Quaternary sediments in the various geomorphic units and determines their expected behavior under structural loading with a view to providing basic data that would guide future development and construction in the region.

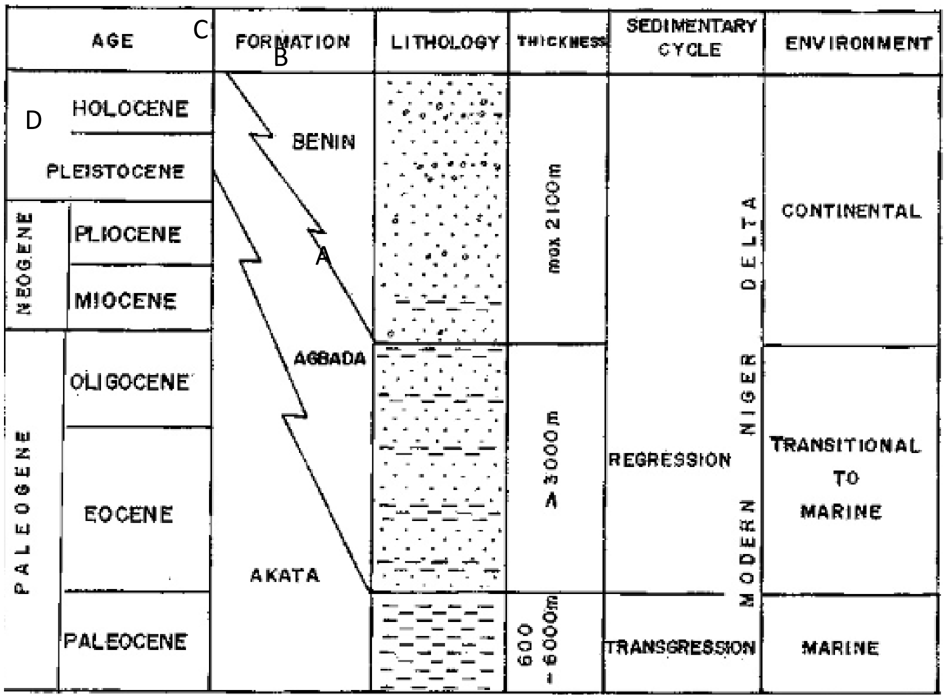


Fig.3: Vertical distribution of geomorphic units (Allen, 1965)

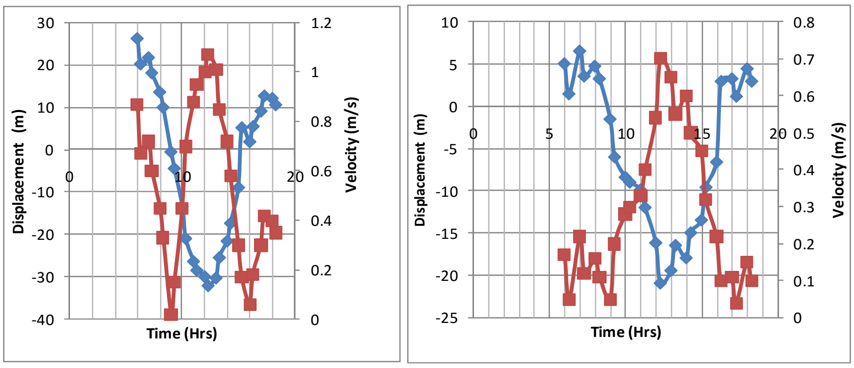
2 Methods of Investigation

This study utilizes both geophysical and geotechnical methods involving field testing and laboratory techniques. VES using Wenner electrode configuration to a current electrode of 50m was carried as part of the geophysical assessment (Keller, G.V and Frischnecht; 1970, Reynolds 1998). Boring using shell and auger percussion drilling to depths between 5m and 40m with in-situ SPT (Lee *et al*; 1983), mostly at 1km interval, along a linear traverse, stretching some 178km in the west and 190km in the east was carried out. The geotechnical properties measured or calculated included undrained strength (derived from triaxial tests, CPT, Vane shear and Pocket penetrometer), natural moisture content, unit weight, and Atterberg limits. The coordinates of each test point in XYZ format was captured with a GPS. Using this, the topography, groundwater level and geo-resistivity were reduced, relative to datum and interpreted in that context. The alignment of the principal test points in relation to the geomorphic units are shown in Figs. 2 and 3.

3 Results and Discussion

3.1Relief and Hydrometeorology

The relief is quite low, with elevation varying from 0m to 45m amsl, generally trending in a north-south direction; with Deltaic swamp complexes being the lowest. The mangrove swamp zone varies in width (1km to 45km) with the widest around the Bonny estuary. The mangrove swamps are subject to diurnal tidal inundations. Maximum spring tidal registration varies from 2.62m in Bonny to 1m in Lagos while the lowest is about 0.31m. The mean velocity in a vertical at the reference cross-section on a spring tide was 0.34m/s. However, tidal velocities vary across tidal cycle, sometimes with a peak of more than 1m/s as evident in Imo River (Fig. 4).



13/9/1987 **14/9/1987**

Fig.4: Variation in average tidal velocities and flow displacement in Imo River

While tidal velocities (aided by waves and currents) transport a variety of sediments and are responsible for coastal erosion, the predominant geomorphic process that regulates the landscape of the mangrove swamp area, tidal inundations, particularly, tidal range determines the vertical zone of influence of tidal velocities. The surface tidal diurnal inundations also extend their influence to the sub-surface groundwater level especially within the Barrier Islands, tidal swamps and sections of the freshwater swamp proximal to the coast, which also fluctuate during the tidal cycle. The variations in the groundwater level not only affects the geostatic stress within depths of engineering significance, but also the water balance of the areas, which accounts for how water is expended and the interactions among the different phases.

Rainfall in the area varies over a wide range in temporal context because of the occurrence of wet and dry seasons. Fig. 5 is a concurrent rainfall and evaporation level for the region to demonstrate the distribution of water in the sub-soil in terms of soil moisture deficiency around the study area.

