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RESEARCH ARTICLE

COMPARATIVE ANALYSIS OF STATIC SHEAR MODULUS AND DYNAMIC SHEAR MODULUS DETERMINED BY GEOPHYSICAL AND GEOTECHNICAL INVESTIGATION

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ABSTRACT

Due to the occurrence of earth tremors which leads to the vibrations of foundations and perhaps failure of buildings and roads, it is therefore important to understand and have knowledge of the geomechanical soil properties for foundation design, assessment of risks and suggestion of mitigation plans in engineering structures and road construction. A total of 3 boreholes were drilled with the Standard Penetration Test (SPT) performed and Downhole Seismic Test (DST) carried out in the boreholes located within Assa to investigate the Geomechanical soil properties in the area. For the geophysical survey, the downhole seismic test was carried out to determine the P-wave and S-wave. The results were processed using the generalized reciprocal method (GRM) with the Seisimager program. The results of soil dynamic modulus (shear, young and bulk modulus) and Poisson ratio recorded from DST conducted in BH1, BH2 and BH3 ranges from 7300 KPa to 72390 KPa, 0.31 to 0.41 for the Poisson ratio. Meanwhile, soil static modulus and Poisson's ratio recorded from SPT conducted in BH1, BH2 and BH3 ranges from 2520 to 44687.0 KPa, 0.20 to 0.55 for the Poisson ratio respectively. The results of this study have shown that there is a wide variation between geomechanical properties derived from geotechnical investigations (static properties) and geophysical investigations (dynamic properties). Based on depth trend analysis, the dynamic and static soil elastic properties all increases with depth. Generally, the dynamic soil properties were significantly higher than the static elastic properties. At shallow depths (<12.0 m), the difference between static and dynamic soil modulus was relatively small, but increased with increasing depth. Meanwhile, the difference between static and dynamic Poisson ratio was high at shallow depth and it decreased with increased depths where they almost overlap. Correlation between the derived static and dynamic properties all revealed positive correlation trends. The strength of the correlation was highest for young modulus (r=0.87) which was closely followed by the shear modulus (r=0.63). Meanwhile, Poisson ratio (r=0.40) and bulk modulus (r=0.23) revealed weak positive correlation trends. The regression models generated from this study were used to derive static elastic properties and compared with the static properties obtained from geotechnical investigation thereby deriving the equations Dynamic Shear Modulus = (1.4207 x Static Shear Modulus) + 5022, Dynamic Young Modulus = (2.0241 x static young modulus) + 5054.8, Dynamic Bulk Modulus = (1.7852 x static bulk modulus) + 15458, Dynamic Poisson's ratio = (0.1812 x Static Poisson's ratio) + 0.3154. The results showed fairly good match between static (geotechnical) shear modulus and static (from regression model) shear modulus, static (geotechnical) young modulus and static (from regression model) young modulus. There was no good match obtained for bulk modulus and Poisson ratio generally, except at shallow depth (< 12 m depth) where Poisson ratio revealed a good match.

KEYWORDS

Shear Modulus, SPT, DST, Bulk modulus

1. INTRODUCTION

Geomechanics is the hypothetical and applied study of the mechanical conduct of geological materials. Its application helps in reducing risks in engineering design of infrastructures, earth dams, wellbore stability, underground structures, oil and gas creation, and geothermal energy advancement. A geological formation will fail when the stress it is exposed to surpass its strength. The purpose of geomechanics is to anticipate when failure would occur, assess its risks, and suggest mitigation plan(s). The shear modulus G relates the change in shear stress to the shear strain, it is determined by measuring the deformation in the solid from applying a force parallel to one surface of a solid, while an opposing force acts on its opposite surface and holds the solid in place (Helmenstine, 2020). The Eqn. is:

$$G = \frac{\tau xy}{\gamma xy}$$

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- G is the shear modulus or modulus of rigidity
- τ_{xy} is the shear stress
- γ_{xy} is the shear strain

