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Determination of elastic moduli and bearing capacity of sediments using geophysical and cone penetration test techniques in Yenagoa, Southern Nigeria

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ABSTRACT

In order to quantify the P- and S-wave velocities, dynamic elastic moduli and bearing capacity of shallow alluvial sediments, seismic refraction and cone penetration test (CPTu) soundings were carried out in two sites in Yenagoa. The seismic refraction data was analysed using the intercept–time technique to obtain the seismic velocities which were subsequently used to estimate the dynamic elastic moduli. The relevant CPTu data were emplaced into an established empirical equation to determine the shear wave velocity (V_s), with which the compressional wave velocity (V_p) was estimated. Combining the compressional and shear wave velocities, the dynamic elastic moduli of the shallow sediments were determined within the depth range of 0.5–8.0 m. On comparison, it was observed that the average values of V_p and V_s from the two methods are fairly in agreement. Significant difference in the average values was only observed in the dynamic elastic moduli. Correlation of the V_s -wave and the dynamic moduli from the CPTu data show linear relationship between S-wave velocity and the dynamic elastic moduli with correlation coefficients (R^2) greater than 0.9 in all cases. These elastic moduli values can be used for the design of foundation of structures, site response and settlement analysis.

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1. Introduction

In the design of foundations for sensitive engineering structures, values of the dynamic elastic moduli of the subsurface are crucial requirements. Dynamic moduli refer to the elastic stiffness of a geomaterial often derived from seismic velocities in combination with density (Fjaer 2019). The dynamic elastic properties prior to rock failure are Young's modulus, shear modulus, bulk modulus and Poisson's ratio. These parameters provide valuable information about the subsurface rock and thus play an important role in solving geomechanical problems. For instance, knowledge of the values of the dynamic elastic properties is useful for the design of foundations of structures on which vibrating machines are placed to avoid resonance during operation (Mcdowell 1990), and in locating and extracting mineral resources (Emujakporue and Ekine 2009). Dynamic moduli values are also essential for dynamic response analysis and soil–structure interaction problems and can play an important role in the study of liquefaction potential under seismic loading (Youd et al. 2001). Aside, in determining soil competent parameters such as concentration Index (Ci), material index (Mi), stress ratio (Si), etc., the dynamic elastic moduli are key input parameters, and thus are useful for the characterisation of soils in terms of geotechnical and

mechanical properties (Robertson et al. 1995). Furthermore, in reservoir studies, rock mass elastic moduli play important role in wellbore stability, fraction prediction (Chang et al. 2006; Abdulraheem et al. 2009) and are key requirements for reservoir-scale modelling (Berard and Cornet 2003).

The dynamic elastic properties have been studied by many authors in different geological settings. For instance, Othman (2005) determined the elastic constants and attenuation coefficients using an ultrasonic technique for cores from an oil well in northeast Qatar. Studies of dynamic moduli were also carried out and reported by Emujakporue and Ekine (2009); Ajayi et al. (2014); Alaminikuma and Omigie (2018); George et al. (2010) in parts of the Niger Delta. Singh et al. (2015) estimated the dynamic elastic moduli values of alluvium sediments for the design of foundations for a structure intended to be used as a nuclear power plant in India using seismic velocities derived from cross-hole seismic survey. The results show that the compressional P-wave velocity varies from 442 to 1287 m/s while the shear wave velocity shows a variation of 228–627 m/s. The Young's modulus varies from 0.29 to 1.62 GPa, the bulk modulus varies from 0.19 to 1.58 GPa, the shear modulus from 0.12 to 0.62 GPa and the Poisson's ratio varies from 0.24 to 0.33.

Inspite of the usefulness of the elastic parameters of the near-surface soil, determination of these parameters has not received adequate attention and thus have remained largely inadequately described in the Niger Delta. Generally, elastic properties of rocks are determined using static (high strain) and dynamic (low strain) methods. Static methods are conducted in the laboratory with specific test equipment that can contain core specimens. In this method, specimens are usually compressed within the equipment until failure is observed. In this approach, stress-strain curves generated are recorded using a computer and the dynamic properties determined from the curves. On the other hand, dynamic methods use compressional and shear wave velocities as input parameters substituted into Hookean equations. Generally, geophysical measurements particularly by seismic pulse techniques are being increasingly used to determine the elastic properties. This is due largely because the tests are carried out in situ at an appropriate strain rate. Geophysical methods used to obtain in situ seismic velocities include crosshole seismics, multi-channel analysis of surface waves (MASW) and surface refraction surveying techniques. However, due to their environmental, time and cost ineffectiveness, surface non-invasive seismic

methods have become more favoured. It is pertinent to mention that in the design of engineering projects, characterisation of the soil elastic moduli is not enough. The soil-bearing capacity and the settlement or sub-grade reaction are additional key factors (Shafiqu et al. 2018). Keceli (1990, 2000) indicated that allowable capacity can be determined using seismic technique.

In this study, attempt is made to evaluate the seismic velocities, dynamic elastic moduli and bearing capacity of shallow alluvial sediments in two sites. For purposes of comparison, seismic refraction and cone penetration methods are used.

2. Location and geological setting of the study area

Yenagoa is the capital city of Bayelsa State. It is located within the Niger Delta Basin in the southern part of Nigeria. The study area is within Yenagoa and environs, an area of about 50 kKm². The coordinates of Yenagoa are longitudes 006° 10' 3.07" and 00 6° 25' 10.53" east of the prime meridian and latitudes 04° 51' 39.73" and 05° .2' 25.53" north of the equator. Geographically, Yenagoa is situated within the coastal area of the Niger Delta sedimentary basin (Figure 1).

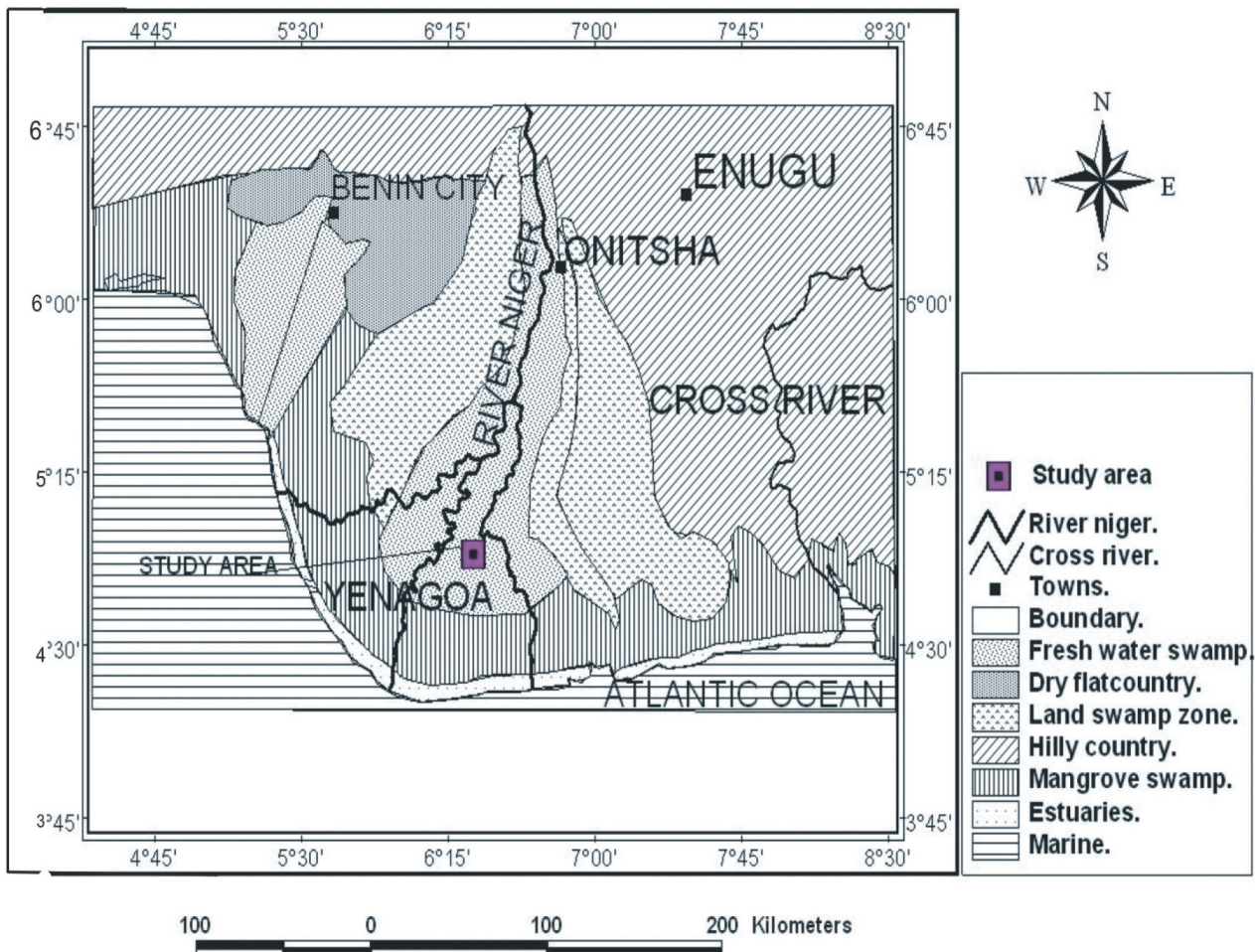


Figure 1. Map of the Niger Delta showing the study area.