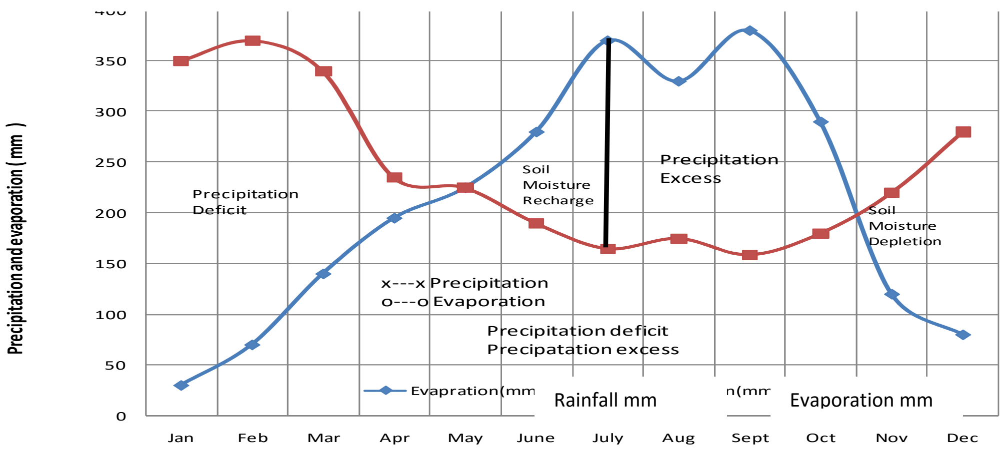


Fig.5: Rainfall and concurrent evaporation at Project area

Analysis of the components indicated that the amount of water entrained as runoff, infiltration and differential storage is comparatively small in relation to that taken up by evaporation.

3.2 Lithostratigraphy and Characteristics of Geomorphic Units

Earlier, the six major geomorphic units that comprise the Niger delta were identified. Observations of present-day hydrological processes give clue to the formation of these units. The lithostratigraphy of boreholes drilled in these geomorphic units in both east and west Niger delta (Fig.6) reveal the sequence of subsoils, relative thicknesses and persistence. Their geospatial locations and basic hydrologic and compositional make-up that affect pertinent geotechnical behavior, particularly strength, compressibility and permeability are described.

The **Barrier Island** also called Beach Ridge constitute the shoreline interface with the Atlantic Ocean and comprises well sorted uniformly graded fine sand, deposited and densified by wave and tidal action. Beneath the dense top sand is an alternating sequence of silty clay and fine sand up to 20m. Most Barrier Islands are receding due to active wave erosion. Groundwater level is usually close to the surface generally between 0 and 1.0m and subject to tidal fluctuation with a small phase difference.

The Mangrove swamps occur in tidal /estuarine zones and are submerged diurnally. They comprise very soft to soft, highly compressible clay rich in fibrous, partially decomposed organic matter and of medium to high plasticity. Although the soils are predominantly marine in origin, they contain substantial amounts of sediments derived from the redistribution of fluvially transported sediments. The soils are usually permeable because of the widespread presence of animal burrows or bioturbation.

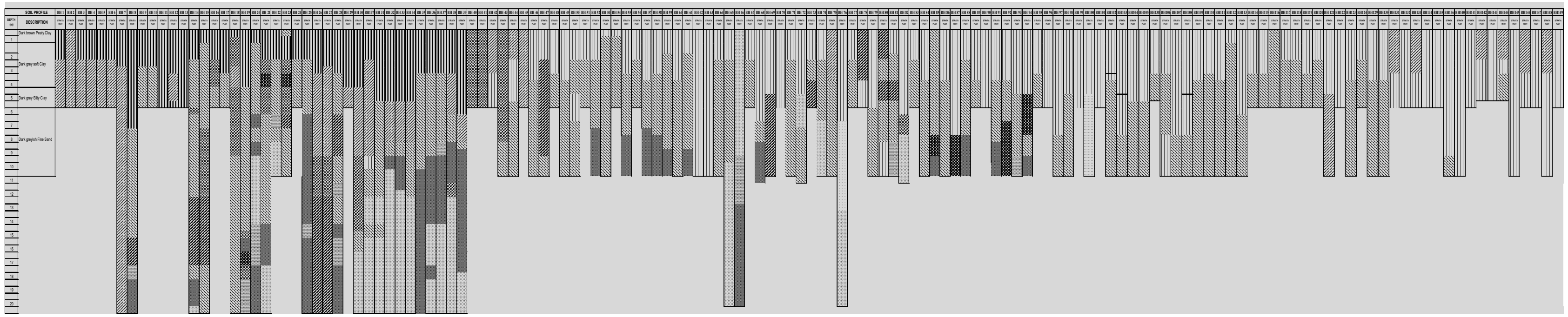
Coastal Plain sands occur in areas in which the groundwater level is at least 1.5m below ground surface and comprise mostly brown to reddish brown sandy clay. These soils are soft, firm and rarely stiff, with the top 1.5m usually subject to desiccation, reflected by undrained strength values that are slightly higher than normal. They are low to medium in compressibility with permeability generally higher than typical clay, between $1x10^{-6}$m/s to $1x10^{-9}$m/s.

Warri-Sombreiro Deltaic Plain is sandwiched between Orashi and Sombreiro Rivers in the east and Ethiope and Asse Rivers to the west and receives seasonal flood waters and sediments from these rivers. They are of slightly higher elevation than the Lower Niger flood plain and flood zone as well as the mangrove swamps but lower than the Coastal plain sands. The soil comprises of a top silty clay not more than 6m in thickness, underlain by medium sand. Groundwater level in this deltaic plain is generally between 0-5m. Comparatively, this plain is not as well drained as the coastal plain sand. The sub-soils are mostly of moderate plasticity.

