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Integrated Geotechnical and Geophysical Evaluation of Soils for Determination of Building Site Suitability in Parts of Bayelsa State

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Abstract
Assessment of foundation conditions in the Niger Delta is complicated by shallow groundwater, lateral lithologic variability, and weak fine-grained near-surface deposits. This study evaluates building-site suitability in selected parts of Bayelsa State, southern Nigeria, using an integrated geotechnical–geophysical approach. Borehole logging, laboratory determination of index properties, Standard Penetration Testing (SPT), Vertical Electrical Sounding (VES), and Multichannel Analysis of Surface Waves (MASW) were combined to characterize lithology, moisture condition, resistivity structure, stiffness, and bearing competence. The shallow subsurface is dominated by soft clay, silty clay, and sandy clay, whereas deeper horizons consist mainly of clayey sand, silty sand, and dense to poorly graded sand. Moisture content ranges from 18.3 to 41.1%, liquid limit from 22 to 73%, and plasticity index from 6 to 41%, indicating wet and moderately to highly plastic shallow soils. SPT N-values increase from about 6 to 20 with depth, reflecting progressive improvement in competence. VES delineates 4–6 geoelectric layers, with shallow conductive clay-rich zones showing resistivity values of 35–63 Ωm in Amassoma and Tombia, whereas deeper sandy units in Opolo attain up to 3278 Ωm. MASW-derived shear-wave velocity increases from about 176 to 606 m/s with depth. Comparative bearing-capacity estimates from SPT, MASW, and laboratory testing show close agreement, with shallow values generally below 85 kPa and deeper sandy horizons commonly exceeding 120 kPa and reaching about 213 kPa. The results demonstrate that the upper 2–3 m are generally unsuitable for untreated shallow foundations, whereas deeper sandy horizons constitute the preferred competent founding strata.

***Keywords**: Building-site suitability, Geotechnical investigation, Vertical Electrical Sounding, Shear-wave velocity, Bearing capacity.*

Introduction

The competence of the ground where civil engineering structures are placed is what the structures get to generate long-term performance. Structural distress may manifest through the following in the presence of weak foundation soils, soil that is highly compressible, waterlogged and that which is subsequently, laterally variable and collapse occurs in severe instances. This issue is particularly severe in young alluvial soils where lithologic diverse transformations take place within a limited period, and the groundwater is superficial. As Bowles (2012) and Roy and Bhalla (2017) noted, the sound foundation design should then have a starting point of proper knowledge of the engineering property of the material in the bottom, instead of just hanging on the surface of the ground.

Niger delta is one of the most challenging environments in terms of characterization of engineering sites in West Africa. The terrain is mainly unconsolidated to weakly consolidated body of coastal plain and alluvial deposits that include clay, silt, peat, clayey sand, silty sand and cleaner sand. Bayelsa State is found in this environment and has had repetitive geotechnical issues that are related to soft near-surface sediments, seasonal saturation, low bearing capacity, and disproportionate settlement. The existing literature in the area has demonstrated that the environment of subsoils changes significantly even over small distance, and generalized assumptions are not safe to undertake foundation design (Nwankwoala & Amadi, 2013; Ekeocha *et al.*, 2015).

Traditional geotechnical inquiry is still very important as it gives a first hand measurement of soil texture, plasticity, density, strength and penetration resistance. But boreholes and laboratory tests are always point specific and can fail to detect lateral variations in lithology or weak areas between points of test. Geophysical techniques overcome this shortcoming by providing continuous pavement and non-destructive imaging of ground (Parolai, *et al.*, 2006). Electrical methods of resistivity are very sensitive to moisture, fine and porosity and clay mineralogy (Oborie & Nwankwoala, 2012), but seismic methods are sensitive to stiffness and density. The combination of geotechnical behavior to measurable physical properties and the development of a more comprehensive engineering-geological site model is indeed possible with an integrated approach (Akinlabi and Adeyemi, 2014; Akintorinwa and Adeusi, 2009; Cosenza *et al.*, 2006).

Geotechnical part of the analysis involved soil boring,

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sample recovery, laboratory, in-situ Standard Penetration Testing (SPT), and triaxial testing, whereas the geophysical part used Vertical Electrical Sounding (VES) and Multi-Channel Analysis of Surface Waves (MASW). This integration was to go beyond the isolated point data and aimed at generating a depth-sensitive, laterally-continuous knowledge of soil competence. VES was applied to locate clay based conductive layers against sandier and more resistive units whereas MASW was applied to measure shear-wave velocity (Vs) and map seismic geotechnical parameters pertaining stiffness of soil, settlement characteristics and bearing capacity.

These objectives included identifying the soil index properties and the competence, simulating the resistivity distribution of soil profile, testing the relationships between resistivity and geotechnical index properties, estimating seismic geotechnical parameters using MASW measurements, and putting together 2D/3D models that assist in the planning of foundation.

The study area lies regionally in the Niger Delta Basin of West Africa whose stratigraphy is traditionally characterized by the Akata, Agbada and Benin Formations which is overlaid by more recent alluvium in most of the surface environments present (Akpokodje, 1979; Doust and omatsola, 1990; Short and Stauble, 1967). The surface section in the researched domains of the Amassoma, Tombia, and Opolo (Figure 1) is significantly covered by the Quaternary to Recent alluvial and coastal plain depositions (Figure 2). As can be demonstrated through these materials, they present a significant contrast in texture and stiffness with depth, which predisposes the area to illustrate the benefits of the integrated geotechnical and geophysical characterization. This investigation, thus, shows that geophysical signatures can be convected to quantifiable geotechnical behavior. The framework created as a result is not only useful in the sites studied, but also in providing a model of assessing similar humid deltaic sites elsewhere in the Niger Delta.

