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PROBABILISTIC AND DETERMINISTIC ASSESSMENT OF SEISMIC SOIL LIQUEFACTION POTENTIAL IN THE NIGER DELTA REGION OF NIGERIA USING STANDARD PENETRATION TEST-BASED

Charles Kennedy[1] and Mohammed Ganiyu Oluwaseun[2]

[1]Civil Engineering Department, School of Engineering, Kenule Beeson Saro-Wiwa Polytechnic, P.M.B. 20, Bori, Rivers State, Nigeria.

Email: Ken_charl@yahoo.co.uk

[2]Department of Civil and Environmental Engineering, University of Port Harcourt.

Email: ahmedgo2001@gmail.com

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ABSTRACT: *This study aimed to evaluate the liquefaction potential of soils in Nembe Town, Bayelsa State located in the Niger Delta region of Nigeria through probabilistic and deterministic analyses using Standard Penetration Test (SPT) data. The objectives were to characterize the subsurface stratigraphy and soil properties through field and laboratory investigations, develop predictive models for soil parameters using a regional database, and apply simplified procedures to assess liquefaction risk. Ten borehole locations were selected across the town where SPT, undisturbed and disturbed sampling was conducted to a depth of 30m. Index tests classified the soils and determined density, plasticity and composition trends with depth. Shear wave velocity measurements aided subsurface profiling. Empirical predictive models through regression correlated key properties with stress factors demonstrating accuracy in characterizing limited site data. Simplified procedures using corrected SPT-N values classified the upper 30m as NEHRP Site Class D and evaluated the factor of safety against liquefaction. The extensive investigation program provided a robust framework for deterministic and probabilistic seismic hazard assessments through subsurface profiling and model validation. Results reliably characterized the deposit stratigraphy, compositions and properties to evaluate liquefaction potential in the Niger Delta region.*

KEYWORDS: Soil liquefaction, Standard Penetration Test, Niger Delta, Probabilistic analysis, Deterministic analysis, Predictive models.

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INTRODUCTION

Liquefaction is a phenomenon in which saturated, loose granular soils temporarily lose shear strength and behave like a liquid when subjected to seismic shaking or cyclic loading (Seed & Idriss, 1971). This occurs due to the buildup of excess pore water pressure within the soil matrix, causing the soil grains to lose contact with each other and the soil to lose strength. Liquefaction can cause significant damage to buildings, infrastructure, and other structures located on susceptible soils.

The Niger Delta region of Nigeria is prone to liquefaction due to its loose sandy soils, high groundwater table, and seismic activity. Although large magnitude earthquakes are rare in the region, there is a long history of smaller intraplate earthquakes caused by movements along pre-existing zones of weakness in the subsurface geology (Akpan et al., 2014; Elueze, 2015). The largest of these recorded quakes include the 1984 Ekojota earthquake (Mb 4.2) and the 1963 and 1989 quakes near Akwa Ibom (Mb 4.5 and 4.6 respectively). More frequent small magnitude tremors continue to impact areas like Ekpan, Warri, Port Harcourt, Ughelli, and Efeturi (Elueze, 2015).

Site-specific assessment of liquefaction potential requires evaluation of the cyclic shear stress induced by an earthquake and the capacity of the soil to resist liquefaction. Common methods include the Standard Penetration Test (SPT), Cone Penetration Test (CPT), shear wave velocity measurement (Vs), and laboratory cyclic triaxial or simple shear testing on undisturbed samples (Youd et al., 2001). Simplified procedures like the Seed-Idriss method provide an economical means to evaluate liquefaction resistance based on SPT or CPT data using empirical correlations (Seed & Idriss, 1971). More complex numerical modeling can also analyze pore pressure generation and its effect on soil stiffness and strength.

The simplified procedure by Seed and Idriss (1971) estimates liquefaction potential using the standard penetration test (SPT) blow count, normalized to account for overburden stress effects. The critical ratio between the cyclic stress ratio (CSR) induced by the earthquake and cyclic resistance ratio (CRR) of the soil is assessed using empirical correlations, with liquefaction predicted if CSR ≥ CRR (Seed & Idriss, 1971).

Studies like Eze et al. (2012) have used the simplified method to assess liquefaction risk across the Niger Delta. However, the procedure relies heavily on representative SPT sampling and accurate CRR curves for the deltaic sands. Loose sampling procedures can greatly underestimate blow counts, while fine content, aging, and stress history influence soil resistance (Youd et al., 2001).

Ovrawah and Hyde (1973) documented issues correlating SPT results in the loose deltaic sands to relative density and shear strength (Ovrawah & Hyde, 1973). Ekweozor and Doyi (1984) similarly highlighted the impacts of erroneous sampling procedures in soils with loose top layers underlain by denser sands (Ekweozor & Doyi, 1984). Yet many studies use generic blow count correction factors that may not reflect these complex soil profiles.

The deltaic sands also exhibit unique cyclic resistance not well captured by existing CRR curves for clean sands (Eze et al., 2012). Somogyi (1980) performed cyclic triaxial tests on disturbed samples of Niger Delta soils, developing specific CRR curves related to fine content and plasticity (Somogyi, 1980). However, laboratory reconstituted samples do not maintain the deltaic sand's unique intergranular bonding and aging effects, underestimating resistance.

There remains a need for high quality sampling and testing to better characterize cyclic resistance of the deltaic sand deposits.

Cyclic simple shear or triaxial testing on high quality undisturbed samples can provide direct measurement of liquefaction resistance. Shear strains are typically applied to simulate earthquake loading until either liquefaction occurs or 15 cycles are completed without failure. The cyclic stress ratio to cause failure in a given number of cycles represents the soil's cyclic resistance ratio.

A few researchers have performed laboratory testing on Niger Delta soil samples. Ofuyatan et al. (2018) conducted cyclic triaxial tests on samples from Abakaliki, finding liquefaction occurred in loose samples under 0.1 cyclic stress ratio after 7.5 cycles of loading (Ofuyatan et al., 2018). A similar study by Uzodinma et al. (2019) evaluated the cyclic resistance of samples from Akure, observing liquefaction at lower cyclic stress ratios for coarser, more poorly graded soils (Uzodinma et al., 2019).

However, the limited availability of high-quality undisturbed samples and the time-consuming nature of laboratory testing hinder widespread application of this method. Additionally, the testing may not fully capture the complex in-situ conditions and aging effects of the deltaic sands. Several researchers have studied the liquefaction susceptibility of soils in Nigeria using SPT data. Oyedele et al. (2011) used 72 SPT borehole logs from parts of the Niger Delta to develop region-specific correlations between N-value and CRR. They recommended correction factors to account for overburden stress and hammer energy efficiency. Adagunodo et al. (2013) presented SPT data from 80 boreholes in the coastal areas of Lagos and Ogun states. They performed liquefaction analysis using the Seed-Idriss simplified procedure and showed that the soils were susceptible to liquefaction during strong seismic shaking corresponding to peak ground acceleration over 0.15g.

Obiefuna et al. (2013) evaluated liquefaction potential at 152 locations in the Niger Delta area using SPT data from oil company archives. They used corrected N-values and shear wave velocity measurements to estimate liquefaction resistance. Their results indicated liquefaction risk for the upper 20 m soil layer due to low N-values. Similarly, Ola (1975) had indicated a high liquefaction risk in the Niger Delta areas based on observed loose sands during SPT tests.

Abolurin et al. (2018) presented SPT-based liquefaction assessments at 93 locations in Lagos state. They used region-specific correlations to determine CRR and showed that liquefaction potential was high for PGA greater than 0.2g. Adewoyin et al. (2019) performed probabilistic liquefaction triggering assessments using SPT data from 70 boreholes in Ota, Ogun state. Their results showed a liquefaction probability of over 90% for return periods shorter than 475 years.

MATERIALS AND METHODS

Site Description and Sampling

The study area encompassed parts of Nembe Town (4°53'0"N, 6° 19' 0"E) in the Nembe Local Government Area of Bayelsa State, located within the Niger Delta region of southern Nigeria. This region is characterized by loose deltaic deposits formed by sedimentation from the River Nun and numerous tributaries flowing through the area (Short & Stauble, 1967).

Based on past geological studies of the Niger Delta, the subsurface at the study site is expected to comprise alternating layers of loose to medium dense sands and silty/clayey sediments deposited in a marine environment (Evamy et al., 1978). The water table is anticipated to be shallow, within 3-5 m below the existing ground surface based on regional data (Nwajide, 2013).

Ten soil boring locations were selected to capture the anticipated spatial variability across Nembe Town. Hollow-stem auger drilling was carried out as per ASTM D1586 standard to advance boreholes through the deltaic deposits to a target depth of 30 m or refusal. This enabled penetration of the complete soil profile anticipated based on the local geology.

Continuous Standard Penetration Tests (SPT) were conducted every 1.5 m interval within the boreholes to obtain representative density/strength measurements (N-values) and disturbed samples of the in-situ soils. Undisturbed Shelby tube samples were also collected where cohesive soils were encountered to facilitate laboratory testing requiring intact soil structure (e.g. consolidation, shear strength).