Lower Niger Flood plain occurs around the upper section of the Niger delta with braided river channels and well defined levees. Sedimentation occurs in the backswamps, behind the levees in areas that seasonally flooded by river overflows in September/October and comprise of top clayey silt and silty sand covers that overlie fairly thick sand units (Fig. 7). A common feature of the particle size distribution is that whereas the D_{10} increased with depth, the mean particle sizes do not necessarily do the same. Abam *et al* (2014) had described soil litho-stratigraphy observed in Kaiama, Opokuma and Sabagreia to exemplify the formation of this flood plain. The water table in this area is usually close to the surface < 4m below surface. They retain flood water up to 1 mounts after annual flood recessions due to their low permeability. As in lateritic soils, surface soil layers are exposed to desiccation, but to a less degree. River bank erosion is a major geohazard in this geomorphic unit due to the rapid recession of flood water in the river channels.

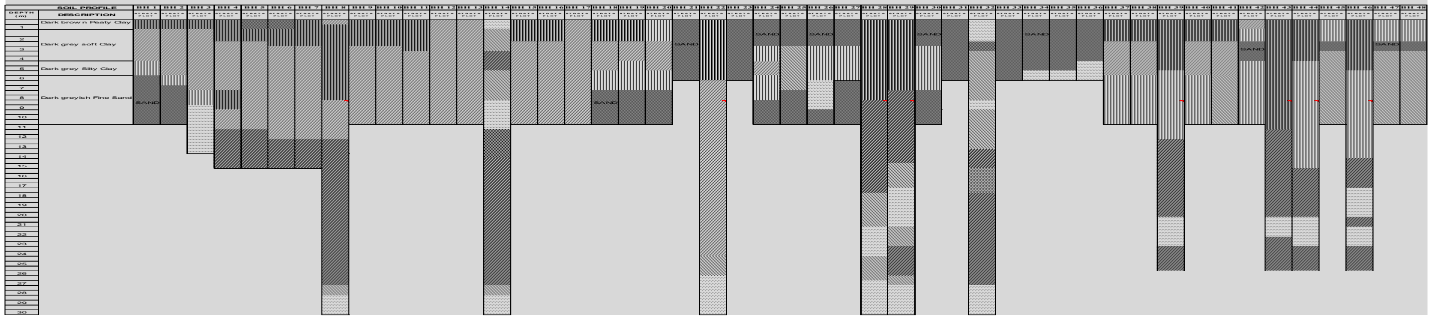
The **Niger flood zone** occurs at the lower part of the basin where the Niger River experiences meandering. It is for this reason, that the sediments in this zone are called **Meander belt** sediments. The sediments here consist mostly of silty clays and are derived from sediments transported in suspension by rivers in the mature stage. These sediments are more frequently flooded in comparison to the flood plain sediments because of their relatively lower elevation. The major geohazards here are flooding and erosion, accentuated by the combination of a dense network of river channels, relatively low elevation, rapid recession of flood water in river channels and widespread weak sediments.

A:Cawthorne Channel B:Obrikom



Eastern Niger delta litho-sequence

C:Omadino/Sapele D:Escravos



Western Niger delta litho-sequence

Fig. 6: Lithostratigraphy of boreholes in both eastern and western Niger delta

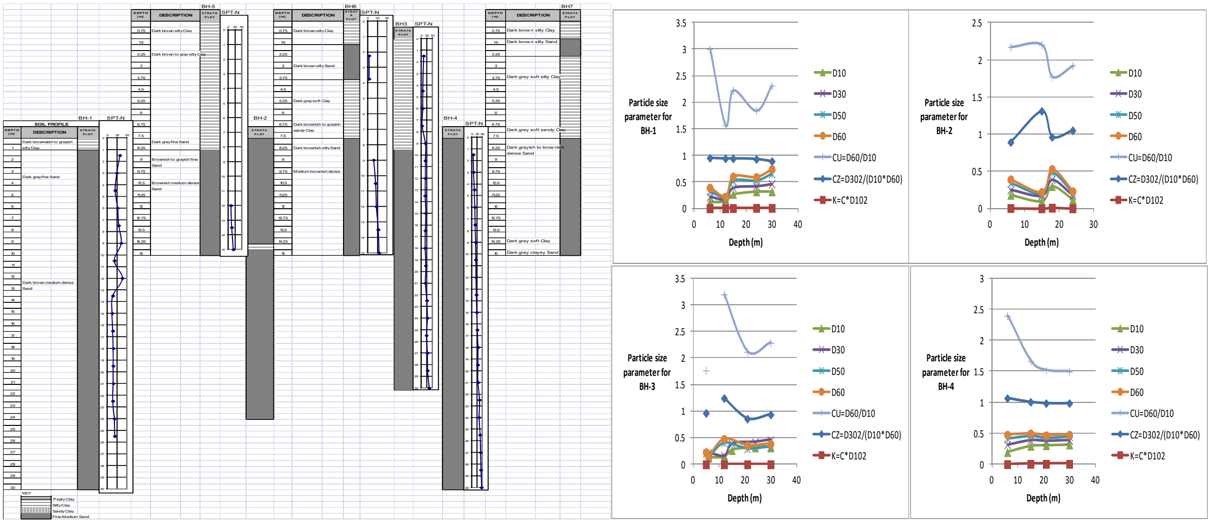


Fig. 7: litho-stratigraphy of boreholes and vertical particle variation at Opokuma (Abam *et al* 2014)

Groundwater

The water table in the area varies with season. Groundwater levels fluctuate in response to rainfall distribution in all but the mangrove swamp sub-environment. The groundwater level, although season dependent, also vary across the Niger Delta region (Fig.8). The variation of the groundwater level mimics the topography to a large degree.