Materials and Methods

An integrated geotechnical-geophysical workflow has been used in the investigation. The first survey that was

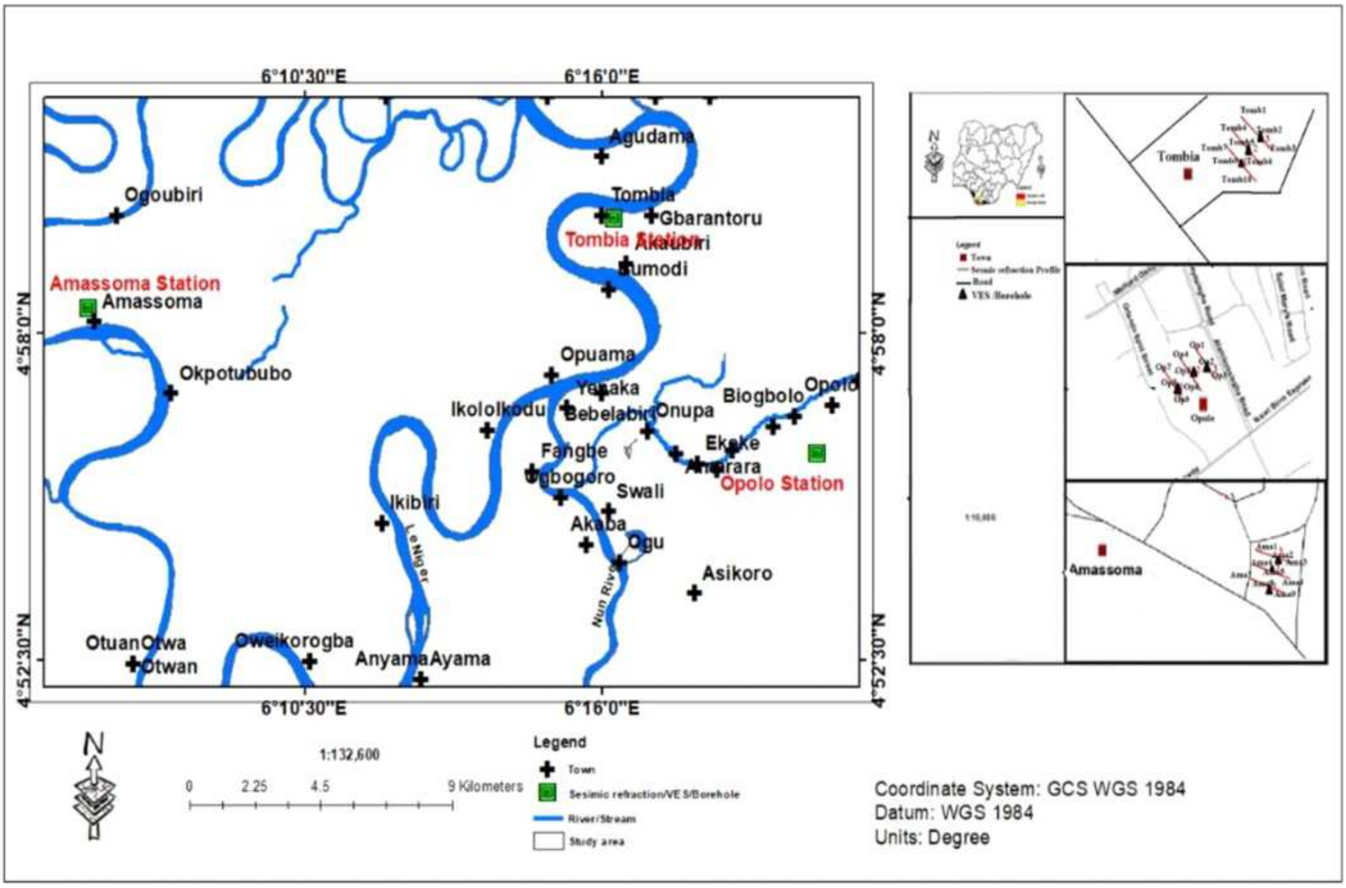

Fig. 1: Fecal-Oral Route F-Diagram (Park, 2023)

made was the reconnaissance survey to identify accessibility, establish correct boring and profile positions and document physiographic conditions in the area. Close enough to each other was positioned boreholes and geophysical points in order to allow making lithologic, geotechnical, resistivity and seismic responses directly comparable. The general plan was aimed at starving representative conditions in the study area.