Shear modulus is important to assess geotechnical designing issues both quantitatively and qualitatively, including earthen structures and most foundations for engineering structures (Makdisi and Seed, 1977). Shear modulus is also used to evaluate susceptibility of soils to liquefaction (Dobry et al., 1981). An elaborate general stress-strain relation for soil is very difficult to analyze in view of the large number of parameters that influence soil behaviour (Hardin and Drnevich, 1972). Shear modulus is influenced by different factors such as strain amplitude, confining pressure, void ratio, overconsolidation ratio, stacking frequency, temperature e.t.c (Hardin and Drnevich, 1972). The decrement of the shear modulus with applied strain has been seen in soil dynamics since the 1970's. Hardin and Drnevich contended that the basic parameter for many soil properties is the shear modulus (G) (Hardin and Drnevich, 1972). The reliance of the shear modulus on strain amplitude was represented for dynamic loading by various scienctist utilizing the resonant column test, Values of G are determined either by measurement in the laboratory on "undisturbed" soil samples or by calculations using shear wave velocity (V) measured in situ, and the mass density of the soil (Hardin and Drnevich, 1972). Mass density may be determined using "undisturbed" soil samples or in situ density tests. The quantitative description of geomechanical properties in soil/ rocks is fundamental in foundation design, road construction, dam construction and mining etc (Baopig and Hongzhi, 2005). Shear Modulus, Poisson's proportion, and compressive strength e.t.c which can be classified as rock mechanical properties, provide useful information in foundation design, fracture prediction, and other engineering construction processes (Chan 2006).

Shear modulus which is a rock mechanical property are normally estimated by employing static and dynamic techniques (Al-Shayea 2004). With the static technique being carried out in the laboratory using advanced testing equipment that contains soil sample and core specimens (Yuming and Guowei, 2000). The dynamic techniques are normally computations of compressional wave velocity (vp) and shear wave velocity (vs), which are obtained from field log data or in laboratory analysis (Guo and Liu, 2015). A group researchers highlighted that when compared, static techniques/strategies are more straightforward and sensible, while dynamic strategies are simpler and progressively ceaseless (Chang et al., 2006). Therefore, broad information on geomechanical properties is required both from laboratory tests and from well logs. Numerous individuals have attempted to enhance the experimental relations between static and dynamic method for acquiring rock mechanical properties for various geological areas with various depositional settings (Horsrud, 2001).

2. Location of The Study Area

The area of interest for this study is within Ohaji/Egbema Local Government Area, which lies in the south-western part of Imo State. It shares common boundaries with Owerri in the east, Oguta LGA in the North and Ogba/Egbema/Ndoni in Rivers State in the south-west.

3. Geology of The Study Area

The geological setting of the study area (Figure 1) reveals that it lies in the eastern section of the Niger Delta Basin. The geological formations in the study area is made-up of the Quaternary sedimentary deposits, and the Tertiary Coastal Plain Sands, which is generally called Benin Formation. The geology of the study area therefore shows the of movements of rivers in the Niger delta and their search for lines of flow to the sea with consequent deposition of transported sediments. The surface deposits in this area comprises silty and sandy- clays. These surface layers are frequently thick (greater than 10m) and would inevitably impact on the road and bridge design.