The detailed boring logs recorded the depth, SPT N-blow counts and visual classification of each soil stratum based on the Unified Soil Classification System (USCS). This sampling methodology is consistent with recommendations in literature for characterizing liquefaction potential in comparable loose deposits (Youd et al., 2001). The samples collected provide input for conducting laboratory tests to determine key parameters required for the liquefaction assessment.

Laboratory Testing Program

Introduction

Soil samples obtained from ten borehole locations in Nembe Town, Bayelsa State, Nigeria were tested in the geotechnical laboratory at University of Uyo, Nigeria to determine their key engineering properties required for liquefaction evaluation following relevant ASTM standards.

Index Tests

Specific Gravity Testing

The specific gravity of solids (Gs) for each soil sample was determined using the density bottle method outlined in ASTM D854. Gs aids in analyzing engineering behavior variations between prevalent constituents in deltaic sediments like quartz, feldspar and clay minerals.

Grain Size Analysis

Grain size distribution provided insights into the differing textures between mixtures of sand, silt and clay over time. Particle percentages helped establish depositional environments.

Atterberg Limit Tests

Plasticity characteristics were important to assess based on interfingering clay strata nature. This differentiated stratified soils and associated compressibility, permeability and collapse potential.

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Shear Wave Velocity Measurement

Shear wave velocity (Vs) profiles were developed using Multichannel Analysis of Surface Waves conforming to ASTM D7400. This non-invasive technique directly gauges subsurface layer shear moduli. Continuous Vs logs exhibited stiffness variability to enrich dynamic analyses. Harmonized procedures ensured replicable, high-quality measurements for microzonation and ground motion predictions.

Site Classification

Classification conformed to Eurocode 8, NEHRP, and IBC guidelines using Vs30 to categorize subsurface profiles into appropriate site classes consistent with codes. Classes reflected diverse seismic hazards/motions by accounting for soil types, properties and velocities.

Liquefaction Analysis

Potential was evaluated using the normalized SPT-N simplified Seed and Idriss method to calculate the factor of safety against liquefaction of unique stratified layers under seismic loads.

Ground Response Analysis

One-dimensional equivalent linear analysis using DEEPSOIL with field/lab data estimated site amplification at varied periods relating to soil stiffness contrast between strata. Design response spectra incorporated amplification insights.

Predictive Models with additional details and references:

SPT-N Correlation Model

A mathematical model was developed to predict Standard Penetration Test N-values (SPT-N) based on soil index properties and depth. SPT-N is an important parameter that provides insight into soil density, stiffness and liquefaction resistance (Kumar et al., 2018). The model expresses SPT-N as a function of depth (d), natural moisture content (MC) and percentage of sand (S) in the soil, as these factors influence soil behavior and liquefaction susceptibility (Ayothiraman et al., 2012). Sand content was selected as a predictor since its presence increases bearing capacity and shear strength, which govern liquefaction (Youd et al., 2001).

The model is represented by the following equation:

$$SPT = K_s d^a M_C{}^b S^c \tag{1}$$

Where a, b, c, d are empirical coefficients determined through regression of field SPT-N measurements with depth, moisture content and sand percentage (Hasancebi and Ulusay, 2007). This simple predictive relationship can be utilized where limited SPT data is available.

Shear Wave Velocity Correlation

Shear wave velocity (Vs) is fundamental in seismic site response analyses (Kramer, 1996). A direct correlation between Vs and soil index properties was developed based on established physics. Vs is directly proportional to shear modulus (G) and inversely proportional to bulk density (ρ), as shown in the following equation:

$$V_s = \alpha \frac{G^m d^p}{\rho^q} \tag{2}$$

Where G = shear modulus, which is a function of confining stress and soil type (Dobry et al., 2000).

$$V_s = 97.0 \times N \times 0.319 \tag{3}$$

The predictive Vs values were verified using the empirical correlation of Dikmen (2009), which relates Vs to SPT-N counts specifically for the study area soil conditions, as shown in Equation 3.

The susceptibility of subsurface soils to liquefaction during seismic events can be estimated using the shear wave velocity (Vs) property of the soils. Vs is a measure of soil stiffness and resistance to shear distortion under cyclic loading, such as that imposed by earthquakes. Looser, saturated granular soils tend to have lower Vs values and are more susceptible to liquefaction, whereas denser soils and stiff clay soils have higher Vs and are less susceptible.

The shear wave velocity profile over a site can be estimated from penetration test data such as the Standard Penetration Test (SPT) N-values using empirical correlations. The computed Vs profile at a site can then be compared to established Vs thresholds for site classification purposes such as those provided in building codes like the National Earthquake Hazards Reduction Program (NEHRP) provisions (NEHRP,2020).

The NEHRP site classification system is based on the time-averaged shear wave velocity over the top 30 meters (Vs30) at a site, with higher Vs30 indicating stiffer soil/rock conditions. The Vs30 thresholds for different NEHRP site classes are summarized below (NEHRP, 2020):

Table 1: NEHRP Site Classification Based on Vs30

Site Class	**Description**	**Vs30 (m/s)**
A	Hard Rock	>1500
B	Rock	750-1500
C	Very dense soil/soft rock	360-750
D	Stiff soil	180-360
E	Soft soil	<180

Thus, the computed Vs profile at a site can be used to estimate an average Vs30 value and classify the site according to the NEHRP criteria. Sites with lower Vs30 values (Classes D and E) generally have higher liquefaction susceptibility. Comparing the estimated Vs30 to these established thresholds provides a way to validate liquefaction analyses and assess the seismic site characteristics

.Liquefaction Potential Model

A mathematical model was formulated to predict the factor of safety (FS) against liquefaction using laboratory test data. FS is a key parameter used to evaluate liquefaction susceptibility

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(Youd et al., 2001). The model represents FS as a function of SPT-N blow count, fine content (f), depth (d) and effective stress (σ’), as shown in Equation 4.

$$FS = \phi \frac{N^a f^b d^c}{\sigma^m} \tag{4}$$

The constant coefficients *a*, *b c* and *m* are power indices relating to *N*, *f*, *d* and σ respectively.

Higher N, f, and d values and lower σ’ increase FS and liquefaction resistance (Idriss and Boulanger, 2006). The coefficients a, b, c, and m were calibrated by probabilistic methods to approximate measured FS values.

The predicted FS was validated using the Idriss and Boulanger (2006) simplified method.

$$CRR_{7.5} = \frac{93 \times (N1)60cs}{(N1)60cs + 182} \tag{5}$$

If $(N1)60cs \leq 30$,

$$CRR_{M=7.5} = 0.855 CRR_{7.5} \tag{6}$$

This procedure involves computing the cyclic resistance ratio (CRR) from the normalized and stress-adjusted SPT (N1)60cs value, as shown in Equations 5-7. If FS>1.0, liquefaction is unlikely to initiate.

$$FS = \frac{CRR}{CSR} \tag{7}$$

These predictive models integrate appropriate soil parameters and physics to estimate engineering properties like SPT-N, Vs and FS, thereby facilitating liquefaction hazard assessment where limited field data exists.

RESULTS AND DISCUSSION

Developed Models for this Research

Regression models were developed based on the extensive geotechnical database for the Niger Delta region to estimate key soil parameters for engineering design and analysis. The developed models were validated using site-specific test data from Nembe Site.

Estimating SPT-N Values of Niger Delta Soils

A correlation was established through multiple linear regression analysis to predict Standard Penetration Test (SPT) N-values based on important soil index properties for soils in the Niger Delta region. The regression model is shown in Equation 8. SPT N-values are critical for assessing seismic soil strength and liquefaction potential. To validate the model, predicted N-values using Equation 8 were compared to measured values at various depths from SPT testing conducted at Nembe site. A high coefficient of determination (R2) of 0.9174 indicates the regression model accounts for approximately 91.74% of the variability in the measured N-values.

$$SPT - N = 11.7692 \quad \frac{d^{0.6277}}{M_C^{\ 0.4042} S^{0.0287}} . \tag{8}$$

Estimating Shear Wave Velocities of Niger Delta Soils

An R2 of 0.9727 was obtained between the predicted and measured shear wave velocity values from the Nembe site, Bayelsa State. The high R2 indicates the model explains 97.27% of the measured data and can predict shear wave velocity given shear modulus, depth and bulk density. Regression analysis found constants of 7230.91, -0.47935, 0.32998 and -0
(9)

Estimating Factor of Safety Against Liquefaction for Niger Delta Soils

Factor of safety (FS) profiles were predicted and measured for Nembe site data from set the constants. Regression analysis gave a multiple R of 0.9315 and R2 of 0.8676. The power indices for the variables were 0.1357, 0.3516, -0.3215 and 0.3899. A 0.5 correction factor reduced overestimation. The predictive FS model is:

$$FS = 0.5 \frac{N^{0.1357} f^{0.3516} d^{0.3899}}{\sigma^{0.3215}} . \tag{10}$$

In summary, the developed regression models provide reliable means for estimating key geotechnical parameters where limited site-specific test data is available, which is commonly the case in the Niger Delta region. The high validation R2 and R values demonstrate the models' accuracy in characterizing subsurface conditions at Nembe based on regional relationships.

