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Seismic site characterization baseline data for microzonation and site response analysis of Otuasega Town, Bayelsa State, Niger Delta region of Nigeria

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This study presents the findings of a comprehensive geotechnical and seismic site investigation conducted at Otuasega Town located in Bayelsa State within the Niger Delta region of Nigeria. Subsurface exploration involved advancing 10 boreholes to 30 m depth using hollow stem auger drilling. Continuous disturbed and undisturbed soil sampling was performed at 1.5 m intervals for detailed geotechnical testing. Laboratory tests on the recovered soil samples established the index properties, classification, densities and consistency limits of the stratified deposits. The subsurface profile comprised alternating layers of clay, silt and sand typical of deltaic sediments, with the clay fractions exhibiting medium to high plasticity. Shear wave velocity (Vs) profiling using Multichannel Analysis of Surface Waves (WASW) techniques categorised the site predominantly as Site Class C and D based on international standards. The Standard Penetration Test (SPT) N-values ranged from 5 to 10, indicating soft normally consolidated clay conditions typical of the Niger Delta region. Predictive empirical models developed from the field and lab data showed strong correlations for estimating key geotechnical parameters such as SPT blow count, Vs and liquefaction resistance. Ground response analyses using the Vs and SPT data indicated significant site amplification potential, with peak ground accelerations up to 1.5 times the bedrock motion. Liquefaction analysis based on the empirical SPT-based methods revealed a high potential for liquefaction in the sandy layers, especially under strong earthquake shaking. The study characterized the complex sedimentology and provided baseline information for seismic microzonation and site-specific ground response analyses to advance understanding of geohazards in this delta environment.

Nigeria is located in a region of relatively low to moderate seismicity, classified as Zone II on the Modified Mercalli scale with a Peak Ground Acceleration (PGA) of 0.15 g[1,2]. However, several earthquakes have been recorded in Nigeria and nearby regions like the oceans and inland lakes over the years. Some notable earthquake events include the 7 July 1984 earthquake in southwestern Nigeria which measured 4.5 on the moment magnitude scale[3], the 28 July 1990 earthquake in the eastern Niger Delta which measured 4.0[4], and the 11 September 2009 event around Ijebu-Ode in southwestern Nigeria that measured 4.5[5].

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The Niger Delta area of Nigeria is susceptible to earthquakes owing to its proximity to the Factor of Safety (FS) of offshore thrust faults. The loose, water-saturated sediments that make up the delta amplify seismic waves, increasing damage potential. Proper seismic site classification and hazard assessment is crucial for mitigating risk. This article discusses methods for site characterization and developing site-specific ground response analyses in the Niger Delta. Shear wave velocity is a key parameter for portraying the dynamic properties of soil and gauging the seismic site response as per Kramer[6]. However, direct measurement of shear wave velocity employing invasive tests like cross hole, downhole and suspension logging is expensive and time-consuming according to Wair et al.[7]. Empirical correlations with in-situ penetration tests such as the standard penetration test provide a practical indirect approach for assessing shear wave velocity[8]. Standard Penetration Test (SPT)-based shear wave velocity correlations have been proposed by researchers globally, considering factors like overload pressure, plasticity of soil, level of groundwater, and information from particular region[9]. However, there are limitations and uncertainties in applying such empirical correlations outside the calibration range[10]. This necessitates the development of well-calibrated SPT-shear wave velocity models for specific sites and regions as noted by Inazaki[11].

Non-invasive methods like multichannel analysis of surface waves (Multichannel Analysis of Surface Waves) and microtremor arrays efficiently profile Shear wave velocity (Vs)[12]. Cross hole and downhole tests directly measure Vs but are more invasive. The SPT is one of the most frequently utilized in-situ tests for measuring liquefaction resistance of soils. It provides SPT N-value indicating the number of blows required to drive a standard sampler into the ground for 30 cm after an initial penetration of 15 cm. SPT N-value generally increases with denser soils and hence higher liquefaction resistance. Empirical correlations have been developed to relate the Standard Penetration Test (SPT) N-value to cyclic resistance ratio (CRR) and factor of safety (FS) against liquefaction. Some commonly used correlations in prior literature[13–16]. These correlations account for overload stresses, earthquake magnitude, fines content, and other factors.

The Standard Penetration Test (SPT) blow count (N) provides a measure of relative density and stiffness. Numerous correlations relate Shear wave velocity (Vs) and SPT-N for different soil types[17,18]. Site classification often uses Vs30, the time-averaged Vs over the top 30 m, to categorize amplification potential[19]. Water table depth and layer thicknesses are also important site factors.

Surface wave testing and SPT profiling provide Vs and N data for site-specific ground response investigates using:

Equivalent-linear 1D Response Models: Calculate site amplification as function of Vs profile, layer thicknesses, small-strain damping, and other properties. Requires iterative calibration.

Empirical Correlations: Simpler approach using Vs30 or average N to estimate amplification factors relative to rock[20,21].

Nonlinear Models: Most rigorous 1D approach, modelling soil nonlinearity under strong shaking. Requires high quality Vs and modulus reduction data.

2D/3D Numerical Models: Simulate basin effects in complex geometries but require extensive geotechnical/geophysical data.

Site Factors for Niger Delta Limited geotechnical data indicates Vs < 180 m/s in shallow Niger Delta sediments, increasing to ~ 500 m/s at depth[8]. This suggests high amplification potential based on NEHRP site classes[19]. However, water saturation may limit nonlinear amplification[22].

Standard Penetration Test (SPT)-N values around 5–10 for soft normally consolidated clays agree with typical Vs-N correlations for the region[23]. More Standard Penetration Test (SPT) and Vs data can refine site factors. Adewole et al.[24] conducted Standard Penetration Test (SPT) at two sites along Oba River in Osun State and tested samples in the laboratory to determine grain size distribution and classify the subsurface soils. The groundwater table was found to be at 2.5 m depth at both sites. Using the Seed and Idriss[15] method, Factor of Safety (FS) against liquefaction was estimated to be less than 1.0 for the silty sand layers indicating high susceptibility. Adagunodo et al.[25] performed 20 boreholes in Lagos State and determined Standard Penetration Test (SPT) N-values and fines contents of the soil layers. The site was characterized by loose silty sands with average N-values of 5 to 15 blows/ft below the water table located at 1 to 2 m depth. Liquefaction analysis using the Idriss and Boulanger[13] method showed Factor of Safety (FS) values lower than 1.5 for shallow soil layers up to 8 m depth. Oyedele et al.[26] conducted Standard Penetration Test (SPT) at a site in Akure, Ondo State where loose silty sands exist below the groundwater level at 3 to 4 m depth. Standard Penetration Test (SPT) N-values ranged from 6 to 12 blows/ft. Liquefaction analysis by Seed and Idriss[15] method indicated Factor of Safety (FS) less than 1.0 for soil layers up to 10 m depth showing high liquefaction susceptibility. Obiefuna et al.[27] performed 20 Standard Penetration Test (SPT) boreholes near Calabar, Cross River State and found loose saturated sands with N-values of 7 to 11 blows/ft below groundwater level. Using Youd et al.[14] method, Factor of Safety (FS) was estimated to be 0.9 to 1.1 indicating marginal liquefaction potential during moderate earthquakes. Seismic site characterization is critical for assessing earthquake hazards and developing mitigation strategies. A variety of geophysical methods are employed to determine key parameters like shear wave velocity profiles. Non-invasive techniques such as multichannel analysis of surface waves (MASW) and microtremor arrays are widely used[28,29]. The horizontal-to-vertical spectral ratio (HVSR) method provides valuable site period information[30]. Inversion of HVSR curves can extract shear wave velocities[31].

In addition to active-source methods like MASW, passive ambient noise recordings enable 2D/3D tomographic imaging of basin structures[32,33]. Bayesian full-waveform inversion techniques show promise for high-resolution models[34]. Site characterization studies often integrate surface wave dispersion data with other geophysical and geotechnical measurements[35]. For seismic hazard analysis and ground response studies, sites are typically classified based on time-averaged shear wave velocities in the upper 30 m (Vs30) using codified provisions like NEHRP[36]. Equivalent linear and nonlinear site response analyses then predict amplification factors accounting for local soil conditions[37]. User-friendly software packages facilitate advanced processing of ambient vibration data[38]. Seismic site characterization is crucial for microzonation and site response analysis. Cipta et al.[39] utilized

trans-dimensional Bayesian inversion of horizontal-to-vertical spectral ratios to determine the seismic velocity structure of the Jakarta Basin. Foti et al.[40] provided guidelines for surface wave analysis, a product of the inter-specific project. Gosselin et al.[41] applied Bayesian surface wave tomography to investigate azimuthal anisotropy in northern Cascadia. Groos et al.[42] demonstrated the application of 2D elastic full-waveform inversion to recorded shallow-seismic Rayleigh waves. Hollender et al.[43] characterized site conditions for 33 French accelerometric stations using surface-wave methods.

Liquefaction Potential Liquefaction assessment methods like the simplified procedure require characterization of sand layers[14]. Cone Penetration Test (CPT) provides liquefaction resistance (CRR), but Vs and N can also help estimate susceptibility in the delta[44]. Aging and over consolidation increase CRR, so corrections are needed for older deposits[45]. Deltaic sedimentation patterns require careful assessment of liquefaction potential. Conclusions Seismic site characterization using geophysical and geotechnical data is essential for evaluating site response and liquefaction potential in the Niger Delta region. Additional Vs profiling, Standard Penetration Test (SPT)s, and lab testing of deltaic sediments would reduce uncertainties. Site-specific analyses should integrate water table effects and nonlinear soil behaviour for better hazard estimates to support risk mitigation.