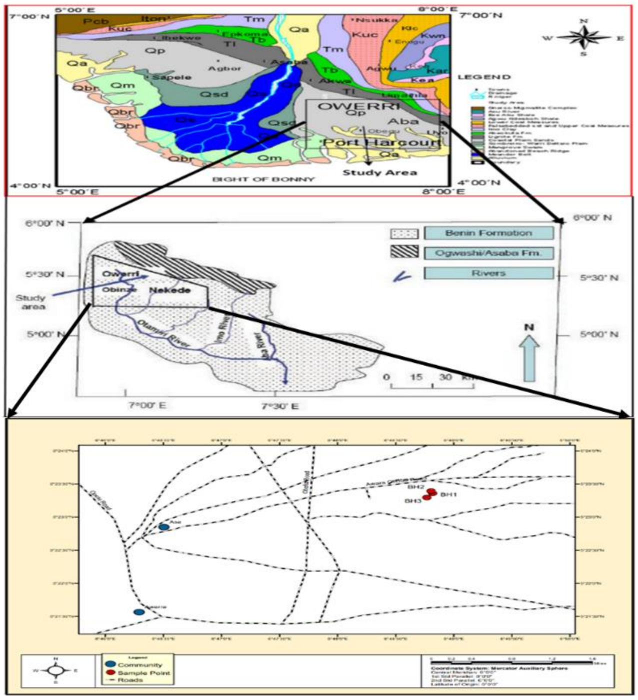

Figure 1: Geological Map of Imo State and Study Area Map

4. Materials and Methods

4.1 Materials

For the geophysical survey, the equipment used are Seismograph, Sledge Hammer**,** Plank**,** Geophones**,** Vehicle while the Percussion Drilling Rig, Split-Spoon Sampler, Standard Penetration Test (SPT) Hammer and drill Rods where used for the geotechnical investigation.

Table 1: Field Tests Utilized for Dynamic Examination of Soil

Low strain (<0.001%)	High strain (>0.01%)
Seismic Reflection Seismic Refraction Steady State Vibration Seismic Borehole Survey (Cross-hole, Down-hole and Up-hole)	Standard Penetration Test (SPT) Cone Penetration Test (CPT) Dilatometer Test (DMT)

Source: Kramer, 1996.

The EG&G 1225 signal enhancement seismograph was used for data acquisition of both P-wave and S-wave refraction logging (Kitsunezaki, 1980). The geophones used were 8 Hz vertical axis for P-wave lines and 4 Hz horizontal axis for S-wave lines. The Shear wave data acquisition system includes an accelerated impact source with a 20-kg weight, a 48-channel receiver cable with 1-m geophone interval and 4-Hz vertical geophones, and two 48-channel, 24-bit Seisimager recording units was used to acquire the shallow seismic data, adapting the configuration shown in Figure 2. The borehole required for the testing is prepared to a depth of 30m according to the ASTM procedures using PVC pipe for casing. The wooden plank is placed on firmed soil after little excavation to get a smooth surface and have good contact with the soil.

It was placed 4m away from the borehole with a 20tons Cone Penetrometer Test (CPT) machine placed on the wooden plank for stability, firmness, and good contact with the soil. The geophone relates to the computer by using the cable and placed at a depth of 1m of the borehole. The S-waves was generated by hitting separately at each end of the wooden plank with hammer and the P waves are generated by hitting wooden plank in downward vertical direction for each test location. The velocities of both P and S waves are received by the geophones and recorded by using the specified computer program. The testing is carried out up to the bottom of the borehole by releasing the geophone every 1m interval to a depth of 23m with the same procedure carried out at the other two boreholes. Rayleigh-wave inversion technique called Multi-Channel Analysis of Surface waves (MASW) to the surface waves isolated from the shot records using the methodology proposed (Park et al., 1996; Park et al., 1999).

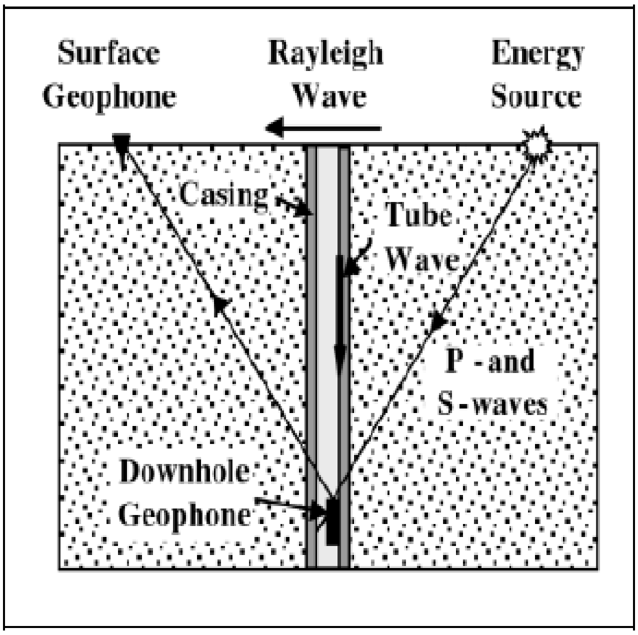

Figure 2: Configuration of the Borehole Seismic Acquisition System (Source: Kitsunezaki, 1980)