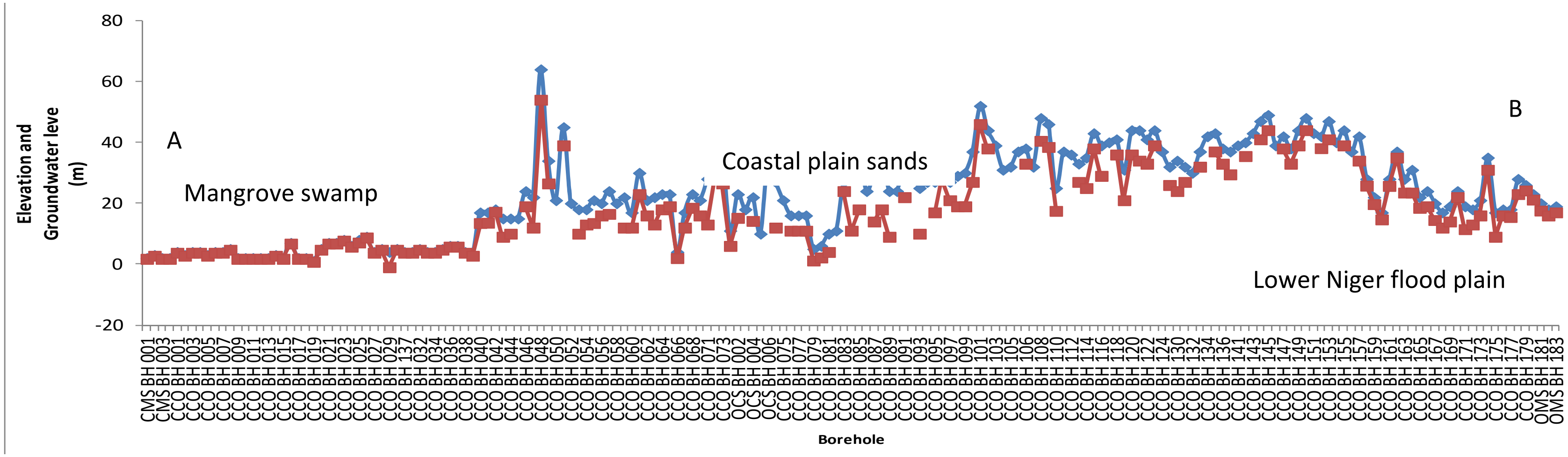


Fig. 8: Groundwater surface elevation along the traverse in the Eastern Niger delta

The maximum depths to groundwater (7-10m) are recorded in the more elevated freshwater. This is followed by the floodplain areas which recorded 0-5m, the Beach ridges 0-1.5m and the mangrove swamp areas with depth to groundwater between 0-0.5m. Historical data on the response of groundwater level to monthly rainfall distribution for the Eleme-Okochiri area behind the PortHarcourt Refinery Company show their seasonal variation (Fig. 9):

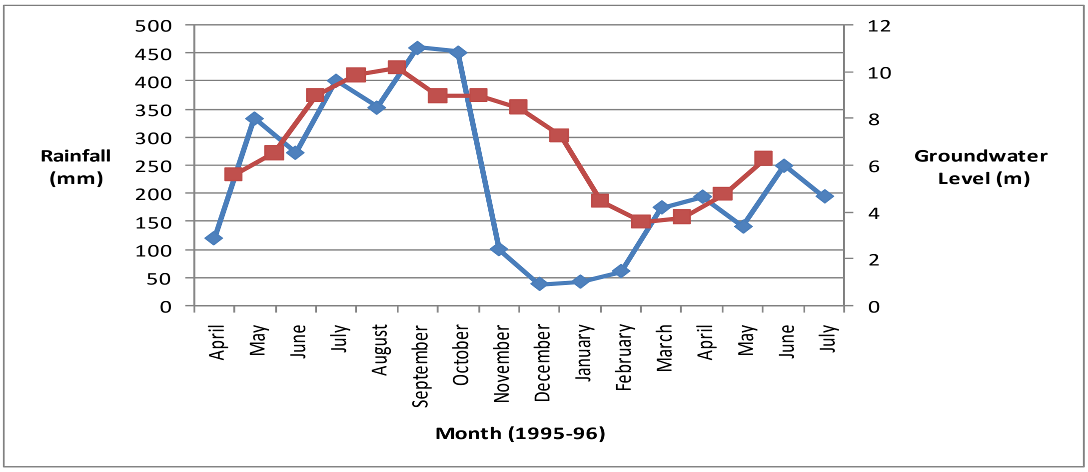


Fig. 9: Rainfall distribution and groundwater level response in the Niger delta

The water table is very close to the ground surface and varies from 0 to 10 meters. 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 overlies relatively thick clay which in turn overlies the regional aquifer resulting in perched aquifers. According to Offodile (1991), the hydraulic conductivities of the sand vary from 3.82×10^{-3} to 9.0×10^{-2}cm/sec indicating a potentially productive aquifer. Specific capacities recorded from different areas within this formation vary from 6700lit/hr/m to 13,500lit/hr/m. Groundwater recharge in the region is mainly by precipitation.

The topography of the vast area of the Niger delta (roughly 30,000km^2) varies from below mean sea level to 45m above mean sea level (Abam *et al* 2015), trending from north to south with an average gradient of 2.4×10^{-4}. Even as the topography has been described as generally gentle, there are undulations which can potentially disrupt the continuity of north-south trending runoffs. The top of the Benin Formation which underlies the quaternary sediments vary in a similar pattern. However, this pattern becomes more unpredictable in the mangrove swamp areas (Abam *et al* 2015). So also is the thickness of the overlying quaternary sediments, which are consistent in the freshwater areas (where they are between 5m and 10m) and less consistent in the mangrove swamp with thicknesses varying from 0-40m and possibly more.

Apparent resistivity values of the shallow horizon (0-3m) and (0-10m) across the geomorphic areas are presented (Fig.10). As expected, the lowest resistivities are recorded in the mangrove swamps with the combination of high salinity, high water level and preponderance of silty and organic clay, confirming earlier findings (Osakuni and Abam, 2004). There is also a distinctive increase with depth as shown by the difference in apparent resistivity between the 0-3m and that of 0-10m depth profiles. This difference is nonexistent in the other areas because of the near homogeneous composition of the soil and fairly consistent groundwater level.