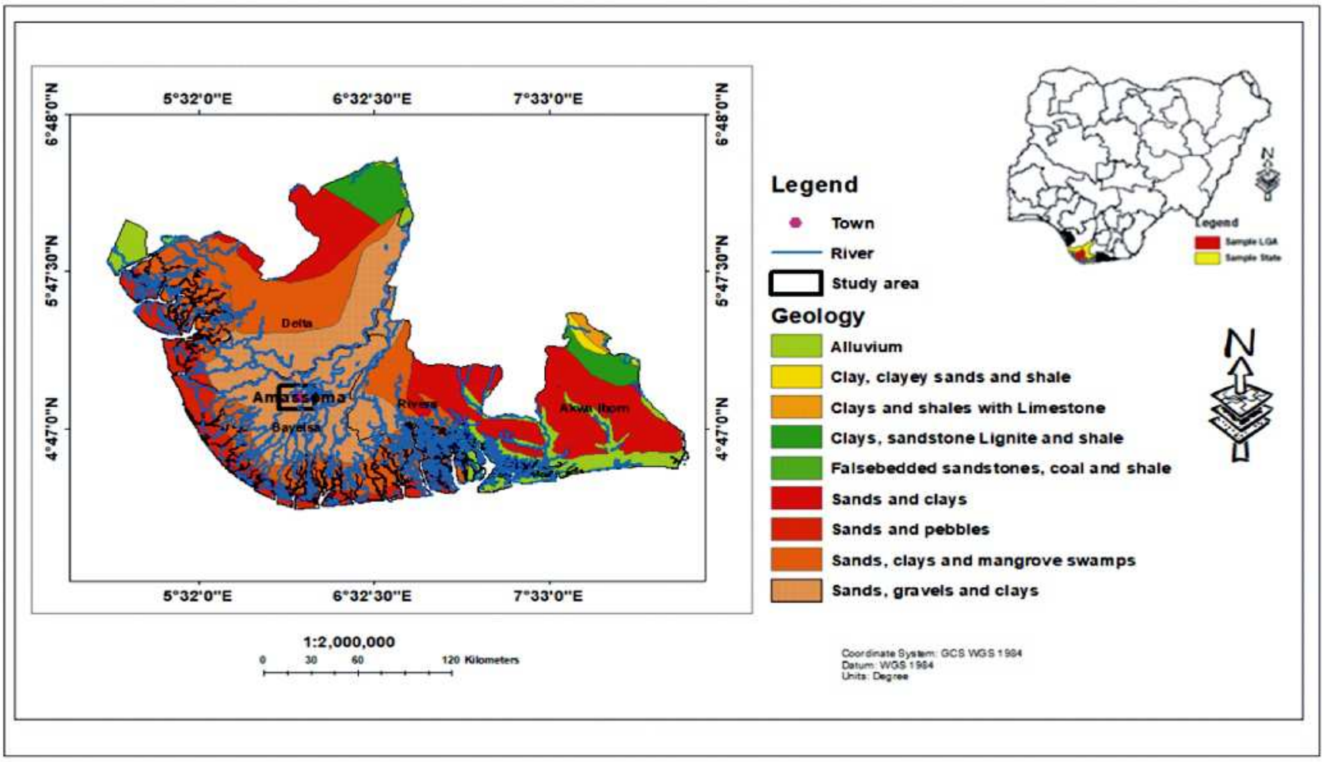

Fig. 2: Geological map locating the study area within the Niger Delta Basin

Geotechnical Data Acquisition and Analysis

The geotechnical programme included: ten (10) soil borings, by means of auger and percussion, visual/tactile logging of the materials recovered, index properties determined in labs, SPT tests, and UU triaxial tests of selected samples. Laboratory analyses included moisture content, Atterberg limits, and particle-size assessment sufficient for USCS classification. These procedures provided the basis for classifying the soils, estimating their moisture sensitivity and plasticity, and evaluating shallow competence in relation to foundation behavior (ASTM, 2017; Head & Epps, 2014; Holtz *et al.*, 2011).

SPT was used as an in-situ index of penetration resistance and competence. For cohesive soils, N-values were used to estimate undrained strength or cohesion, whereas for cohesionless soils they were related to internal friction and relative density. Triaxial testing complemented the SPT data by providing laboratory-based shear parameters and bearing-capacity estimates under undrained conditions for representative materials recovered from the field.

Geoelectric Data Acquisition and Processing

Eight (8) VES were conducted in close proximity to the borehole locations using the SAS 1000 ABEM terrameter. The Schlumberger array was adopted for the field work. Apparent resistivity was computed from measured resistance and the corresponding geometric factor. The data obtained from the field was interpreted using IPI2WIN computer inversion Software. The latter automatically calculates the resistivity versus thickness from the measured apparent resistivity, after which the sounding curves were interpreted into layered-earth models. Curve types such as HA, HK, and KH were identified and interpreted in engineering terms using lithologic control from nearby boreholes.

Seismic Data Acquisition and Processing

The MASW field work was conducted across 9 traverses close to the borehole and VES points using the ABEM Terraloc Mark 6, a 12-channel geophone to ensure a thoroughly imaged subsurface profile. Each survey profile spanned 60 meters, with geophones placed at 5-meter intervals along the traverse. The energy source was by means of plate and hammer. Striking the 5kg sledge hammer against a base plate generated seismic waves, which were detected by the geophones and recorded as seismograms by the seismograph. Easy MASW software was used to conduct the data processing.

The data on surface-wave dispersion were inverted, to obtain shear-wave velocity (Vs) as a function of depth. Other seismic geotechnical parameters were also obtained based on Vs model and its density assumptions which included primary-wave velocity (Vp), shear modulus (o) and Oedmodulus (Ec) and bulk modulus (K), estimated N-value and allowable bearing Capacity.

Integration of Field and Laboratory Data

The 2D and 3D modeling of the seismic and borehole data was applied using rockwork 4.6. With this software, lithological data said to be gathered on the boreholes could be combined to form a detailed 2-D and 3-D model of the underground. Experimental dispersion curves by Rockwork 4.6 was done by comparing the initial parameters of the geotechnical model including layer thickness, density, with experimental dispersion curves. The subsurface layers were classified into clusters using cluster analysis; the classification was done according to the geophysical properties of the layers. The result of the cluster analysis was included in the final model of 3D geology, which gave a detailed account of the underground. The geographical distribution of the data was then created as a spatial distribution map using ArcGIS software; this visualized the spatial distribution of the data. This mapping will be undertaken as a part of the process of comprehending the spatial variation of the subsurface properties in the study area.The analytical core of the study was based on integration of all datasets (Table 1). Geophysical interpretations were checked by borehole logs, VES resistivity correlates with plasticity and moisture content, and SPT and conversion of MASW to stiffness were compared with soft strength tests done on a laboratory level. Concordance of lithology, index properties, in-situ resistance, geoelectric layering, and seismic stiffness were all therefore used to provide the final site-suitability interpretation, not on a single dataset.

Results

Soil Description and Lithostratigraphic Pattern

Observation and palpation revealed the undeniable spatial and vertical fluctuation, and the overall trend is

Table 1: Integrated investigation framework

Investigation component	Purpose in the study	Output used in interpretation
Sampling and Borehole logging	Determine succession lithologic and soil samples.	Visual–tactile description, sample recovery, and lithology
Moisture content test	At site Dampness and probable solidity.	Competence assessment and water content
Atterberg limits	Compressibility and plasticity of the soils, and classification of fine-grained soils.	Liquid Limit (LL) Soil Liquid Plastic Limit(PL) Plasticity index (PI) soils Bearing Soil Casagrande chart analysis.
Grain-size analysis	Quantification of the gradation and textural variation of the grain sizes.	Classification soil fractions
SPT	The on-site resistance is measured and the competence is deduced.	The values of bearing-capacity indices, in the form of N-values, which are approximations of the cohesion/friction.
UU triaxial test	Acquire short-term strength of the samples	Cu, ϕ and bearing capacity
VES (Schlumberger)	Determine the lithology with depth and map resistivity layers	The depth to competent horizons, thickness, layer resistivity
MASW	Determine seismic rigidity and get engineering moduli.	Shear velocity (V s), compression velocity (V p), shear modulus (0), Oedmetric modulus (E c), bulk modulus (K), calculated N-value, and bearing capacity.

quite the same in the three industries. Sandy clay, silty clay and soft clay are found in shallow horizons. Intermediate depths are characterized by the prevalence of mixed soils, e.g., clayey sand, clayey silty sand and silty sand. Deeper horizons, particularly in Opolo, are progressively becoming occupied by sand containing coarse grains, sand of low grade and also denser sandy horizons.

The borehole logs (Figure 3) are informative since they do not depict the occurrence of single soil types, but also the sequence within the occurrence of those materials. At Amassoma and Tombia the coherent blanket is not so noted to be so consistent, but at Opolo the step out into sandier elements opens sooner. This stratigraphic distinction prefigures the subsequent resistivity and MASW performances and partly the reason why Opolo documents the best deep founding conditions of the sites under study.