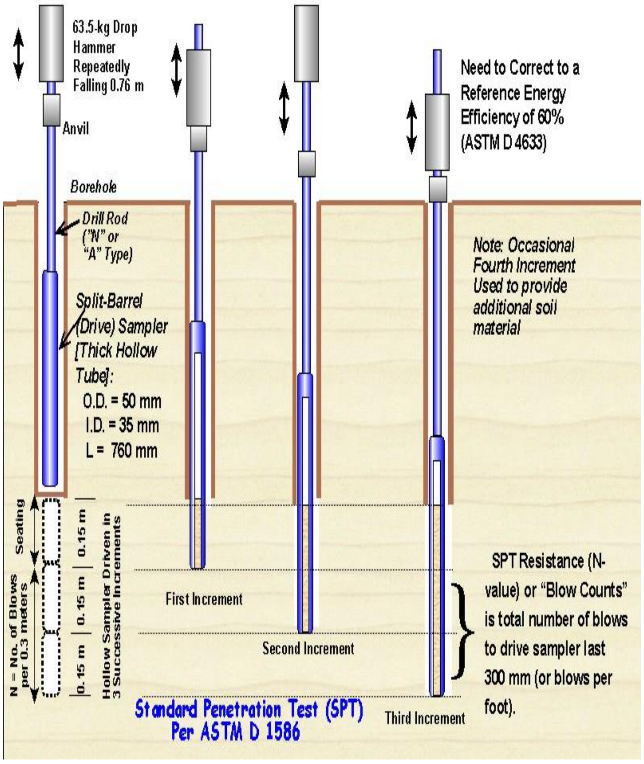

Figure 3: Driving Sequence of SPT (Source: FHWA NHI Course 132031 Subsurface Investigations)

The Standard Penetration Test is done to characterize the shear strength of subsurface materials by taking note of the number of hammer blows that are required to penetrate a given depth. The test was conducted in a borehole by means of a standard split spoon sampler. After the drilling is done to the desired depth, the drilling tool is removed and the sampler is placed inside the borehole. By means of a drop hammer of 63.5kg mass falling through a height of 750mm at the rate of 30 blows per minute, the sampler is driven into the soil. This is as per ASTM. The number of blows of hammer required to drive a depth of 150mm is counted. Further it is driven by 150 mm and the blows are counted (figure 2). Similarly, the sampler is once again further driven by 150mm and the number of blows recorded. The number of blows recorded for the first 150mm is not taken into consideration. The number of blows recorded for last two 150mm intervals are added to give the standard penetration number (N). If the number of blows for 150mm drive exceeds 50, it is taken as refusal and the test is discontinued.

The shear modulus was calculated from the equation

$G = 250 * (N + 15)$ (Murthy, 2002)

4.2 Methods

The geophone is connected with the computer by using the cable and placed at a depth of 1m of the borehole. The S-waves was generated by hitting separately at each end of the wooden plank with hammer and the P waves are generated by hitting wooden plank in downward vertical direction for each test location. The velocities of both P and S waves are received by the geophones and recorded by using the specified computer program. The testing is carried out up to the bottom of the borehole by releasing the geophone every 1m interval to a depth of 23m with the same procedure carried out at the other two boreholes. The results were processed using the generalized reciprocal method (GRM) with the seisimager program. In addition to the generalized reciprocal method processing, the S-wave results were also analysed using a monotonic velocity depth increase method. The method assumes a monotonic velocity increase with depth, which is a feature commonly seen in the shear wave records for unconsolidated sediment sequences. The data analysis involves dividing the subsurface into a number of horizontal layers each with discrete velocities and thicknesses. The lithologic information obtained from the three boreholes was used to constrain the inversion results of the P and S waves. The Young's Modulus (E), Shear Modulus (G), Bulk Modulus (k) and Poisson's ratio were derived using the P wave and S wave velocities.