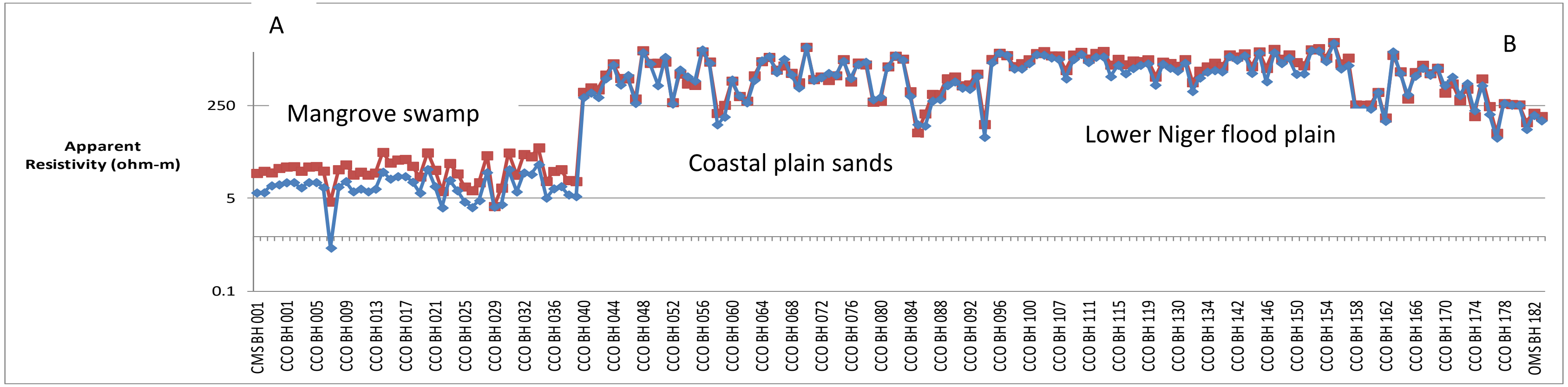


Fig. 10: Apparent Resistivity of surface layers (0-10m) along the traverse in the Eastern Niger delta

The variation in the geotechnical properties across the geomorphic units in both eastern and western Niger delta are presented in Figs. 11 to 17, and summarized in Table (1). The moisture content averages 23% in the coastal plain sand and increases to between 100% and 200% in the mangrove swamp areas. The bulk unit weight averaged 19.5kN/m^3 in the coastal plain sands and decreased to about 14.5kN/m^3 in the mangrove swamp areas. Similarly, the Liquid limit and Plasticity Index gave values of between 40-45% and 18-25% respectively for the coastal plain sand, while for the mangrove area they recorded between 60-200% and 55-120% respectively. On the basis of the plasticity chart (Fig. 11), Coastal plain sands classify as low to medium plasticity, while Mangrove swamp soils classify as medium to very high. The wide distribution of the plotted points is reflective of variety of sediment sources in this area.

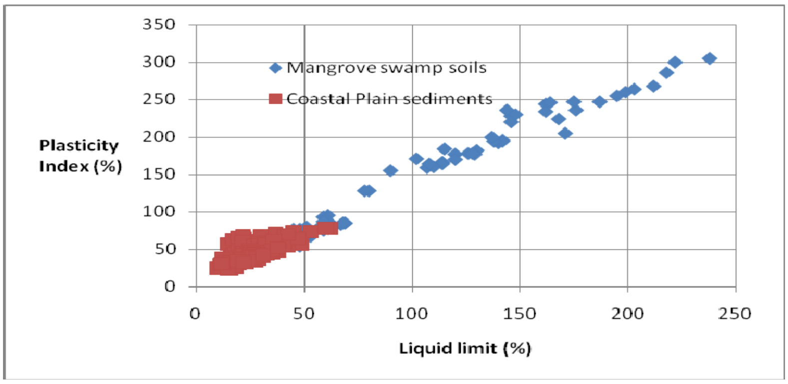


Fig.11: Plasticity chart for Coastal Plain and Mangrove swamp sub-soils

The undrained strength values were determined by four methods. Undrained strength values derived directly from Cone Penetration Tests results were based on the well established relationships (Robertson and Campanella 1983, Hisham & Timothy 1998 and Tomlinson; 1999):

$$C_u = \frac{q_c - \sigma'_{vo}}{N_k}$$

Where

$q_c - \sigma'_{vo}$ = net cone resistance

A cone factor N_k of 17.5 applicable to the Niger delta soils (EGA and Abam 2004) was utilized.
The undrained strength with the coastal plain sediments averaged 50kPa while for the mangrove swamps it was 12kPa. The computed undrained strength values were averaged for 0-3m and 0-10m and plotted along the selected traverse. The results clearly show the mangrove soils as the weakest, with undrained strength range of 0-20kPa with a high probability of sudden increase in firmness or soil progression to sandy units between 3m and 10m. The increase in undrained strength in the other geomorphic units on the other is attributed largely to normal consolidation with overburden pressure playing a leading role.

Although the undrained strength values measured in the triaxial tests and by Vane shear and Pocket penetrometer were not necessarily within 10m depth, it is evident that all methods of undrained strength determination show the soil in the mangrove swamp as by far the weakest followed by those of the flood plain and subsequently the freshwater areas with more elevated lateritic soils. The undrained strength profile within the mangrove swamp. The natural moisture content, unit weight, and Atterberg limits. Although, in general terms, the topography shows a gradual decent towards the coastal limit of the Coastal plain sediments, where it meets the Mangrove swamp sediments, some undulations occur. The flood plain sub-environment is distinctive lower in elevation compared to the coastal plain sand but higher than both the Mangrove swamp and Beach ridge.

The bearing capacity values have been computed using undrained strength derived from CPTs and averaged between 0-3m and 0-10m depth. In the same vein the consolidation settlement was assessed for a net foundation load of $\boldsymbol{\Delta\sigma = 30}$kPa corresponding to the loading of a fully loaded pipeline, using the basic relationships:

$$S = m_v \cdot \Delta\sigma \cdot H_0$$

Where s = total settlement
Ho = thickness of compressible layer
m_v = coefficient of volume compressibility
$\Delta\sigma$ = increase in vertical stress due to applied pressure

Consolidation settlement was then predicted from the summation of the vertical strains at an interval of 20cm caused by the foundation load in line with de Beer and Martens (1957) and Smith, and Pole (1980) in which Constant of compressibility, $C_s = 1.9\ C_r/Po_1$

Where Cr = static one resistance (kN/m^2)
Po_1 = effective overburden pressure at point tested.

$$\text{Total immediate settlement, } p_i = \frac{HLogeP_{o_2} + \Delta\sigma_z}{C_s P_{o_2}}$$

Where $\Delta\sigma_z$ = vertical stress increase at the center of the consolidating layer of thickness H.
Po_2 = effective overburden pressure at the center of the layer before any excavation or load application.