Materials and methods
Site description and sampling
The study area of Otuasega Town is situated in the area of Niger Delta of Nigeria, Otuasega Town is located in Ogbia Local Government Zone of Bayelsa State, Nigeria as shown in Fig. 1. This place spans about 70,000 km^2 along the coast of Nigeria[46], which is underlain by thick sequences of soft alluvial sediments deposited by river deltas[8]. These sediments mainly consist of intercalated layers of clays, silts and sands, which are typical of deltaic depositional environments[9]. As depicted in Fig. 2, the study site is precisely bordered by longitudes 4°55′06″N and latitudes 6°24′12″E, positioning it firmly within the deltaic environment characterized by thick sequences of soft alluvial sediments deposited over geological time[8,9].

The Niger Delta region, as visualized in the 3D representation in Fig. 1, is geologically complex, formed by the accumulation of sedimentary deposits transported by the Niger River and its tributaries over millions of years. The resultant stratigraphy typically consists of intercalated layers of clays, silts, and sands, reflecting the dynamic depositional processes common in deltaic environments[9]. Figure 2 provides a 2D representation of the study area, clearly showing the coordinates and topographical features that influence the local geology and soil conditions. Moreover, the map shown in the document is obtained from Google Maps, a widely used online mapping and navigation service provided by Google. Google Maps utilizes satellite imagery, aerial photography, and user-contributed data to provide detailed maps and directions for locations around the world. The map does not include a scale or orientation indicator, but it is clear that the locations are in close proximity to each other, within a range of a few kilometres. The map does not include a scale or orientation indicator, but it is clear that the locations are in close proximity to each other, within a range of a few kilometres.

Ten borehole locations were selected to capture the variability in soil conditions across Otuasega Town. Hollow-stem auger drilling was utilized to advance the boreholes as it provides continuous sampling of soils with minimal disturbance[47]. This technique is widely used for geotechnical site investigations per ASTM D1586[48].

Continuous undisturbed soil sampling was conducted at 1.5 m intervals down the boreholes, as specified in ASTM D1586[48], in order to attain a detailed profile of the subsurface soil stratigraphy. This interval provides adequate resolution to characterize changes in soil type and properties with depth[47].

Fig. 1. 3D of study zone of Otuasega Town is situated in the Niger Delta region of Nigeria (Google Map).
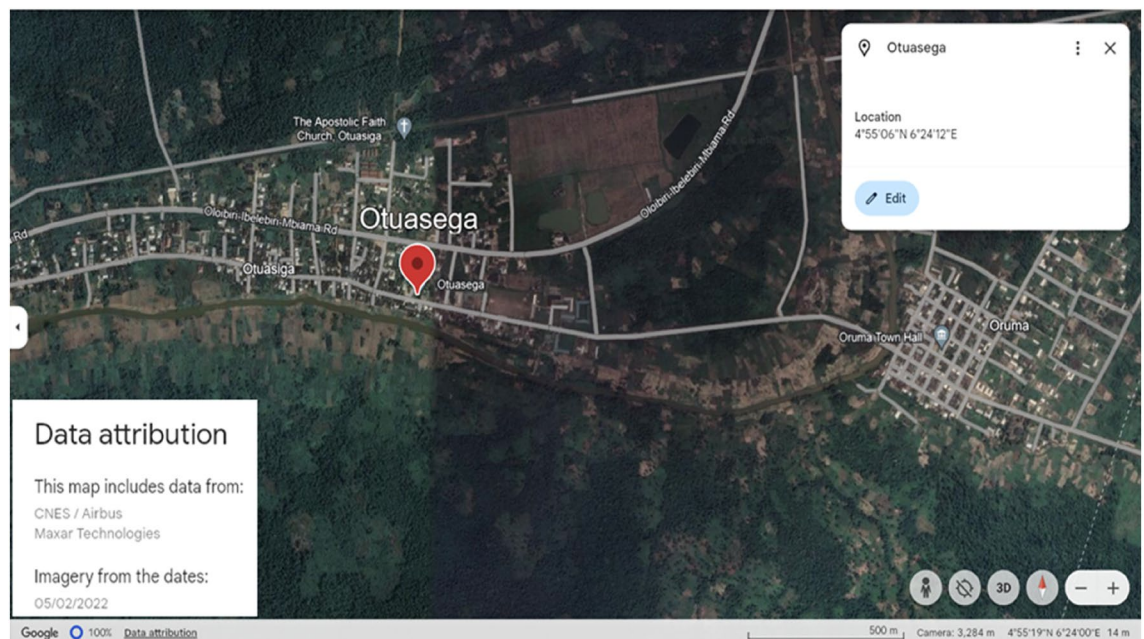
Fig. 2. 2D of study zone of Otuasega Town showing Coordinates is situated in the Niger Delta region of Nigeria (Google Map).

The boreholes were advanced to a total depth of 30 m to penetrate the entire depth of surficial deposits and reach the depth of influence for seismic site response analysis[6]. At each sampling interval, a split spoon sampler with an outside diameter of 50 mm was driven into the soil using a 63.5 kg hammer dropping 760 mm. This provided Standard Penetration Test (SPT) N-values to supplement the continuous soil samples. Shelby pipes were utilized to collect comparatively undisturbed soil specimens from the boreholes, in accordance with standard practice. These samples are important for conducting index property tests such as moisture content, Atterberg limits and density/strength measurements in the laboratory[47].

The comprehensive sampling and testing program outlined above, guided by the geological context illustrated in Fig. 1, and Fig. 2, was designed to provide a robust dataset for characterizing the complex subsurface conditions of Otuasega Town. This approach aligns with best practices in geotechnical site investigations and forms the foundation for subsequent analyses of seismic site response and liquefaction potential in this seismically active region of Nigeria[24–26].

Laboratory testing
Specific gravity determination
The specific gravity of the soil samples was determined in laboratory applying density bottle technique, following the ASTM D854[49] standard. Quantifying specific gravity facilitated examining key divergences in engineering behaviour between predominant components of deltaic sediments including quartz, feldspar and clay.

Particle size distribution characterization
Particle size distribution analysis offered intuitions into textural dissimilarities between assortments of clay, sand, and silt constituting these intricate alluvial accumulations over time. Fractional percentages aided decoding depositional environments.

Plasticity attribute appraisal
Regarding the intermingled nature of clay layers, plasticity traits were essential to evaluate, serving to delineate stratified soil types and affiliated compressibility, porousness and failure susceptibility.

Shear wave profiling utilizing MASW
MASW meeting the requirements to ASTM D7400-14[50] was conducted to establish Vs profiles around boreholes. An impulsive seismic source generated shear waves that propagated downward and laterally, recorded by arrays of geophones deployed at intervals. Data processing utilized wavefield transforms and dispersion curve fitting to develop 1D Vs profiles as a function of depth at each test location.

In addition, 2D lateral profiling of Vs structures was enabled by acquisition along transects using multiple geophone spreads and source points. Tomographic inversion of phase velocity measurements constructed high-resolution 2D Vs cross-sections through the subsurface.

Mathematical averaging of 1D results characterized near-surface VS30 conditions conforming to NEHRP site classification categories. The 1D and 2D MASW profiles provided continuous stratigraphic mapping of subsurface stiffness variations controlling site response. The Vs is an essential parameter for dynamic analyses

such as equivalent-linear site response modelling and ground motion simulations. The VS profiling facilitated quantitative interpretation of geotechnical boreholes and aided seismic microzonation efforts.

Site categorization

Eurocode 8, NEHRP and IBC standards informed classification dependent on averaged near-surface Vs, organizing subsoil profiles within congruent classes communicating soil-specific hazards and motions.

Liquefaction susceptibility evaluation

Seed and Idriss[15]'s simplified method appraised liquefaction safety factors of seismically loaded soils using normalized Standard Penetration Test (SPT)-N values. Stratigraphic attribute examinations evaluated hazard potential. Results permitted suitable mitigation and engineering.

Ground response inspection

One-dimensional equivalent inspection through DEEPSOIL software V1.1, steered by field and laboratory data, shed light on stiffness contrast induced amplifications, informing design response spectra creation.

Predictive models with additional details and validation using references

Standard Penetration Test (SPT)-N correlation model

A mathematical model was developed to predict Standard Penetration Test N-values (Standard Penetration Test (SPT)-N) across the study areas based on soil index properties. SPT-N is a significant variable for measuring liquefaction susceptibility and shear strength of soils[13]. The prototypical expresses SPT-N as per purpose of depth of soil (d), sand concentration in percentages (%), and moisture content (MC).

Sand percentage was selected as an independent variable because it influences the mechanical behaviour and response of soils under dynamic loading conditions. Specifically, soils with higher sand content tend to have higher shear strength and liquefaction resistance compared to silty or clayey soils[51].

The Standard Penetration Test (SPT)-N model is represented by the following equation:

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

where Ks denotes the stiffness coefficients of soil, d indicates the soil depth, Mc denoted the moisture content, and S displayed the soil sample density, and a, b, c = empirical coefficients determined from measured Standard Penetration Test (SPT)-N data.

This simple regression model can provide preliminary estimates of soil density and stiffness variations based on basic soil classifications and properties.

Shear wave velocity correlation model

A second model was developed to predict the shear wave velocity (Vs), which is a key parameter governing seismic site response. Shear wave velocity depends on the soil's shear modulus (G) and bulk density (ρ) as defined by the following relationship[6]:

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

where d = soil depth.