The ground surface is relatively flat and the sloping is gentle seawards (Okiongbo and Mebine 2015). Its mean elevation is about 8 m above mean sea level (Akpokodje and Etu-Efeotor 1987). The area has a tropical rain forest climate characterised by rainy season and dry season. April to October constitute the rainy season with a very brief dry period in August, while November to March is the period for the dry season. The average annual rainfall is about 4,500 mm (Akpokodje 1986), and much of the rain falls during the rainy season. Temperature variation is between 25 and 32°C. The people are mainly into subsistence fishing and farming.

Akpokodje (1986) reported that Yenagoa is within the freshwater and meander belt geomorphic unit of the Niger Delta basin. The Niger Delta is an alluvial plain consisting of various types of Quaternary sediments. These sediments overlie the Benin Formation. The Quaternary deposits are made up of floodplain deposits such as clay, silt, silty-clayey sand (Abam 1999). The geostratigraphy of the sediments consists of a fining-up sequence of sand overlain by silt and clay which indicate a fluvial environment of deposition (Short and Stauble 1967; Amajor 1991). Most small and medium civil engineering structures are constructed on the Quaternary deposits which vary greatly both in type and depth. The nature and properties of the sediments are dependent on the types of depositional environment under which they were formed. The Benin, Agbada and Akata formations are the key subsurface formations reported in the Niger Delta Basin. The Benin Formation is fluvial in origin and is overlain by Quaternary sediments.

The Benin Formation is the regional aquifer and is reported to be very porous and highly permeable. The sediments of the Benin Formation are lenticular in places and unconsolidated and are composed of coarse-medium-fine grained sands with localised intercalations of clay/shale. The sediments are poorly cemented and moderately sorted (Mbonu et al. 1991).

3. Theoretical foundation

The foundation in a building responds to both static and dynamic loading. Dynamic loading includes both natural and man-made vibrations such as machine vibrations, seismic loading, liquefaction and cyclic transient loading (Teme 1990). The dynamic elastic soil parameters related to dynamic loading are shear wave velocity, Poisson's ratio, Young's modulus, shear modulus and bulk modulus. These are used to measure the degree of stiffness of the subsurface (Clayton 2011). These parameters are usually computed using Hookean elastic equations using compressional and shear wave velocities as input parameters usually determined from low strain dynamic tests such as seismic refraction.

3.1. Seismic velocities, dynamic elastic moduli and bearing capacity from seismic refraction

3.1.1. Seismic velocities

Using seismic refraction data, the P-wave velocity is usually obtained as the reciprocal of the slope of the various segments of the regression line of the travel-time versus distance graphs. The relationship between shear wave velocity (V_s) and primary wave velocity (V_p) according to Adewoyin et al. (2017) is expressed as

$$V_p = 1.7 V_s \quad (1)$$

3.1.2. Poisson's ratio (σ)

The Poisson's ratio represents the lateral extension to longitudinal contraction. It is a measure of the geometrical change in the shape of an elastic body. Its value is 0.5 for fluids, and it approaches 0 for very hard indurated anisotropic rocks. Poisson's ratio can be determined using the following equation.

$$\sigma = \frac{V_s^2}{V_p^2} \quad (2)$$

Thus, Poisson ratio (σ) may be expressed as

$$\sigma = \frac{1 - 2\alpha}{2 - 2\alpha} \quad (3)$$

where V_p and V_s are compressional and shear wave velocities and α is the velocity squared ratio. Weak materials have higher Poisson's ratio and vice versa.

3.1.3. Shear modulus (μ)

The shear modulus (μ) is the ratio between shear stress and shear strain. Shear stress cannot be applied to ideal liquids and gases. For these substances $\mu = 0$. Only solids possess the physical properties described by the shear modulus. The shear modulus may be written in terms of the shear wave velocity (V_s) as

$$\mu = \frac{\rho V_s^2}{g} \quad (4)$$

where ρ is the density and g is the gravity acceleration.

3.1.4. Young's modulus (E)

Young's modulus (E) is a material property that describes elastic stiffness and thus considered as one of the key properties required in engineering design. Young's modulus (E) is the ratio of stress applied to the strain produced on the loading plane along the loading direction. Young's modulus can be related to shear modulus (μ) and Poisson's ratio (σ) using the expression:

$$E = 2\mu(1 + \sigma) \quad (5)$$

3.1.5. Bulk modulus (K)

When a compressive or tensile stress is uniformly applied on a body, the relative change observed in the volume of the body is called bulk modulus. It gives an idea of the resistance of the substance to compression when load is applied to the substance.

Bulk modulus, $K =$

$$\frac{E}{3(1 - 2\sigma)} = \frac{2\mu(1 + \sigma)}{3(1 - 2\sigma)} \quad (6)$$

where μ is the shear modulus and σ is the Poisson's ratio.

3.1.6. Lames constant (λ)

The Lamé parameters are also called the Lamé coefficients, Lamé constants or **Lamé** moduli, and is denoted by symbol λ . The Lames constant can be determined using the equation

$$\lambda = \frac{E\sigma}{(\sigma + 1)(1 - 2\sigma)} \quad (7)$$

Subgrade coefficient

The subgrade coefficient is expressed as

Subgrade coefficient

$$(k_s) = 4\gamma V_s \quad (8)$$

But the unit mass density (γ) is given as

$$\gamma = \gamma_0 + 0.002V_p \quad (9)$$

Thus,

$$k_s = 4(\gamma_0 + 0.002V_p)V_s \quad (10)$$

Unit mass density is expressed in kNm^{-3} (Tezcan et al. 2009)

γ_0 is the reference unit weight value in KN/m^3 . The value of γ_0 is 16 for loose, sandy and clayey soils (Terzaghi and Peck 1967). Subgrade coefficient (k_s) is expressed in $\text{Nm}^{-2}\text{s}^{-1}$ (Bowles 1982)

3.1.7. Ultimate and allowable bearing capacity

The ultimate bearing capacity (Q_{ult}) can be expressed as

$$Q_{ult} = \frac{k_s}{40} = \frac{4\gamma V_s}{40} = 0.1\gamma V_s \quad (11)$$

The allowable bearing capacity (q_{all}) can be expressed as

$$Q_{all} = \frac{Q_{ult}}{n} = \frac{0.1\gamma V}{n} \quad (12)$$

For soils the safety factor n is ($n = 4.0$).

3.2. Seismic velocities, dynamic elastic moduli and bearing capacity from cone penetration test (CPTu) sounding

The dynamic elastic moduli and bearing capacity can also be determined using data from conventional geotechnical methods such as cone penetration test (CPTu) sounding. Using this method, the dynamic elastic moduli and bearing capacity including the compressional (P) wave velocity and shear (S) wave velocity can be evaluated using the following established empirical equations.

3.2.1. Shear wave velocity

Using CPTu data, the shear wave velocity can be determined using the equation of McGann et al. (2014)

$$V_s = 2.27q_t^{0.412}I_c^{0.989}Z^{0.033} \quad (13)$$

where q_t = corrected cone tip resistance in kPa

I_c = soil behaviour index

Z = depth (m)

The soil behaviour index is determined using the equation of Robertson and Wride (1998)

$$I_c = \left[\left(3.47 - \log_{q_{c1N}} \right)^2 + (\log F + 1.22)^2 \right]^{0.5} \quad (14)$$

$$F = \left[\frac{f_s}{(q_c - \sigma_v)} \right] \times 100 \quad (15)$$

where

$$q_{c1N} = \left(\frac{q_c}{P_{a2}} \right) \left(\frac{P_a}{\sigma_v^1} \right)^{0.5} \quad (16)$$

q_{c1N} = normalised cone penetration resistance corrected for overburden stress

F = normalised friction ratio in percent

q_c = cone penetration resistance in MPa

f_s = CPTu sleeve friction

σ_v = total overburden stress in MPa

P_a = is a reference pressure in the same units as σ_v^1 (i.e. $P_a = 100$ kPa if σ_v^1 is in kPa)

P_{a2} = is a reference pressure in the same units as q_c , i.e. $P_{a2} = 0.1$ MPa if q_c is in MPa.

Using the values of the shear wave velocity, the P-wave velocity can be determined using Equation 1.

3.2.2. Shear modulus

Using the corrected cone tip resistance (q_t) and effective stress values obtained from the CPTu sounding, the small-strain shear modulus is calculated using the equation of Robertson (2009)

$$\text{Shear modulus}(G) = 0.018 \times 10^{(0.55I_c + 1.68)} [q_t - \sigma_v^1] \quad (17)$$

where q_t is the corrected cone tip resistance (MPa) and σ_v^1 is the effective stress (MPa).

3.2.3. Young's modulus

The Young's modulus can be estimated using the equation

$$E = 2G(1 + \sigma) \quad (18)$$

where σ^1 is the Poisson's ratio equal to 0.2. This is used when the conditions are drained, i.e. sandy soil. σ_u is the Poisson's ratio equal to 0.5. This is used when the conditions are undrained, i.e. clayey soil, and G is the shear modulus. Other parameters such as bulk modulus (K), Lame's constant (λ), subgrade coefficient (k_s), ultimate and allowable bearing capacity can be calculated using Equations 6, 7, 10, 11 and 12.

4. Methodology

4.1. Site selection

Two sites (Opolo and Tombia) within Yenagoa and environs were used for this study (Figure 2). The selection of these two sites was based on the results of previous geophysical investigations carried out in the study area (Okiongbo and Gede 2017; Okiongbo and Soronnadi-Ononiwu 2018). The stratigraphic sequence of Opolo consists of top soil, clay and sand while the Tombia site consists of top soil, silty sand and sand. The stratigraphic sequence of Opolo is

prevalent in the study area and covers over 80% of the subsurface stratigraphy.