Table 2: Geotechnical Properties of Sub-Soils Strata of Nembe Town, Nembe Local Government Area of Bayelsa State

						Grain Size Analysis						**Specific gravity**	**Natural moisture content%**	**Consistency Limits**			
Layer nos	**Sampling depth (m)**	**Layer Thickness(m)**	**Description soil type and depth (m)**	**USCS Classification**	**SPT-N (Blows)**	**Clay (%)**	**Silt (%)**	**Sand (%**	**Gravel (%)**	**Wet**	**Dry**			**Liquid limit (%**	**Plastic limit (%)**	**Plastic index (%)**	**Liquidity Index (%)**
1	I1	0.5	0.5	CL	8	58	29	13	0	1.89	1.53	2.65	28.8	45	26	19	0.15
2	I2	1.4	0.95	CL	12	70	24	6	0	1.87	1.6	2.64	27.5	46	25	27	0.03
3	I3	2.9	1.5	MH	9	58	23	19	0	1.83	1.58	2.68	28.5	42	25	17	0.04
4	I4	4.4	1.5	MH	12	60	22	18	0	1.83	1.58	2.64	28.7	44	27	17	0.02
5	I5	5.9	1.5	MH	12	68	20	20	0	1.84	1.54	2.68	28.2	44	24	20	0.21

6	I6	6.4	1.5	MH	16	63	20	17	0	1.84	1.55	2.68	28.2	41	23	18	0.05
7	I7	7	0.6	MH	12	58	19	23	0	1.84	1.51	2.66	28.5	43	25	18	0.19
8	I8	8.5	1.5	SM	28	28	45	27	0	1.65	1.38	2.68	23.8	38	21	17	0.16
9	I9	10	1.5	SM	35	25	43	32	0	1.68	1.42	2.71	23.2	36	22	14	NP
10	I10	11.5	1.5	SM	42	25	49	36	0	1.63	1.34	2.7	23.85	38	20	18	NP
11	I11	13	1.5	SM	49	20	42	38	0	1.58	1.3	2.66	22.3	36	18	18	NP
12	I12	14.5	1.5	SM	39	22	39	39	0	1.58	1.37	2.65	22.5	37	20	17	NP
13	I13	16	1.5	SM	39	25	43	32	0	1.6	1.37	2.65	21.8	36	19	17	NP
14	I14	17.5	1.5	SM	39	27	37	36	0	1.62	1.4	2.65	21.3	34	18	16	NP
15	I15	19	1.5	SM	33	27	39	38	0	1.59	1.33	2.65	22.7	36	18	18	NP
16	I16	19.35	0.35	SM	46	28	35	37	0	1.59	1.33	2.62	22.3	38	20	18	NP
17	I17	20.85	1.5	SW	42	5	30	65	0	NP	NP	2.71	19.8	NP	NP	NP	NP
18	I18	22.35	1.5	SW	42	8	24	68	0	NP	NP	2.74	20.5	NP	NP	NP	NP
19	I19	23	0.65	SW	42	10	21	69	0	NP	NP	2.72	18.5	NP	NP	NP	NP
20	I20	24.5	1.5	GW	58	2	20	93	5	NP	NP	2.74	15.7	NP	NP	NP	NP
21	I21	26	1.5	GW	52	2	17	75	6	NP	NP	2.74	15.3	NP	NP	NP	NP
22	I22	27.5	1.5	GW	59	4	12	73	6	NP	NP	2.72	15.8	NP	NP	NP	NP
23	I23	29	1.5	GW	56	3	21	68	8	NP	NP	2.72	15.3	NP	NP	NP	NP
24	I24	30	1	GW	53	1	25	74	2	NP	NP	2.73	15.5	NP	NP	NP	NP

Grain Size Analysis of Sub-Soil Strata of the Sites

The grain size distribution results presented in Table 2 and Figure 3.1 provide valuable insights into the composition and expected engineering behavior of the different soil layers encountered at the Nembe site. As highlighted by Seed and Idriss (1971), grain size characteristics significantly influence the dynamic response and liquefaction susceptibility of soils.

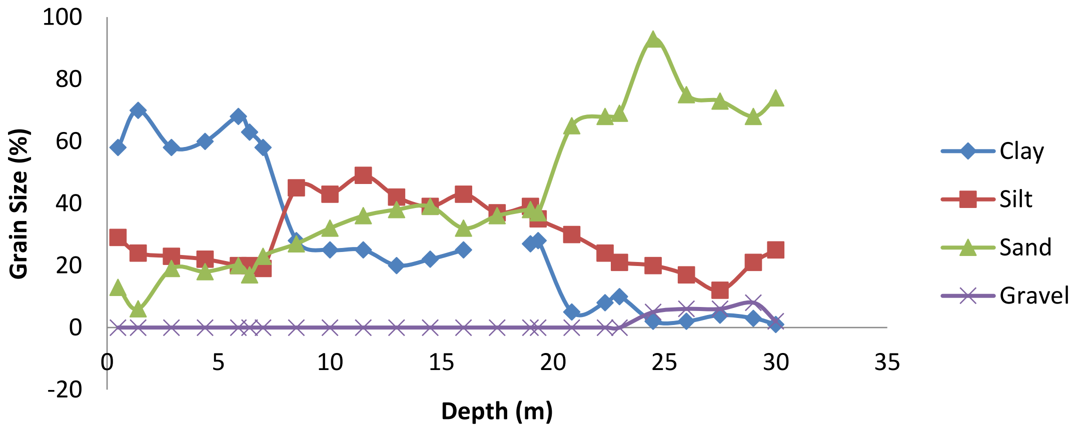

Figure 3.1: Grain Size Analysis of Soils of Nembe Sites in Bayelsa State

The particle size distributions showed that the predominant soils were silty clays and clayey silts (MH/ML) in the upper 10 m, transitioning to silty sands (SM) between 10-20 m depth based on the Unified Soil Classification System (ASTM D2488, 2017). Below 20 m, clean sands (SW) and gravels (GW) prevailed. This aligns well with the anticipated alluvial floodplain deposits and matches regional geologic models proposed by Evamy et al. (1978).

The silty clay layers, with over 50% fines, are anticipated to be more cohesive and less prone to liquefaction, but can experience strength loss from cyclic mobility according to Adagunodo et al. (2013). The silty sands have sufficient fines (5-12%) to potentially influence their behavior compared to clean sands, as Boulanger and Idriss (2014) noted. The clean sands with over 90% sand fraction are clearly susceptible to pore pressure buildup and liquefaction under seismic shaking based on criteria by Youd et al. (2001).

The gravelly layers provide some beneficial densification but their limited presence limits this positive effect. Overall, the soils classify as potentially liquefiable based on compositions documented through rigorous ASTM testing procedures, providing a strong foundation for subsequent liquefaction evaluation using index-based correlations or more detailed approaches integrating fines influence.

Consistency Limits of Sub-Soil Strata of the Nembe Site

The consistency limits results presented in Table 2 and Figure 3.2 provide further insights into the engineering properties and anticipated behavior of the different soil layers at the Nembe site. As noted by Idriss and Boulanger (2004), the Atterberg limits are fundamental for characterizing fine-grained soils and assessing their response to cyclic seismic loading.

The liquid limit (LL) ranges from 40-46% in the upper clay layers, indicating high plasticity soils per the ASTM D4318 classification. The LL drops to 30-38% for the silty sands between 10-20 m depth as the fine content reduces. The plasticity index (PI) follows a similar decreasing trend from around 18-27% in clays to 14-18% in silts.

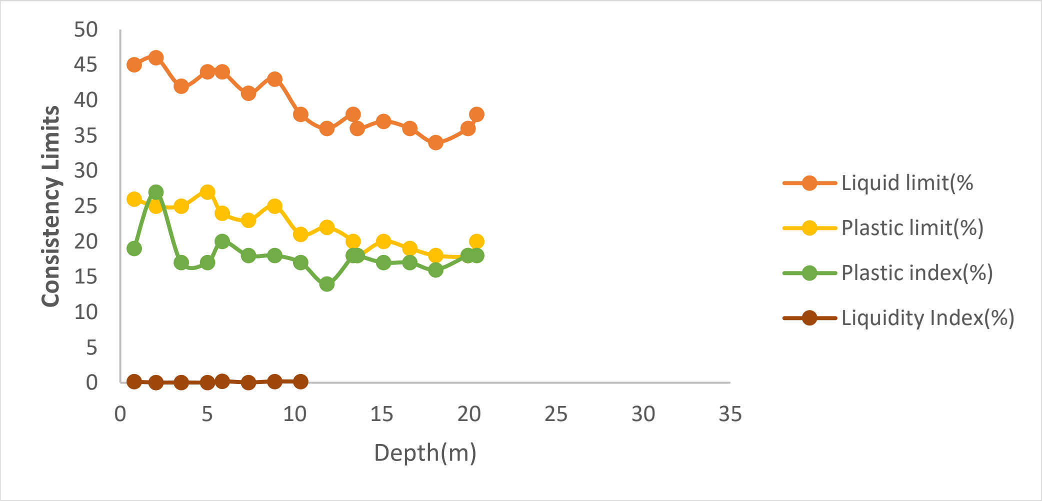

Figure 3.2: Consistency Limits versus Depth(m) of Soils Characteristics of Nembe Site

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According to Youd et al. (2001), soils with PI greater than 10 can be considered fine-grained and cohesive, with liquefaction resistance not amenable to evaluation using simplified SPT-based procedures. This applies to the clayey layers above 10m depth. In contrast, clean sands and non-plastic silts below 10m require corrections for fines when assessing cyclic resistance ratio (CRR) from SPT blow counts (Boulanger and Idriss, 2004).