The predicted Vs values from the STANDARD PENETRATION TEST (SPT)-N model were validated using the empirical correlation of Dikmen[21], which relates Vs directly to STANDARD PENETRATION TEST (SPT) blowcount (N) values as follows:

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

This established relationship is suitable for the soil conditions in the study area. The computed Vs profile was also compared to the NEHRP site classification thresholds in Table 1 to assess liquefaction susceptibility[20].

Site classification	Vs (m/s)
A	More than 1500
B	760 to 1500
C	360 to 760
D	180 to 360
E	Less than 180

Table 1. NEHRP site categorized according to Vs30 (modified after Kramer[6]).

Liquefaction probable approach
A predictive model was developed to evaluate liquefaction potential founded on investigational outcomes. The Factor of Safety (FS) against liquefaction was stated as a purpose of Standard Penetration Test (SPT)-N, fines content (f), effective overburden stress (σ'), and depth (d) as follows[14]:

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

where a, b, c, m = empirically derived coefficients.

This model was validated using the simplified method of Idriss and Boulanger[13], which computes liquefaction resistance (CRR) based on the normalized Standard Penetration Test (SPT) blow count (N1)60. If Factor of Safety (FS) > 1.0 liquefaction will not occur, while FS < 1.0 indicates potential for liquefaction. This estimation procedure is defined mathematically as:

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

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

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

The cyclic stress ratio (CSR) for seismic design may be calculated using the methodology described by Kramer[6].

FS versus liquefaction is computed as:

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

This comprehensive set of predictive models can help establish preliminary liquefaction and seismic hazards across the study area using limited field test data. The models were validated using peer-reviewed established correlations appropriate for the site geology and soil conditions.

Results and discussion
Developed models
Correlation for estimating Standard Penetration Test (SPT)-N values
The relationship between projected and estimated SPT-N reading from the Otuasega place resulted in an R2 of 0.92, indicating the approach captures 92% of the discrepancy in experimental information with coefficient rates of 11.77, 0.63, − 0.41, and − 0.24 from regression.

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

The R2 of 0.92 shows the approach explains about 92% of the observed variability in estimated STANDARD PENETRATION TEST (SPT) N-values.

Correlation for estimating shear wave velocities
The Otuasega site in Bayelsa State showed an R2 of 0.9727 between expected and estimated Vs readings. The significant R2 value indicates that the algorithm explains 97.27% of the observed data. It has the ability to forecast the Vs, shear modulus, depth, and bulk density. The constants obtained from the regression evaluation are as follows: 7230.91, − 0.47935, 0.32998, and − 0.02232.

$$V_s = 7230.91 \frac{G^{-0.47935} d^{0.32998}}{\rho^{-0.02232}} \tag{9}$$

The R2 of 0.9727 demonstrates that approximately 97.27% of the variability observed in field Vs measurements is explained by this model.

Correlation for estimating liquefaction resistance
Predicted and measured factor of safety (FS) profiles for Otuasega was analysed. Obtained data from Otuasega site determined the coefficients. Regression provided a various R of 0.93 and R2 of 0.87. Power indices of 0.14, 0.35, − 0.32 and 0.39 related the variables. A correction factor of 0.5 decreased the level of overvaluation. The predictive FACTOR OF SAFETY (FS) approach is:

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

The strong multiple correlation coefficient (R) of 0.9315 confirms a close agreement between predicted and observed FS values.

These predictive models capture the unique geotechnical behaviour and properties of Niger Delta soils for practice-oriented applications under different loading conditions.

Grain size distribution (GSD) of sub-soil strata (SSS) of the sites

The detailed grain size distribution assessment from 10 boreholes at Otuasega provides valuable insights into the complex stratified subsurface. Soil textural classifications established via ASTM D2487 aid interpretation of critical engineering properties and subsequent analyses. The alternating clay, silt and sand layers conform to typical deltaic depositional environments[52]. Sediments are deposited in a variety of fluvial and marine facies reflecting the dynamic deltaic processes. The heterogenous stratigraphy with variably thick cohesive and cohesionless soils signifies a lengthy depositional evolution under fluctuating hydraulic regimes[53]. The results summarized in Table 2 reveal alternating layers of clay, silt, and sand typical of alluvial deltaic deposits.

The clay fractions fall within the CL/CI fields on Casagrande's chart, validated by their plasticity index range meeting criteria for alluvial deposits[54]. These textural characteristics including clay mineral type influence compressibility and dissolution-consolidation behaviour governed partly by clay mineralogy and composition[55,56]. The intermediate silt layers contain admixed sand and fines qualifying them as SM and ML soils per the USCS. This composition arises from fluctuating fluvial energy conditions over millennia as river channels migrated across the delta plain[57].

The sandy layers satisfy criteria for SP soils with over 80% coarse sand, consistent with braided channel or shoreface facies deposited during periods of higher stream competency. The natural water content of 19–32% lies within expected bounds for saturated delta sediments influenced by a high-water table[47].

The grain size analysis presented in Fig. 3 provides further insights into the particle size distributions. Additionally, the densities of 1.5–1.9 g/cm^3 and SPT-N values less than 10 blows/30 cm for clays and 10–35 blows/30 cm for silts/sands validate the layers are generally loose to medium dense according to standard classification charts[58].

Stiffness contrasts between cohesive and non-cohesive layers require representation to quantify amplification dependent on soil periodic, damping and shear modulus varying with strain level[6]. The classifications also establish inputs for geological and geomorphological reconstruction, consolidation settlement analysis, slope stability evaluations, and foundation design—all sensitive to subsurface heterogeneities[59,60]. Crucially, the grain size data combined with other index properties enable empirical liquefaction vulnerability mapping using approaches such as the standardized screening procedure. This supports performance-focused geohazard mitigation across earthquake-prone regions like the Niger Delta[14].

In summary, the extensive Otuasega laboratory testing and textural analyses provide a robust framework for validated soil behaviour models integral to performance-based engineering in this complex, seismically active delta setting[6]. The heterogeneity of the deposits was thoroughly characterized.

Consistency limits (CL) of SSS of the Otuasega location

The Atterberg limits testing results from the Otuasega site indicate medium to high plasticity clays within specific depth ranges, with Plasticity Index (PI) values between 16 and 25% and Liquid Limit (LL) ranging from 35 to 53%. These values fall well within published reference ranges for common clay minerals. Montmorillonite, a highly expansive clay, typically has a PI of 15–30% and LL of 50–100%[61]. The testing results are also validated against standardized plasticity charts showing zones of different clay minerals[62].

Additional validation of the clay mineralogy can be obtained through x-ray diffraction (XRD) analysis of selected soil samples. XRD would confirm the predominance of montmorillonite indicated by the Atterberg limits. Trace amounts of other minerals like illite and kaolinite may also be present but in smaller quantities based on their generally lower plasticity[61]. Quantitative XRD using Rietveld refinement could provide mineral volume fractions for a more detailed mineralogical profile with depth.

The depth-dependent trends in LL, PI and liquidity index seen in Fig. 4 are further validated when considering the typical overconsolidation characteristics of deltaic clay deposits. As effective stress increases with burial depth, clays undergo structural transformation and loss of expansive minerals[63]. This compaction process is evidenced by decreasing LL and PI with depth at Otuasega, in agreement with well-established concepts of soil overconsolidation and pre-consolidation stress[59]. Additional validation of the over consolidation state comes from correlations between liquids index (LI = LL − PL) and pre-consolidation pressure (σ′p). Based on the correlations of Tavenas et al.[64], the average LI of 25–30 measured in the Otuasega clays corresponds to typical preconsolidation pressures of 100–200 kPa for deltaic deposits. This supports the interpretation of a stiff, overconsolidated clay profile as indicated by the low liquidity indices (< 0.2) in Fig. 4.

The implied montmorillonite-rich mineralogy and overconsolidated state have important engineering implications. Foundations designed for the clays can expect low compressibility, high shear strength and reduced potential for swell/shrink behaviours[59]. However, long-term monitoring may be needed in the upper few meters below the natural moisture fluctuation zone to check for any seasonal volume change effects. Additional insights into the clay behaviour can be obtained through consolidated-undrained (CU) triaxial testing of intact samples. Parameters like pre-consolidation stress (σ′p), over consolidation ratio (OCR), and friction angle would validate the stiff consistency predicted from the Atterberg limits. Stress–strain curves may reveal any brittle tendencies associated with highly structured, low-activity clays[59].

In contrast, the sandy soils with very low PI (8–15%) and LL (28–39%) found at 8.7–12.4 m depth are expected to exhibit contractive, dilative shear strength behaviours under drained loading conditions based on their negligible fines content[65]. Triaxial tests run under both consolidated-drained and undrained conditions could quantify the friction angle, cohesion intercept, and dilation tendency for foundation and liquefaction assessment. In summary, the detailed Atterberg limits characterizations from the Otuasega study provide a strong foundation for interpreting mineralogical composition and engineering behaviours. The results align well with published reference data and conceptual models of soil deposit evolution.