5. Results and Discussion

5.1 Results

5.1.1 Results of Geophysical Investigation

The results of P and S-waves geophysical survey conducted at BH1, BH2 and BH3 to a total depth of 23 m are presented in Table 1. The result shows that P-waves generally increases with depth from 850 to 1890 m/s in BH1, 1020 to 1600 m/s in BH2 and 830 to 1880 m/s in BH3. Meanwhile S-wave ranges from 450 m/s to 700 m/s in BH1, 380 m/s to 710 m/s in BH2, and between 370 and 700 m/s in BH3. No particular trend was identifiable on the S-wave values (Table 1). The Shear modulus derived from P and S-waves downhole geophysical investigation is presented in Table 2 for BH1, BH2 and BH3 respectively.

5.1.2 Results of Geotechnical Investigation

The results of standard penetration test (SPT) geotechnical investigation for BH1, BH2 and BH3 are presented in Table 3. The results of measured SPT(N) values ranges from 6.0 to 33.0, 5 to 19 and 7 to 40 in BH1, BH2 and BH3 accordingly. SPT(N) values were acquired from the surface to a depth of 45 m in all three boreholes. The results of the derived Shear modulus based on the acquired SPT(N) values are presented in Table 4.

5.1.3 Results of Depth Trend Analysis

The graphical plot showing the behavior of static (geotechnical) and dynamic (geophysical) soil properties with depth obtained from BHI, BH2 and BH3 are presented in Figures 4. Figure 4 shows the static and dynamic behavior of shear modulus in soils. The difference and percentage difference between the static and dynamic curves for the shear modulus at various depths in BH1, BH2 and BH3 were calculated, documented and presented in Tables 5. The difference and percentage difference between the static and static from regression analysis for the shear modulus at various depths in BH1, BH2 and BH3 were calculated, documented and presented in Tables 6. A graphical plot showing comparison of soil static Shear modulus derived from SPT and soil static Shear modulus properties derived from regression analysis with depth obtained from BH1, BH2 and BH3 are presented in Figure 5.

5.1.4 Results of Correlation and Cross-Plot Analysis

Correlation of soil static Shear modulus and soil dynamic Shear modulus are presented as cross-plots in Figures 6. The linear equation model was used to fit the scattered points. The strength of the relationship is presented by the regression coefficient on each curve in Figures 6. Some of the plots showed strong relationships while others showed weak relationships. Also, a graphical plot showing comparison of shear modulus derived from SPT, Empirical model and DST with depth obtained from BH1, BH2 and BH3 are presented in figure 6

Table 1: Results of P and S-Waves Obtained from Downhole Geophysical Survey Conducted in the Study Area

Depth	BH1		BH2		BH3	
	P-wave velocity	**S-wave velocity**	**P-wave velocity**	**S-wave velocity**	**P-wave velocity**	**S-wave velocity**
(m)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
0.00	850.00	480	1020.00	600.00	830.00	490.00
1.00	850.00	450	1020.00	600.00	830.00	490.00
2.00	850.00	460	1020.00	600.00	830.00	370.00
3.00	850.00	481	1020.00	380.00	830.00	370.00
4.00	850.00	502	1020.00	480.00	830.00	480.00
5.00	850.00	521	1020.00	610.00	830.00	480.00
6.00	850.00	522	1020.00	630.00	830.00	630.00
7.00	1210.00	547	1020.00	660.00	1120.00	620.00
8.00	1210.00	547	1020.00	690.00	1120.00	610.00
9.00	1210.00	569	1020.00	710.00	1120.00	635.00
10.00	1890.00	580	1020.00	680.00	1880.00	700.00
11.00	1890.00	595	1020.00	650.00	1880.00	700.00
12.00	1890.00	600	1020.00	630.00	1880.00	600.00
13.00	1890.00	610	1020.00	610.00	1880.00	600.00
14.00	1890.00	610	1020.00	610.00	1880.00	600.00
15.00	1890.00	639	1190.00	610.00	1880.00	600.00
16.00	1890.00	660	1190.00	610.00	1880.00	600.00
17.00	1890.00	670	1190.00	610.00	1880.00	600.00
18.00	1890.00	680	1190.00	610.00	1880.00	580.00
19.00	1890.00	680	1190.00	610.00	1880.00	580.00
20.00	1890.00	690	1190.00	610.00	1880.00	580.00
21.00	1890.00	690	1600.00	610.00	1880.00	580.00
22.00	1890.00	700	1600.00	610.00	1880.00	580.00
23.00	1890.00	700	1600.00	610.00	1880.00	580.00

