Integrated Geophysical and Geotechnical Characterization of the Nigerian Coastal Beach Ridges in Lagos, Brass, Bonny and Eket

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Abstract
Beach ridges and barrier islands along the Nigerian coastline are a critical geomorphic unit which serve as foundation for several significant engineering structures, yet their geotechnical behavior remains unevenly characterized. This study synthesizes existing sedimentologic, geotechnical, and geophysical data to characterize the engineering properties of Nigerian beach-ridge and barrier–island systems, with emphasis on the barrier–lagoon complex of Lagos, Brass, Bonny and Eket. The study identified hidden, shallow, incompetent, and highly compressible plastic clay/peat layers beneath the predominant seemingly stable sand, which can lead to significant consolidation settlement or building collapse. The near-surface sediments reveal poorly graded sands or silty sands, with high natural moisture content, low plasticity, moderate to high hydraulic conductivity, and decreasing relative density and relative compaction within the depth of significance to shallow foundation construction. Grain-size analyses from multiple barrier beaches indicate predominantly fine sands that are moderately to well sorted, reflecting moderately high wave-energy swash and backwash processes and indicating high susceptibility to coastal erosion. Integrated geophysical–geotechnical approaches have proven effective in mapping these contrasting strata and in estimating relative density and compactness, compressibility and settlement distribution and suitable foundation depths. This study further shows that a sandy top of thickness 3.5m can present an average safe bearing pressure for shallow foundation of 100kN/m^2 and that satisfactory foundation performance may be expected, provided the bearing resistance of the soil at 3.5m depth is not less than 10% of the structural load placed on the surface. The combined evidence indicates that while Nigerian beach ridges and barrier islands often provide adequate near-surface materials for light to moderate structures, careful site-specific characterization is essential to account for underlying soft sediments, shoreline erosion, and associated geohazard risks.

Keywords: Geotechnical, Resistivity, Characterization, Beach Ridges, SPT(N), Relative density, Compaction, Compressibility

Introduction

Coastal beach ridges in Nigeria host and serve as foundations for storage tanks, pump stations, pipelines and other important infrastructure for the petroleum industry. Beach ridges and barrier-ridge systems are typically unconsolidated, low-lying, and highly erodible, so failing to characterize them properly before development or hazard planning can lead to multiple risks. This is especially the case for oil and gas infrastructure which have rigid skid systems that are sensitive to foundation settlement. For example, the stability of storage tank, pumps and pipelines, depend on shear strength, density, drainage and layering of near-surface beach soils (White *et al.,* 2015), while high salinity, shallow groundwater and tidal flooding can make soils highly conductive and severely corrosive. In such cases, according to Abam & Ngah, (2014) resistivity surveys along an onshore pipeline route are required to quantify the extent of corrosivity and guide cathodic protection (CP) and groundbed design. Geo-electric characterization therefore provides baseline data to size CP systems, select coatings, and place anode beds to avoid interference with existing systems. Consequently, understanding their geological and geotechnical characteristics is crucial for the satisfactory performance of this infrastructure during their service life.

According to Ishola *et al.,* (2022) and Adamu et al., (2024) geotechnical and geo-electric characterization of beach ridges provide insights into shallow subsurface conditions and potential construction challenges. The integration of geotechnical and geophysical technics combines the complimentary perspectives of both methods and therefore enhances the understanding of these structures, ensuring safer and more effective construction practices. Okiotor *et al.,* (2023) relied on geological properties of beach ridges in the identification of potential risks, such as subsidence or instability, which can affect structural integrity. Oladunjoye, etal (2024) and Olatinsu, et al., (2025) on the other hand have used multi-parameters and multi-technique approaches to assess soil liquefaction potential as well as suitability for construction in barrier lagoon and wetland areas of Lagos, Southwestern, Nigeria.

Several researchers (Oyeyemi, et al., 2020, and Beličević, 2024) employed the integration of geological data with engineering practices to ensure that construction projects are designed to withstand environmental changes and geological challenges. Okiotor (2023) on the other hand investigated the geological structure beneath Okerenkoko Primary School, identifying four geoelectric layers, including unstable peat/clay/sandy clay. This characterization is crucial for assessing site suitability for civil construction and understanding subsurface conditions affecting structural integrity. Oyeyemi *et al.,* (2020) on the other hand conducted subsoil characterization using a combination of geotechnical and geophysical tests, revealing lithological units of loose silty sand and compacted clayey sand, which are crucial for determining suitable foundation types for civil construction, particularly pile foundations. Similarly, geotechnical techniques were used to characterize near-subsurface geomaterials in Lagos, identifying lithologies like loose sand and clay/peat, which are crucial for assessing foundation stability in civil construction projects (Oyeyemi et al 2016). Table (1) provides a summary of the dominant material and the engineering behaviour of the beach ridge at different locations within the Nigerian coastline based on reports of various geotechnical investigations.

Table 1 Beach location, dominant material and engineering behavior along Nigerian coasts.

Sub-region / unit	Dominant material & behaviour	Engineering / coastal implication
Lagos barrier–lagoon beaches	Fine–coarse, moderately–well sorted sands	Erosion-prone where finer; supports typical shallow foundations
Brass beach	Poorly graded sand, medium to very high permeability,	Good road subgrade; highly permeable aquifer
Bonny beach	Poorly graded sand, very high permeability,	Good road subgrade; highly permeable aquifer
Andoni barrier–beaches	Fine–Medium, moderately–well sorted sands	Erosion-prone where finer; supports typical shallow foundations
Eket beach	Poorly graded sand, medium to high permeability,	Good road subgrade; highly permeable aquifer

According to Otvos (2000), Taylor and Stone (1996) Beach ridges are relict semi-parallel, multiple wave- and wind-built landforms that originated in the inter- and supratidal zones formed through sediment deposition and represent ancient shorelines, providing a record of coastal evolution during the Quaternary period. Beach ridges are relatively stable features at the landscape scale (centuries–millennia), but their construction and internal architecture are highly dynamic, responding to waves, storms, tides, and sediment supply on time scales from individual events to decades (Allen 1965). From a regional coastal morphodynamic perspective, barrier–lagoon and beach-ridge coasts along the Bight of Benin are simultaneously shaped by wave climate, alongshore sediment supply disruptions, local subsidence and intense human modification, resulting in widespread erosion and flooding hazards (Leknettip et al., 2025). The resultant changes to the shoreline have been documented severally (Adegoke et al 2010, Obowu and Abam 2014, Dada et al., 2016). Studies have shown that these ridges can reach significant thicknesses (Johnston et al., 2002), with depositional units identified through Ground Penetrating Radar (GPR). Abam (2016) described the Beach Ridge as constituting the shoreline interface with the Atlantic Ocean in the Niger delta as evident in Fig (1) and comprises well sorted uniformly graded fine sand, deposited and densified by wave and tidal action.