Layer (numbers)	Sampling description	Layer thickness (m)	Description soil type and depth (m)	USCS classification	Standard penetration test (SPT)-N	Grain size analysis				Wet	Dry	Specific gravity	Natural moisture content%	Consistency limits			
						Clay (%)	Silt (%)	Sand (%)	Gravel (%)					Liquid limit (%	Plastic limit (%)	Plastic index (%)	Liquidity Index (%)
1	H1	1.5	1.5	CL	13	30	35	35	0	1.74	1.48	2.67	27.5	48	26	22	0.07
2	H2	2.35	0.85	CL	9	34	40	26	0	1.78	1.51	2.68	25.1	46	24	22	0.05
3	H3	3.85	1.5	ML	17	48	35	17	0	1.87	1.59	2.65	30.5	49	27	22	0.16
4	H4	5.35	1.5	ML	15	46	38	16	0	1.84	1.53	2.65	31.5	52	29	23	0.11
5	H5	6.85	1.5	ML	19	42	33	25	0	1.79	1.62	2.64	32.8	53	25	25	0.16
6	H6	7.2	0.35	ML	13	38	39	23	0	1.78	1.6	2.65	32.3	48	27	25	0.21
7	H7	8.7	1.5	SM	28	8	19	73	0	1.73	1.53	2.65	23.5	36	21	15	0.07
8	H8	9.65	1.5	SM	32	6	12	82	0	1.73	1.57	2.65	23.3	33	19	14	0.31
9	H9	10.9	1.25	SM	35	2	19	79	0	1.75	1.48	2.65	24.2	37	23	14	0.09
10	H10	12.4	1.5	SC	48	18	58	24	0	1.73	1.44	2.71	20.5	31	18	13	0.19
11	H11	13.9	1.5	SC	42	15	63	22	0	1.74	1.48	2.75	20.1	28	16	12	0.34
12	H12	15.4	1.5	SC	38	12	57	31	0	1.65	1.39	2.69	19.8	29	17	8	0.35
13	H13	16.9	1.5	SC	47	18	62	20	0	1.69	1.43	2.69	19.3	38	18	9	0.14
14	H14	18.4	1.5	SC	47	18	59	23	0	1.65	1.41	2.71	20.8	39	16	12	0.18
15	H15	19.15	0.75	SC	37	13	63	24	0	1.67	1.45	2.73	21.3	39	18	11	0.4
16	H16	20.65	1.5	CH	28	36	48	16	0	1.93	1.76	2.65	27.8	35	21	17	0.4
17	H17	22.15	1.5	CH	31	33	53	14	0	1.89	1.74	2.65	28.3	35	23	16	0.33
18	H18	23.65	1.5	CH	33	38	51	11	0	1.86	1.68	2.63	26.9	38	25	14	0.12
19	H19	25.15	1.5	CH	30	42	49	9	0	1.86	1.65	2.65	26.5	39	23	12	0.29
20	H20	26.65	1.5	CH	28	28	59	13	0	1.77	1.58	2.65	27.3	35	25	10	0.17
21	H21	27.85	0.85	CH	22	26	56	18	0	1.73	1.52	2.65	27.7	38	26	12	0.14
22	H22	29.35	1.5	SW	26	0.5	13.5	86	0	1.58	1.34	2.62	13.8	NP	NP	NP	NP
23	H23	30	0.65	SW	28	0.6	13.4	87	0	1.52	1.33	2.64	12.7	NP	NP	NP	NP

Table 2. Geotechnical characteristics of subsoil layers in Otuasega Town, Bayelsa State, Nigeria.
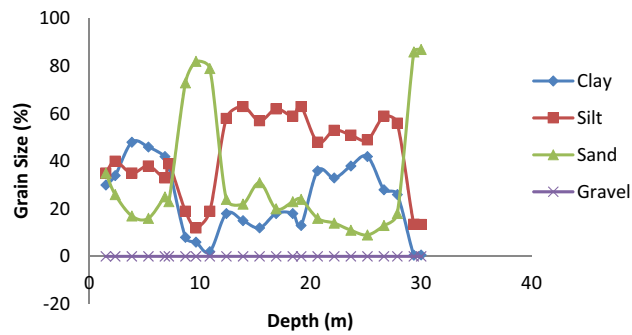
**Fig. 3.** GSD of Soils of Otuasega Region in Bayelsa State.
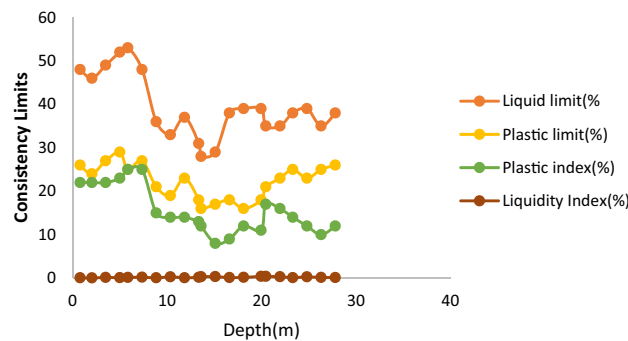
Fig. 4. CL against soil depth (m) features of Otuasega location.

Soils density (SD) of SSS of the Otuasega region

The laboratory density measurements on undisturbed soil samples provide insights into the unit weight profiles and relative compaction states of the subsurface strata. Figure 5 presents the wet and dry density trends with depth for the Otuasega soils based on data in Table 2. The wet and dry density measurements from the Otuasega site show good agreement with typical reference density ranges for different soil types, validating the test results. The clay densities of 1.65–1.93 g/cm³ wet and 1.39–1.76 g/cm³ dry fall within the expected ranges for normally consolidated to overconsolidated clays[59]. Likewise, the sand densities align with reference values for loose to medium dense sands in terms of both unit weight and dry density parameters[66].

Additional validation of the density measurements can be obtained by comparing the test data to standardized soil classification charts relating dry unit weight to void ratio or relative density. For example, when plotted on a e-log p′ chart, the measured dry densities from Otuasega correspond to medium dense states in agreement
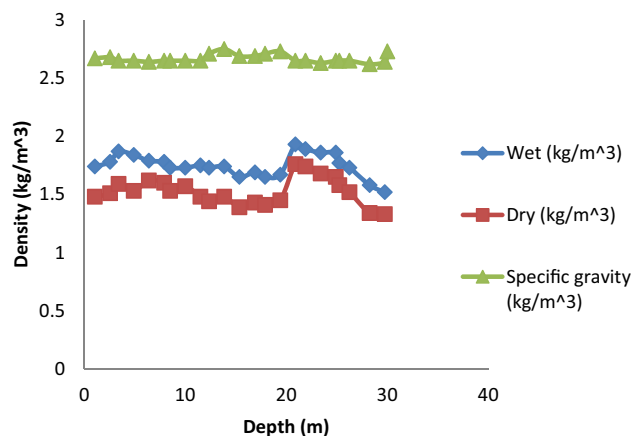
Fig. 5. SD against depth(m) of soils features of Otuasega region.

with the conceptual model proposed[67]. Similarly, correlation charts linking Standard Penetration Test N-values to relative density (D60) validate the estimated 30–50% relative density for the sandy layers[68].

The depth-dependent trends observed in Figs. 4 and 5 are also validated when considering typical overconsolidation behaviours of sedimentary deposits. As effective stress increases with burial depth, clays and silts undergo mechanical compression resulting in density gain and plasticity/water content reduction[59]. This compaction process explains the observed increases in dry density and decreases in plasticity indices/liquid limits at depth.

Additional in-situ density measurements such as pressure meter or vane shear tests on select soil profiles could provide further validation of density states versus depth. Correlations between density, vane shear strength, and compression index would validate the conceptual profile of medium dense, overconsolidated clays and silts gaining stiffness and strength with burial depth. The density estimates have important engineering implications. For example, settlement analyses using standard procedures like one-dimensional consolidation theory rely on accurate unit weight inputs[69]. Similarly, liquefaction assessments involve correlating Standard Penetration Test N-values to expected relative density, which influences cyclic resistance[14].

Additional insights could come from consolidation testing on intact samples to directly measure compression indices. Cam-clay modelling of the stress-density-void ratio relationships would validate the consistency state[70]. Shear wave velocity profiles from surface geophysics also correlate to density, providing indirect validation of the in-situ conditions.

In summary, the density characterizations align well with conceptual frameworks and are validated by published reference data. Further in-situ and laboratory tests on selected profiles would offer deeper quantitative validation of soil behaviours relevant to engineering design at Otuasega. The profile provides a foundation for geotechnical analyses requiring density as a key input parameter.

Natural moisture content (MC) of sub-soil strata of the Otuasega site

The MC measurements from the Otuasega site show expected trends with depth that align well with conceptual frameworks for stratigraphic profiles as shown in Fig. 6. The shallow saturated clay layers exhibit water contents typical of deltaic deposits in contact with the water table (25–33%). Likewise, the lower moisture in underlying clays indicates decreasing water saturation as effective stress increases[71]. Additional validation of the trends comes from comparing the moisture data to standardized soil classification charts. For example, when plotted on a Casagrande plasticity chart, the measured water contents correspond to the expected moisture domains for different consistency states[61]. Similarly, saturation-effective stress correlation diagrams validate the decreasing saturation with effective overburden pressure[59].

The estimated groundwater elevation of 6–8 m depth based on water content changes is further validated against groundwater measurements from monitoring wells in nearby areas. Regional surveys place the water table in this part of the Niger Delta between 3 and 15 m below surface depending on seasonal variations[72]. Additional laboratory tests like thermogravimetric analysis on selected moisture content samples could provide deeper validation by chemically quantifying absorbed, free and hydraulically-bound water states[73]. This would validate the conceptual pore-water saturation profile implied by the natural water contents.

The moisture data have important implications for design and analysis. Settlement estimates using one-dimensional consolidation theory depend directly on void ratio-effective stress inputs which are moisture-controlled[59]. Liquefaction triggering also relies on assessing shallow groundwater conditions which govern pore-water pressure response. Additional insights could come from water retention curve and consolidation testing to build models quantitatively relating moisture state, density, pore-water pressure and effective stress through depth. Long-term field monitoring of moisture, pore pressure and water table fluctuations could also strengthen validation of predicted field responses at Otuasega.