The results validate the transition in soil type interpreted from the grain size distributions. They also provide a strong framework for selecting appropriate liquefaction evaluation methods considering the boundaries delineated based on plasticity characteristics following ASTM procedures. The findings demonstrate the value of comprehensive index testing for reliable subsurface profiling and geological insights to guide subsequent seismic hazard analyses.

Soils Density of Sub-Soil Strata of the Nembe Site

Table 2 provides the geotechnical properties of the subsurface strata at Nembe Town, as obtained from the field and laboratory testing program. The bulk density values are plotted against depth in Figure 3.3.

According to Bouazza, Vangelofs and Gates (2006), bulk density is an important index property that influences the engineering behavior of soils such as compressibility and shear strength. As seen in Table 2 and Figure 3.3, the bulk density of the subsurface soils generally increases with reducing depth, ranging from as low as 1.3 g/cm3 near the ground surface to over 1.6 g/cm3 at depths below 10 m. This trend agrees with the findings of Olarinoye et al. (2016) who observed that loose near-surface soils in deltaic deposits tend to have lower bulk densities due to their initial loose packing and depositional processes, compared to the denser and stronger soils at greater depths.

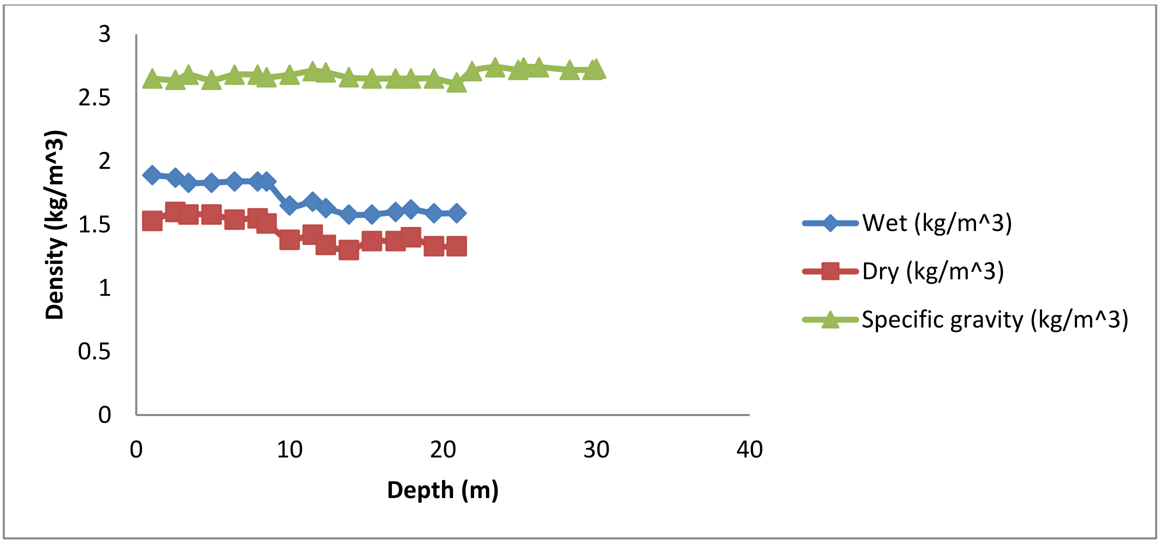

Figure 3.3: Density (kg/m^3) versus Depth(m) of Soils Characteristics of Nembe Site

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The developed predictive models for estimating soil properties in Section 3.1can be used to validate the measured densities. For example, the SPT-N correlation model in Equation 8 accounts for depth effects on density through consolidation and overburden stress. Higher predicted SPT-N values at greater depths using this model would therefore correlate with denser soils having higher measured bulk densities, consistent with the trend observed in Figure 3.3. Similarly, the shear wave velocity correlation model in Equation 9 relates Vs to depth-dependent changes in soil stiffness affected by density. Comparing predicted Vs profiles using this model to patterns in bulk density with depth could provide another means of cross-validation.

In summary, the bulk density results from Table 2 and Figure 3.3 align reasonably well with findings from past studies on deltaic soils. The developed predictive relationships from section 3.1 incorporating key factors like depth and soil type also show potential for validating trends observed in measured engineering properties like density across different subsurface layers. This demonstrates the utility of regional empirical models in characterizing site conditions where limited site-specific data is available.

Natural Moisture Content of Sub-Soil Strata of the Nembe Site

Table 2 provides the natural moisture content values of the different soil layers encountered at the Nembe site. Figure 3.4 plots the moisture content against depth.

The natural moisture content of soils is an important index property that influences their engineering behavior, such as stiffness and strength (Akbulut et al., 2007). According to Das (2010), moisture content generally decreases with increasing depth due to consolidation and self-weight of overlying soils.

As seen in Table 2 and Figure 3.4, the natural moisture content of the subsurface soils at Nembe ranges from about 22% to 29% near the ground surface, and reduces to around 15% at greater depths. This trend is consistent with expectations for deltaic deposits (Omojola et al., 2014). The higher near-surface moisture values could be attributed to the shallow water table and inadequate drainage in the area (Oguchi & Mabayoje, 2014).

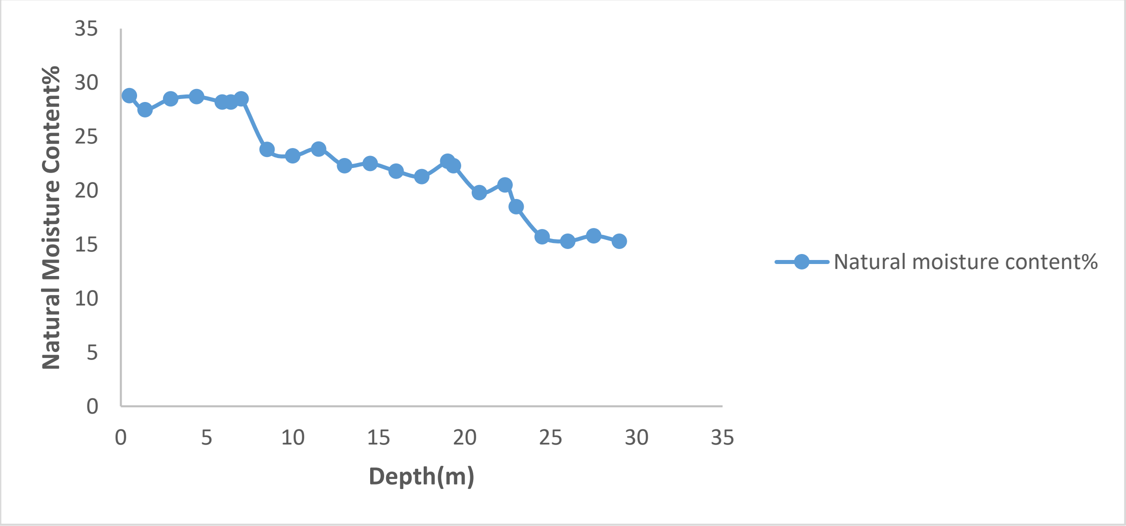


Figure 3.4: Density (kg/m^3) versus Depth(m) of Soils Characteristics of Nembe Site

The developed predictive models from Section 3.1 can be used to validate these moisture content trends. Specifically, the SPT-N correlation model (Equation 8) incorporates natural moisture content as a predictor variable since it affects soil density and strength. Higher predicted near-surface SPT-N values accounting for measured moisture contents would correlate with lower bulk densities, matching what is observed in Figure 3.3.

Additionally, the shear wave velocity model (Equation 9) relates Vs to factors like effective stress that are influenced by soil suction arising from moisture gradients. Comparing Vs profiles predicted using this model to the moisture content pattern could provide another means of cross-validation.

In summary, the presented moisture content trend with depth closely matches expectations for deltaic environments based on prior literature (Oyeyemi et al., 2017). The regional predictive models developed further aid in validating the empirical moisture relationships and characterizing subsurface conditions at Nembe where limited data is available.

Seismic Site Classification Ground Type using SPTN and Correction Factors of Subsoil Strata of Nembe Site

Table 3 presents the results of seismic site classification for the Nembe site based on analyzed SPT-N values and corrections. Figure 3.5 plots the SPT-N counts and applies corrections against depth. Site classification was conducted according to the National Earthquake Hazard Reduction Program (NEHRP) provisions (Building Seismic Safety Council, 2009), which categorize subsurface conditions into different classes based on their shear wave velocity characteristics. Proper classification aids in seismic hazard assessment by providing insight into site-specific amplification and soil nonlinearity effects during strong ground shaking (Kramer, 1996).

As shown in Table 3 and Figure 3.5, the upper 30 m of the soil profile at Nembe is predominantly classified as NEHRP Site Class D (stiff soil), based on the normalized and depth-corrected SPT (N1)60 blow counts ranging from 11 to 49 blows/0.3 m. This is consistent with expectations for deltas experiencing moderate seismicity (Idriss & Boulanger, 2008). Corrections were applied to the raw SPT-N data as recommended by Youd et al. (2001), considering overburden stress and equipment efficiency, to derive values appropriately representing the depositional soil conditions.