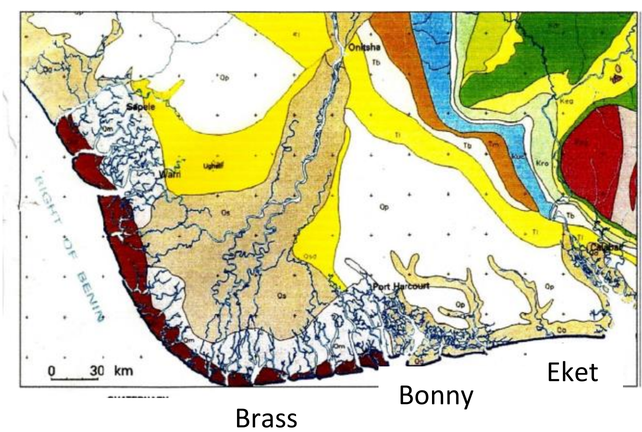

Figure 1: Geological map of the Niger Delta (Reijers, 2011)

Beneath the dense top sand is an alternating sequence of silty clay and fine sand up to 50m. Most Barrier Islands are receding due to active wave erosion associated with breaking waves on the exposed shorelines. These breaking waves aside from playing significant role in the longshore transport of massive amounts of sand, they can also generate localized rip currents which intensify erosional action. The intensity and height of these waves vary seasonally, with stronger, more energetic waves occurring during the wet season (May to October) and calmer conditions during the dry season (Dada et al., 2016). Steeper, coarser-grained beaches, like those around Lagos, foster plunging breakers, while gentle, low-gradient beaches as in Bonny tend to have spilling breakers. Coastal engineering projects like port construction can interfere with longshore sand transport and significantly alter the coastline. Sea-level rise and increased wave run-up exacerbate coastal erosion and flooding events in settlements along the Nigerian coastline. It follows therefore that while beach ridges offer valuable geological insights, their dynamic nature and susceptibility to erosion and climate change pose challenges for long-term civil engineering projects.

Methods of Investigation

Both geophysical and geotechnical methods are described in this section. The Geophysical Approach involves field resistivity measurements along pipeline route under using calibrated Terameters, equipped with a digital microprocessor and classifying the layers based on their corrosivity (Table 2). The investigation utilized the Wenner electrode configuration of the Vertical Electrical Sounding (VES) technique, which is well-suited for shallow subsurface profiling and is particularly effective in evaluating near-surface soil corrosivity along linear infrastructure such as pipelines.

Table 2: A correlation of soil resistivity with soil corrosivity (Safeway, 2018)

Resistivity (Ohm.m)	Corrosivity Rating
< 10	Extremely Corrosive
10 - 30	Highly Corrosive
30 - 50	Corrosive
50 - 100	Moderately Corrosive
100 - 200	Mildly Corrosive
> 200	Non-Corrosive

In this study, twenty-eight (28) shallow electrical resistivity measurements were acquired along a 14.0 km segment of the Beach ridge. Since the investigation was concerned with depths of engineering significance, a total electrode spread of 30 meters was adopted, providing an effective depth of investigation for pipelines that are buried between 1.5m and 5m. In general, the measured apparent resistivity value corresponds to the average resistivity of the soil at a depth roughly equivalent to 30% of the total current electrode separation. For instance, if the outer (current) electrodes are spaced 20 meters apart, the estimated investigation depth is approximately 6.0 meters.

Additionally, deep resistivity sounding using the Schlumberger array configuration was conducted at strategic well sites to investigate subsurface resistivity profiles down to depths above 60 meters. These measurements are essential for the placement and design of deep well anode ground beds: a critical infrastructure component for long-term and large-scale cathodic protection of high-value buried assets. This method enables the mapping of subsurface resistivity variations that are influenced by the density, porosity, and salinity of the geologic materials, all of which affect the electrical conductivity of the ground. These properties are critical when evaluating potential locations for deep anode groundbeds in cathodic protection design, as they influence anode performance and system longevity.

The geotechnical approach involved borings using the light shell and auger hand rig. During the boring operations, both disturbed and undisturbed samples were regularly collected at depths in consonance with EN ISO 22475-15. All samples recovered from the boreholes were examined, identified and roughly classified in the field in line with EN ISO 22475-15 Parts 1&3. Standard Penetration Tests (SPT) were performed every 1.5m advance through cohesionless soils since it is widely considered suitable and effective for evaluating the geotechnical properties of granular materials (Kumar etal 2016), particularly because it is often the only available method to obtain samples and determine relative density in cohesionless soils. The main objective of this test is to assess the relative densities of the cohesionless soils penetrated. The SPT data was corrected for dilatancy according to Terzaghi and Peck (1969) using the equation: $N_{corrected\ for\ dilitancy}$=15+0.5*(C3-15) before deriving other geotechnical parameters using empirical relationships.

The parameters derived from the SPT(N) included Relative Density, Relative Compaction and Angle of Internal friction. The empirical relationships used to derive Relative density was: Relative Density RD (%) = $(N_{cor}*((0.23+0.06/0.36)^{1.7})/9*(98/(Z*9)))^{0.5}*100$.
Using Lee & Singh (1971), Relative Compaction (γ_d/γ_{max}) (%) was evaluated as:
Relative Compaction = 80+0.2*RD

The Angle of Internal Friction (Deg) was derived using Dalai & Patra (2019) $=8.103*N_{cor}^{0.458}$
An alternative approach using Shioi and Fukui (1982) where angle of internal friction is given as $=3.5*(E3)^{0.5}+21$ was also explored for comparison purposes:

Cone Penetration Testing (CPTU)

The geotechnical investigation also involved the use of hydraulically operated, GMF type, Electric piezocone penetrometer of 200kN capacity in the cone resistance soundings. Continuous sounding procedure was adopted in the test. The Cone Penetration Tests were driven to refusal.

Geotechnical Laboratory Testing

Furthermore, geotechnical laboratory tests were carried on the samples recovered from the borings. The tests were performed strictly in accordance with the Eurocode 7 and British standards (BS 1377 of 1990). These tests include natural moisture content, unit weight, liquid and plastic limits and grain size distribution by dry sieve and hydrometer. In addition, direct shear test, quick undrained unconsolidated as well as consolidated undrained triaxial tests, and 1-dimentional oedometer consolidation tests were performed.