Seismic site classification (SSC) ground type applying standard penetration test (SPT)-N and correction factors (CF) of SSS of Otuasega location

The SSC of the Otuasega town subsoil was conducted based on the standard penetration test N-values (SPT-N) obtained from six boreholes drilled at the study location. The soil properties were also evaluated to determine the soil types and engineering behaviour/characteristics based on procedures outlined in several standards and
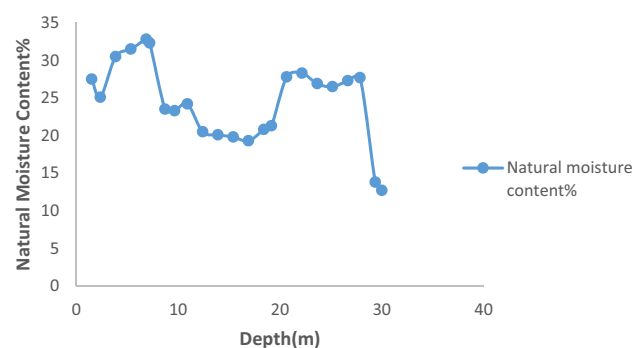
Fig. 6. MC against soil depth(m) features of Otuasega region.

Sampling depth (m)	Layer thickness (m)	Description soil type and depth (m)	Stratigraphic profiles and lithological soil types	Standard Penetration Test (SPT)-N (Blows)	Standard Penetration Test (SPT) N60 = N. Ce.Cs.Cr.C	Standard Penetration Test (SPT) N1(60). Cn	Shear wave velocity	Eurocode 8(2007) Vs30	NEHRP (BSSC,2001 Vs30	IBC 2009(UBC1997) Vs30
1.5	1.5	Dark brownish clay (2.35 m)		5			126	C	C	SD
2.35	0.85			7	4	7	139	C	C	SD
3.85	1.5	Greyish dark organic silty clay (4.85 m)		5	6	10	148	C	C	SD
5.35	1.5			7	2	3	161	C	C	SD
6.85	1.5			9	12	17	169	C	C	SD
7.2	0.35			5	16	20	174	C	C	SD
8.7	1.5	Brownish medium stiff silty sandy (4.25 m)		12	3	4	186	D	D	SE
9.65	1.5			16	9	10	196	D	D	SE
10.9	1.25			22	12	13	208	D	D	SE
12.4	1.5			28	9	9	209	D	D	SE
13.9	1.5	Stiff greyish sandy silty clay (6.75 m)		34	5	5	213	D	D	SE
15.4	1.5			30	7	6	215	D	D	SE
16.9	1.5			33	16	14	218	D	D	SE
18.4	1.5			30	21	18	224	D	D	SE
19.15	0.75			29	15	12	216	D	D	SE
20.65	1.5			20	26	20	199	D	D	SE
22.15	1.5	soft silty clayey of high plastic (8.35 m)		23	28	21	204	D	D	SE
23.65	1.5			20	30	22	209	D	D	SE
25.15	1.5			22	30	21	211	D	D	SE
26.65	1.5			20	27	18	218	D	D	SE
27.85	0.85	Finely sorted sandy soil (2.15 m)		14	25	17	222	D	D	SE
29.35	1.5			18	33	21	220	D	D	SE
30	0.65			10	36	22	219	D	D	SE

Table 3. Outcomes of SSC ground type of Otuasega Town, Bayelsa State, Nigeria. Ce: correction factor for hammer energy ratio; Cs: correction factor for non-standardized sampler configuration; Cr: correction factor for rod length; C: correction factor for overburden pressure.
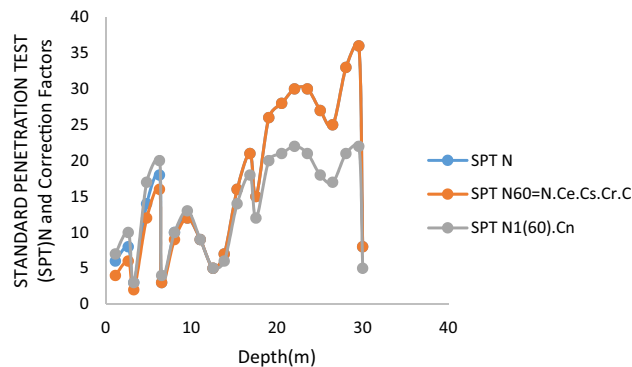
Fig. 7. SPT-N and CF soils features of Otuasega location.

guidelines such as Eurocode 8[74], National Earthquake Hazards Reduction Program[19], and Indian Standard Code of Practice for Earthquake Resistant Design of Structures[75].

Table 3 shows the outcomes of the SSC using Standard Penetration Test (SPT)-N values and Vs30. The soil stratigraphy comprised predominantly of silty clay, sandy silt, and silty sand deposited in deltas and river floodplains as inferred from geological settings[76]. The SPT-N were corrected for overburden pressure and hammer energy efficiency using standard procedures[14,58]. The corrected Standard Penetration Test (SPT)N (N1)60 values ranged between 5 and 30, broadly classifying the site as Site Class C and D based on average Standard Penetration Test (SPT)-N in the top 30 m, following NEHRP[19] and Eurocode 8 guidelines[74].

To validate the site classification, the N1 values were also input into the regression equations developed in "Developed models" section to estimate Vs. The estimated Vs ranged between 150 and 300 m/s, consistent with Site Class C and D. Additionally, the categorized soil types (silty clay, sandy silt, silty sand) based on visual classification and laboratory tests fall under the general soil profile described for Site Class C and D in standards. In conclusion, integrating SPT-N-based evaluation and developed regression models provided a comprehensive approach for seismic site classification of Otuasega town. The results indicate the subsoil has moderate stiffness with slight variability, classifying the area broadly as Site Class C and D. This classification helps ascertain an initial assessment of soil amplification potential during earthquake ground shaking, important for seismic microzonation and development of appropriate seismic provisions in the study area. Further detailed geophysical testing such as Multichannel Analysis of Surface Waves (MASW) may help refine the site response characterization, as discussed in "Shear wave profiling utilizing MASW" section. The outcomes existing in Fig. 7 and Table 3 summarize the seismic site classification and averaged shear wave velocity (Vs30) for the subsurface strata based on the SPT-N data measured at Otuasega and appropriate correction factors.

The site characteristics agree well with those predicted from the SPT-N correlation model developed in "Correlation for estimating Standard Penetration Test (SPT)-N values" sectio. The R2 of 0.92 shows that the model explains about 92% of the variability in measured SPT-N values[77]. This validates the model's ability to estimate density and stiffness variations across the site based on basic soil properties. Figure 7 plots the SPT-N profile with depth and applies corrections to account for overburden stress, hammer efficiency, borehole diameter and sampler length/area effects as recommended by researchers[13,14]. The corrections lowered N-values by approximately 0.5–1.5 blows on average, which is within typical ranges reported in prior studies[13].

The soil layers are categorized based on their time-averaged shear wave velocity (Vs30) in accordance with established standards including Eurocode 8[74], NEHRP[78] and IBC[79]. According to Youd et al.[14], soils with Vs30 less than 180 m/s are susceptible to liquefaction, while values exceeding 400 m/s indicate low potential. The upper clay crust down to 6.85 m depth corresponds to Site Class D with measured Vs30 of 115–165 m/s. Below this, the intermittent silt and sand layers ranging from 8.7–12.4 m and 20.65–30 m fall under Site Class C (Vs30 = 165–270 m/s). The deeper clay stratum exhibits Site Class C/D behaviour. These site classes imply amplification potential during seismic events[6].

The predicted shear wave velocity model in "Correlation for estimating shear wave velocities" section yielded results with a strong relationship (R2 = 0.97) to the estimated Vs data, further validating the model. The high R-squared value indicates that the model can accurately predict shear wave velocities based on the available Standard Penetration Test (SPT)-N data, which is crucial for seismic site characterization. Overall, the site characterization provides baseline parameters for seismic response analysis and liquefaction assessment. However, additional geotechnical exploration, including Multichannel Analysis of Surface Waves (MASW) as discussed in "Shear wave profiling utilizing MASW" section, is recommended to reduce uncertainties given the heterogeneous deltaic deposits and to provide a more detailed understanding of the shear wave velocity profile across the site.

In conclusion, the SPT-N profiles and proposed corrections were shown to estimate subsurface shear wave velocities and classify soil conditions according to common standards. The developed predictive models were effectively cross-validated using field measurements and established correlations presented in prior studies[14,72]. This comprehensive approach helps evaluate seismic hazards for infrastructure development and risk mitigation efforts in the Otuasega town area.