4.2. Seismic refraction survey

Seismic refraction survey was carried out as a low strain dynamic test to determine the seismic velocities in the sites. The seismic refraction survey was carried out along straight profiles using 12-Channel ABEM Terraloc MK8 seismograph with a sledgehammer and a plate (energy source). In each site, three profiles were surveyed. The geophones were connected in an in line split spread configuration (Figure 3), using a geophone spacing of 5 m, with shots points located at 30 m from the first and last geophones of each spread. The geophones were firmly pinned to the ground and their take-outs placed on small wooden stands about 25 cm above the ground, in order to prevent wind, moisture, etc., from influencing the recording.

The trigger cable reel connects the sledgehammer to the equipment and each time it is triggered, by hitting the hammer on a base plate, the seismogram records a seismic event. Data was acquired from the two ends of the traverse of each profile. Hitting the ground vertically generated the seismic P-waves, and 3–4 stacks were made per every P-wave shot. The seismic line was about 60 m and was covered by 12 geophones (Figure 3). The recording time was 500 ms, and the sampling rate was 500 μ s. The data were stored in SEG-2 format. Samples of the recorded P-wave seismogram are shown in Figures 4(a) and 5(a), respectively.

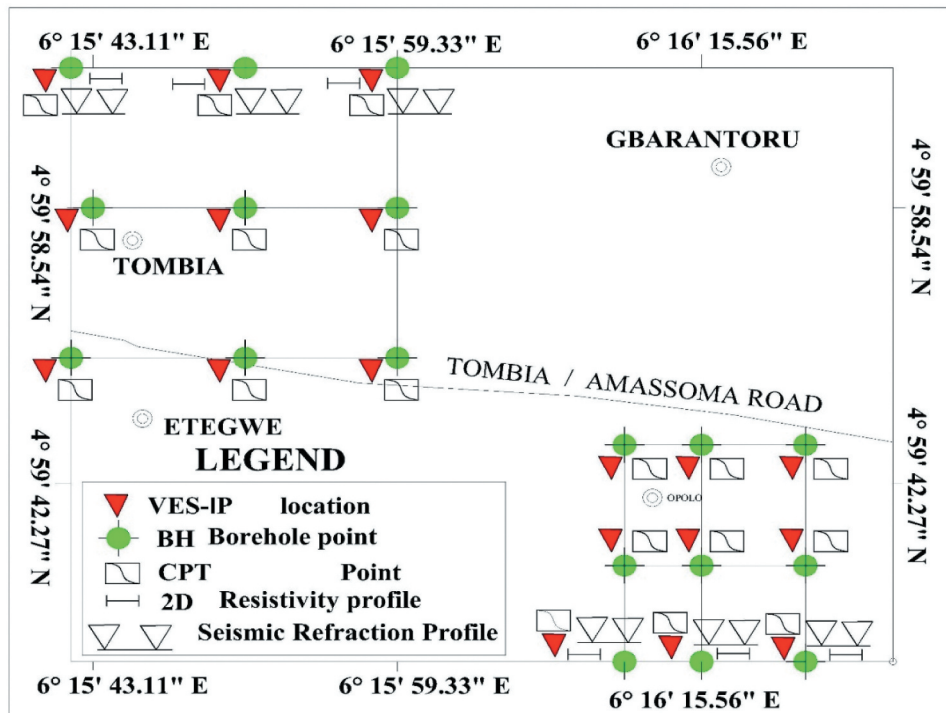


Figure 2. Location map of the study area.

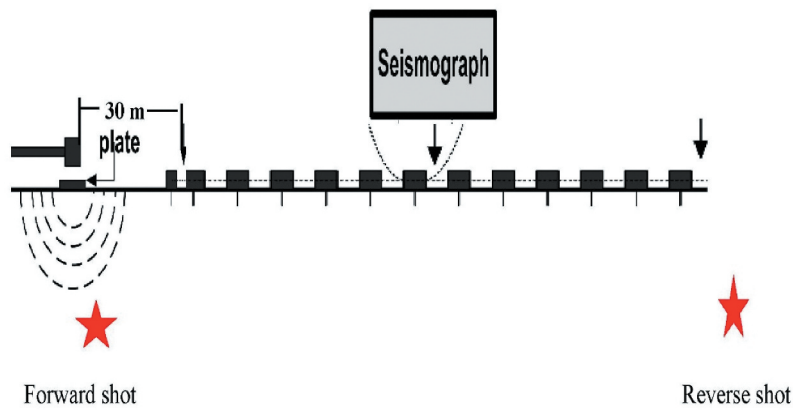


Figure 3. Seismic refraction equipment arrangement.

In processing the data, the first step included accurate picking of the first arrival time (first breaks) from the shot records. The arrival times were plotted against offset distance. The P-wave velocity was obtained as the reciprocal of the slope of the various segments of the regression line of the travel-time versus distance graphs. The Easy Refract seismic software which is based on the generalised reciprocal method (GRM) was used to generate the velocity-depth models. The various elastic moduli such as Poisson's ratio, bulk modulus, shear modulus (rigidity) and Young's modulus including the bearing capacities were determined using the compressional P-wave and shear wave velocities (Abdulraheem et al. 2009) obtained using eEquations 1–12.

4.3. CPTu sounding

In order to determine in situ dynamic elastic moduli of the sub-soil at the study sites, cone penetration tests were also carried out using a Dutch cone penetrometer with a capacity of 10 tons. The procedure followed for the cone penetration tests is in agreement with ASTM D3441 (2016). A total of nine CPTu test was carried out at each site. The field test locations are shown in Figure 2.

The equipment has a cylindrical probe with an area of about 10 cm^2 and a tip apex angle of 60° and a side friction sleeve with a surface area of 150 cm^2 . The test involved advancing the 60° steel cone into the ground so as to obtain the degree of compaction or stiffness of the soil. The field operation consisted of balancing the winch frame on the ground by means of two anchors. With these anchors, the CPTu system has sufficient power to push the cone into the ground at the rate of 2 cm/s by exerting pressure on the outer sounding tube. As this goes on, parameters such as resistance to penetration, sleeve friction, etc., are recorded. Pore pressure was measured through a filter element placed between cone tip and sleeve. The sounding depths range between 4 and 8 m. The tests were terminated at depths where the machine anchors began to pull out of the ground.

Parameters recorded by the CPTu sounding test include cone resistance, sleeve friction and pore pressure readings. These parameters are usually plotted against depth and displayed (Figures 6 and 7). Emplacing the CPTu data into empirical equations, the seismic velocities and dynamic elastic moduli including the bearing capacity of the geomaterials in the study sites were determined.

5. Results and discussion

Sample records of the seismic P-wave from the study sites, plots of travel time against source receiver distance and depth-velocity model showing vertical distributions of velocity with depth in each site are shown in Figures 4 and 5, respectively. The results show two-layered ground models. Table 1 (a,b)) shows the thicknesses and velocities obtained from analysis of the seismic refraction data using the intercept-time method (Barton and Barker 2003). Also shown in Table 1 are the elastic moduli, Lames constant and the bearing capacity. The results show that in the Opolo site, the first layer thickness and P-wave velocity vary from 10–12 m and 127–157 m/s with an average of 134 m/s, while the S-wave velocity vary from 64 to 92 m/s with an average of 77 m/s. The P-wave and S-wave velocity of the second layer vary between 224 and 374 m/s with an average of 304 m/s and 132–220 m/s with an average of 179 m/s. We attribute the limitation in the depth of coverage to the energy source that was used or length of profile deployed. Drill test hole in the Opolo site shows that the depth interval of 0–12 m corresponds to Plio-Pleistocene and recent superficial deposits composed mainly of clay while the second layer is made up of sand. The contact between layers 1 and 2 is characterised by a relatively high acoustic impedance contrast considering the fairly high P-wave velocity contrast between the first and second layers. In the Tombia site, the thickness and P-wave velocity of the first layer vary between 5–13 m and 123–152 m/s with an average of 141 m/s, respectively. The S-wave velocity of the first layer varies between 72–89 m/s with an average of 83 m/s. In the second layer, the P-wave and S-wave velocity vary