Computed Geotechnical Parameters

Geotechnical parameters to support foundation design within the beach ridge were computed including bearing resistance and settlement

Bearing Capacity Computations and Analysis

The bearing capacity of beach sediments was assessed from two perspectives, namely computing allowable pressure for C & Ø soils from Terzaghi's ultimate net bearing capacity equation and as net allowable bearing pressure for 25.4mm settlement for sandy units. The ultimate net bearing capacity q_n of a shallow foundation was calculated using the relationship:

(for strip) $q_{nu} = CN_c + P_o (N_q) + 0.5\gamma BN_\gamma$

where: γ = the bulk density of the soil below the foundation level
C = the undrained shear strength of the soil
P_o is the effective overburden pressure at the foundation level
N_c, N_q, N_γ = Terzaghi's bearing capacity factors obtained from charts

While computation of the net allowable bearing pressure for 25.4mm settlement relied on Bowles (1977) who modified Meyerhoff (1956) equations using SPT(N) values to:

$$q_{\text{all(net)}}\,(\text{kN/m}^2) = 11.98 N_{\text{cor}} \left(\frac{3.28B + 1}{3.28B}\right)^2 F_d \left(\frac{S_e}{25}\right) \qquad (\text{for } B > 1.22 \text{ m})$$

where F_d = depth factor = $1 + 0.33(D_f/B) \leq 1.33$
S_e = tolerable elastic settlement, in mm

Values of the net allowable pressure were computed using the above equation for q_c values averaged within the top 10m. Undrained strength values were derived directly from Cone Penetration Tests results based on the well-established equation as described by Tomlinson (1999):

$$Cu = \frac{q_c - \sigma^1{}_{vo}}{N_k}$$

Where

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

N_k = Cone factor = 17.5

Using combinations of these relationships, the ultimate bearing pressures were obtained for various foundation depths, footing widths and aspect ratios (L/B). Safety factors of about 3.0 are applied to the ultimate bearing pressures to obtain the maximum safe pressures of the soil.

Settlement of Foundation

Soil compressibility was assessed from both results of oedometer and CPT tests. Immediate settlement was evaluated based on the elastic theory, while consolidation settlement relied on the relationships as described below using results from both oedometer and CPT:

$$S = m_v.\Delta\sigma.\ H_o$$

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

Prediction of the settlement is made from the summation of the vertical strains caused by the foundation load. The soil beneath the foundation is divided into layers and the coefficient of volume compressibility m_v is obtained for each layer. For clays the m_v value is obtained from the oedometer results.

The method of prediction generally used is that proposed by de Beer and Martens (1957) and Meyerhoff (1965):

$$\text{Constant of compressibility, } C_s = 1.9\ \frac{C_r}{Po_1}$$

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

$$\text{Total consolidation settlement, } p_i = \frac{H}{C_s} \text{Loge} \frac{Po_2 + \Delta\sigma_z}{Po_2}$$

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.

These relationships were reliably used to estimate settlement.

Deformation Properties

The soil's moduli were derived from established empirical correlations. For the cohesive materials it was deduced from the undrained shear strength while the SPT blow count was used to obtain modulus of the sand formations (Bowles 1997). Also derived were the Poisson's ratio and shear modulus.

Results and Discussion

Sample results of curve matching for the profiling as well as for the deep groundbed are presented in Figs. (2 and 3). Table 3 is also sample of summary interpreted of geo-electric layers, depth, thicknesses and corrosivity rating for soils at all sounding locations. A sample ground model of the VES output for deep groundbed is presented in Fig (4) showing the significant occurrence of silty clay soil to serve a possible groundbed horizon for the optimum cathodic protection of an oil and gas asset. Similarly, a linear surface topography of the profile alignment was captured (Fig.5) so that the ultimate geo-electric ground model or tomograph can be corrected for elevation to aid the decision of depth of pipeline placement. Figure 6 is the result of the generated geo-resistivity section across the survey profile alignment for a pipeline case study within the project area, synthesized with elevation corrected to reflect the natural topography. The horizons of low resistivity coincide of shallow occurrences of clay and groundwater table and swampy zones surrounding creeks.

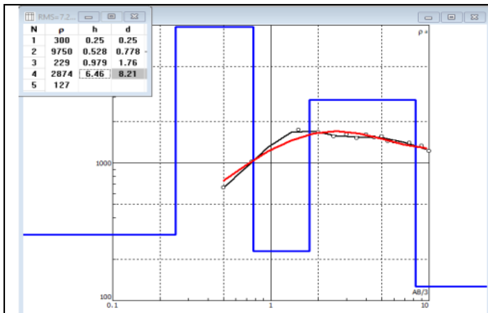

Fig. (2) 1-D resistivity curve for (EE1)

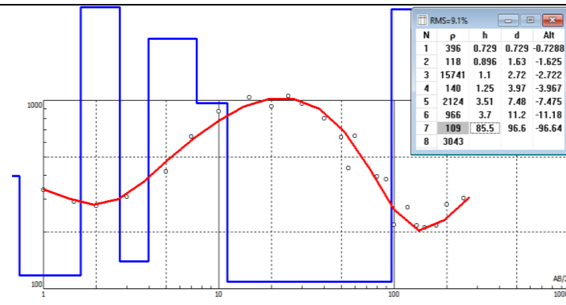

Figure 3: 1-D resistivity curve obtained from interpretation of field acquired groundbed data (V1)

Table 3: Results of soil geoelectric layers and associated corrosivity ratings

ERT NO.	Layer	Resistivity **Ohm.m**	Thickness **m**	Depth range **m**		Corrosivity
EE1	1	300	0.25	0	0.25	Non-Corrosive
	2	9750	0.528	0.25	0.778	Non-Corrosive
	3	229	0.979	0.778	1.76	Non-Corrosive
	4	2874	6.46	1.76	8.21	Non-Corrosive