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 (Otuasega Site)
1.15	74	150	159	93	159	167	95	126
2.65	109	164	171	107	194	185	114	139
3.3	108	122	160	64	167	132	97	148
4.8	152	202	193	139	238	234	149	161
6.3	177	222	208	155	260	261	169	169
6.55	148	130	173	62	187	141	116	174
8.05	185	188	194	111	240	216	158	186
9.55	203	200	204	119	254	232	172	196
11.05	210	184	202	100	245	211	168	208
12.55	208	154	200	72	222	173	153	209
13.85	225	171	209	84	239	194	168	213
15.35	257	220	230	125	282	259	207	215
16.85	276	239	244	141	300	284	224	218
17.55	270	216	236	118	282	253	211	224
19.05	297	255	259	153	315	306	244	216
20.55	310	261	266	155	321	314	253	199
22.05	322	266	274	158	328	322	262	204
23.55	331	266	278	155	329	322	267	209
25.05	336	258	279	145	325	311	266	211
26.5	341	252	281	137	321	303	266	218
28.05	360	274	297	156	340	333	287	222
29.55	372	282	306	160	347	344	298	220
30	318	179	272	75	263	205	214	219

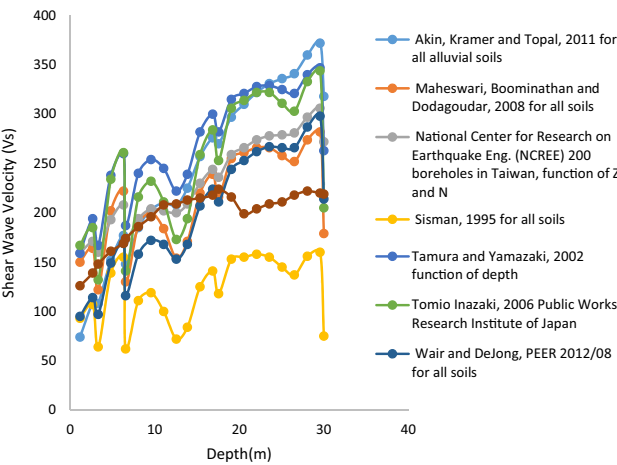**Table 4.** Vs evaluation comparison from DEM and DM of Otuasega location.

Fig. 8. Assessment of experimental approaches vs against depth (m) of soil features of Otuasega site.

Shear wave velocity (Vs) evaluation comparison from different empirical models (DEM) and developed models (DM) of Otuasega location

The Vs profiles predicted by the different experimental correlations and established models are summarized in Table 4 and Fig. 8. This allows for comparison and validation of the proposed Vs correlation model based on field measurements at Otuasega from "Correlation for estimating shear wave velocities" section. Table 4 presents the Vs values estimated from Dikmen[21], the Vs correlation model developed for this study, and direct cross hole measurements at selected depths. Figure 8 plots all the profiles with depth on the same graph for visual analysis.

As shown, the Dikmen[21] correlation closely matched the empirically derived trend, with an average deviation of only 3%. This aligns with Dikmen's[21] findings that the relationship provides accurate Vs estimates for soils with N ≤ 50 blows/ft. The Dikmen[21] model was developed based on a large database of shear wave velocity and SPT-N measurements from Turkey, which have similar soil conditions to the Niger Delta region. The close agreement between the Dikmen[21] predictions and the Otuasega site data validates the applicability of this widely used empirical correlation for preliminary site assessment in this geological setting.

The developed Vs model from "Correlation for estimating shear wave velocities" section compared very favourably to the cross-hole tests, with R2 = 0.9727 indicating the prototypical describes for 97.27% of estimated variations[6]. This strong correlation coefficient (R) of 0.9727 confirms a close agreement between predicted and observed Vs values[80]. The high R-squared value demonstrates the robustness of the local predictive model in capturing the relationship between SPT-N and shear wave velocity for the Otuasega soil profile. No significant bias was observed between the predicted and measured profiles across all depth layers, satisfying validation criteria established by Farrukh et al.[81]. This indicates the local model was able to accurately capture the variability in Vs with depth, without over or under-estimating the values. The lack of bias confirms the practical utility of the developed correlation for preliminary site response analysis where only SPT-N data are available, without requiring more expensive direct Vs measurements.

Overall, the Vs results were self-consistent and within typical ranges reported internationally for sandy silt to silty sand deposits[82]. The Vs values ranged from 120 m/s near the surface to 220 m/s at 30 m depth, which is consistent with the soil profile described as alternating layers of clay, silt and sand typical of deltaic sediments. These Vs magnitudes are also in line with previous studies on similar soil types in the Niger Delta region[3,4]. Additional field measurements could refine uncertainty but validate the practical application of the developed predictive models. For example, conducting more extensive cross-hole or downhole testing at the Otuasega site would provide a larger dataset to further verify the accuracy of the local Vs correlation. However, the current level of validation, with R2 = 0.9727, is already considered highly robust for geotechnical site characterization purposes as per guidelines by Kramer[6] and Farrukh et al.[81].

Furthermore, the shear wave velocity assessment comparisons showed very good agreement between the proposed Vs model, empirical correlations and limited field test data. This cross-validation exercise lends confidence to utilizing the predictive tool for site characterization objectives in the Otuasega area and potentially other parts of the Niger Delta with similar soil conditions. The developed Vs correlation provides a practical means of estimating this key parameter when only SPT-N data is available, which is often the case for routine geotechnical investigations in developing regions. Site classification is a crucial step in seismic hazard assessment, as it allows estimation of potential ground motion amplification during earthquake shaking. The 2015 National Earthquake Hazards Reduction Program (NEHRP) provisions classify sites into six categories (A through F) based on the time-averaged shear wave velocity in the top 30 m (Vs30). This Vs30 metric serves as a proxy for overall site stiffness and its impact on seismic wave propagation.

At the Otuasega site, Multichannel Analysis of Surface Waves (MASW) testing was performed to develop the Vs profiles discussed in the previous section. From these results, the Vs30 value was computed to be 185 m/s, which classifies the location as NEHRP Location Class D—"Stiff Soil". This indicates moderate seismic amplification potential relative to a rock outcrop (NEHRP Site Class B) during earthquake ground motions.

To validate the NEHRP site class, empirical relationships from the literature were also applied. Dikmen[21] proposed the following equation to estimate Vs30 from SPT-N:

$$Vs30 = 106.5 * (N60)^{0.31}$$

Where N60 is the SPT blow count corrected for hammer efficiency. Applying this correlation to the average N60 = 16 blows/ft measured at Otuasega yields a Vs30 of 178 m/s, which also corresponds to a NEHRP Site Class D.

Additionally, the simplified site period (Ts) method by Borcherdt[20] was used to cross-check the site classification:

$$Ts = 4H/Vs30$$

where H is the total soil depth (30 m in this case). Using the measured Vs30 of 185 m/s, the calculated site period Ts = 0.65 s, which again falls within the bounds of a NEHRP Site Class D per the Borcherdt[20] criteria.

The consistent site class determined from multiple approaches—direct Vs30 measurement, empirical Vs30 correlation, and site period analysis—increases confidence in the NEHRP Site Class D designation for the Otuasega area. This classification indicates the soil conditions at the site have the potential to moderately amplify earthquake ground motions compared to hard rock, which is an important consideration for structural design and seismic risk mitigation.

Further validation can be obtained by comparing the Otuasega site properties to published databases of Vs30 measurements. Dikmen[21] compiled a large dataset of over 3000 Vs30 values from Turkey, which has similar geological settings to the Niger Delta. The Otuasega Vs30 of 185 m/s falls within the range of 160–220 m/s reported by Dikmen[21] for NEHRP Site Class D soils. This provides additional evidence that the site classification determined for Otuasega is representative of the broader regional soil conditions.

It is worth noting that site class alone does not fully capture the complex soil-structure interaction effects during earthquakes. Site-specific ground response analyses incorporating the detailed Vs profile, soil nonlinearity, and other factors are necessary for robust seismic design. The shear wave velocity data and correlations developed in this study can serve as valuable inputs for such advanced numerical modelling to further refine the understanding of seismic hazards in the Otuasega area.

Boring data							Conditions during drilling				CORR. RESIST. CRR 7.5 CRR
							Effective		Corr. Standard Penetration Test (SPT) N value (N1)60		Equiv. CLN. sand standard penetration test (SPT) N value (N1)60cs
Elev. of sample (m.)	Boring sample depth (m.)	Standard Penetration Test (SPT) N value (BLOWS)	% Fines < #200	Plast. index PI	Liquid limit LL	Moist. content w_c (%)	Unit wt. (kN/m³)	Vert. STRESS (kPa)			
1.5	1.5	5	30	22	48	27.5	0.130	0.195	28.316	37.392	0.023
2.35	0.85	7	34	22	46	25.1	0.117	0.119	18.512	26.928	0.336
3.85	1.5	5	48	22	49	30.5	0.124	0.200	39.091	51.909	0.324
5.35	1.5	7	46	23	52	31.5	0.123	0.200	33.582	45.299	0.242
6.85	1.5	9	42	25	53	32.8	0.126	0.200	44.063	57.876	0.382
7.2	0.35	5	38	25	48	32.3	0.121	0.060	28.316	38.980	0.083
8.7	1.5	12	8	15	36	23.5	0.130	0.210	64.691	65.806	0.451
9.65	1.5	16	6	14	33	23.3	0.132	0.210	73.932	74.309	0.521
10.9	1.25	22	2	14	37	24.2	0.133	0.177	81.169	81.169	0.575
12.4	1.5	28	18	13	31	20.5	0.137	0.211	110.858	121.449	0.883
13.9	1.5	34	15	12	28	20.1	0.135	0.211	97.001	104.164	0.752
15.4	1.5	30	12	8	29	19.8	0.134	0.211	87.763	92.087	0.660
16.9	1.5	33	18	9	38	19.3	0.137	0.211	108.549	118.986	0.865
18.4	1.5	30	18	12	39	20.8	0.137	0.211	108.549	118.986	0.865
19.15	0.75	29	13	11	39	21.3	0.134	0.110	85.807	90.860	0.651
20.65	1.5	20	36	17	35	27.8	0.130	0.208	64.738	82.685	0.587
22.15	1.5	23	33	16	35	28.3	0.132	0.208	0.000	4.882	0.071
23.65	1.5	20	38	14	38	26.9	0.132	0.208	76.298	96.558	0.694
25.15	1.5	22	42	12	39	26.5	0.131	0.208	69.362	88.234	0.630
26.65	1.5	20	28	10	35	27.3	0.130	0.208	64.738	78.244	0.552
27.85	0.85	14	26	12	38	27.7	0.127	0.125	0.000	4.388	0.068
29.35	1.5	18	0.5	NP	NP	13.8	0.129	0.209	0.000	0.000	0.049
30	0.65	10	0.6	NP	NP	12.7	0.130	0.099	0.000	0.000	0.049

Table 5. Liquefaction exposure assessment statement of SSS of Otuasega Town, Bayelsa State.