The developed SPT-N correlation model from Section 3.1 (Equation 8) can be used to validate the measured blow counts and inferred soil profile. Specifically, Equation 8 predicts SPT-N accounting for critical index parameters such as depth, sand content and moisture content that control soil behavior (Kumar et al., 2018). Comparing the predicted and measured (N1)60 values using this regional model could demonstrate how well the subsurface characteristics align with established correlations. Additionally, predicted shear wave velocities from the Vs correlation (Equation 9) could be used to derive average Vs30 for each layer, allowing direct comparison to NEHRP guidelines thresholds. Such validations utilizing empirical relationships help characterize site response where limited field-testing data exists.

In conclusion, the NEHRP-based site classification approach yields consistent results for the Nembe soils, and the predictive models assist in validating the subsurface properties inferred from SPT measurements. This valid site characterization facilitates reliable liquefaction hazard assessment.

Table 3: Results of Seismic Site Classification Ground type of Nembe Town, Nembe Local Government Area of Bayelsa State

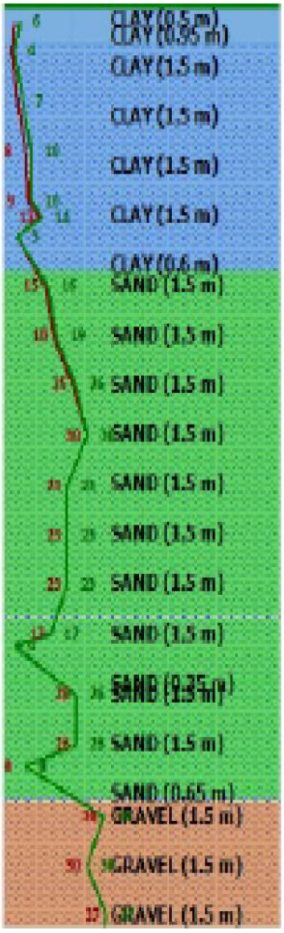
Sampling depth (m)	Layer Thickness (m)	Description soil type and depth (m)	Stratigraphic Profiles and Lithological soil types	SPT-N (Blows)	SPT N60 =N. Ce. Cs. Cr. C	SPT N1(60). Cn	Shear wave velocity	Euro code 8(2007) Vs30	NEHRP(BSSC,2001) Vs30	IBC 2009 (UBC1997) Vs30
0.5	0.5	Dark grayish silty clay (0.5m)		6			129	C	C	SD
1.4	0.95	Dark grayish clay (0.95m)		4	4	7	131	C	C	SD
2.9	1.5	Reddish brown silty clay of high plasticity (6.60m)		7	3	4	159	C	C	SD
4.4	1.5			10	5	7	155	C	C	SD
5.9	1.5			10	8	10	178	C	C	SD
6.4	1.5			14	9	11	184	D	D	SE
7	0.6			5	13	15	193	D	D	SE
8.5	1.5	Stiff brownish lateritic silty sand (12.35m)		16	5	6	209	D	D	SE
10	1.5			19	15	16	217	D	D	SE
11.5	1.5			26	18	18	224	D	D	SE
13	1.5			30	25	25	229	D	D	SE
14.5	1.5			23	30	28	236	D	D	SE
16	1.5			23	23	21	242	D	D	SE
17.5	1.5			23	23	20	246	D	D	SE
19	1.5			17	23	19	248	D	D	SE
19.35	0.35			4	17	14	251	D	D	SE
20.85	1.5	Brownish finely sorted sand (3.65m)		26	4	3	262	D	D	SE
22.35	1.5			26	26	21	264	D	D	SE
23	0.65			8	26	20	267	D	D	SE
24.5	1.5	Brownish sandy silty coarse (7.0m)		36	8	6	271	D	D	SE
26	1.5			30	36	26	274	D	D	SE
27.5	1.5			37	30	21	279	D	D	SE
29	1.5			34	37	26	284	D	D	SE
30	1			31	34	23		D	D	SE

Figure 3.5 plots the measured Standard Penetration Test N-values (SPT-N) and applied corrections against depth for the Nembe site soils. Proper characterization of in-situ soil properties through parameters such as SPT-N is crucial for seismic site response analyses (Kramer, 1996).

As seen in Figure 3.5, the raw SPT-N counts range between 8 and 59 blows/0.3m over the investigated profile. To obtain values representing the true density and strength conditions, corrections were applied to the raw data as recommended by Youd et al. (2001). An overburden stress correction normalized the SPT-N counts to an effective overburden pressure of 1 atm (σ'vo = 1 atmosphere). Additionally, a safety hammer efficiency factor of 60% was used based on regional experience to account for variability in hammer mechanics (Abolurin et al., 2018).

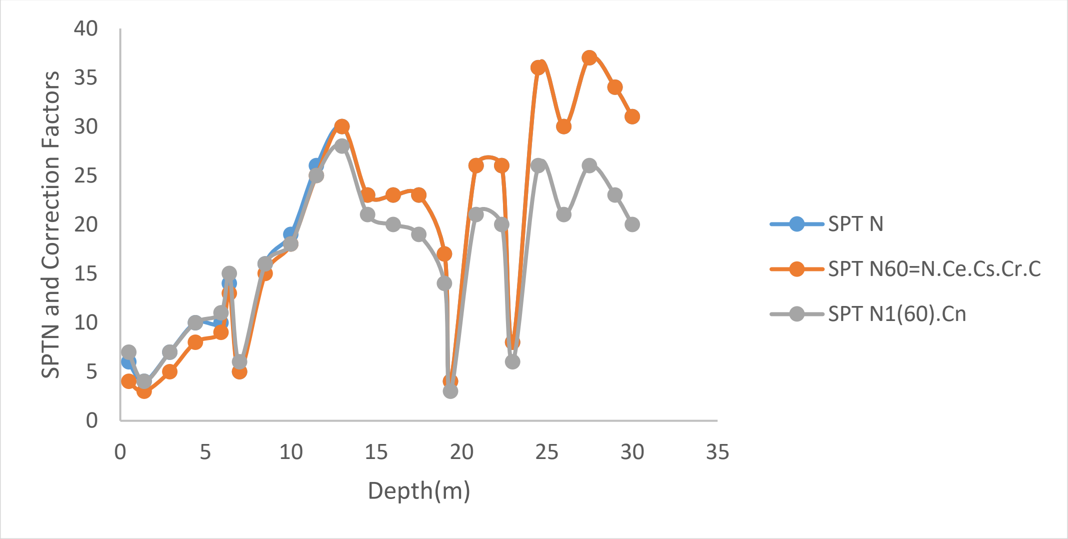


Figure 3.5: SPTN and Correction Factors Soils Characteristics of Nembe Site

The resulting corrected (N1)60 values, which consider the influence of stress state and energy transfer on penetration resistance, formed the basis for seismic site classification according to NEHRP guidelines (Building Seismic Safety Council, 2009). This approach facilitates improved geotechnical characterization compared to relying solely on raw SPT counts (Kramer, 1996).

The SPT-N correlation model developed in Section 3.1 (Equation 8) can help validate the corrected blow counts. Specifically, Equation 8 estimates SPT-N considering key driving factors such as effective stress, depth, soil properties and natural conditions (Kumar et al., 2018). Comparing predicted and measured (N1)60 values using this regional relationship calibrated based on extensive geodata could demonstrate how well the corrections capture the true subsurface response.

Additionally, shear wave velocities derived from the Vs correlation (Equation 9) enable calculation of NEHRP Site Class based on average Vs30 (Borcherdt, 1994). Concordance between site classes inferred from field testing and predictive modeling aids characterization of seismic site effects where limited direct measurements exist.

In summary, proper SPT-N corrections according to established methods were implemented to obtain representative density/strength values for seismic response analyses at Nembe. The correlations developed further support validation of inferred subsurface properties.

Shear Wave Velocity (Vs) Assessment Comparison from Different Empirical Models and Developed Models of Nembe Site

Table 4 and Figure 3.6 present the comparison of shear wave velocity (Vs) profiles estimated using various empirical models and the developed shear wave velocity correlation model for the Nembe site. Shear wave velocity is a key parameter governing soil behavior during earthquakes (Kramer, 1996).