Moisture Content, Atterberg Limits and Plasticity Behaviour

The moisture-content and Atterberg limit results as shown in Table 2, reveal persistently wet shallow conditions. The values reported in the study range from 18.3 to 41.1%, with the largest values associated with clay-rich shallow materials. Such water contents are high enough to reduce shear strength and to make the soils sensitive to disturbance and loading. The values are consistent with the floodplain setting, shallow groundwater, and the dominance of fine-grained alluvial sediments in the upper profile.

Atterberg-limit testing shows that many of the fine-grained samples have liquid limits above 40% and plasticity indices high enough to place them in the medium-to-high plasticity range. This is particularly evident in Amassoma and Tombia, where samples within the CH and CL classes dominate the upper part of

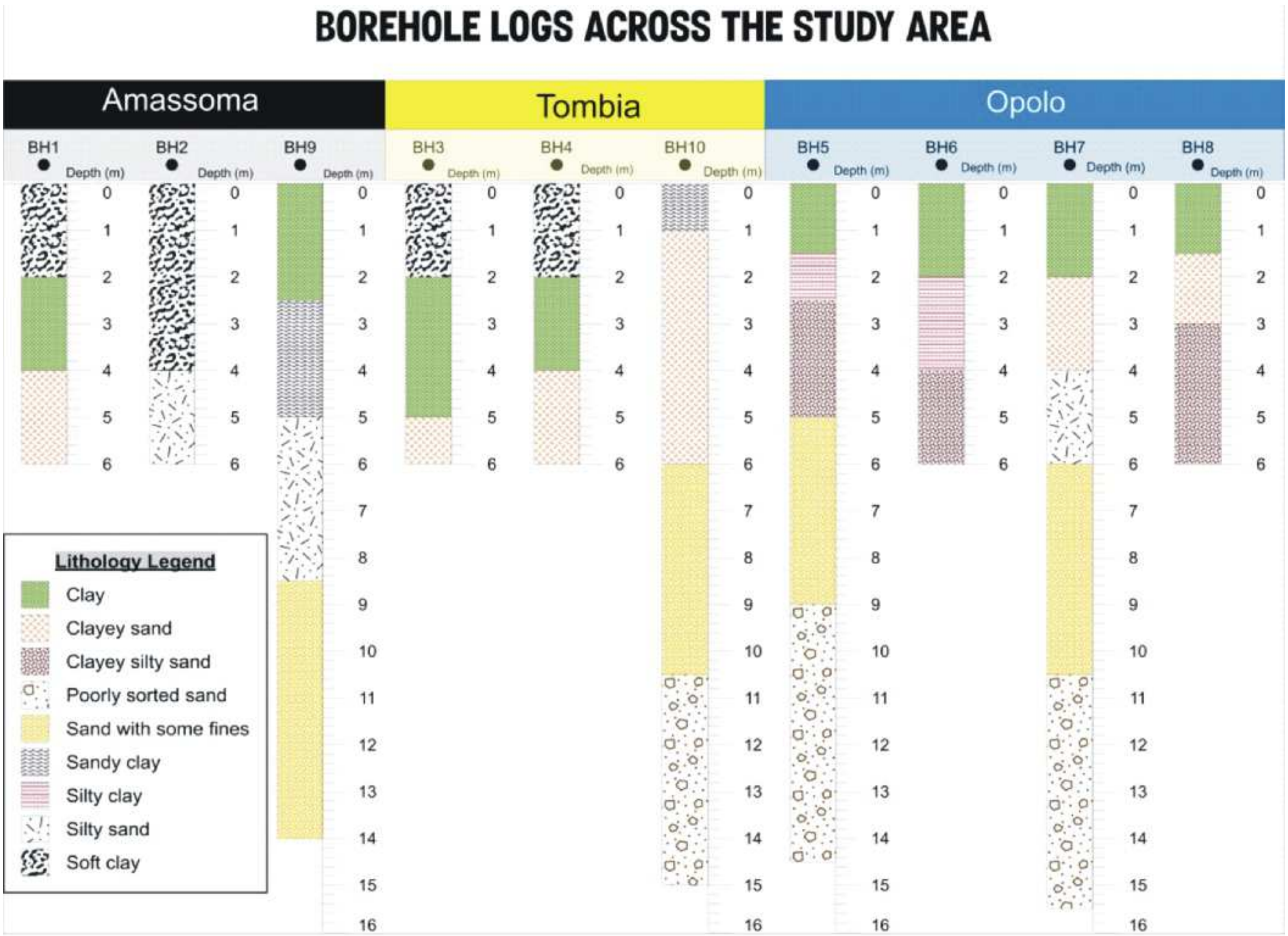

Fig. 3: Borehole logs in the research area

the profile. Opolo shows comparatively lower plasticity in places, but still contains cohesive near-surface horizons that are unfavourable for direct shallow foundations.

Table 2: Summary of moisture content and Atterberg-limits

Location	Moisture content range (%)	Liquid limit range (%)	Plasticity index range (%)	Dominant fine-grained response
Amassoma	18.3–41.1	22–73	6–41	High plasticity in shallow clays; the strongest swell/shrink tendency
Tombia	20.5–39.4	27–65	9–29	Moderate to high plasticity; clayey shallow cover
Opolo 1	19.2–35.8	24–62	6–34	Shallow cohesive soils over an increasingly sandy profile
Opolo 2	19.5–29.5	26–48	6–20	Lower plasticity relative to Amassoma/Tombia

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Grain-Size Distribution and Uscs Classification

The grain-size results confirm that the granular soils are dominated by fine to medium sand, with lesser coarse-sand and gravel contents. The results show that coefficients of uniformity generally between about 2.8 and 4.3 and coefficients of gradation between about 0.77 and 2.1. On this basis, many of the sandy materials are poorly graded to only marginally well graded, although they remain much stronger than the overlying clays and silts.

USCS classification Daryati *et al.*, (2019) derived from the Atterberg-limit and grain-size data identifies a shallow dominance of CH, CL, MH, and ML soils, while deeper sections are increasingly grouped as SC, SM, SC–SM, SP–SM, and SP. The value of this development is practical: as the profile deepens it stops being plastic, becomes less absorptive, is more resistant and becomes more mechanically capable.