The resulting consolidation settlement along the selected traverse is plotted (Fig. 13). The results show the mangrove swamp as the most compressible with settlements of up to 180mm, followed by flood plain sediments and then the lateritic soils in the more elevated areas for an incremental vertical load of 30kPa.

The spatial variation in geotechnical properties across the geomorphic units in the western segment of the Niger delta (Fig. 14) appears similar to the pattern in the eastern segment. Since bearing capacity is a function of undrained strength, it is no surprise that the bearing capacity profile across the geomorphic units has a similar pattern with the undrained strength (Fig.17). The computed range of values of the bearing capacity and CBR for the various geomorphic units are summarized in (Table 1),

Table (1) Summary of Geotechnical properties for geomorphic units

Geomorphic Units	**Depth (m)**	**Bearing Capacity**	**California Bearing Ratio CBR**	**Undrained Strength UU (kPa)**	**Unit Weight (kN/m^3)**	**LL (%)**	**PL(%)**	**PI(%)**	**Moisture Content WC(%)**
Mangrove Swamp	0-3 0-10	5-30 30-100	1-2 1.5-6	12 55	14-16	55-300	20-80	50-220	50-90
Coastal Plain sands	0-3 0-10	10-150 150-250	3-5 10-20	50 120	17-20	35-50	10-25	17-25	12-27
Lower Niger Flood	0-3	60-110	3-5	35	16.8-20	35-49	9-20	10-23	18-25

Plain	0-10	120-230	8-15	110					
Barrier Island	0.3 0-10	100-180 125-280	6-16 8-30		17-21 18-22				11-18
Niger flood zone (Meander Belt)	0-3 0-16	20-80 40-150	1-6 2-8	8-63	12-18.4	35-174	11.5-45	11.7-113	38-430

Overall, the percentage clay, silt and organic contents increase seawards but for the Barrier Island which consists mostly of fine sand. The geotechnical properties are influenced by the relative proportions of sand, silt and organic matter.

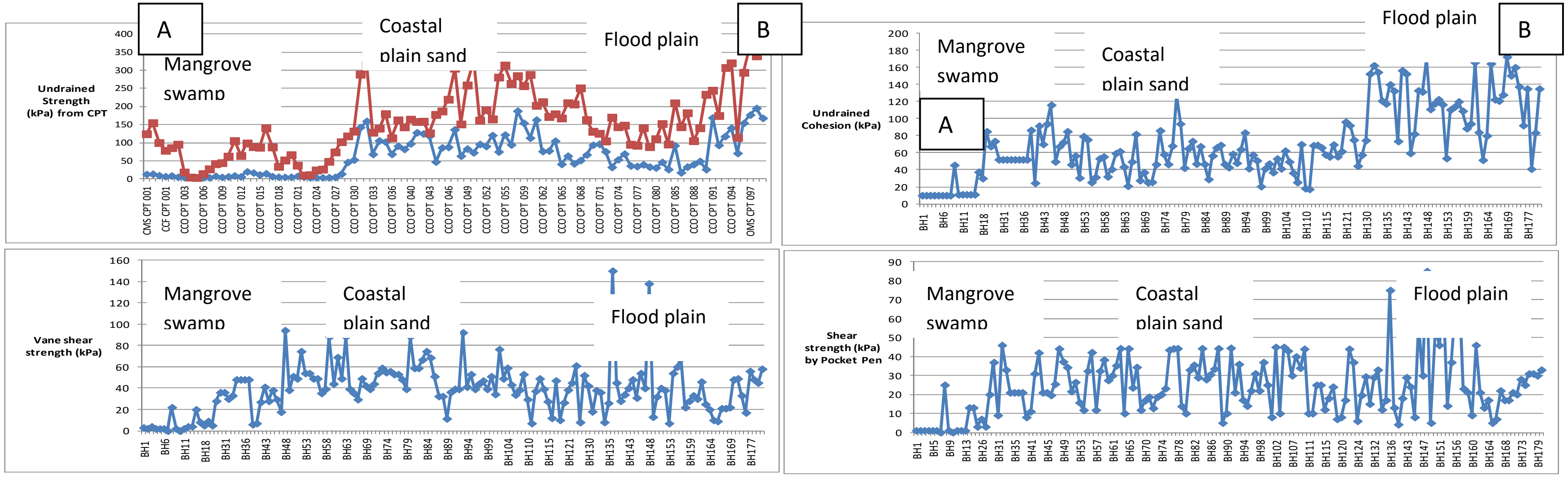


Fig. 12: Average undrained strength (0-10m) from CPT, Triaxial test, Vane and Pocket Penetrometer along the traverse in the Eastern Niger delta

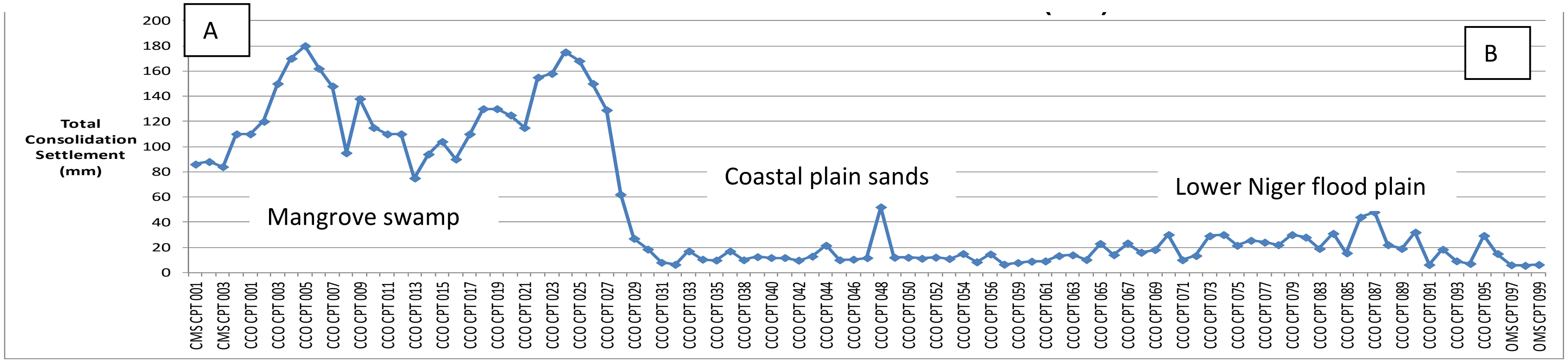


Fig. 13: Predicted Total settlement from CPT for stress increment of 30kPa along the traverse in the Eastern Niger delta