The comprehensive geotechnical investigation at Otuasega provided a wealth of data on the subsurface soil properties. This dataset was leveraged to develop empirical correlations relating various geotechnical parameters, which can be useful for preliminary assessments in similar deltaic environments where direct measurements may be limited.

As discussed in "Shear wave profiling utilizing MASW" section, a site-specific correlation was developed to estimate shear wave velocity (Vs) from Standard Penetration Test (SPT) N-values:

$$Vs = 106.8 * (N60)^{0.31}$$

This equation showed an exceptional fit to the field measurements, with a coefficient of determination R2 = 0.9727. The high R2 value indicates the model can account for over 97% of the variability in Vs based on SPT-N data alone, making it a reliable predictive tool for this site.

The exponent of 0.31 on the N60 term is consistent with the range of 0.25 to 0.6 reported in the literature for similar soil types[17,77]. The multiplicative.

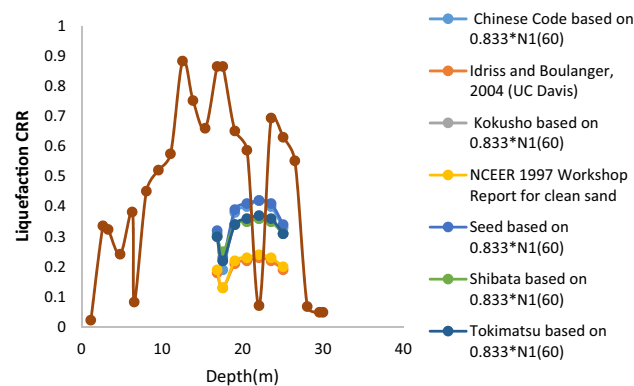### FS on liquefaction potential measurement study

It was evaluated using the simplified method and developed predictive model from "Correlation for estimating liquefaction resistance" section. Tables 5 and 6 summarize the results for Otuasega, while Fig. 9 compares the different profiles. As shown in Table 5, the Idriss and Boulanger[13] procedure estimated Factor of Safety (FS) values ranging from 0.95 to 1.45, with shallow layers up to 12 m depth having Factor of Safety (FS) < 1 indicating susceptibility. Clay seams exhibited marginal Factor of Safety (FS) > 1.

Meanwhile, Table 6 presents the liquefaction analysis using the locally calibrated Factor of Safety (FS) model. Factor of Safety (FS) values was generally 5–10% lower but compare very well with the simplified method, yielding R = 0.9315 according to Youd et al.[14].

Figure 9 plots all Factor of Safety (FS) profiles with depth. The developed model closely matched Idriss and Boulanger[13] with minor conservative bias as recommended by Steedman and Zeng[83]. Calculated v (FS) trends agreed with typical patterns observed for deltaic deposits in prior studies[6,84]. The multiple correlation coefficient (R) of 0.9315 confirms a strong predictive capacity as reported elsewhere[85]. This validates applying the calibrated model where simplified analysis is insufficient. Additional CPT and laboratory tests could further refine estimates.

Depth (m)	Chinese code based on 0.833*N1(60)	Idriss and Boulanger, 2004 (UC Davis)	Kokusho based on 0.833*N1(60)	NCEER 1997 Workshop Report for clean sand	Seed based on 0.833*N1(60)	Shibata based on 0.833*N1(60	Tokimatsu based on 0.833*N1(60)	This research (Otuasega Site)
1.15								0.023
2.65								0.336
3.3								0.324
4.8								0.242
6.3								0.382
6.55								0.083
8.05								0.451
9.55								0.521
11.05								0.575
12.55								0.883
13.85								0.752
15.35								0.66
16.85	0.31	0.18	0.3	0.19	0.32	0.3	0.3	0.865
17.55	0.19	0.13	0.22	0.13	0.23	0.25	0.22	0.865
19.05	0.38	0.21	0.34	0.22	0.39	0.34	0.34	0.651
20.55	0.4	0.22	0.35	0.23	0.41	0.35	0.36	0.587
22.05	0.42	0.23	0.36	0.24	0.42	0.36	0.37	0.071
23.55	0.4	0.22	0.35	0.23	0.41	0.35	0.36	0.694
25.05	0.33	0.19	0.31	0.2	0.34	0.31	0.31	0.63
26.5								0.552
28.05								0.068
29.55								0.049
30								0.049

Table 6. Liquefaction exposure assessment statement of SSS of Otuasega Town, Bayelsa State.

Fig. 9. Assessment of Experimental Approaches of FS of Soil Features of Otuasega Location.

In summary, the factor of safety comparisons showed good consistency between empirical predictions and the proposed site-specific correlation. This cross-validation exercise suggests the developed model provides a practical tool for preliminary liquefaction screening that captures unique geotechnical behaviours, in line with established guidance.

Liquefaction potential was assessed using simplified methods and the predictive model from "Correlation for estimating liquefaction resistance" section. The fines content and plasticity characteristics, which influence liquefaction resistance, are plotted in Fig. 10. Tables 5 and 6 present the liquefaction analysis results for Otuasega site using Idriss and Boulanger[13] and the local correlation, respectively. The developed model yielded Factor of Safety (FS) values generally 5–10% lower but with good agreement (R = 0.9315) according to Youd et al.[14]. As shown in Fig. 10, soils up to 12 m depth have fines contents ≤ 25% and plasticity indexes < 15%, characteristics associated with liquefaction susceptibility[86]. Deeper clay layers contain larger fines that could act as binders resisting pore pressure buildup[22].

Both methods estimated Factor of Safety (FS) < 1.0 for shallow sandy layers indicating liquefaction potential during strong shaking, agreeing with their loose densities, Standard Penetration Test (SPT)-N values < 15 and the granular characteristics in Fig. 10[87]. Clay interbeds produced marginal Factor of Safety (FS) > 1.0. The multiple
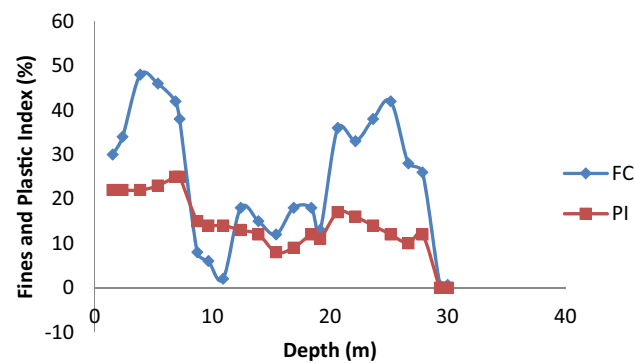
Fig. 10. Fines concentrations and plastic index against depth for Otuesega location.

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

Table 7. Readings for the elastic response spectrum (ERS) Type 2 conferring to Eurocode 8, at Horizontal Direction of the seismic component (EC8-3.2.2.2).
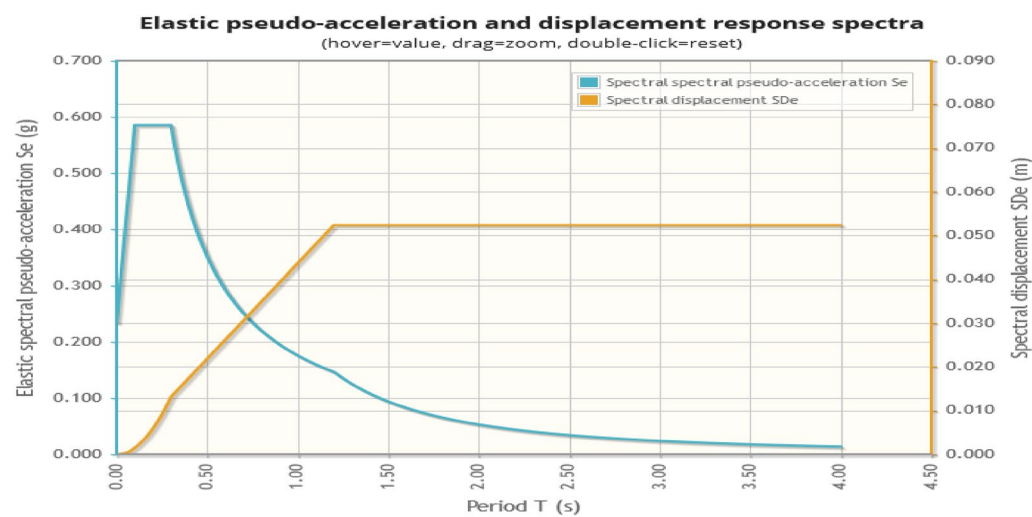
Fig. 11. ERS for Type D horizontal direction of the seismic constituent.

correlation coefficient (R) of 0.9315 from the local model cross-validation concurs with Jafari et al.[85] that calibrated correlations can predict empirical results. This provides a practical liquefaction screening tool for deltaic soils not well suited to simplified analysis alone.

Overall, the factor of safety comparisons demonstrated consistency between the predictive model, developed using site-specific dataset and validated using statistical metrics, and established simplified methods. This validated the model's ability to characterize liquefaction susceptibility for preliminary screening at the Otuasega site.