SPT, Triaxial and Laboratory Bearing Capacity

Table 3: SPT, triaxial and bearing capacity results

Location / depth	Soil type	SPT N-value	Derived competence / strength	Allowable bearing capacity (kPa)
Amassoma, 2 m	Clay	7	Soft	78
Amassoma, 6 m	Clayey sand	11	Moderately dense	124
Tombia, 2 m	Silty clay	6	Soft cohesive soil	73
Tombia, 6 m	Silty sand	10	Improved resistance with depth	120
Opolo 1, 2 m	CL–ML	8	Weak shallow competence	80
Opolo 1, 6 m	SP–SM	15	Medium-dense competent horizon	152
Opolo 2, 2 m	CL	6	Low competence	61
Opolo 2, 12 m	SP	20	Dense competent sand	213

The SPT depth resistance systematical resistance confirms that the depth resistance rises progressively with depth as shown in Table 3. The cohesive horizons tend to form N-values between 6-10 in the upper 2-4 m and this indicates very soft to soft consistency as well as low penetration resistance. In deeper areas below the Opolo region, N-values escalate to 1120 in sandy or mixed horizons pointing at more favorable competent conditions of foundation.The trend of represented triaxial follows very closely with the SPT trend. Standard values of allowable bearing capacity are on the range 58.5-74.7 kPa on small shallow weak soils and under and around 120-213 kPa in more deep sandy units.

VES-Derived Geoelectric Layering

Table 4: VES layering formation, type of curve and interpretation of the geotechnical interpretation.

VES Location	Low-resistivity layer (Ωm)	Interpretation	Higher-resistivity (Ωm)	Engineering implication
VES1–VES4 (Amassoma/ Tombia)	35–63	Clay / silty clay in upper 2–4 m	112–482	It improves competence and still poor conductive cover.
VES5 (Opolo 1)	62.5 in shallow fine layer	Clayey topsoil over sandier sequence	109–370	Mixed profile; underground expertise in the minor fines.
VES6–VES7 (Opolo)	48.2–92.5	Fines and mixed sandy clay horizons	625–3278	Deep sands are very resistant that indicate coarse grained strata.
VES8 (Opolo 2)	95.4 in intermediate layer	Mixed fine-to-sandy horizon	348–594	Greater geotechnical quality than areas dominated with clay.

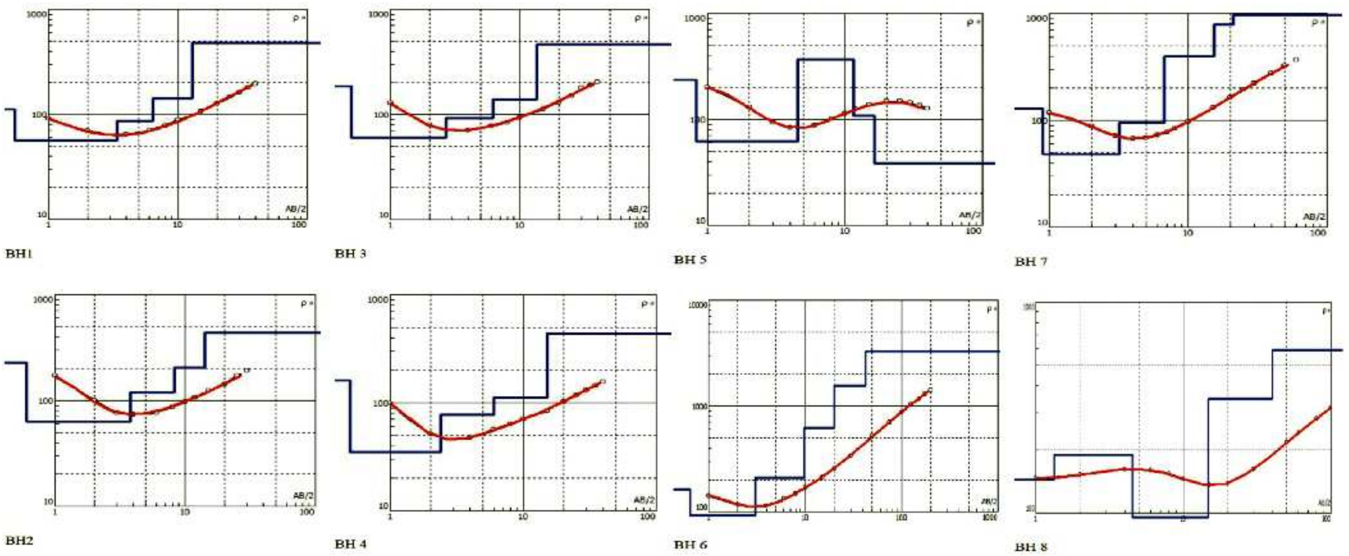

Fig. 4: Marked modelled VES curves of selected borehole-related sites.

The results of the VES (Table 4 and Figure 4) reveal the outline of 46 geoelectric layers in the study area. At Amassoma and Tombia the upper conductive layers are typically that resistively between 35 and 63 ohms directly and appear to be clay or silty clay. Under these, layers of mixed clayey-sand horizontal extend to more resistant sandy layers. This vertical series of resistive topsoil, conductive weak intermediate material and increasingly resistive intervals of competent depth is seen in the predominance of HA-type curves in these sectors.

Opolo has more growth of resistivity with depth and tends to be higher in deep-layer values than in the other sectors. In VES6, e.g., the resistivity of the uppermost layer is 163 Ωm, whereas of the deepest interpreted unit is 3278 O 5, which is a strong indication that it is composed of dense sandy material. These comparisons are in line with the borehole logs and the seismic evidence of the existence of the deep foundations in a better state at Opolo.

MASW-Derived Seismic Geotechnical Parameters

The MASW results as presented in Tables 5-8 and Figures 5-10, show a remarkably consistent increase in stiffness with depth. Vs rises in Amassoma in a range of values of 176223 m/s in the surface layer to about 589606 in the lower layers. The same trend is seen in Tombia whereby the distance is the same at the same height of around 200m/s and 231m/s respectively to a depth of 550m/s and 630m/s respectively. Opolo is the same and has almost surface Vs value of approximately 200209 m/s but over 550 m/s in the deep layers. This advancement is an indication of the changing soft soils to dense and more competent underground foundations.

Table 5: Synthesis of site-based trends of MASW shear-wave velocity.