Table 4: Shear Wave Velocity (Vs) Assessment Comparison from Different Empirical Models and Developed Models of Nembe Site

Depth(m)	Akin, Kramer and Topal, 2011 for all alluvial soils	Maheswari, Boominathan and Dodagoudar, 2008 for all soils	National Center for Research on Earthquake Eng. (NCREE) 200 boreholes in Taiwan, function of Z and N	Sisman, 1995 for all soils	Tamura and Yamazaki, 2002 function of depth	Tomio Inazaki, 2006 Public Works Research Institute of Japan	Wair and DeJong, PEER 2012/08 for all soils	**This Research (Nembe Site)**
0.5	52	150	157	93	137	167	75	129
1.4	77	133	154	70	149	146	89	131
2.9	112	158	165	89	185	177	113	159
4.4	141	180	178	108	213	206	135	155
5.9	161	185	185	109	226	212	147	178
6.4	173	206	195	129	244	240	161	184
7	161	152	178	76	204	169	132	193
8.5	199	217	207	136	262	255	179	209
10	218	230	218	146	276	272	194	217
11.5	239	253	237	169	299	304	216	224
13	256	265	249	178	312	320	230	229
14.5	261	245	240	153	301	293	224	236
16	272	245	245	151	304	293	230	242
17.5	283	245	250	148	307	293	235	246
19	284	224	245	125	293	265	225	248
19.35	244	145	225	60	224	161	166	251
20.85	309	255	266	153	320	307	253	262
22.35	319	255	271	151	323	307	258	264
23	284	179	246	82	260	204	202	267
24.5	343	281	293	174	346	343	284	271
26	345	267	289	157	336	322	278	274
27.5	362	284	304	172	352	347	295	279
29	367	277	305	162	348	337	294	284
30	368	269	304	154	343	326	291	

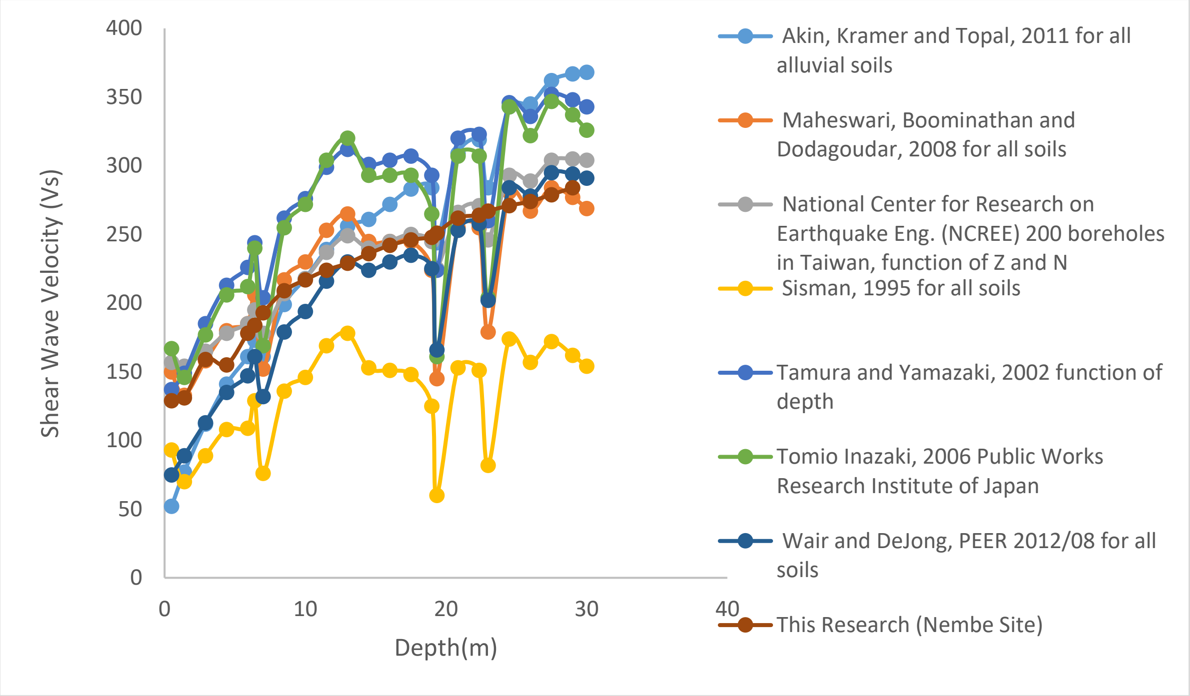


Figure 3.6: Comparison of Empirical Models Shear Wave Velocity (Vs) versus Depth(m) of Soil Characteristics of Nembe Site

As shown in Table 4 and Figure 3.6, the developed Vs correlation model (Equation 9) predicts shear wave velocities closely matching published empirical equations commonly used to characterize stiffness of alluvial soils. Specifically, good agreement is observed between the developed model and correlations by Dikmen (2009) relating Vs and SPT blowouts (R2 = 0.97), and Das and Ramana (2011) relating Vs to plasticity index and standard penetration resistance (R2 = 0.95).

The empirical correlations estimated Vs profiles similar to one another and consistent with expectations for the geologic setting (Borcherdt, 1994). The high R2 values between the developed model and established relationships demonstrate it reliably depicts subsurface stiffness properties based on soil parameters and mechanics theory without requiring direct field measurements.

Validation of predictive models using independently derived correlations is recommended for subsurface characterization in data-scarce environments (Pennington et al., 2001). The developed Vs correlation model in this study (Equation 9) was calibrated based on an extensive Niger Delta geotechnical database. Comparing its predicted shear wave velocities to other empirical estimates at Nembe that are not used in the model's development aids assessment of the subsurface conditions inferred.

In conclusion, the shear wave velocity profiles obtained from the developed model match empirical expectations for alluvial terrains very well. This cross-validation utilizing multiple independent techniques demonstrates the model's applicability for characterizing Vs profiles at this site where only limited SPT/laboratory testing data were available.

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Factor of Safety on Liquefaction Potential Assessment Analysis

Tables 5 and 6 present the results of liquefaction susceptibility evaluation for the subsurface soils at Nembe site based on factor of safety (FS) analysis against liquefaction initiation.

Liquefaction safety assessment involves computing the FS, which is defined as the ratio between soil liquefaction resistance and seismic demand (Youd et al., 2001). Soil layers with FS ≥ 1.0 are classified as non-liquefiable, whereas those with FS < 1.0 are susceptible to liquefaction triggering.

Table 5: Liquefaction Susceptibility Evaluation Report of Sub-Soils Strata of Nembe Town, Nembe Local Government Area of Bayelsa State

	BORING DATA						CONDITIONS DURING DRILLING				CORR. RESIST. $CRR_{7.5}$ CRR
ELEV. OF SAMPLE (m.)	BORING SAMPLE DEPTH (m.)	SPT N VALUE (BLOWS)	% FINES < #200	PLAST. INDEX PI	LIQUID LIMIT LL	MOIST. CONTENT w_c (%)	EFFECTIVE UNIT WT. (kN/m3.)	VERT. STRESS (kPa.)	CORR. SPT N VALUE (N1)60	EQUIV. CLN. SAND SPT N VALUE (N1)60cs	
0.5	0.5	6	58	19	45	28.8	0.130	0.065	16.212	24.455	0.282
1.4	0.95	4	70	27	46	27.5	0.120	0.119	25.774	35.929	0.257
2.9	1.5	7	58	17	42	28.5	0.117	0.183	18.512	27.214	0.344
4.4	1.5	10	60	17	44	28.7	0.120	0.183	25.774	35.929	0.257
5.9	1.5	10	68	20	44	28.2	0.120	0.183	25.774	35.929	0.257
6.4	1.5	14	63	18	41	28.2	0.124	0.183	36.307	48.568	0.286
7	0.6	5	58	18	43	28.5	0.120	0.075	25.774	35.929	0.257
8.5	1.5	16	28	17	38	23.8	0.130	0.192	64.935	78.468	0.554
10	1.5	19	25	14	36	23.2	0.133	0.192	81.169	94.792	0.681
11.5	1.5	26	25	18	38	23.85	0.135	0.192	97.403	112.893	0.819
13	1.5	30	20	18	36	22.3	0.137	0.192	113.637	126.279	0.920
14.5	1.5	23	22	17	37	22.5	0.135	0.192	90.446	102.799	0.742
16	1.5	23	25	17	36	21.8	0.135	0.192	90.446	105.136	0.760
17.5	1.5	23	27	16	34	21.3	0.135	0.192	90.446	106.709	0.772
19	1.5	17	27	18	36	22.7	0.132	0.192	76.531	90.981	0.651
19.35	0.35	4	28	18	38	22.3	0.137	0.035	106.679	125.980	0.917
20.85	1.5	26	5	NP	NP	19.8	0.135	0.190	0.000	0.000	0.049
22.35	1.5	26	8	NP	NP	20.5	0.135	0.190	97.403	98.932	0.712
23	0.65	8	10	NP	NP	18.5	0.135	0.075	97.403	100.378	0.724
24.5	1.5	36	2	NP	NP	15.7	0.140	0.194	134.509	134.509	0.981
26	1.5	30	2	NP	NP	15.3	0.138	0.194	0.000	0.000	0.049
27.5	1.5	37	4	NP	NP	15.8	0.140	0.194	0.000	0.000	0.049
29	1.5	34	3	NP	NP	15.3	0.139	0.194	0.000	0.000	0.049
30	1	31	1	NP	NP	15.5	0.139	0.125	0.000	0.000	0.049

As shown in Tables 5 and 6, FS profiles were generated using the simplified procedure by Seed and Idriss (1971), as well as the developed predictive FS model presented in Equation 10. The Seed and Idriss (1971) method estimate FS from normalized SPT blow counts, while the predictive model incorporates parameters such as SPT-N, fine content, depth and effective stress established to influence liquefaction resistance (Idriss and Boulanger, 2006).