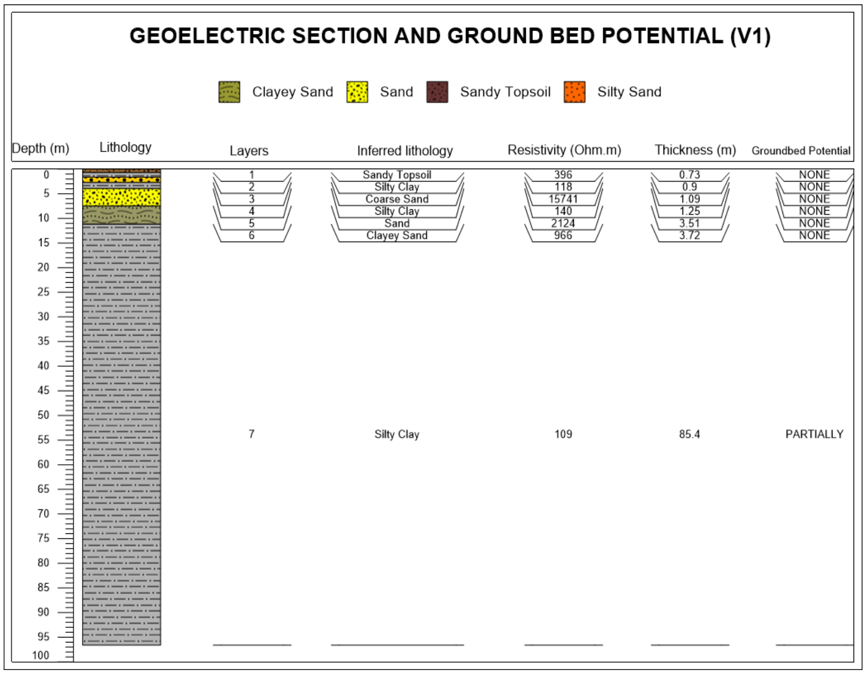

Figure 4: Geoelectric Section and ground bed potential for V1 VES survey point

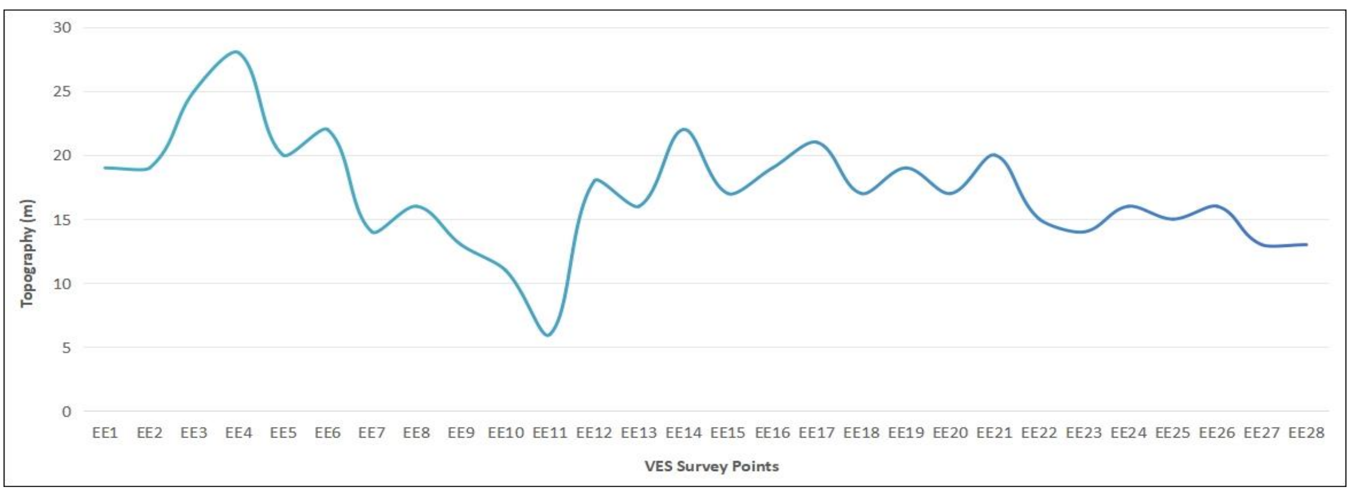

Figure 5: Cross section showing the topographic profile of the area

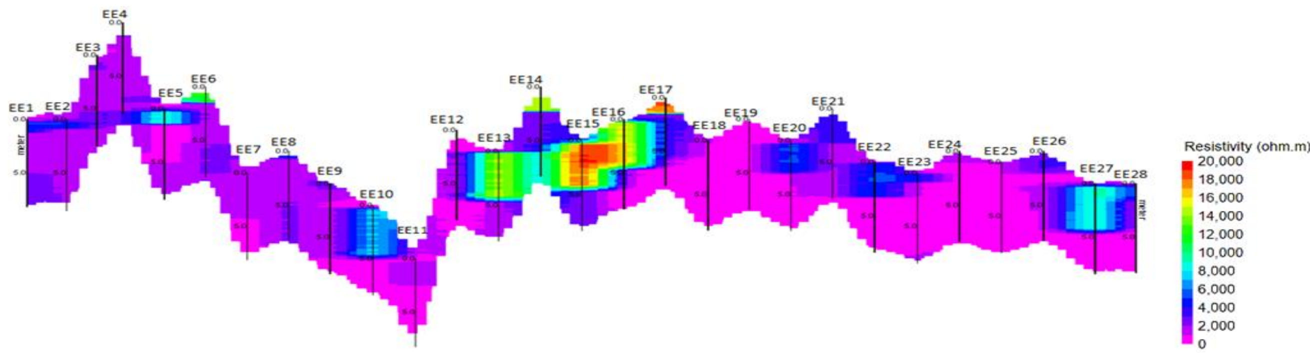

Figure 6: Resistivity section across all VES survey points

Soil Stratigraphy

The boreholes drilled within the beach ridge are juxtaposed to provide a perspective of a composite structure (Fig. 7). In addition, were geo-rectified and transformed into a 3-D Fence diagram (Fig.8) to provide a 3-D perspective of the sub-surface geology of the beach ridge. The soil profiles revealed a 3-layer soil structure comprising top thin organic silty clay underlain by silty-sand and fine sand which is then followed by medium dense to dense. This sandy units have occasional clay laminations as intercalations which occur in BH2, BH3, BH5 and BH6. Apart from the top clay, the other occurrences of clay within the depth explored are non-persistent and could nonetheless have profound effect on foundation settlement. Groundwater level was encountered at shallow depth, generally between 0 and 2.0m below ground level and subject to tidal fluctuation with a small phase difference. Fresh groundwater on the beach ridge exists as a mound (Abam 2016). Consequently, its extent and depth are a function of the size of the ridge. Since, its shallow, groundwater is highly vulnerable to contamination within the environment of the beach ridge.

The CPT met refusal at about 13m at the depth corresponding the occurrence of firm to hard sandy clay approaching dense sand formation. The Standard Penetration Test SPT results recorded during boring compare favorably with the SPT (N-60) predicted by the CPT.