Site location	Representative Vs range (m/s)	Near-surface response	Deep-layer response	Eengineering significance
Amassoma	176.05–605.64	Soft, low-stiffness shallow soils dominate upper 3 m	Stiffer sandy layers below 6 m	Shallow foundations risky without treatment
Tombia	200–570	Soft clay/silty clay near surface	Competence improves downward into mixed sands	Moderate-to-good founding possible at depth
Opolo	200.16–574.82	Weak shallow cover present but thinner in places	Dense sands yield highest stiffness and bearing capacity	Most favorable deep foundation strata among studied sectors

Table 6: Representative MASW-derived seismic geotechnical parameters for Amassoma profile 1

S/N	Depth (m)	Vs	Vp	μ (MPa)	Ec (MPa)	K (kPa)	N-value	Qa (kPa)
1	1.00	214.88	402.01	83.11	290.90	180.08	6.28	62.81
2	2.23	266.25	498.12	127.60	446.61	276.48	7.78	77.82
3	4.21	314.73	588.80	178.29	624.03	386.30	9.20	92.00
4	5.55	373.59	698.93	251.23	879.30	544.33	10.92	109.20
5	7.81	424.72	794.57	324.69	1136.42	703.50	12.41	124.14
6	9.12	473.48	885.81	403.54	1412.38	874.33	13.84	138.40
7	10.22	531.42	994.19	508.33	1779.16	1101.38	15.53	155.33
8	11.66	589.68	1103.19	625.90	2190.64	1356.11	17.24	172.36

Table 7: Representative MASW-derived seismic geotechnical parameters for Tombia profile 1

S/N	Depth (m)	Vs	Vp	μ (MPa)	Ec (MPa)	K (kPa)	N-value	Qa (kPa)
1	1.04	201.06	376.14	72.76	254.67	157.65	5.88	58.77
2	2.08	253.17	473.63	115.37	403.79	249.97	7.40	74.00
3	3.61	303.03	566.92	165.29	578.52	358.13	8.86	88.58
4	4.76	355.07	664.28	226.93	794.27	491.69	10.38	103.79
5	5.79	405.99	759.54	296.69	1038.43	642.83	11.87	118.67
6	7.78	454.09	849.52	371.15	1299.02	804.16	13.27	132.73
7	9.43	500.96	937.21	451.73	1581.05	978.74	14.64	146.43
8	10.49	551.19	1031.19	546.87	1914.03	1184.88	16.11	161.11

Effects of parametric derivations, shear modulus, oedmetric modulus, and bulk modulus indicate the pattern of Vs. The very surface layer of cohesiveness is largely comprised by low values and is even more so in the deeper sandy sections. The obtained N-values and N-values of MASW also tend to rise with the depth. The results can be matched to three shallow engineering

Table 8: Representative MASW-derived seismic geotechnical parameters for Opolo profile 1

S/N	Depth (m)	Vs	Vp	µ (MPa)	Ec (MPa)	K (kPa)	N-value	Qa (kPa)
1	0.60	200.93	375.90	72.67	254.34	157.45	5.87	58.73
2	1.89	256.89	480.59	118.78	415.74	257.37	7.51	75.09
3	3.11	302.15	565.27	164.33	575.16	356.05	8.83	88.32
4	4.25	359.85	673.21	233.08	815.78	505.01	10.52	105.18
5	6.27	408.23	763.73	299.97	1049.90	649.94	11.93	119.32
6	7.34	453.55	848.51	370.27	1295.94	802.25	13.26	132.57
7	8.81	498.46	932.54	447.23	1565.32	969.01	14.57	145.70
8	11.46	564.09	1055.31	572.75	2004.63	1240.96	16.49	164.88

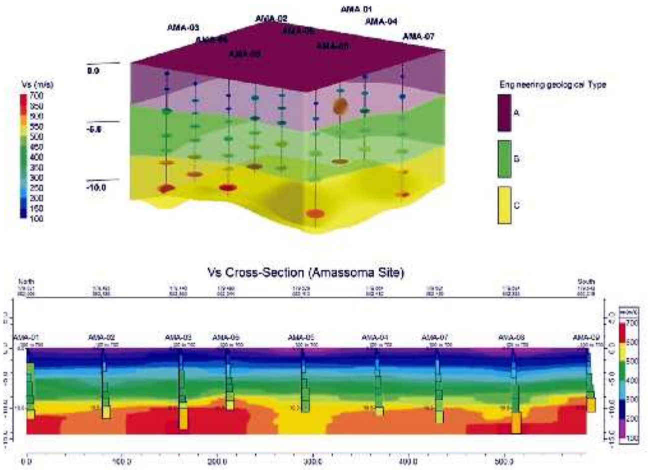

Fig. 5: 3D and 2D Shear wave velocity models in Amassoma

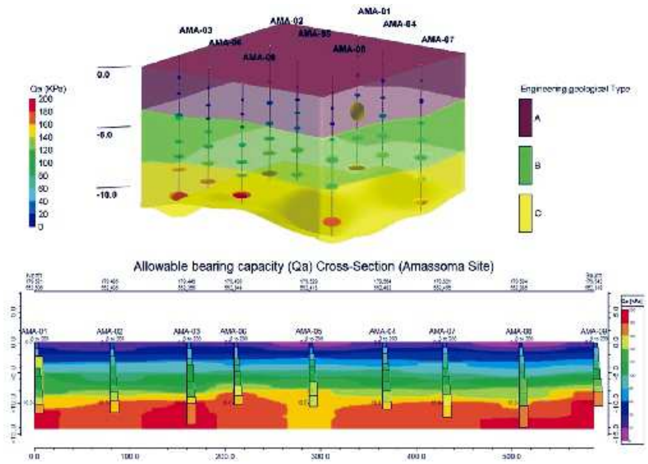

Fig. 6: 3D and 2D Allowable bearing capacity models in Amassoma

depictions, which are shallow weak sands (0-3 m), middle layered mixed sands (3-7 m), and deep-rooted competent sands (>7 m).