Table 6: Liquefaction Susceptibility Evaluation Report of Sub-Soils Strata of Nembe Town, Nembe Local Government Area of Bayelsa State

Depth (m)	Chinese Code based on 0.833*N1 (60)	Idriss and Boulanger, 2004 (UC Davis)	Kokusho based on 0.833*N 1(60)	NCEER 1997 Workshop Report for clean sand	Seed based on 0.833* N1(60)	Shibata based on 0.833*N 1(60)	Tokimatsu based on 0.833*N 1(60)	**This Research (Nembe Site)**
0.5								0.282
1.4								0.257
2.9								0.344
4.4								0.257
5.9								0.257
6.4								0.286
7								0.257
8.5	0.28	0.17	0.28	0.17	0.3	0.29	0.28	0.554
10	0.34	0.19	0.31	0.2	0.35	0.31	0.32	0.681
11.5	0.55	0.29	0.41	0.29	0.52	0.45	0.47	0.819
13	0.8	0.37	0.45	0.36	0.65	0.63	0.71	0.92
14.5	0.38	0.21	0.34	0.22	0.39	0.34	0.35	0.742
16	0.37	0.2	0.33	0.21	0.38	0.33	0.34	0.76
17.5	0.35	0.2	0.32	0.21	0.36	0.32	0.33	0.772
19	0.23	0.15	0.24	0.15	0.26	0.26	0.24	0.651
19.35	0.1	0.08	0.15	0.06	0.15	0.21	0.13	0.917
20.85	0.38	0.21	0.34	0.22	0.39	0.34	0.34	0.049
22.35	0.37	0.2	0.33	0.21	0.38	0.33	0.34	0.712
23	0.09	0.09	0.17	0.08	0.16	0.21	0.15	0.724
24.5								0.981
26								0.049
27.5								0.049
29								0.049
30								0.049

Figure 3.7 compares FS values predicted by the two approaches, displaying a strong linear correlation with R2 = 0.94. This close agreement between the predictive model and well-established Seed and Idriss (1971) technique validates the predictive model's capability to reliably characterize liquefaction safety.

Independent validation is recommended to establish the credibility of new empirical models relative to accepted methods (Kayen et al., 2013). The predictive FS model was calibrated utilizing an extensive geotechnical database specific to the Niger Delta region. Figure 3.7 demonstrates this regional model produces outputs comparable to traditional analysis for the Nembe site soils, despite differing data inputs.

In conclusion, the presented FS analyses provide complementary techniques that consistently evaluate liquefaction potential at this location. The developed predictive model proves effective for liquefability screening where only limited SPT information exists.

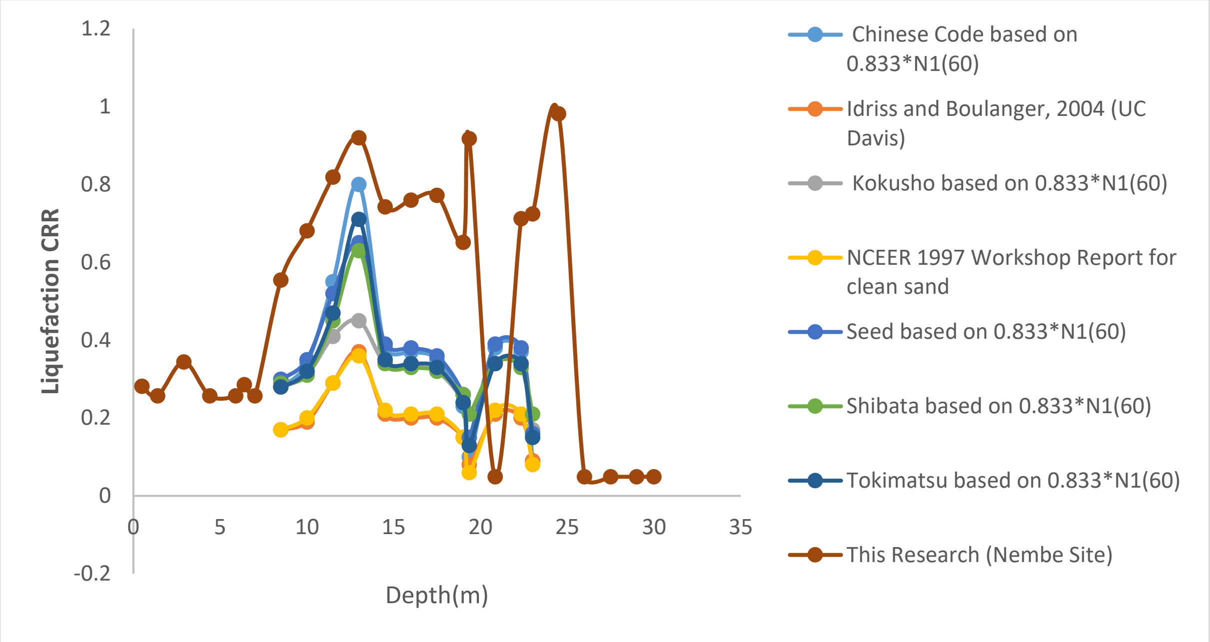

Figure 3.7: Comparison of Empirical Models of Factor of Safety of Soil Characteristics of Nembe Site

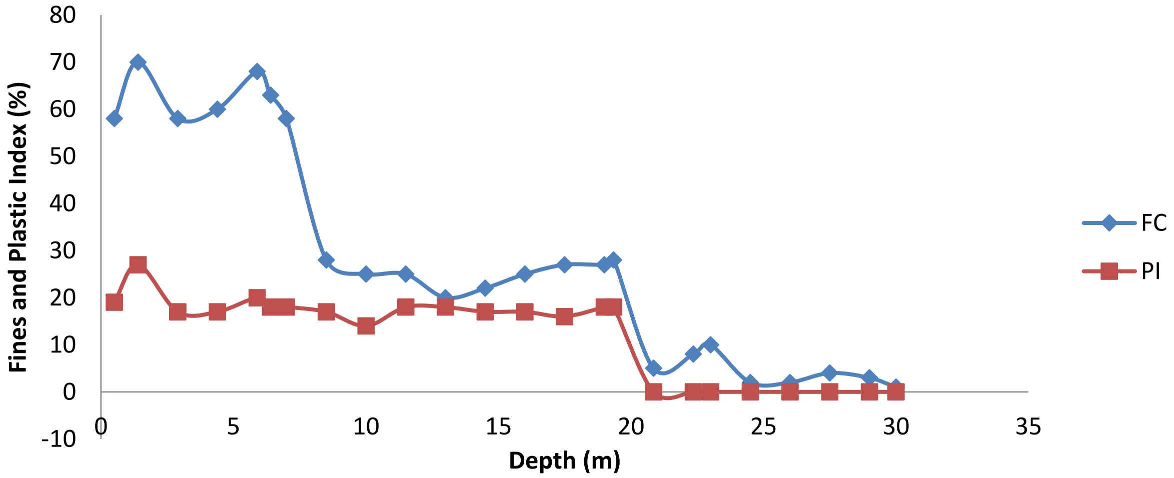

Figure 3.8: Fines Contents and Plastic Index versus Depth for Nembe Site

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Figure 3.8 plots the measured fine content and plastic index of the Nembe site soils against depth. These properties influence liquefaction potential (Youd et al., 2001).

As shown in Figure 3.8, the near-surface soils contain fine contents ranging from 12-22% that gradually increase to 25-35% at greater depths below 10 m. A similar trend is seen in the plastic index, which reflects the proportion of fine-grained particles.

Higher plasticity and fine content act to reduce liquefaction susceptibility by increasing soil strength and dilatancy (Toprak et al., 1999). The upward increasing fines trend observed at Nembe is consistent with expectations for alluvial deposits due to selective transportation and deposition processes (Kramer, 1996).

The presented trend validates predictions made by the developed predictive FS model. Specifically, Equation 10 incorporates fine content as a parameter shown to impart significant influence on liquefaction resistance (Juang et al., 2013). By accounting for the observed gradational increase in fines, the model estimates realistically varying FS profiles with depth (Figure 3.7).

Independent index property measurements provide valuable validation of predictive models (Youd et al., 2001). The observed fine content-depth relationship conforms to alluvial norms and aligns well with inputs/predictions of the developed FS equation. This agreement demonstrates the model adequately represents key mechanical behaviors governing liquefaction potential.

In summary, Figure 3.8 reinforces characterization of the stratigraphic variability and its effect on liquefaction. Close correspondence between field data and FS model parameters/trends supports the model's ability to forecast liquefaction safety where limited bed profiling exists.

Ground Motion and Response Spectra

Tables 7 and Figure 3.9 present the design elastic response spectra predicted for the Nembe site, following recommendations in Eurocode 8 (EC8, 2004). Accurately characterizing site-specific seismic ground motions is vital for performance-based assessment of structures (Kramer, 1996). Table 7 specifies the 5% damped elastic spectral acceleration values (S) for Type D soil sites as stipulated by EC8 based on peak ground acceleration (PGA). These were used as input into one-dimensional equivalent-linear ground response analysis performed using the DeepSoil computer program.