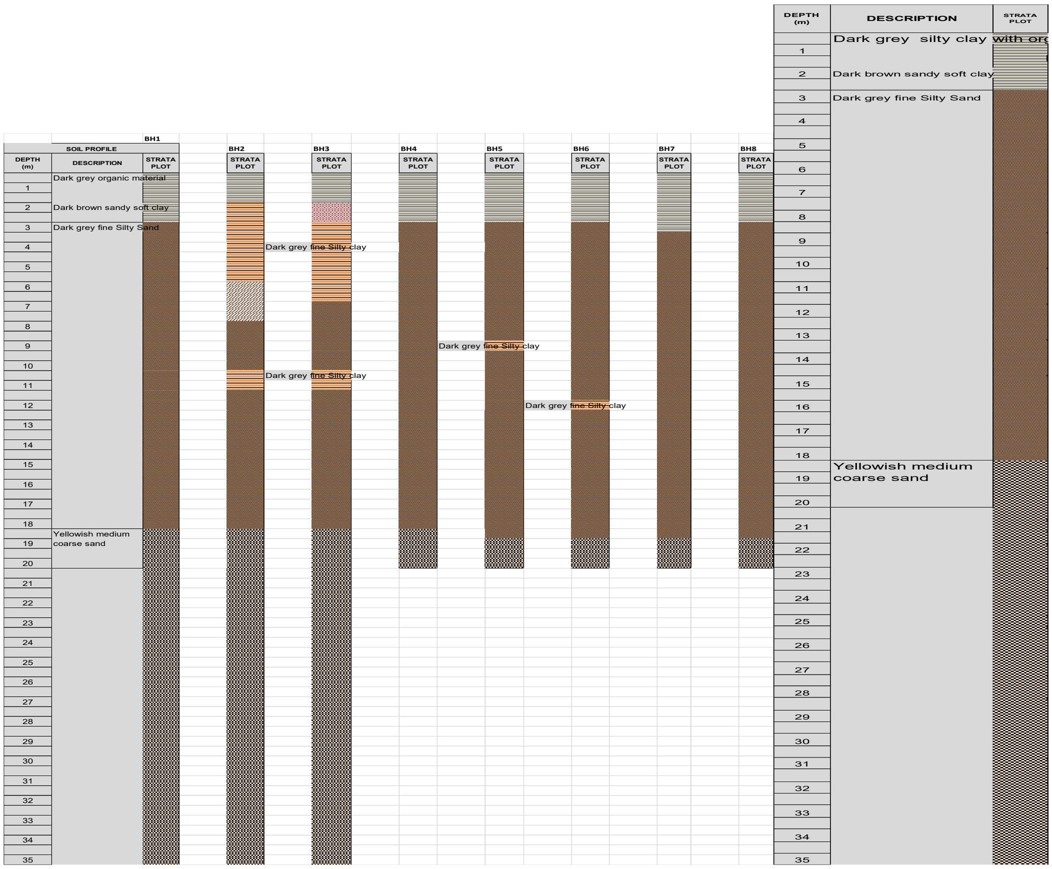

Fig.7: Composite Stratigraphy

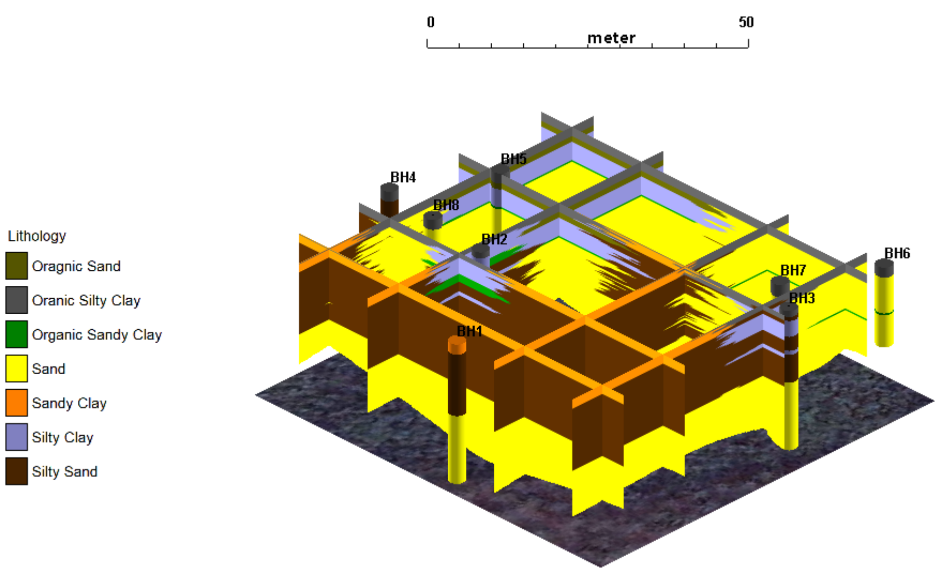

Fig.8: Fence Diagram of 3-D layout of Soil Stratigraphy

Geotechnical Engineering Properties of the Soils

Index Properties

Classification, strength and compressibility characteristics of the soils were determined from the laboratory and in-situ tests. The relevant index and engineering parameters of the soils are summarized in Table (4). The classification of the plasticity of the clays using the Casangrande chart (Fig.9) reveals that whereas the top clays are of intermediate plasticity, the lower clay that occur beneath the sand formation classify as a mixture of clays and silts of high plasticity and compressibility.

Table (4) Index Properties of cohesive soils

BH	Depth (m)	Moisture content, %	Unit Weight, γ (KN/m^3)	Submerged Unit Weight γ' (KN/m3)	Dry Unit Weight γ_d (KN/m3)	Liquid Limit LL (%)	Plastic Limit PL (%)	Plasticity Index PI (%)	Liquidity Index LI	Porosity, %
1	1.5	55.7	15.6	11.17	10.02	76	46	30	0.32	55.81
2	1.5	61	15.4	11.5	9.57					
	3	47.2	16.6	11.32	11.28	88	55	33	-0.24	53.23
	4.5	42.7	16.9	11.17	11.84					
	6	62.9	16.9	13.19	10.37					
3	1.5	62	16.5	12.7	10.19					
	3					64	46	18		
	4.5	56	17.3	12.9	11.09					
4	1.5	62.7	16.9	13.17	10.39	60	36	24	1.11	65.13
5	1.5	65.2	16.3	12.82	9.87	53	33	20	1.61	64.33
6	1.5	47.2	16.4	11.12	11.14	71	33	38	0.37	52.59
7	1.5	68.1	16.9	13.71	10.05	68	32	36	1.00	68.46
8	1.5	65.7	17	13.57	10.26	88	62	26	0.14	67.40

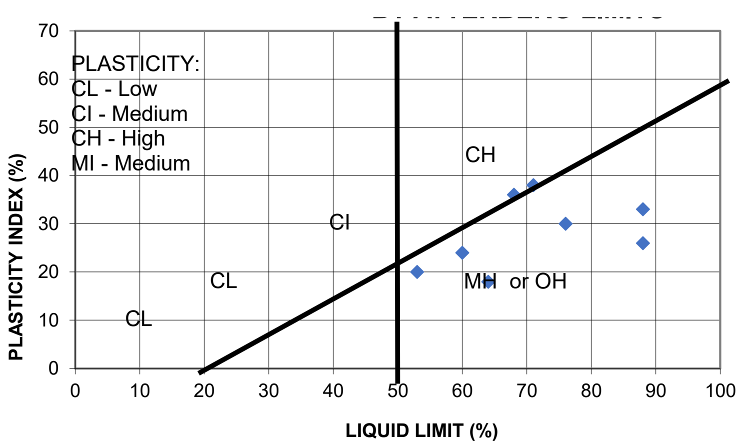

Fig. 9: Plasticity Chart for cohesive sediments in the Beach ridge

The clay materials encountered within the boreholes are of soft to firm consistency with liquid limit ranging from 53% to 88% and averaging 65%. The highest liquid limit values were recorded in BH-2&8 which classified as high plasticity. The Plasticity Index ranged from 18 to 38%. The moisture content of the clay layer ranged from 42.7- 68.1%. The bulk density of the clays ranged from 15.4 kN/m^3 to 17.3kN/m^3.

Strength Properties

The results of undrained unconsolidated strength parameters of the cohesive soils (Table 5) indicate that they are moderately of high natural content and contain silt which is responsible for the low frictional component of the strength.

Table (5) Strength parameters of Cohesive Soils

BH	DEPTH	Natural Moisture Content %	Unit Weight (kN/m^3)	Dry Unit Wt (kN/m^3)	Undrained Cohesion (kN/m^2)	Angle of Internal Friction (Deg.)
1	1.5	55.7	15.6	10.02	22	2
2	1.5	61	15.4	9.57	18	2
	3	47.2	16.6	11.28	31	2
	4.5	42.7	16.9	11.84	29	3
	6	62.9	16.9	10.37	65	3
3	1.5	62.0	16.5	10.19	18	2
	4.5	56.3	17.3	11.07	29	3
	6	44.9	16.1	11.11	63	3
4	1.5	62.7	16.9	10.39	15	2
5	1.5	65.2	16.3	9.87	35	2
6	1.5	47.2	16.4	11.14	15	2
7	1.5	68.1	16.9	10.05	25	3
8	1.5	65.7	17.0	10.26	27	2

The undrained cohesion of the clay deposits varies between 15kN/m^2 to 65kN/m^2 and averages 24kN/m^2. The angles of internal friction vary between 2 and 3 degrees. In terms of strength rating, the cohesive materials can be described as mostly soft to firm. Undrained strength analysis is considered critical for this material in view of the potential effect of groundwater.