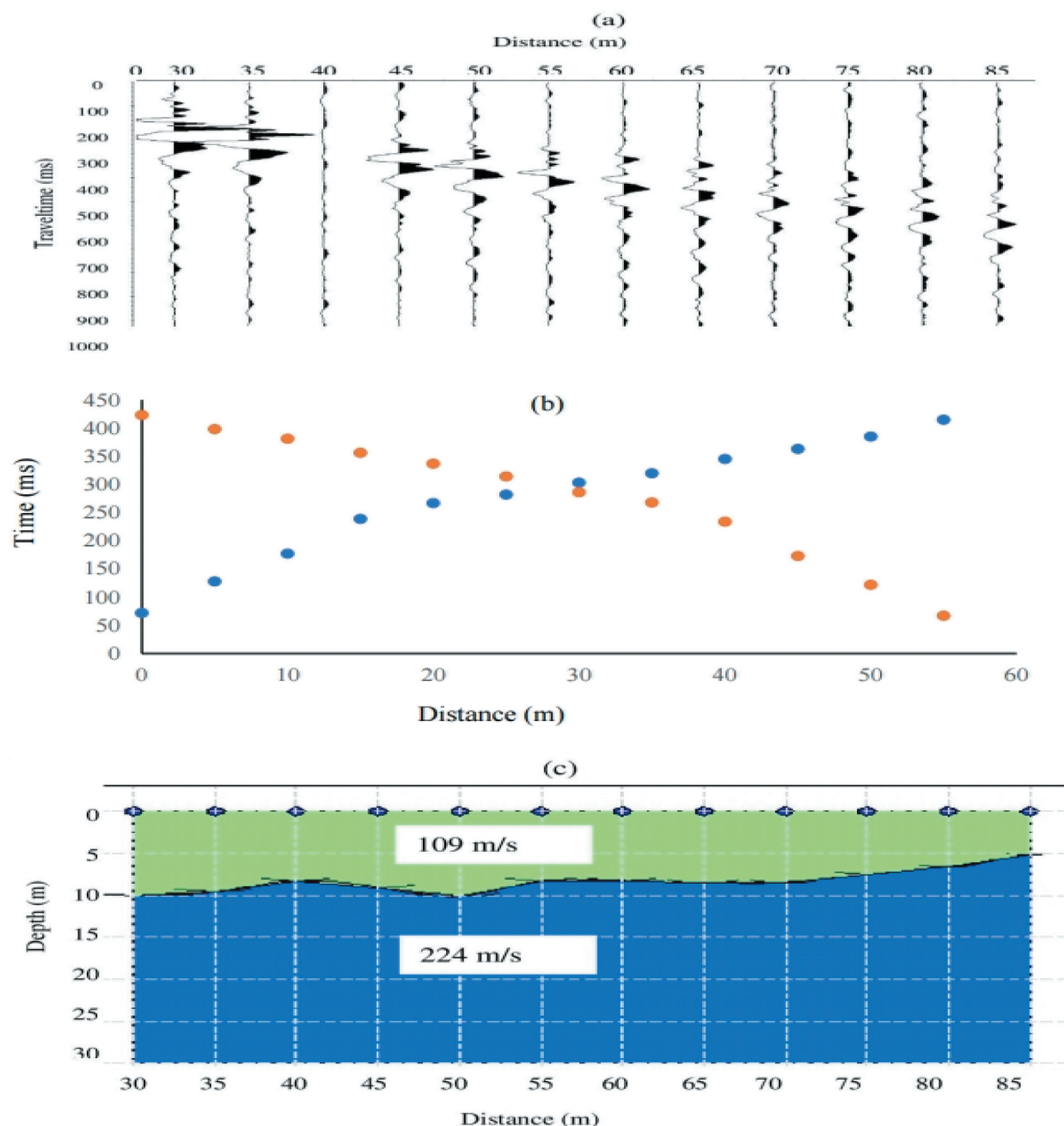


Figure 4. (a) Sample record of seismic P-wave from the Opolo site; (b) plot of travel time against source receiver distance; (c) depth-velocity model showing vertical distributions of velocity with depth in the layer.

between 176–204 m/s with an average of 188 m/s and 103–120 m/s with an average of 110 m/s. The variation in velocity even in the same layer is attributed to variations in lithology, grain size, porosity and saturation (Salem 2000). The low velocities especially in the first layer are presumably due to the presence of fine deposits such as clays and silts. In general, the velocity of the second layer is higher than the velocity of the first layer consistent with the fact that velocity increases with depth as porosity decreases (Salem 1993).

The P-wave velocity results of the shallow alluvial sediments in this study are fairly in agreement with those reported in the study of Alaminikuma and

Omigie (2018) in the first layer in the Eastern Niger Delta (Bonny Island) within the depth range of 0–10 m, although the S-wave velocities are slightly higher than the values obtained in this study. The results of the seismic velocities (V_p and V_s) from the western Niger Delta (Escravos Area) reported by Ajayi et al. (2014) are higher than the values in this study within the shallow depths. The Poisson's ratio varies between 0.232 and 0.239 with an average of 0.236 and 0.234–0.235 with an average of 0.235 in the first and second layers in the Opolo site but vary between 0.234 and 0.235 with an average of 0.254 and 0.235–0.242 with an average of 0.238, respectively, in

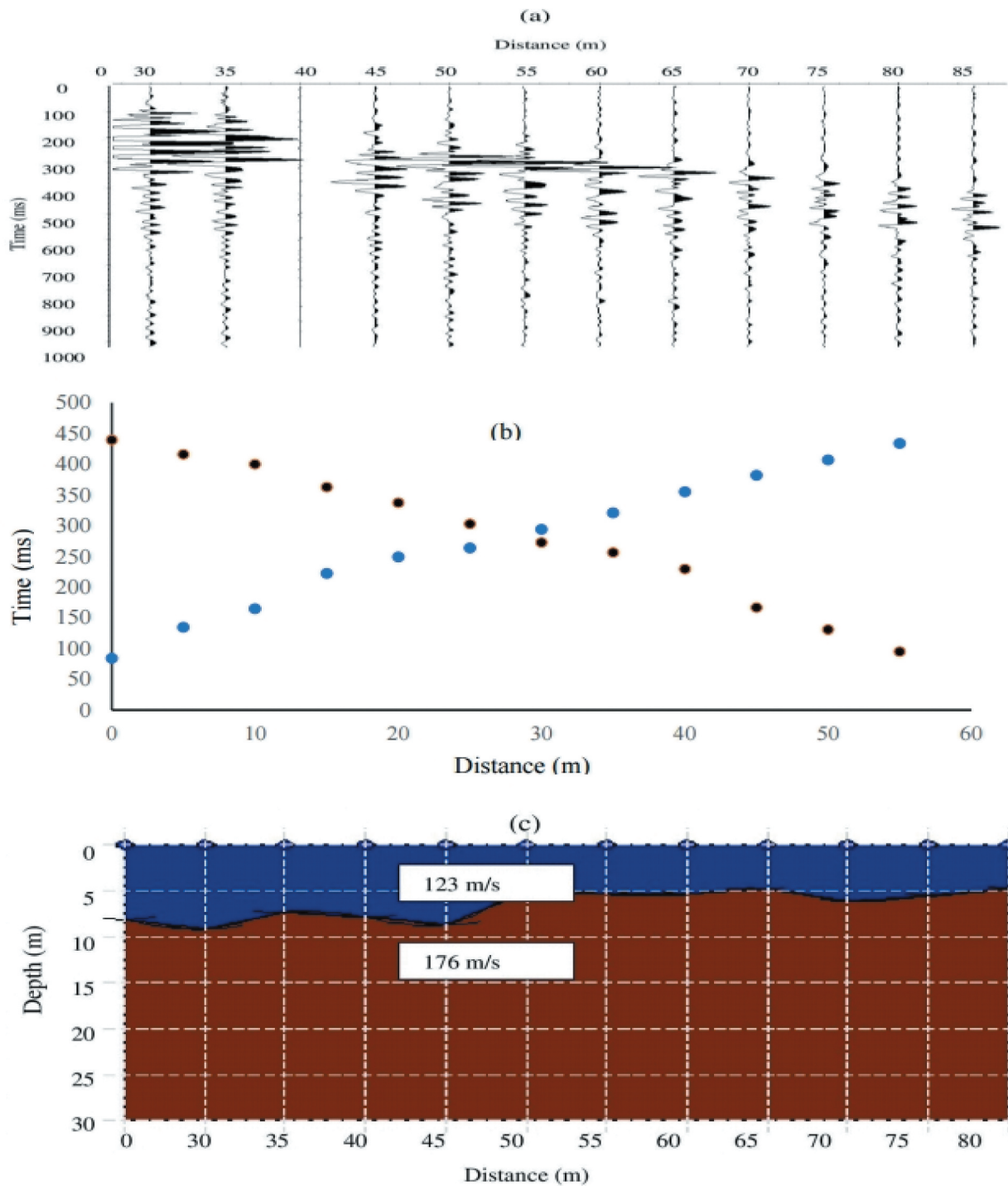


Figure 5. (a) Sample record of seismic P-wave from the Tombia site; (b) plot of travel-time against source receiver distance; (c) depth-velocity model showing vertical distributions of velocity with depth in the layer.

the Tombia site in the first and second layers. The values of the Poisson's ratio in this study are consistent with those reported by Salem (2000) and Singh et al. (2015).

Based on the soil description scale in respect to Poisson's ratio in terms of soil competence (Sheriff and Geldart 1986), the geomaterials within the study site could be described as competent materials. The shear modulus or rigidity values range between $10.9 \times 10^6 \text{ Nm}^{-2}$ – $22.4 \times 10^6 \text{ Nm}^{-2}$ with an average of $16.1 \times 10^6 \text{ Nm}^{-2}$ and 12.8×10^6 – $91.7 \times 10^6 \text{ Nm}^{-2}$

with an average of $50.2 \times 10^6 \text{ Nm}^{-2}$ in the first and second layers in the Opolo site. In the Tombia site, the shear modulus values range between 13.7×10^6 – $21.0 \times 10^6 \text{ Nm}^{-2}$ with an average of $18.3 \times 10^6 \text{ Nm}^{-2}$ and 28.1×10^6 – $30.0 \times 10^6 \text{ Nm}^{-2}$ with an average of $29.1 \times 10^6 \text{ Nm}^{-2}$ in the first and second layers in the Tombia site. The values of the Young's modulus range from 26.9×10^6 – $31.7 \times 10^6 \text{ Nm}^{-2}$ with an average of $39.7 \times 10^6 \text{ Nm}^{-2}$ in the first layer and 11.4×10^6 – $31.7 \times 10^6 \text{ Nm}^{-2}$ with an average of $21.9 \times 10^6 \text{ Nm}^{-2}$ in the second layer in the