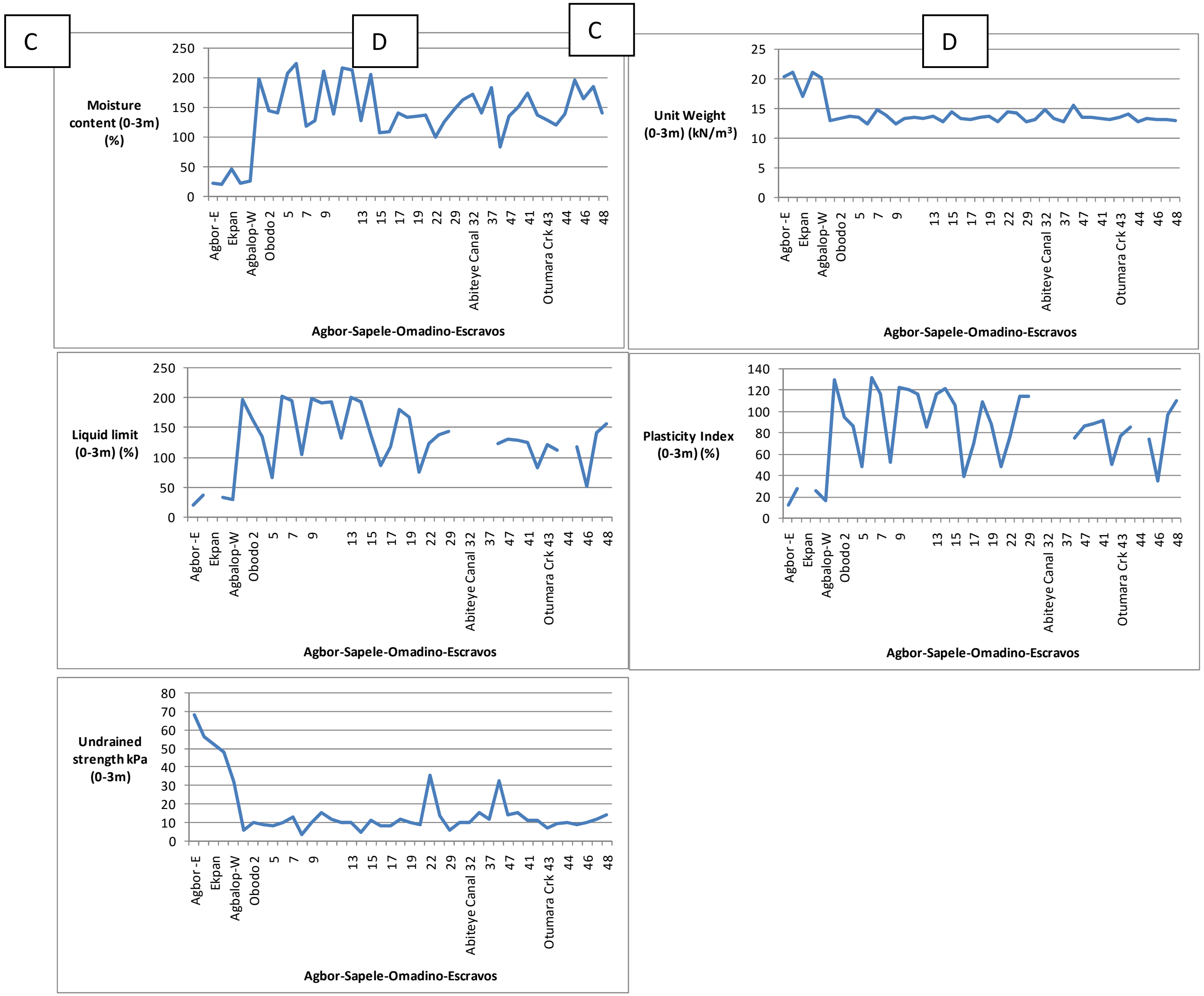


Fig. 14: Geotechnical properties along the traverse in the Western Niger delta

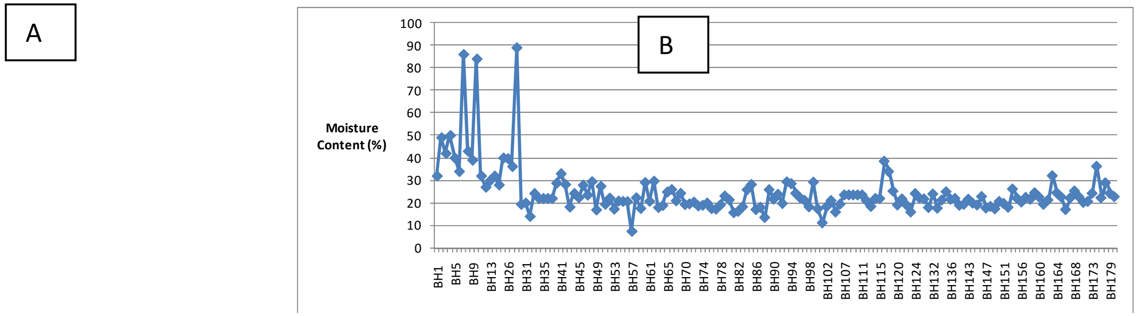


Fig. 15: Variation of Moisture content along the traverse in the Eastern Niger delta