The sand layers which pervade the beach ridge are noted as silty fine sand in size, medium to dense in consistency at the upper layers based on their SPT(N-values) and computed relative density as well as from shear box test results. The angle of internal friction ranges from 23° to 35° with most around 30°.

Particle Size Distribution

The sandy units extended from top to up to 50m only interrupted by clay intercalations. These sand units can be described as uniformly graded (SaU) based on the particle size analysis with Coefficients of Uniformity largely 2 and 3 Fig (10). The effective size of the sediments varies largely between 0.1mm and 0.2mm while mean particle sizes are between 0.2mm and 0.4mm. A plot of D_{10} and D_{50} with depth (Figs11) indicate a tendency of coarsening with depth. There is also a tendency for increasing permeability with depth (Fig. 12).

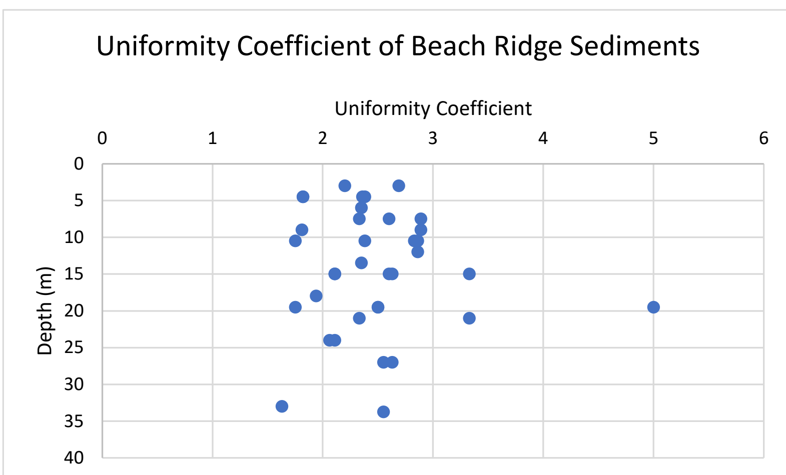

Fig.(10) Variation of Uniformity Coefficient with depth in the Beach Ridge

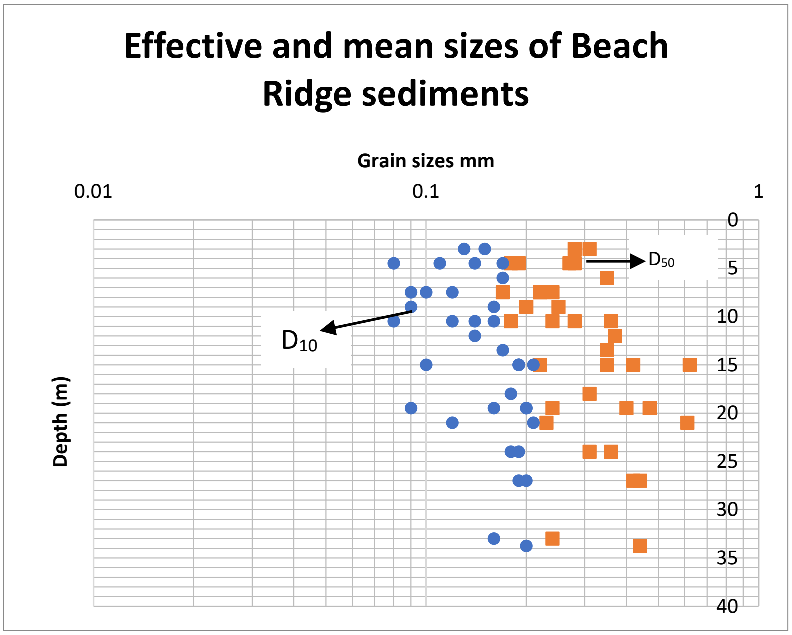

Fig.(11) Variation of Effective and Mean Particle sizes with depth in the Beach Ridge

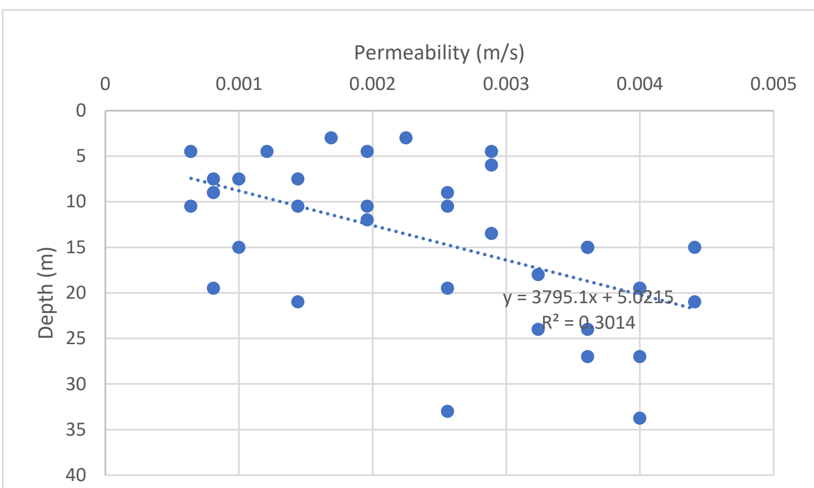

Fig.(12) Variation of Permeability with depth in the Beach Ridge

Standard Penetration Test Results

The SPT values in the Sand deposit shows perceptible similarity for the boreholes that were performed within the area. The N-values for the sand body after dilatancy correction indicated dense to very dense relative density at shallow depths and becomes medium dense at deeper levels (Fig.13) in the four beach ridges of Lagos, Brass, Bonny and Eket. A furthermore evidence of the highly compacted nature of the shallow depth of the Beach ridge sediments is the fact that the Relative density is generally higher than relative compaction (Fig. 13). This is understandable when viewed from the perspective of energy of deposition. The impact of the wave energy at deposition is higher for shallower sand formations than the deeper sand units due to the intervening water body.