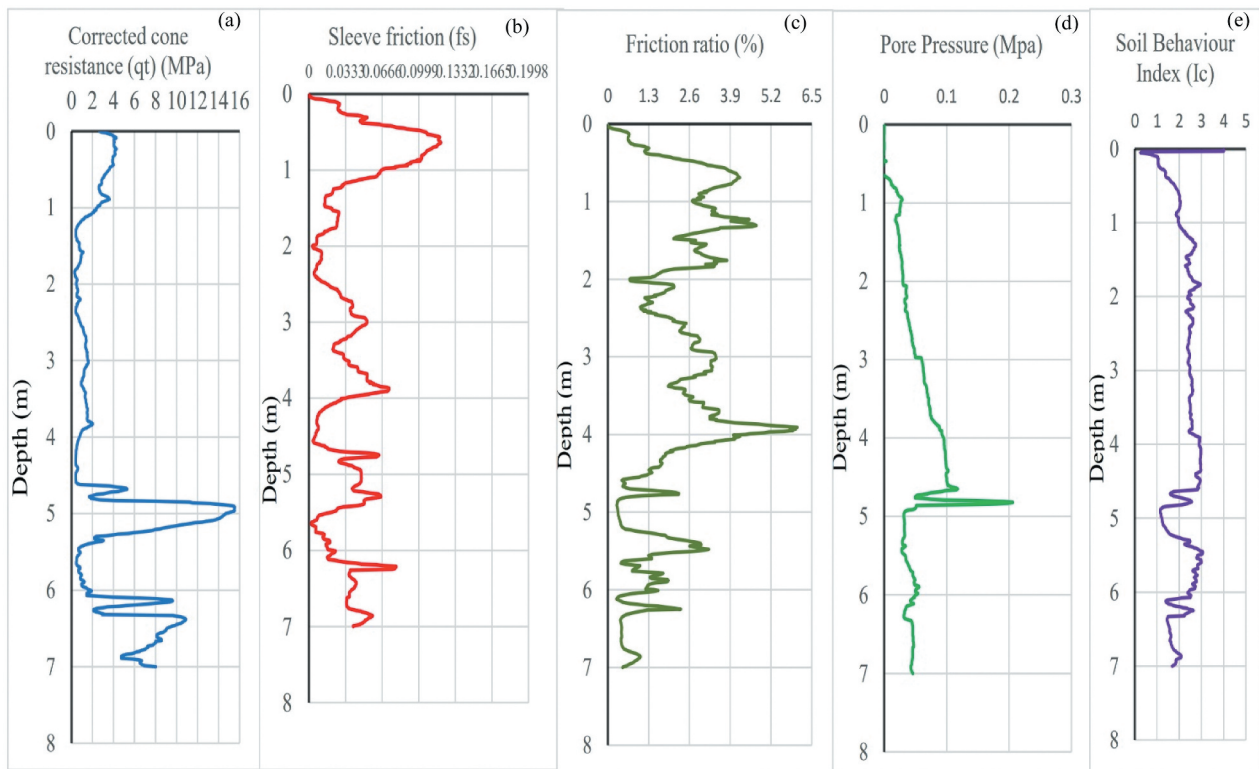


Figure 6. Example of CPTu-based soil profile at Opolo showing (a) corrected cone tip resistance, (b) sleeve friction, (c) friction ratio, (d) pore pressure and (e) soil behaviour index (I_c) to illustrate the soil type description

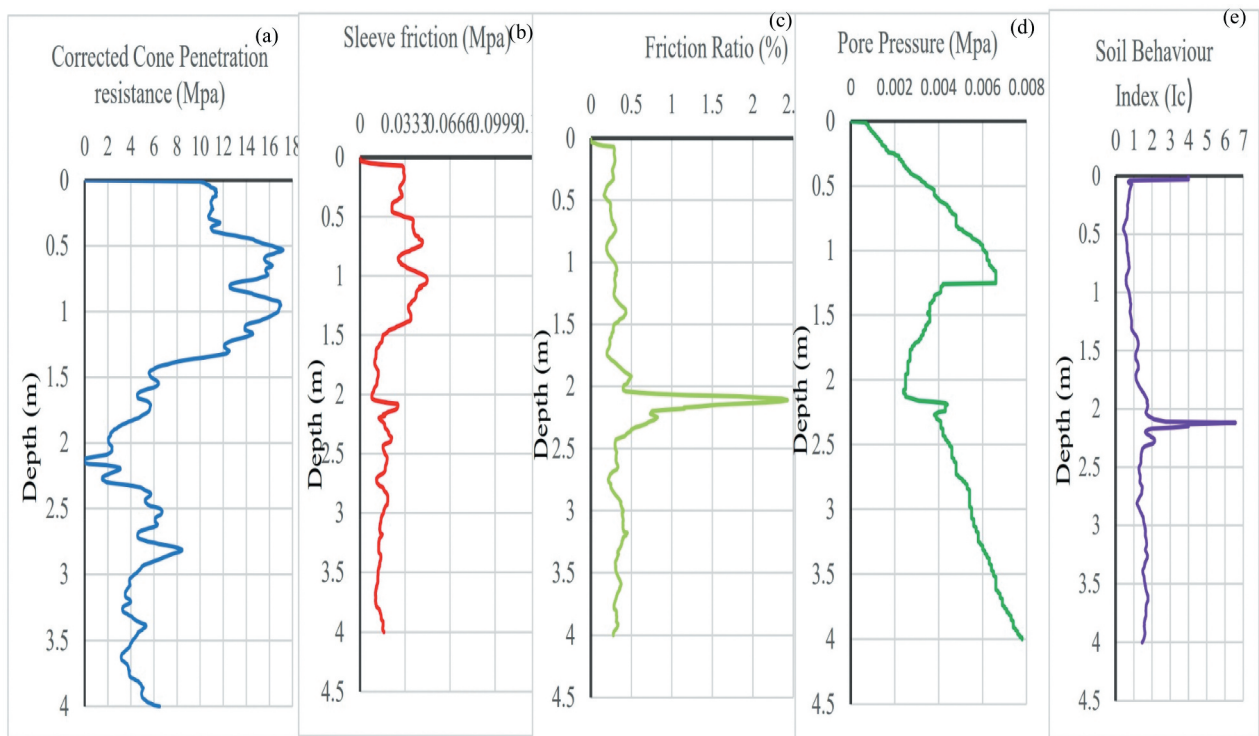


Figure 7. Example of CPTu-based soil profile at Tombia: (a) corrected cone tip resistance, (b) sleeve friction, (c) friction ratio, (d) pore pressure and (e) soil behaviour Index (I_c) to illustrate the soil type description.

Opolo site. In the Tombia site, the Young's modulus values are from 34.1×10^6 – $52.0 \times 10^6 \text{ Nm}^{-2}$ with an average of $45.2 \times 10^6 \text{ Nm}^{-2}$ in the first layer and 69.7×10^6 – $76.5 \times 10^6 \text{ Nm}^{-2}$ with an average of $80.2 \times 10^6 \text{ Nm}^{-2}$ in the second layer. The bulk

modulus values range from 17.0×10^6 – $35.4 \times 10^6 \text{ Nm}^{-2}$ with an average of $25.1 \times 10^6 \text{ Nm}^{-2}$ in the first layer and 20.0×10^6 – $71.4 \times 10^6 \text{ Nm}^{-2}$ with an average of $35.1 \times 10^6 \text{ Nm}^{-2}$ in the second layer in the Opolo site. In the Tombia site, the bulk modulus values range

Table 1. Seismic velocity, elastic moduli and bearing capacity of Opolo and Tombia sites obtained from geophysical method

Layer 1											
Site	Profile	h (m)	V_p (m/s)	V_s (m/s)	Poisson's ratio	Shear modulus (μ) (10^6 Nm^{-2})	Young's modulus (E) (10^6 Nm^{-2})	Bulk modulus (K) (10^6 Nm^{-2})	Lames' constant (λ) (10^6)	Qult Nm^{-2}	Qall Nm^{-2}
Opolo	Profile A	11	109	64	0.237	10.9	26.9	17.0	9.8	104	25.9
	Profile B	10	127	75	0.232	14.9	36.7	22.9	12.9	122	30.5
	Profile C	12	157	92	0.239	22.4	55.6	35.4	20.5	150	37.5
Tombia	Profile A	5	123	72	0.288	13.7	34.1	21.8	12.6	117	29.2
	Profile B	9	148	87	0.236	20.1	49.6	31.3	17.9	142	35.4
	Profile C	13	152	89	0.239	21.0	52.0	33.2	19.2	145	36.3
Layer 2											
Site	Profile	V_p (m/s)	V_s (m/s)	Poisson's ratio	Shear modulus (μ) (10^6 Nm^{-2})	Young's modulus (E) (10^6 Nm^{-2})	Bulk modulus (K) (10^6 Nm^{-2})	Lames' constant (λ) 10^6	Qult Nm^{-2}	Qall Nm^{-2}	
Opolo	Profile A	224	132	0.234	46.2	11.4	71.4	40.6	217	54.3	
	Profile B	374	220	0.235	12.8	31.7	20.0	11.4	369	92.1	
	Profile C	316	186	0.235	91.7	22.6	14.2	81.3	309	77.3	
Tombia	Profile A	176	103	0.242	28.1	69.7	44.6	25.9	168	42.1	
	Profile B	204	120	0.235	28.2	94.3	59.4	34.0	197	49.0	
	Profile C	184	108	0.237	30.9	76.5	48.5	27.9	177	44.2	

Table 2. Soil description with respect to Poisson's ratio (Sheriff and Geldart 1986)

Soil description parameter	Incompetent to slightly competent	Fairly to moderately competent	Competent materials	Very high competent
Poisson's ratio (σ)	0.4–0.49	0.35–0.27	0.25–0.16	0.12–0.03

between $21.8 \times 10^6 - 33.2 \times 10^6 \text{ Nm}^{-2}$ with an average of $28.8 \times 10^6 \text{ Nm}^{-2}$ and $44.6 \times 10^6 - 59.4 \times 10^6 \text{ Nm}^{-2}$ with an average of $50.8 \times 10^6 \text{ Nm}^{-2}$. The results of the elastic moduli values in this study compare well with those reported by Singh et al. (2015) and Alaminikuma and Omigie (2018).