Comparison of Bearing Capacities of SPT, Lab Tests and MASW

Results of the results of the comparative analysis (Table

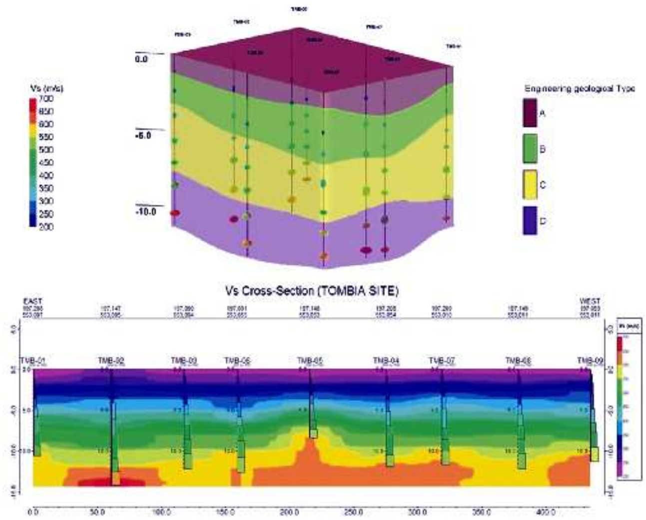

Fig. 7: 3D and 2D Shear wave velocities models at Tombia

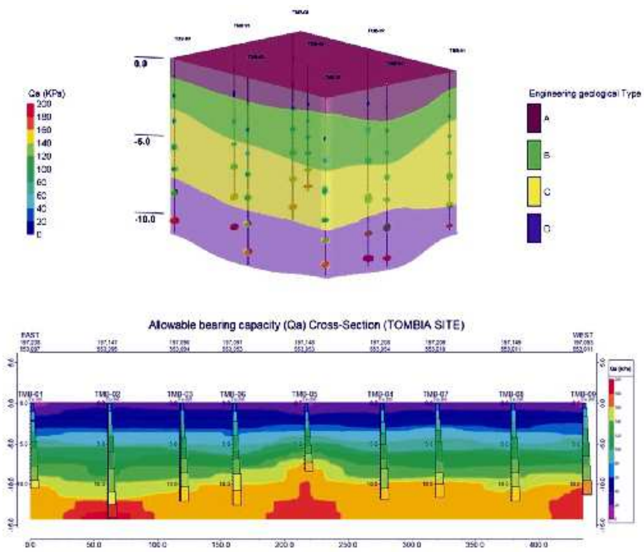

Fig. 8: 3D and 2D Allowable bearing capacity models at Tombia

9) indicate that there is a near value in the three methods. The bad performance of the top cohesive layer is testified by the fact that restricted norm of less than 85

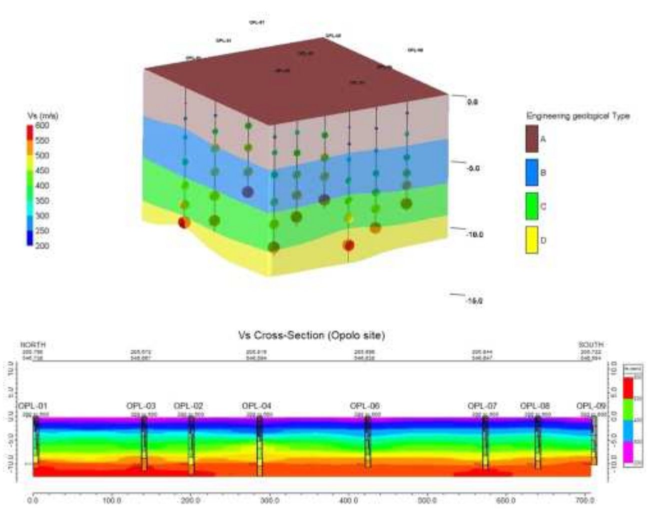

Fig. 9: 3D and 2D Shear wave velocities models at Opolo

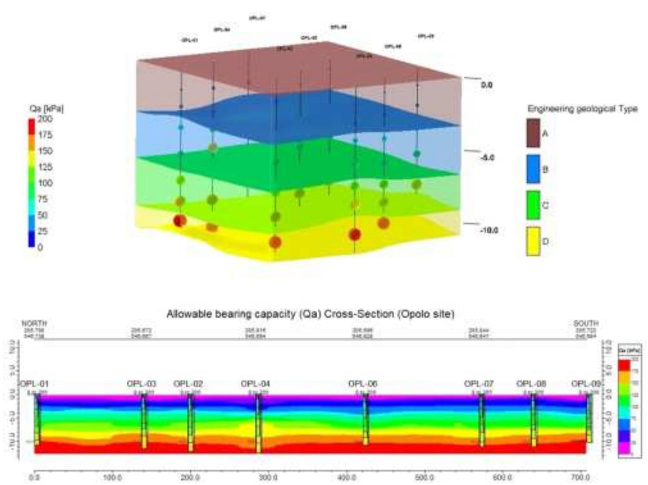

Fig. 10: 3D and 2D Allowable bearing capacity models at Opolo

Table 9: Comparison of SPT, MASW and laboratory data of bear-capacity of soils.

BH / depth	Resistivity (Ωm)	SPT-based qa (kPa)	MASW-based qa (kPa)	Laboratory qa (kPa)	USCS
BH5 / 2 m	79	79.8	78.1	72.3	CL–ML
BH5 / 6 m	437	150.0	152.4	152.3	SP–SM
BH7 / 2 m	42	57.5	61.3	58.5	CL
BH7 / 12 m	903	212.5	205.1	199.2	SP
BH9 / 2 m	83	78.4	82.8	71.0	CL
BH9 / 6 m	311	134.0	139.1	127.5	SC–SM
BH10 / 2 m	125	73.4	74.0	69.3	CS
BH10 / 6 m	286	128.5	123.7	120.0	SP–SM

kPa is generally allowable in regards to shallow bearing capacity. The deeper the values are high which are normally over 120 kpa and in some cases up to as much as 200 kPa in the deep sandy units. The compatibility across methods is generally within a range of an estimated 10 percent and this gives the assurance to the joint interpretation.

A methodological pattern also exists and is observed via comparison. In rare occasions at shallow depth MASW may produce slightly higher values than SPT and laboratory tests due to the fact that small-strain stiffness may be large in comparison to operating strength. More deeply SPT always provides the highest ratings with the drained soils and the laboratory ratings are slightly lower because of swirling the sample and loss of containment with the field. However, the competent horizons are defined by any means.

Discussion of Results

The data displayed in the records of the bore holes show that the soft clay and silty clay are found at the lower borehole depth; the data of moisture-content and Atterberg-limit displays that it is a wet and plastic material; SPT values displays that the substance undergoes low resistance; VES offer the material low-resistivity layers and MASW give the substance the lowest resistivity and bearing capacity indices. The reality of the study is that the study has validated this finding with the help of a large volume of independent data sets as opposed to a chain of evidence.

The interpretation is brought about by the negative relationship between the moisture content and the plasticity and resistivity. As the degrees of moisture and fines increase, resistivity goes down. This operates in compliance to the advance conductor behaviour of soils that contain enormous contents of clay in which the surface conduction and persistence in pore fluid lessens bulk resistivity (Abu-Hassanein *et al.*, 1996). Practically, it implies that the existence of low-resistance layers beneath the territory under investigation is not only a geophysical anomaly, but, more to the point, it is bound to be potentially dangerous to engineering spheres, as it is associated with loose, wet, compressible substances.