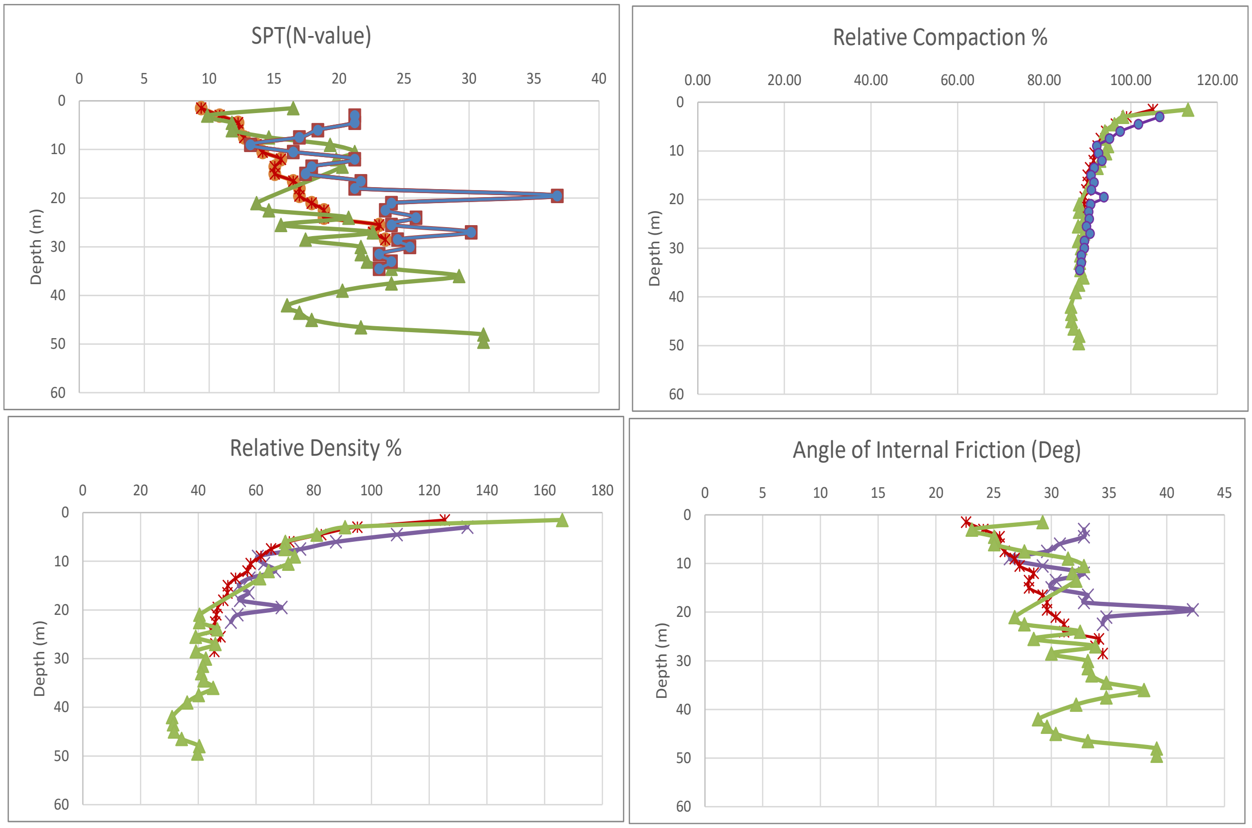

Fig.(13) Variation of density related geotechnical parameters for selected boreholes in Eket Beach Ridge

When the relative density is low (even if relative compaction appears high, such as 85-90%), the soil is in a loose state, which has several negative impacts on engineering performance (Mujtaba etal 2020). Loose soils are highly compressible and prone to significant subsequent settlement under structural loads. This is so because, Loose deposits have many large pores and a low dry density, so a large volume reduction is possible when loaded. In disturbed or naturally loose loess, the compression deformation coefficient is higher at lower dry density, indicating greater compressibility; as dry density is increased by compaction, compressibility decreases because pore space and particle mobility are reduced. In saturated granular soils, low relative density significantly increases the risk that large water pressures will cause the soil to liquefy during seismic events.

The deduced friction angle ranged between 25° ~ 38°. The estimated relative density (%) of the sand ranges from 87 to 100%. The upper section of the sand layer revealed a very dense state of compaction as indicated by not only high relative density but also by the high relative compaction based on Lee & Sigh (1971). The angle of internal friction on the other hand increased with depth (Fig. 14).

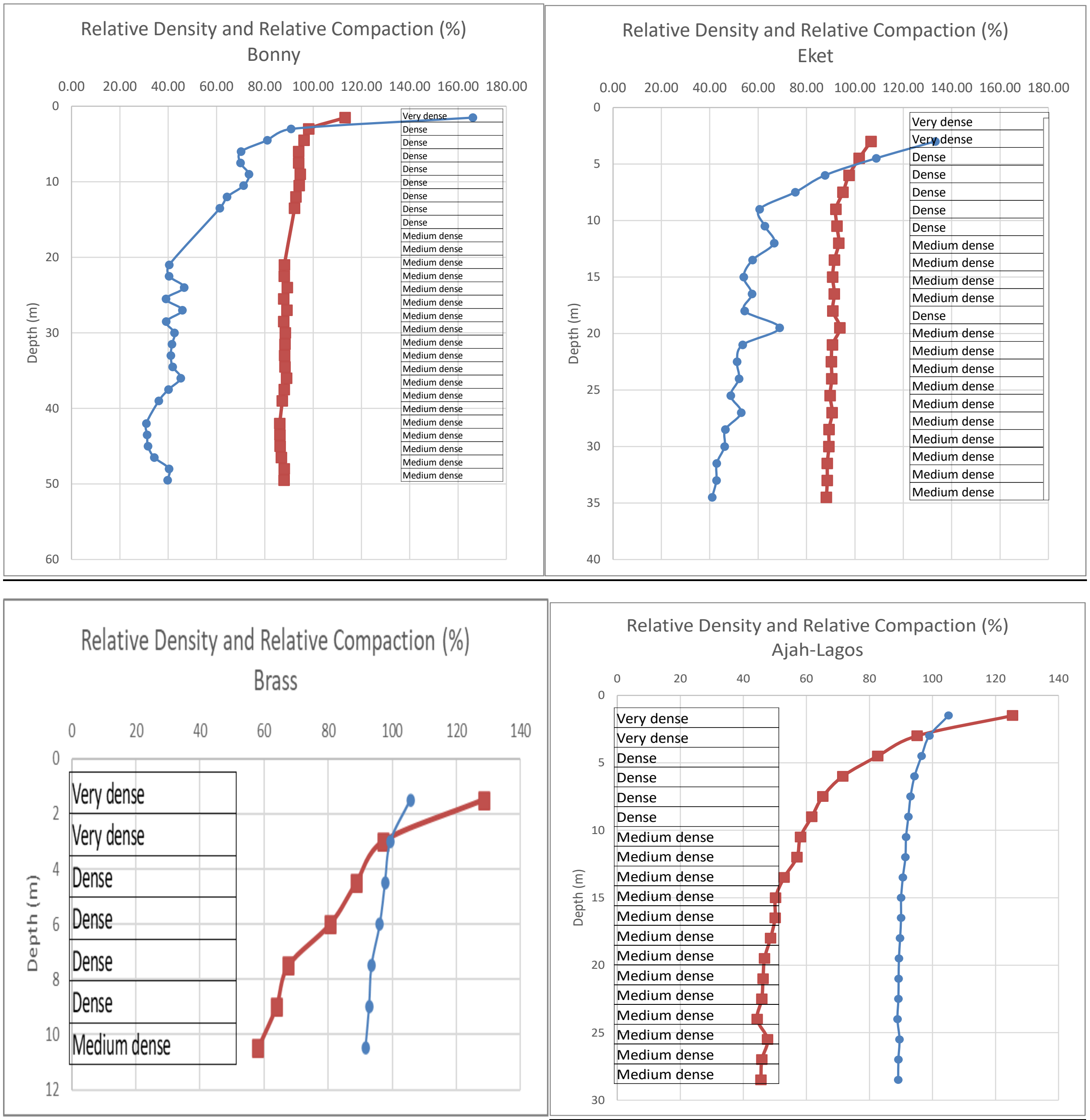

Fig.(14) Variation of Density related geotechnical parameters across the Nigerian Beach Ridge