The Lames constant (λ) values range from $9.8 \times 10^6 - 20.5 \times 10^6$ with an average of 14.4×10^6 in the first layer but range between $11.4 \times 10^6 - 81.3 \times 10^6$ with an average of 44.4×10^6 in the second layer in the Opolo site. In the Tombia site, the Lame's constant (λ) values range from $12.6 \times 10^6 - 19.2 \times 10^6$ with an average of 16.6×10^6 in the first layer but varies from $25.9 \times 10^6 - 34.0 \times 10^6$ with an average of 29.3×10^6 in the second layer. The ultimate bearing capacity in the Opolo site range between 104 and 150 Nm^{-2} with an average of 125.3 Nm^{-2} in the first layer but varies between 217 and 369 Nm^{-2} with an average of 298.3 Nm^{-2} in the second layer. In the Tombia site, the ultimate bearing capacity values range from 117 to 142 Nm^{-2} with an average of 134.7 Nm^{-2} in the first layer but varies from 168 to 197 Nm^{-2} with an average of 180.7 Nm^{-2} in the second layer. The allowable bearing capacity in the Opolo site range between 25.9 and 37.5 Nm^{-2} with an average of 31.3 Nm^{-2} in the first layer but range from 54.3 to 92.1 Nm^{-2} with an average of 74.5 Nm^{-2} in the second layer. In the Tombia site, the allowable bearing capacity values range between 29.2 and 36.3 Nm^{-2} with an average

of 33.6 Nm^{-2} in the first layer but range between 42.1 and 49.0 Nm^{-2} with an average of 45.1 Nm^{-2} in the second layer.

In order to compare the seismic velocity, elastic moduli and bearing capacity values determined using geophysical with those obtained from conventional geotechnical methods at the same point, CPTu soundings were also carried out in the study sites (Figures 6 and 7). The values of the compressional and shear wave velocities and elastic moduli from a depth of 0.5–8.0 m obtained using the CPTu data are shown in Tables 3 and 4, respectively. Figures 8a and 9a show the variation of compressional and shear wave velocity with depth. In Figure 8a, the compressional wave velocity increases from 174 m/s at 0.5 m depth to 303 m/s at 8.0 m depth. The average compressional velocity within the depth range of 0.5–8.0 m is 227 m/s. The shear wave velocity also increases from 103 m/s at 0.5 m depth to 178 m/s at 8.0 m depth. The average shear wave velocity within this depth range is 134 m/s. Drill test hole information in the Opolo site shows that the depth range 0.5–8.0 m is a clayey formation. In the Tombia site (Figure 9a), the compressional wave velocity increases from 136 m/s at 0.5 m depth to 244 m/s at 6.0 m depth with an average of 197 m/s while the shear wave velocity increases from 80 to 144 m/s at 6.0 m depth with an average of 116 m/s. Drill test hole information in this site shows that this depth range consists mainly of silty sand. The compressional wave velocity increases from 256 m/s at 6.5 m depth to 710 m/s at 8.0 m depth with an average of 387 m/s while the shear wave velocity increases from 151 m/s at 6.5 m depth to 418 m/s at 8.0 m depth with an average of 228 m/s (Table 4). The lithological information shows that this depth range consists of sand.

On comparing the average values of the seismic velocities of the formations derived from the two methods,

Table 3. Elastic moduli and bearing capacity obtained from CPTu data in Opolo site

Depth (m)	V_p (m/s)	V_s (m/s)	Poisson ratio (σ)	Shear modulus (Nm^{-2})	Young's modulus (Nm^{-2})	Bulk modulus (Nm^{-2})	Lames constant (λ)	Qult Nm^{-2}	Qall Nm^{-2}
0.5	174	103	0.230	22	67	41	23	168	42
1.0	192	113	0.235	27	81	51	29	185	46
1.5	182	107	0.236	23	70	44	25	175	44
2.0	163	96	0.234	18	53	33	19	157	39
2.5	173	102	0.234	20	59	37	21	167	42
3.0	186	110	0.231	25	75	46	26	180	45
3.5	173	102	0.234	22	65	41	23	167	42
4.0	209	123	0.235	39	117	74	42	202	50
4.5	237	140	0.232	42	126	78	44	231	58
5.0	264	156	0.232	61	183	114	64	258	64
5.5	227	134	0.233	43	130	81	46	220	55
6.0	276	162	0.237	56	167	106	61	268	67
6.5	299	176	0.235	68	203	128	73	292	73
7.0	294	173	0.235	70	208	131	75	287	72
7.5	283	166	0.238	62	186	118	68	275	69
8.0	303	178	0.237	72	217	137	79	296	74

Table 4. Elastic moduli and bearing capacity obtained from CPTu data in Tombia site

Depth (m)	V_p (m/s)	V_s (m/s)	Poisson ratio (σ)	Shear modulus (Nm^{-2})	Young's modulus (Nm^{-2})	Bulk modulus (Nm^{-2})	Lames const λ	Qult Nm^{-2}	Qall Nm^{-2}
0.5	136	80	0.235	12	37	23	13	130	33
1.0	133	78	0.238	13	39	25	14	127	32
1.5	134	79	0.234	19	56	35	20	129	32
2.0	153	90	0.235	21	64	40	23	147	37
2.5	181	106	0.239	30	91	58	34	173	43
3.0	214	126	0.235	40	121	76	43	207	52
3.5	209	123	0.235	40	121	76	43	202	50
4.0	235	138	0.237	52	157	99	57	227	57
4.5	258	152	0.234	64	191	120	68	251	63
5.0	229	135	0.234	39	118	74	42	222	56
5.5	235	138	0.237	39	118	75	43	227	57
6.0	244	144	0.233	45	148	92	52	237	59
6.5	256	151	0.233	49	210	131	74	249	62
7.0	291	171	0.236	70	206	130	75	284	71
7.5	290	171	0.233	69	206	129	73	284	71
8.0	710	418	0.235	56	168	106	60	728	182

we observed that the CPTu-derived average values of the velocities in the Opolo site in the clayey formation are slightly greater than the average values of the velocities derived using the seismic refraction technique. We also observed the same pattern in the Tombia site. Based on the ASSHTO Guidelines for the seismic design of Highway Bridges, soils are classified into six groups namely, A, B, C, D, E and F with reference to shear wave velocity. Group A represents hard rock with measured shear wave velocity greater than 600 m/s, while E and F classes represent weak to very weak soil with measured shear wave velocity values less than 180 m/s (Hammam and Eliwa 2013). The results of the shear wave velocities shown in Tables 3 and 4 and Figures 6 and 7 are less than 180 m/s and thus classified as class E.

The Poisson's ratio values vary between 0.230 and 0.238 with an average of 0.234 in the Opolo site (Table 3). In the Tombia site (Table 4), the Poisson's ratio ranges between 0.233 and 0.235 with an average of 0.235 within the depth range of 0.5–6.0 m corresponding to the silty sand but varies from 0.233 to 0.235 with an average of 0.234 within the sandy formation. Figure 8b shows that Poisson's ratio increases as with depth increases in the Opolo site but decreases as depth increases in the

Tombia site (Figure 9b). Generally, the range of Poisson's ratio values derived using the CPTu method is consistent with those derived using the seismic refraction method.

The shear modulus exhibits a range between 18 and 72 Nm^{-2} with an average of 42 Nm^{-2} in the Opolo site but varies between 12 and 45 Nm^{-2} with an average of 35 Nm^{-2} between 0.5 and 8.0 m depth (silty sand) in the Tombia site and varies between 49 and 70 Nm^{-2} with an average of 61 Nm^{-2} between 6.0 and 8.0 m depth. Shear modulus increases with depth in both sites (Figures 8 and 9 (c)). Values of the Young's modulus in the Opolo site range between 53 and 217 Nm^{-2} with an average of 125 Nm^{-2} , but vary between 37 and 148 Nm^{-2} between the depth range of 0.5–6.0 m and 168–210 Nm^{-2} between 6.0 and 8.0 m depth in the Tombia site. In both sites, the Young's modulus increases with depth (Figures 8 and 9 (c)). The bulk modulus values range between 41 and 137 Nm^{-2} with an average of 79 Nm^{-2} in the Opolo site, but vary between 23 and 120 Nm^{-2} with an average of 66 Nm^{-2} in the Tombia site within the depth range of 0.5–6.0 m and 106–131 Nm^{-2} with an average of 124 Nm^{-2} between 6.0 and 8.0 m depth. In