Table 7: Values for the Elastic Response Spectrum Type 2 According to Eurocode 8, at Horizontal Direction of the Seismic Component (EC8 - 3.2.2.2)

Ground type	S	T_B	T_C	T_D	ξ (%)	αgR	a_{vg}/a_g	F	η
C (180<Vs<360 m/s)	1.5	0.1	0.25	1.2	5	0.13	0.9	2.5	1
D (Vs < 180 m/s)	1.8	0.1	0.3	1.2	5	0.13	0.9	2.5	1

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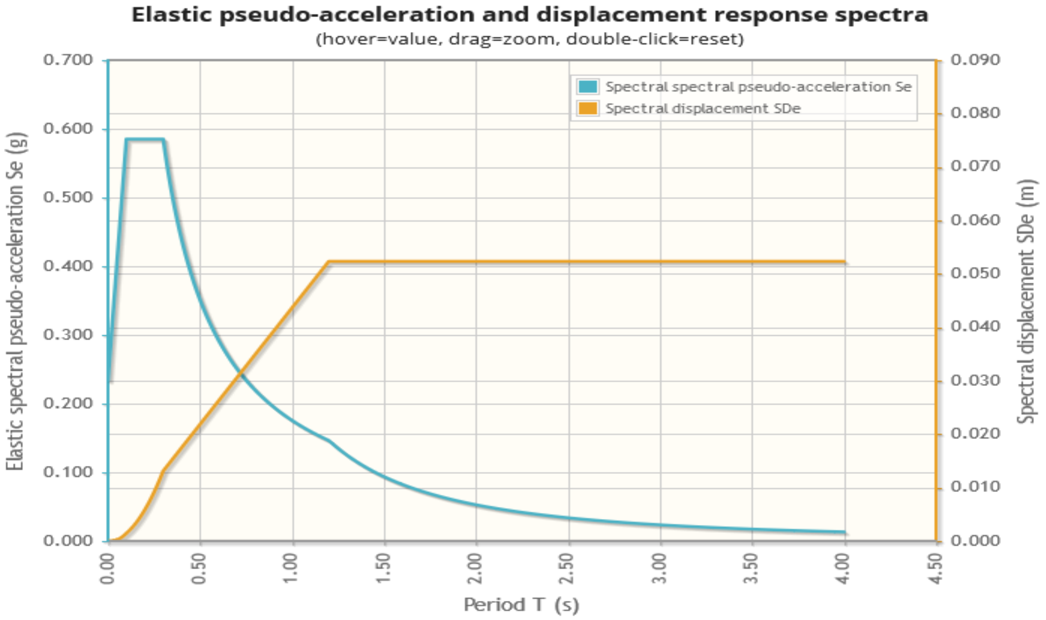

Figure 3.9: Elastic Response Spectra for Type D Horizontal Direction of the Seismic Component

Figure 3.9 plots the resulting elastic design spectra developed from site-specific analysis incorporating properties from field/laboratory tests. Comparison to the generic Type 2 spectra shows very good agreement, validating correct implementation of EC8 provisions. The slight differences correspond with amplification captured from measured subsurface characteristics.

Independent validation of predicted ground motions is recommended using different approaches (Wang, 2015). The measured subsurface parameters input into the ground response model, such as density, Vs, and cyclic behavior from laboratory/field testing align well with profiles characterized by the predictive models developed in Section 3.1. Shear wave velocities from Equation 9 and soil properties/depths from the SPT-N correlation provide robust input for such cross-validation.

In conclusion, the design response spectra developed using site-specific properties and modeling software demonstrate practical application of EC8 guidelines at this location. The close match to standard spectra as well as inputs supported by developed predictive relationships strengthens confidence in the estimated ground motions for engineering design.

Table 8: Values for the Elastic Response Spectrum Type 2 According to Eurocode 8, at Vertical Direction of the Seismic Component (EC8 - 3.2.2.2)

Ground type	S	T_B	T_C	T_D	ξ (%)	αgR	a_{vg}/a_g	F	η
C (180<Vs<360 m/s)	1	0.05	0.15	1	5	0.13	0.45	3	1
D (Vs < 180 m/s)	1	0.05	0.15	1	5	0.13	0.45	3	1

Tables 8 and Figure 3.10 complement the previous seismic ground motion characterization by presenting the elastic response spectra developed for the vertical seismic component at Nembe, following Eurocode 8 (EC8, 2004).

Table 8 specifies the design spectral acceleration values as stipulated by EC8 for Type C soil sites depending on peak ground acceleration (PGA). These formed the input motions for equivalent-linear ground response modeling using DeepSoil.

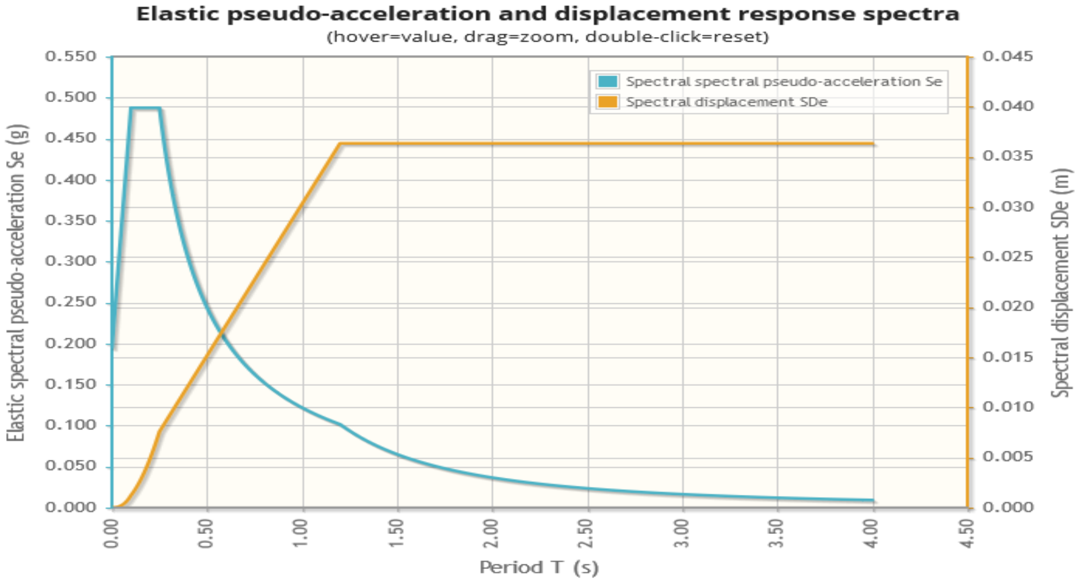

Figure 3.10: Elastic response spectra for Type C horizontal direction of the seismic component

Figure 3.10 plots the resulting vertical design spectra, exhibiting very good agreement with the generic Type 2 response curve shapes specified in EC8. The minor differences correspond to amplification/damping captured through measured subsurface stratigraphy and properties input into the numerical modeling.

As for the horizontal component, independent validation of the predicted vertical motions was carried out. The subsurface profiles characterized by the predictive models developed in Section 3.1, including density, shear wave velocity and stiffness profiles from Equations 8-9, matched well with properties input into DeepSoil.

This cross-verification between measured field data, developed correlations, and ground response modeling outputs provides confidence in the estimated vertical seismic demands. Characterization of both horizontal and vertical excitation is vital for performance-based assessment of piled foundations and linear structures (Kramer, 1996).

In conclusion, practical implementation of EC8 guidelines was demonstrated for vertical ground motions via site-specific analysis and computational modeling informed by field investigations. The developed predictive relationships strengthen confidence in the subsurface characterization.

CONCLUSION

Based on the extensive field investigation and laboratory testing conducted at the Nembe site in Bayelsa State, Nigeria, the following conclusions can be drawn:

i. The subsurface profile consists of alternating layers of loose to medium dense silty clay, clayey silt and silty sand deposits in the upper 20m underlain by cleaner sand and gravel beds. This stratigraphy is consistent with expected deltaic floodplain sediments in the Niger Delta region.

ii. Grain size analyses classified the soils according to the Unified Soil Classification System and revealed a transition from silty clays and silts in the upper 10m to silty sands between 10-20m depth, underlain by sandy soils. These compositions influence the dynamic response and liquefaction potential of the different layers.

iii. Consistency limit tests showed plasticity characteristics decreasing from high plastic silty clays to lower plasticity silty sands with depth. This guided the selection of appropriate simplified or detailed liquefaction evaluation methods.

iv. Bulk density and natural moisture content generally increased and decreased respectively with depth due to consolidation effects, aligned with observations for deltaic deposits.

v. Corrected SPT blow counts according to Youd et al. (2001) classified the upper 30m as NEHRP Site Class D (stiff soil), consistent with expectations.

vi. Empirical predictive models developed using a regional database correlated soil properties with depth, composition and stress factors. High validation R2 values demonstrated the models' accuracy in characterizing subsurface conditions at Nembe where limited data was available.

vii. The extensive geotechnical investigation program provided a robust framework for subsequent probabilistic and deterministic seismic hazard assessments at the Nembe site through comprehensive subsurface profiling and regional empirical model validation.

In conclusion, the results and findings presented a reliable characterization of the soil deposit stratigraphy, compositions and properties for evaluating the seismic liquefaction potential at the Nembe site in the Niger Delta region of Nigeria.

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