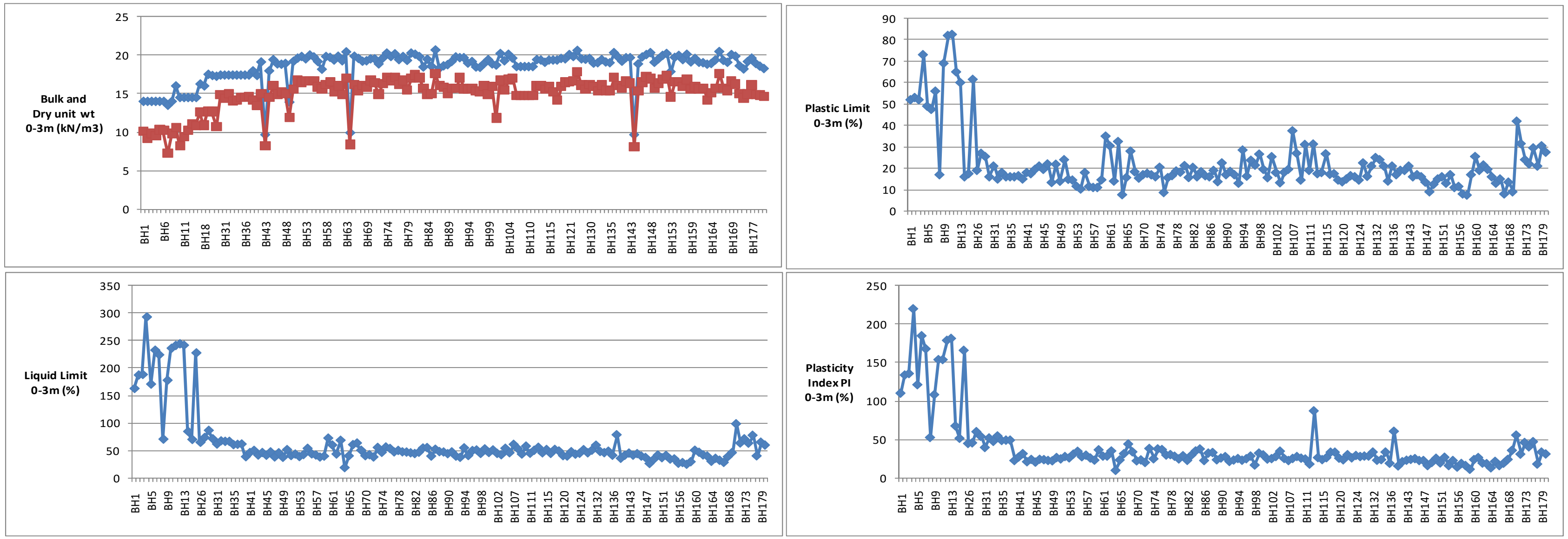


Fig. 16: Bulk unit weight and Atterberg's limits along the traverse in the Eastern Niger delta

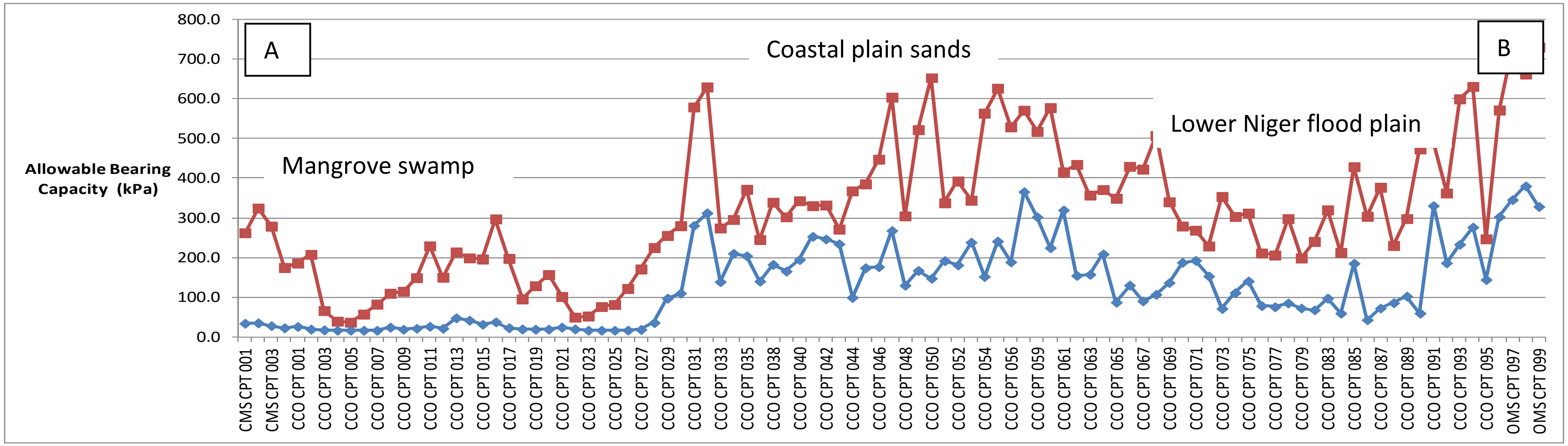


Fig. 17: Allowable Bearing Pressure along the traverse in the Eastern Niger delta derive from CPT

4 Conclusion

The geomorphic sub-environments of the Niger delta which are differentiated by their mode of formation and geologic history exhibited characteristic geotechnical and geophysical properties. The topography is not as flat as had been described as some undulations with geotechnical engineering significance occur. The water table is season dependent and at the same time varies across the Niger delta region. Similarly, Apparent resistivity also varies across the geomorphic units with the largest values recorded in the lateritic soil of the freshwater units. The mangrove swamp exhibited the lowest apparent resistivity values at depth between the 0-3m but these are often rapidly increased between 3-10m depth because of the highly heterogeneous composition within this soil horizon in this area. Undrained strength values derived from CPT, Triaxial, vane shear and pocket penetrometer, all similarly showed characteristic variations across the geomorphic units, with the mangrove soils as the weakest. In most cases, undrained strength increased with depth between 0-10m in all the geomorphic units as a result of normal consolidation. The mangrove swamp remains the most compressible geomorphic unit in the Niger delta. There are similarities in the patterns of spatial variability in geotechnical properties across the geomorphic units in both eastern and western segments of the Niger delta.

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