Cone Penetration Test Results

Results extracted from CPT test and used for settlement computation indicate layer by layer contribution to consolidation settlement (Fig.15). The summation of these individual layer contributions plotted against depth resulted into a cumulative settlement which asymptote is the total consolidation settlement (Fig.16) and in this case amounts to 28mm.

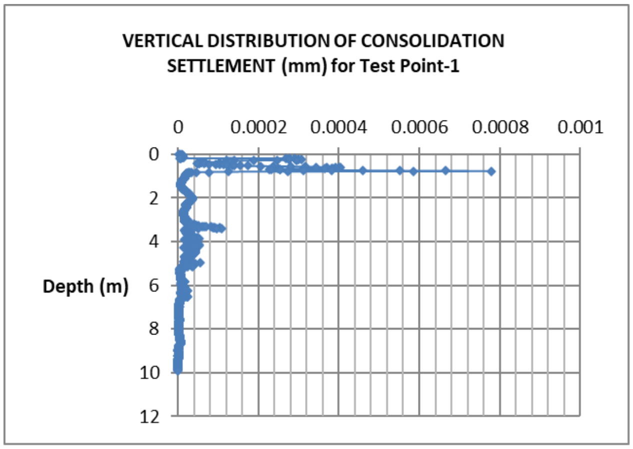

Fig.15: Vertical distribution of Settlement

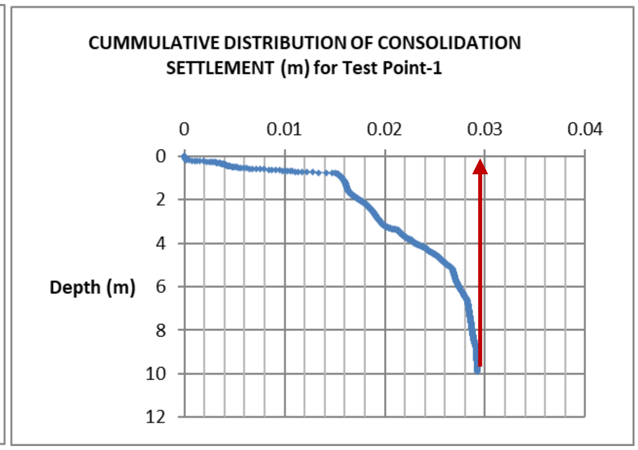

Fig.16: Cumulative Consolidation Settlement

Deformation Properties

For the cohesive materials, the Poisson's ratio ν, averages at 0.48 whereas the average value obtained for the sand layer is 0.30. For the underlying sand deposits, the value of the soil modulus is found to range between 9.8MPa and 16.93MPa while for the clay soils it ranged between 4.5MPa and 10.5MPa.

Application to Foundation Design

Evaluating bearing resistance in multilayer soil involves analyzing distinct geotechnical properties for each layer, considering the equivalent layer/weighted average and the potential shear failure mechanisms. In this case, a simplified approach involving the determination of an equivalent soil profile based on the properties of the layers within the influence zone of the foundation was adopted. Analysis depends on whether the top layer is stronger or weaker than the lower layer, affecting whether failure is punching, localized, or general shear. In general, where we have sandy top ($H \geq 3.5$m) over clay, whether fine, medium or dense in relative density, an average safe bearing pressure for shallow foundation of 100kN/m^2 can be expected. Satisfactory foundation performance may be expected, provided the bearing resistance of the soil at 3.5m depth is not less than 10% of the structural load placed on the surface.

The soil profile in the Eket beach area revealed a 3-layer soil structure comprising a silty clay with organic matter (0-2.5m depth) which grades into silty-sandy clay in some areas where it extended to roughly 7m. Beneath the silty clay and silty-sandy clay soil is a mostly silty fine sand, medium to dense (2.5m to 18.25m). This sandy layer has occasional clay laminations which occur in sections of the beach. The silty sand layer is underlain by mostly medium dense sand from 18m to 35m where most of boreholes were terminated. Apart from the top clay, the other occurrences of clay within the depth explored are non-persistent.

The depth to water table varied from 0 to 2m and may be subject to tidal influence. The low-lying environment and proximity to the sea in an environment characterized by annual rainfall averaging 2,900mm suggest that the site will be prone to flooding.

The CPT met refusal at about 13m at the depth corresponding the occurrence of firm to hard sandy clay approaching dense sand formation. The low Cone tip resistances encountered supported by laboratory undrained triaxial tests indicate that the superficial soils between 0-2m are significantly weak and possess low bearing resistance. The predicted total foundation Settlement for stress increment of $100kN/m^2$ is considered moderate to high due largely to the weak and compressible top 2m thick top layer. In areas where the clay occurs at deeper levels, much lower settlement can be expected due to lower operational stress increments. In effect, where bearing resistance and foundation settlement need to be improved, the following recommendations can be considered: (i) excavate 1.5m of poor soil in areas designated for sensitive structures and replace with granular materials preferably sand. This recommendation might be difficult to implement since it may require working below groundwater level. (ii) Preload areas designated for construction of sensitive structures to pre-consolidate the soil, and by extension improve bearing resistance and settlement.

Conclusion

Nigerian beach-ridge complexes (especially the Lagos, Brass, Bonny and Eket sectors) although dominated by fine, medium sands have hidden clay intercalations of variable strength and compressibility with potential to control settlement and stability. This variability has major implications for foundation safety and erosion risk. The integrated geotechnical and geophysical characterization of Nigerian coastal beach ridges and barrier islands underscores the complexity and vulnerability of these low-lying systems and links subsurface structure and soil behavior to coastal hazards, groundwater, and foundation safety. Both geotechnical and Electrical resistivity and laboratory testing consistently reveal near-surface soft, highly compressible peats, clays and silty sands with low bearing capacity and elevated groundwater, conditions that predispose coastal foundations to settlement and structural distress. Based on the PSD, these sands are reasonably well sorted and show a tendency to coarsening with depth. The sand beaches show non-corrosive attributes, however, in low lying areas such as riverbanks with clay presence, apparent resistivities which classify as corrosive environment have been identified. Careful, site-specific geotechnical and geophysical characterization is essential before coastal infrastructure development.

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