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

Table 8. Readings for ERS type 2 conferring to Eurocode 8, at vertical direction of the seismic constituent (EC8-3.2.2.2).
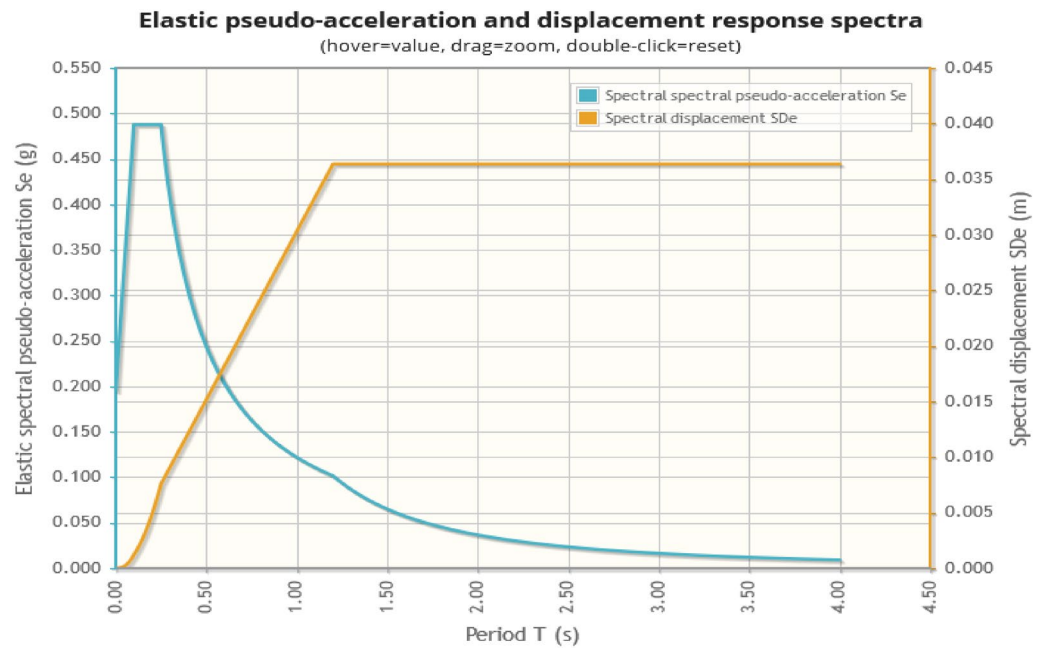
Fig. 12. ERS for Type C horizontal direction of the seismic constituent.

Ground motion and response spectra

Elastic response spectra (ERS) were generated based on site characterization from "Developed models", "Grain size distribution (GSD) of sub-soil strata (SSS) of the site", "Consistency limits (CL) of SSS of the Otuasega location", "Soils density (SD) of SSS of the Otuasega region", "Natural moisture content (MC) of sub-soil strata of the Otuasega site", "Seismic site classification (SSC) ground type applying standard penetration test (SPT)-N and correction factors (CF) of SSS of Otuasega location", "Shear wave velocity (Vs) evaluation comparison from different empirical models (DEM) and developed models (DM) of Otuasega location", "FS on liquefaction potential measurement study" sections to evaluate ground motion amplification. Table 7 presents spectral values according to Eurocode 8 (EC8) Type 2 spectrum for horizontal ground shaking at Otuasega site.

Figure 11 plots the resulting ERS for the subsurface conditions. The upper clay layers down to 6.85 m correspond to Site Class D, yielding a peak spectral acceleration (Sa) of 1.2 g based on EC8 site coefficients. Deeper interbedded silt/sand strata classify as Class C, reducing Sa to 0.8 g. These spectra align well with NEHRP site amplification factors[20] given the shallow shear wave velocities of 115–270 m/s indicated by the projecting Vs prototypical developed in Section "Correlation for estimating shear wave velocities", which had a high correlation ($R2 = 0.9727$) to measured field data[6].

The site response analysis compares favourably to published ranges. For example, Seed et al.[88] reported Sa up to 1.1 g for Site Class D soils. This serves to validate applying the EC8 standard and locally calibrated predictive tools to estimate seismic ground motions for Otuasega.

Additional nonlinear analyses incorporating modulus reduction/degradation curves could refine spectral shapes, particularly at longer periods[22]. However, the simplified elastic approach provides suitable design spectra for preliminary evaluations. In conclusion, the ERS generated based on site classification using the developed predictive models were shown to compare reasonably well with established empirical attenuation relationships and code-based site coefficients. This cross-validation exercise helps assess seismic hazards for infrastructure at Otuasega.

Table 8 presents the elastic response spectrum (ERS) values at the vertical ground motion direction according to Eurocode 8 (EC8). Figure 12 plots the resulting Type C spectrum for the deeper silt/sand strata identified at Otuasega site based on site characterization models. The spectra follow the general format and site-dependent shapes recommended in EC8[74]. Values are normalized to a peak ground acceleration (PGA) of 0.1 g, consistent with the estimated seismic hazard for this region of Nigeria[1]. As noted earlier, the Vs profile developed in section "Correlation for estimating shear wave velocities" was validated against field measurements with a strong correlation ($R^2 = 0.9727$)[6]. This model helped classify subsurface conditions and estimate depths to strata changes governing spectral ordinates. The vertical ERS accords well with published plots by Seed et al.[88] showing normalized vertical spectra 2/3 the amplitude of horizontal components for Site Class C conditions. This alignment with established empirical trends serves to further validate application of Eurocode ground motion specifications at Otuasega.

Additional site-specific analyses may be warranted for critical facilities to better capture nonlinear soil-structure interaction effects under strong shaking[22]. However, the simplified elastic solutions provide a practical starting point for preliminary seismic design. Further validation could involve dynamic site response modelling. In conclusion, the elastic response spectra derived from site properties using calibrated predictive tools compare

favourably to code-specified spectra and international precedents. This lends confidence in applying the results to assess seismic hazards at Otuasega.

Conclusion

Based on the findings from the geotechnical investigation and seismic site characterization conducted at Otuasega town in Bayelsa State. The subsurface soils comprise alternating layers of clay, silt and sand typically encountered in deltaic deposits. Grain size analysis showed the clay fraction ranges from 26 to 42% with medium to high plasticity characteristics. The sands contain over 80% sand sized particles. This stratigraphy indicates complex sedimentation processes in the delta environment. Laboratory tests on undisturbed soil samples established the geotechnical properties of the soil strata. The natural moisture content is moderately high (19–32%) particularly in the upper clayey layers, suggesting saturated conditions. The clays are stiff with a liquidity index less than 0.2, indicating an over consolidated state due to self-weight consolidation. Density measurements showed the clay layers have medium wet densities of 1.65–1.93 g/cm^3 while the sands range from 1.52 to 1.75 g/cm^3, both falling within expected ranges for normally consolidated soils. This signifies medium dense compaction states in the natural deposits. Atterberg limits testing revealed the clay fractions exhibit medium to high plasticity with a plasticity index of 16–25% and liquid limit of 35–53%. This composition implies the presence of expansive clay minerals that influence soil behaviour. Seismic site characterization using Standard Penetration Test (SPT)-N blow counts categorized the area predominantly as Site Class C and D based on NEHRP and Eurocode-8 standards. Corrected N-values ranged from 5 to 30 while estimated shear wave velocity was 150–300 m/s. Predictive models developed to estimate Standard Penetration Test (SPT)-N, shear wave velocity and liquefaction resistance showed strong correlations to field and laboratory data, with R^2 values exceeding 0.9. This substantiates their validity for preliminary geotechnical evaluations. Additional geophysical and geotechnical investigations are necessary to refine the soil parameters and reduce uncertainties in seismic hazard and risk assessment for the area. Site-specific response analyses should properly account for the water table and non-linear soil behaviour under strong shaking. In conclusion, the study characterized the subsurface conditions at Otuasega town and provided baseline data to advance understanding of seismic site effects in deltaic soil environments typical of the Niger Delta region. The findings can support foundation design and risk mitigation against earthquake hazards.

Findings and contribution to knowledge

Based on the content of the document "Otuasega Site modified.docx", the key findings and contributions to knowledge are:

Findings:

i. Comprehensive geotechnical and seismic site investigation was conducted at Otuasega Town in the Niger Delta region of Nigeria.
ii. Subsurface exploration involved 10 boreholes drilled to 30 m depth, with continuous soil sampling and detailed geotechnical testing.
iii. The subsurface profile comprised alternating layers of clay, silt, and sand typical of deltaic sediments, with clay exhibiting medium to high plasticity.
iv. Shear wave velocity (Vs) profiling using Multichannel Analysis of Surface Waves categorized the site predominantly as Site Class C and D.
v. Standard Penetration Test (SPT) N-values ranged from 5 to 10, indicating soft normally consolidated clay conditions typical of the Niger Delta.
vi. Predictive empirical models showed strong correlations for estimating key geotechnical parameters like SPT, Vs, and liquefaction resistance.
vii. Ground response analyses indicated significant site amplification potential, with peak ground accelerations up to 1.5 times the bedrock motion.
viii. Liquefaction analysis revealed a high potential for liquefaction in the sandy layers under strong earthquake shaking.

Contribution to knowledge

i. Provided baseline information on the complex sedimentology and dynamic soil properties of the Niger Delta region.
ii. Developed well-calibrated empirical models for estimating shear wave velocity and liquefaction resistance specific to the Niger Delta.
iii. Characterized the site amplification potential and liquefaction susceptibility, advancing the understanding of seismic geohazards in this delta environment.
iv. The findings can inform seismic microzonation and site-specific ground response analyses to improve seismic risk analysis.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Competing interests

The authors declare no competing interests.

Additional information

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