One can explain this by reference to the grain-size and USCS data because of why competence goes up to such a large extent due to depth. It is associated with transformation of CH/CL/MH-type materials to SC/SM/SP-SM and, lastly, with the SP sands that is distinguished by the increased resistivity, increased SPT N-value, and high silt stiffness that are realized through the application of MASW. Some of the deeper sands are found to be poorly graded not ideally well graded, but even then much superior to the more clay-saturated horizons above them in support of foundation. Their increased settling potential as is shown by higher moduli and their increased shear-wave velocity means that they are less susceptible to settlement and have increased ability to withstand structural loads.

Comparison of sites between Amassoma as against Tombia demonstrates that the two regional areas are more profoundly affected by the cohesive shallow cover as opposed to Opolo. The layers of low-resistivity containing clay are thinner and more durable in Amassoma and Tombia and the values of liquid-limit are generally big. In its turn, Opolo switches to sandier units earlier and captures the highest deep resistivity and stiffness of the MASW. This does not eliminate care in Opolo--that veil of it is still weak--but it indicates that there are more competent founding-strata that can be more easily accessible at Opolo.

The fact that the 2D and 3D models produced with the use of MASW may be utilized in converting the point based geotechnical data into progressive spatial form is of importance to the point. The modeling does not depict an isolated column form of every borehole, as in the modeling a form of weak and competent total variability is depicted transversely. This is required in the Niger Delta where the differential settlement may occur, both due to the low average strength, and due to the sharp changes of the conditions of the localized region in the lateral direction. These 3D models therefore bring the interpretation closer to the real engineering decision in real life where horizontal variance is as important as vertical stratification.

The methodological validity of the combined method can be supported by the fact that SPT, laboratory and MASW-based estimates of bearing-capacity are very close. MASW never excludes the geotechnical testing but neither VES alone nor site characterisation tools in the presence of borehole control and laboratory control they are all the mechanical properties. The dissertation thus presents a good argument in support of using geophysical methods as not an addition, but as part and parcel of the geotechnical investigation on soft deltaic terrains.

The findings in the design incline towards 3 zone construction design (Table 10). Zone I consists of the cover of shallow soft clay/silty clay that is 03m deep but there are cases where it may have depth of 3m and width of 10cm with low resistivity, bitter in terms of moisture content and plasticity, low Vs, and low bearing capacity. The moderately competent zone within the depth of about 37m is zone II and it is constituted by clayey sand and silty sand. Zone III is found underneath approximately 7 m and is characterized by the most resistant sand which is relatively dense sand having the greatest resistivity plus the greatest seismic stiffness and best-favored bearing capacity. It should also be recommended that foundations be depth sensitive and should extend to the deeper competent about where the structure loads need it.

Table 10: Integrated engineering zoning and foundation connotations based on the results of the dissertation.

Engineering zone	Approximate depth	Typical materials	Characteristic indicators	Recommended foundation implication
Zone I	0–3 m	Soft clay, silty clay, sandy clay	High moisture condition, LL/PI high, low resistivity, Vs Vs lower than 300 m/s, qa average lower than 85100 kPa.	Shall not be used: Unstabilised shallow footing: Replacement, piling or preloading.
Zone II	3 7 m	Clayey sand, silty sand, sand with fines	Normal resistivity, normal stiffness, qa occasionally 120150 Kpa.	Raft potential are almost ornamental clogged post-settlement foundations that are planned to be.
Zone III	>7 m	Dense sand / poorly graded sand	large resistivity, that which is expected; Vs large more than one half thousand m/s; large moduli; largest N-values, qa.	Favourable good founding legacy. Deep foundation systems.

Summary and Conclusion

The paper has incorporated standard penetration test (SPT), Vertical Electrical sounding (VES) and Multichannel Analysis of Surface Waves (MASW) to determine the suitability of building location during the choice of few site in the Bayelsa state such as Amassoma, Tombia and Opolo. The findings indicate that the upper soil profile in the area under study is mostly constituted of soft clay, silty clay as well as other moisture sensitive fine-grained materials. These are the almost surface soils, which are actually moist and moderately or highly plasticity, low resistivity and low penetration resistance as well as poor engineering competency.

The outcomes of Unified Soil Classification System (USCS) indicate that CH, CL, MH and ML soils have been gradually changing towards surface to deeper areas where the soils change into SC, SM, SP-SM and SP sands. This kind of texture modification is associated, and directly connected with improvement of engineering properties and foundation competence. The scores of SPT test and the triaxial test also indicate that the two deep of the ground materials are characteristic of poor allowable bearing capacity, and most of them between the range of 120 kPa and 200 kPa greatly improve bottom sandy layers.The VES results successfully delineated conductive, clay-rich weak zones at shallow depths and increasingly resistive sandy materials downward. Most of the sounding curves are of the HA type, while Opolo recorded the highest deep resistivity values and the clearest evidence of competent sandy strata. In addition, empirical relationships established in the study show that resistivity decreases with increasing moisture content and plasticity, thereby confirming the usefulness of geoelectrical methods as an effective preliminary tool for identifying weak fine-grained zones.

The MASW results demonstrate a systematic increase in shear-wave velocity (Vs), compressional-wave velocity (Vp), and elastic moduli with depth, thereby supporting a three-layer engineering model made up of shallow weak fine-grained soils, intermediate mixed sandy layers, and deeper competent sands. Furthermore, the comparative bearing-capacity values derived from SPT, MASW, and laboratory testing show close agreement, which confirms the reliability and consistency of the integrated interpretation adopted in this study

Conclusion

Building site suitability in the investigated parts of Bayelsa State is chiefly controlled by depth-related variations in lithology, moisture content, and stiffness. The upper 2–3 m generally consists of weak, wet, plastic, and compressible soils, making it unsuitable for untreated conventional shallow foundations. These conditions are consistently indicated by low resistivity, low SPT N-values, low seismic stiffness, and low allowable bearing capacity. Beneath this weak near-surface layer occur intermediate sandy materials of moderate competence and deeper sandy horizons that constitute the most suitable founding strata. The study further establishes that integrated geotechnical and geophysical investigation provides a more reliable basis for site characterization, foundation design, and planning than single-method assessment in the complex subsurface conditions of the Niger Delta.

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