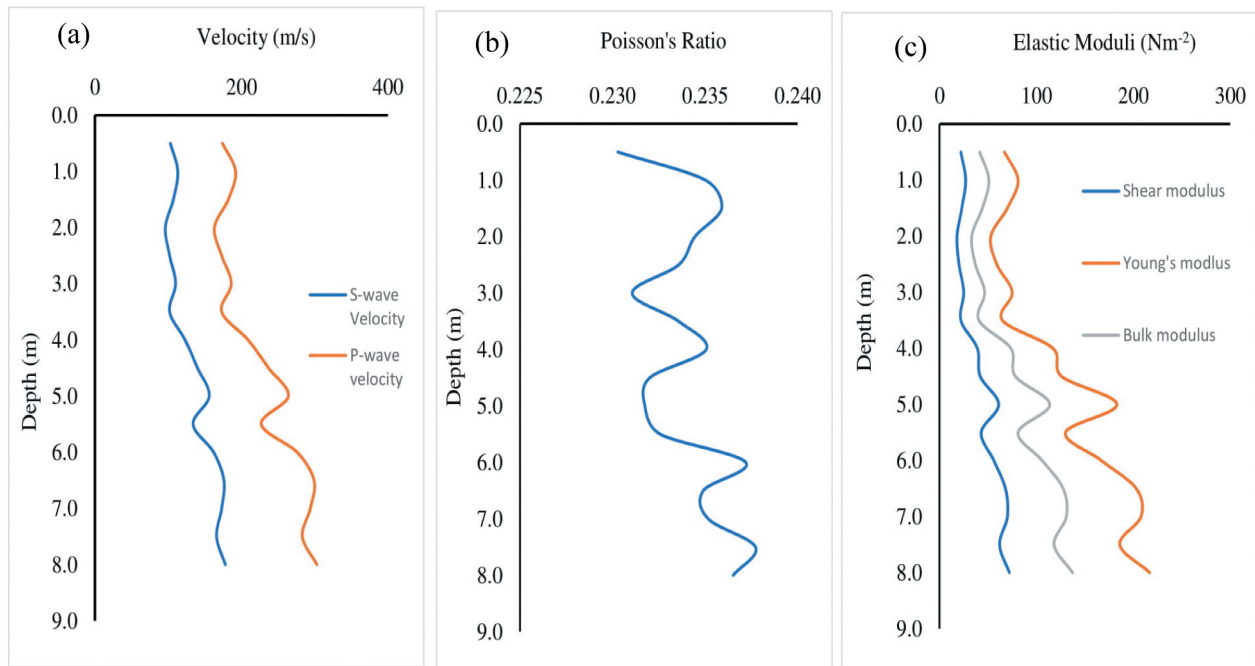


Figure 8. Variation of (a) seismic velocity, (b) Poisson's ratio and (c) elastic moduli with depth derived from CPTu data at the Opolo site.

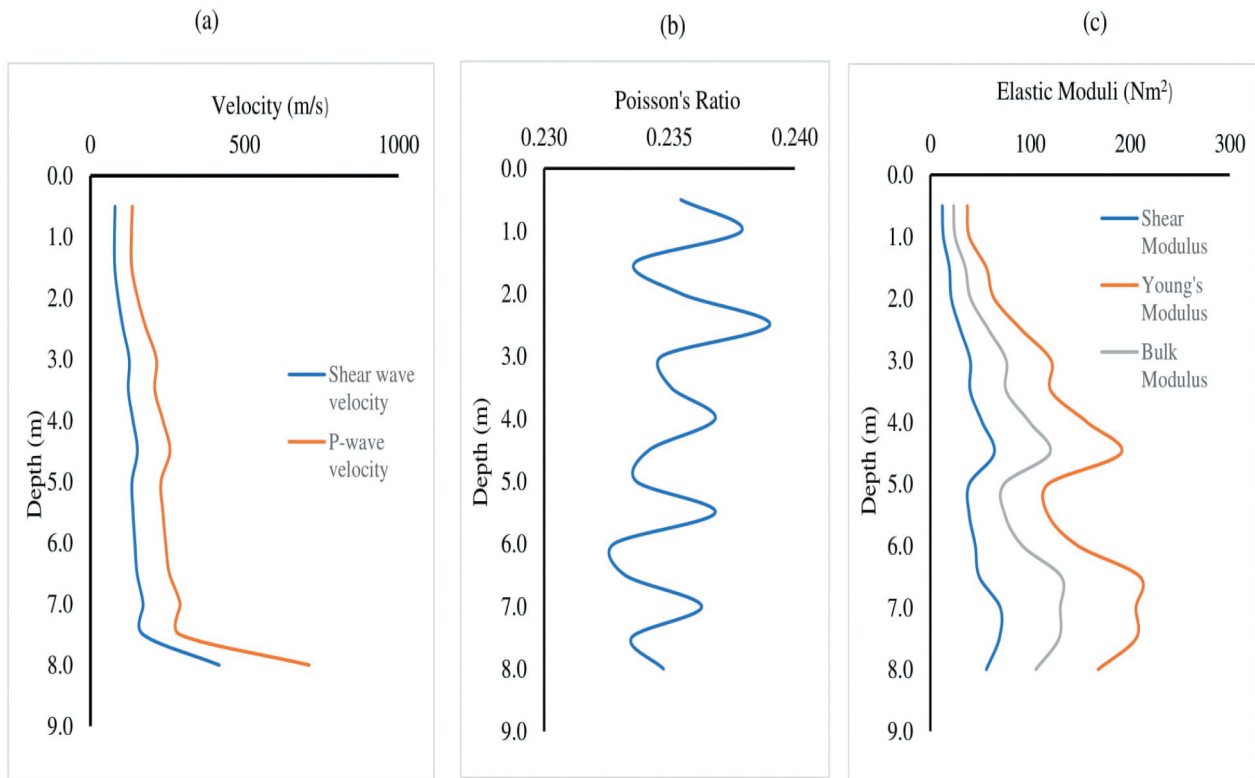


Figure 9. Variation of (a) seismic velocity, (b) Poisson's ratio and (c) elastic moduli with depth derived from CPTu data at the Tombia site.

both sites, the Young's modulus increases with depth (Bowles 1982).

The Lamé's constant varies between 19 and 79 with an average of 45 in the Opolo site. In the Tombia site, the Lamé's constant varies between 13 and 68 with an

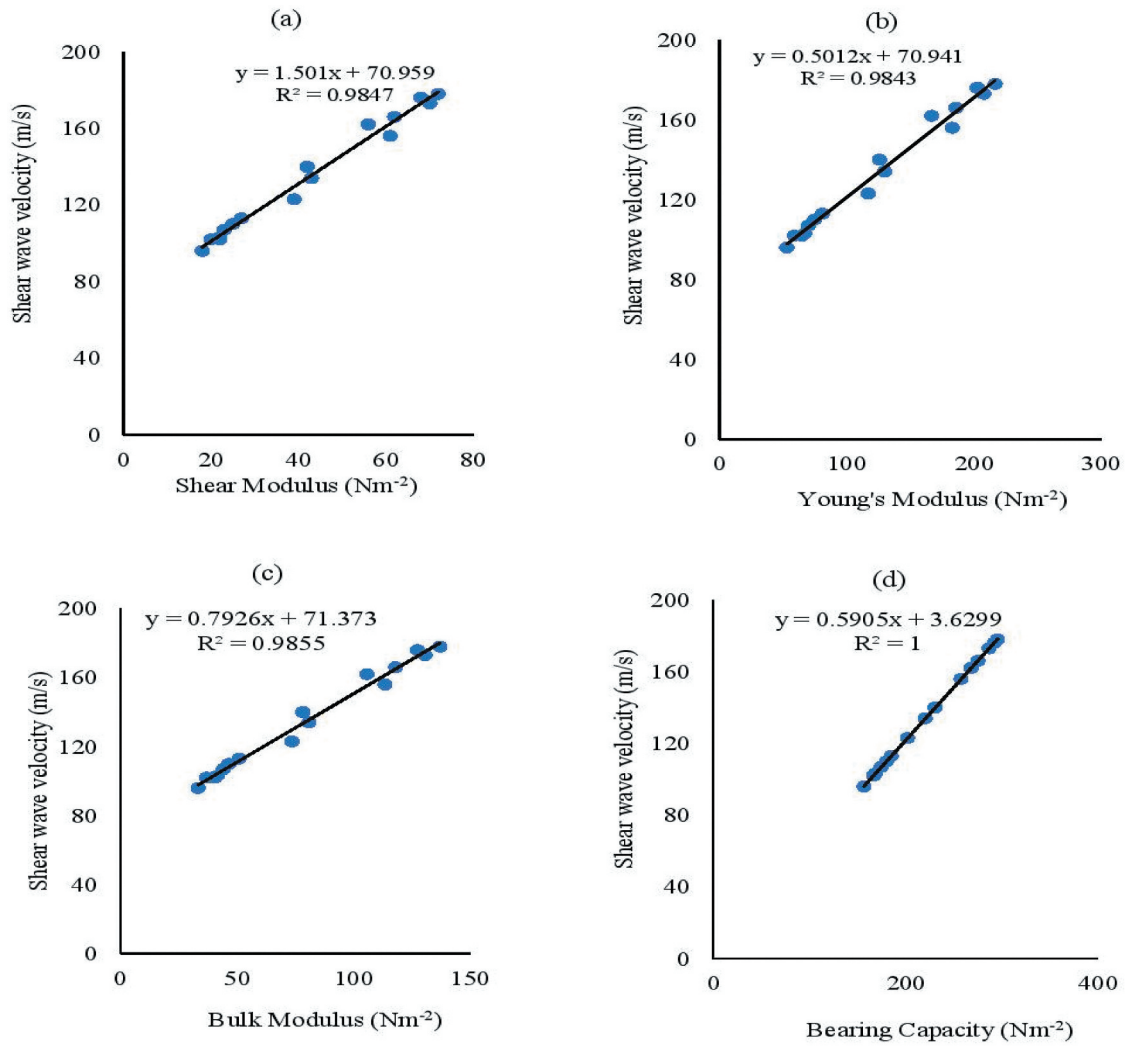


Figure 10. Correlation of elastic moduli and S-wave velocity in the Opolo site

average of 38 in the depth range of 0.5–6.0 m and 60–75 with an average of 71 between 6.0 and 8.0 m depth. In the Opolo site, the ultimate and allowable bearing capacity values vary between 168 and 296 Nm^{-2} with an average of 220 Nm^{-2} and 39–74 Nm^{-2} with an average of 55 Nm^{-2} . In the Tombia site, between the depth range of 0.5–6.0 m, the ultimate and allowable bearing capacity values range between 127 and 251 Nm^{-2} with an average of 190 Nm^{-2} and 32–63 Nm^{-2} with an average of 47 Nm^{-2} . Between the depth range of 6.0–8.0 m, the ultimate and allowable bearing capacity values range between 249 and 728 Nm^{-2} with an average of 386 Nm^{-2} and 62–182 Nm^{-2} with an average of 97 Nm^{-2} .

Generally, the elastic moduli values derived using the seismic refraction method (small strain 10^{-4} % test) are greater than the elastic moduli values derived using the CPTu (large strain measurement) method. This is consistent with the observation of Seed et al. (1986) and Do et al. (2018), who opined that differences exist between Young's modulus values derived

from small strain (10^{-4} %) down hole test and values from large strain measurement such as the CPTu. Similar observations are also reported by Fjær (2009), Martínez-Martínez et al. (2012) and Brotons et al. (2016) for studies carried out in heterogeneous geomaterials. Kolesnikov (2009) observed that the difference is due to differences in non-linear elastic response at different strain amplitudes, the effect of pore fluids, etc (Kolesnikov 2009).

5.1. Correlation between CPTu-derived elastic moduli and S-wave velocity

The least-squares regression technique was used to analyse the CPTu-derived elastic moduli results and S-wave velocity. The results show a linear relationship between shear modulus, Young's modulus, bulk modulus and bearing capacity with S-wave velocity (Figures 10 and 11). Also shown in Figures 10 and 11 are the regression equation and the correlation coefficient (R^2) determined for each regression. The

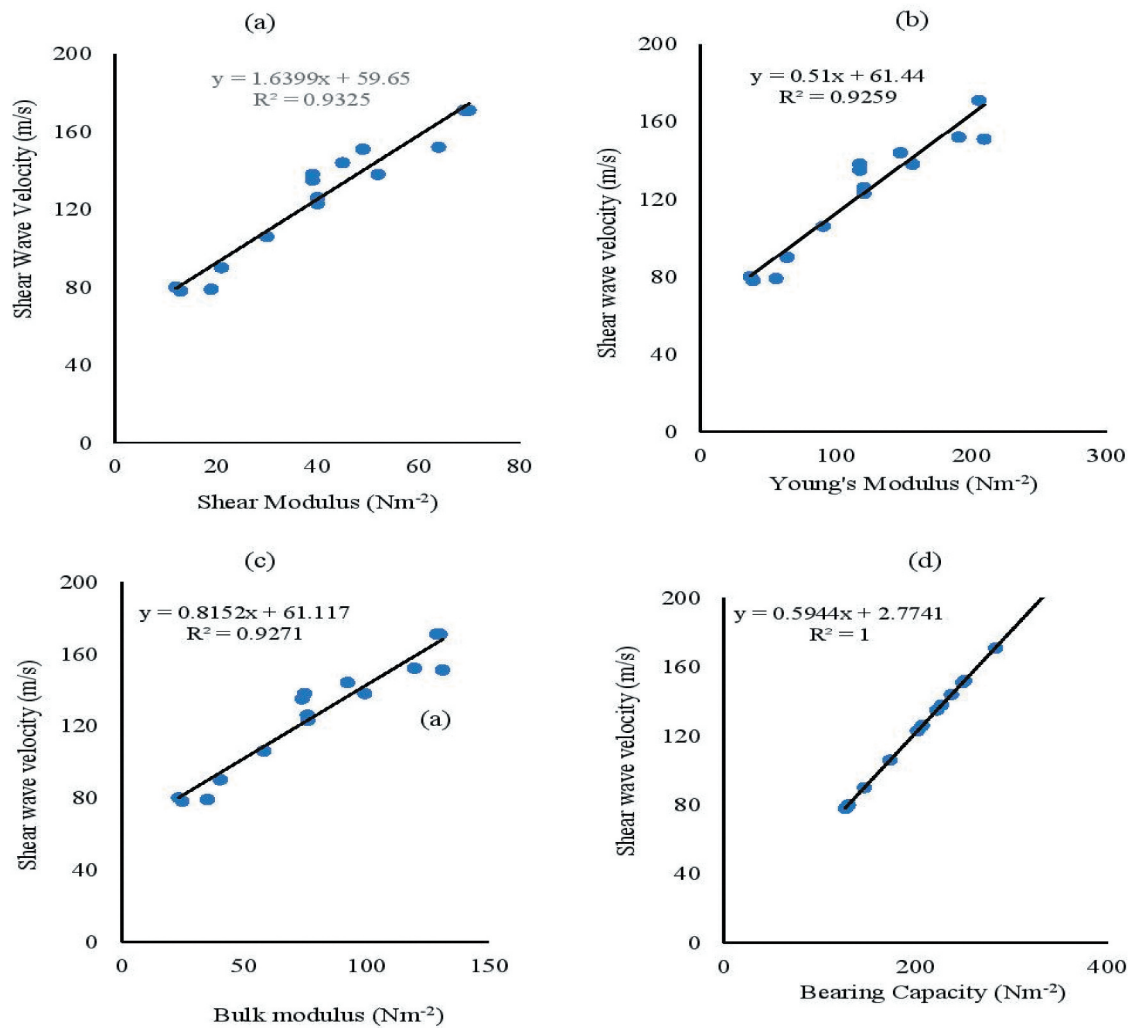


Figure 11. Correlation of elastic moduli and S-wave velocity in the Tombia site

best fit lines were straight lines for all cases. In general, the elastic moduli increase with increase in P-wave velocity. The correlations are highly significant with correlation coefficients (R^2) greater than 0.90. The good correlation indicates a linear relationship exists between the elastic moduli and S-wave velocity of the alluvial sediments.

Altindag (2012) reported similar results by correlating P-wave velocity and elastic moduli in sedimentary rocks. The strong correlation of shear wave velocity with the various dynamic elastic moduli demonstrates the utility of shear wave velocity in geotechnical studies. The shear wave velocity is a key parameter in the design of geotechnical structures that may undergo dynamic loading (Kuo et al. 2011; Hammam and Eliwa 2013). In site response analysis, evaluation of liquefaction, etc., shear wave velocity is indispensable and thus plays a very important role in the design of foundation of structures. The shear wave velocity represents the material and structural condition of a soil. It is required in the evaluation of layer structure, degree of compaction or consolidation of soft soil or linearments within a site (Bang and Kim 2009).

6. Conclusions

In this paper, we present results of seismic velocities, dynamic elastic moduli and bearing capacity obtained from the analysis of seismic refraction data and CPTu soundings. The study sites consist of quaternary alluvial sediments. Field measurements include low-strain seismic refraction and high strain CPTu soundings. The seismic refraction data was analysed using the Intercept-time technique to obtain the seismic velocities which were subsequently used to estimate the dynamic elastic moduli. The CPTu data such as corrected cone tip resistance and soil behaviour index were emplaced into established empirical equation to determine the shear wave velocity, with which the P-wave velocity was estimated. Combining the V_p and V_s , the dynamic elastic moduli of the shallow sediments were determined within the depth range of 0.5–8.0 m.

The results show that the average values of the compressional and shear wave velocity in the Opolo site obtained from the seismic refraction method in the first layer are 131 and 77 m/s, Poisson's ratio is

0.236, the shear modulus, Young's modulus and bulk modulus are $16.1 \times 10^6 \text{ Nm}^{-2}$, $39.7 \times 10^6 \text{ Nm}^{-2}$, and $25.1 \times 10^6 \text{ Nm}^{-2}$, respectively. The Lames constant, ultimate and allowable bearing capacity are 14.1×10^6 , 125 Nm^{-2} and 31.3 Nm^{-2} , respectively. In the Tombia site, the average values of the compressional and shear wave velocities in the first layer are 141 and 83 m/s, respectively. The Poisson's ratio is 0.234. The shear modulus, Young's modulus and bulk modulus are $18.3 \times 10^6 \text{ Nm}^{-2}$, $45.2 \times 10^6 \text{ Nm}^{-2}$ and $28.8 \times 10^6 \text{ Nm}^{-2}$, respectively. The Lames constant, ultimate and allowable bearing capacity are 16.6×10^6 , 135 Nm^{-2} and 34 Nm^{-2} , respectively. From the CPTu data in the Opolo site, the average values of the compressional and shear wave velocity values are 227 and 133 m/s. The Poisson's ratio is 0.234. The shear modulus, Young's modulus and bulk modulus are 42, 125 and 79 Nm^{-2} , respectively. The Lames constant, ultimate and allowable bearing capacity are 45, 220 Nm^{-2} and 55 Nm^{-2} , respectively. In the Tombia site, the average values of the compressional and shear wave velocity values are 244 and 144 m/s. The Poisson's ratio is 0.235. The shear modulus, Young's modulus and bulk modulus are 42, 128 and 81 Nm^{-2} , respectively. The Lames constant, ultimate and allowable bearing capacity are 46, 229 Nm^{-2} and 60 Nm^{-2} , respectively. When the results from the two methods were compared, it was observed that the average values of V_p and V_s from the two methods are fairly in agreement in that the relative difference between the average values were small. Significant difference in the average values was only observed in the dynamic elastic moduli. Analysis of the S-wave and the dynamic moduli from the CPTu data shows that a linear relationship exists between S-wave velocity and the dynamic elastic moduli with correlation coefficients (R^2) greater than 0.9 in all cases. The determined dynamic moduli, i.e. shear wave velocity, shear modulus, Young's modulus and bulk modulus, can be used for the design of structures based on the Eurocode (CEN 2004), site response (Reiter 1990) and settlement analysis. The shear wave velocity is also widely used in the assessment of liquefaction (Kramer 1996).

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Disclosure statement

There is no conflict of interest in this paper.

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