Table 2: Results of Derived Dynamic Soil Shear Modulus Obtained from Downhole Geophysical Survey Conducted in BH1, BH2 and BH3

	BH1	**BH2**	**BH3**
Depth (m)	**Shear Modulus** (kPa)	**Shear Modulus** (kPa)	**Shear Modulus** (kPa)
0.00	7300.00	7350.00	9150.00
1.00	7300.00	7350.00	9150.00
2.00	10150.00	10470.00	13280.00
3.00	10150.00	10470.00	13280.00
4.00	10150.00	10470.00	13280.00
5.00	10150.00	10470.00	13280.00
6.00	10150.00	10470.00	13280.00
7.00	10150.00	10470.00	13280.00
8.00	10150.00	10470.00	13280.00
9.00	10150.00	10470.00	13280.00
10.00	10150.00	10470.00	13280.00
11.00	10150.00	10470.00	13280.00
12.00	10150.00	10470.00	13280.00
13.00	15350.00	15190.00	18370.00
14.00	15190.00	15190.00	18370.00
15.00	15190.00	15190.00	18370.00
16.00	15190.00	15190.00	18370.00
17.00	15190.00	15190.00	18370.00
18.00	19170.00	18620.00	18620.00
19.00	19170.00	18620.00	21350.00
20.00	19170.00	18620.00	21350.00
21.00	19170.00	18620.00	21350.00
22.00	19170.00	18620.00	21350.00
23.00	19170.00	18620.00	18620.00

Table 3: Results of SPT(N) Obtained from Soil Geotechnical Investigation Conducted in the Study Area

BH1		**BH2**		**BH3**	
Depth (m)	SPT(N)	Depth (m)	SPT(N)	Depth (m)	SPT(N)
1.50	6.00	3.00	8.00	3.00	7.00
7.50	8.00	6.00	10.00	6.00	8.00
9.00	8.00	9.00	11.00	9.00	8.00
10.50	33.00	12.00	13.00	10.50	10.00
12.00	23.00	13.50	10.00	12.00	10.00
13.50	18.00	15.00	12.00	13.50	11.00
15.00	15.00	16.50	11.00	15.00	12.00
16.50	15.00	18.00	15.00	16.50	17.00
18.00	24.00	19.50	18.00	18.00	18.00
19.50	23.00	21.00	14.00	19.50	16.00
21.00	22.00	22.50	10.00	21.00	20.00
24.00	22.00	24.00	12.00	22.50	25.00
25.50	22.00	25.50	6.00	24.00	27.00
27.00	10.00	27.00	5.00	25.50	34.00
28.50	9.00	28.50	6.00	27.00	22.00
30.00	12.00	30.00	6.00	28.50	40.00
31.50	11.00	31.50	8.00	30.00	16.00
33.00	11.00	33.00	11.00	31.50	21.00
34.50	11.00	34.50	13.00	33.00	25.00
36.00	12.00	36.00	14.00	34.50	29.00
37.50	20.00	37.50	14.00	36.00	25.00
39.00	21.00	39.00	16.00	37.50	23.00
40.50	21.00	40.50	15.00	39.00	27.00
42.00	23.00	42.00	17.00	40.50	20.00
43.50	23.00	43.50	17.00	42.00	13.00
45.00	25.00	45.00	19.00	43.50	12.00

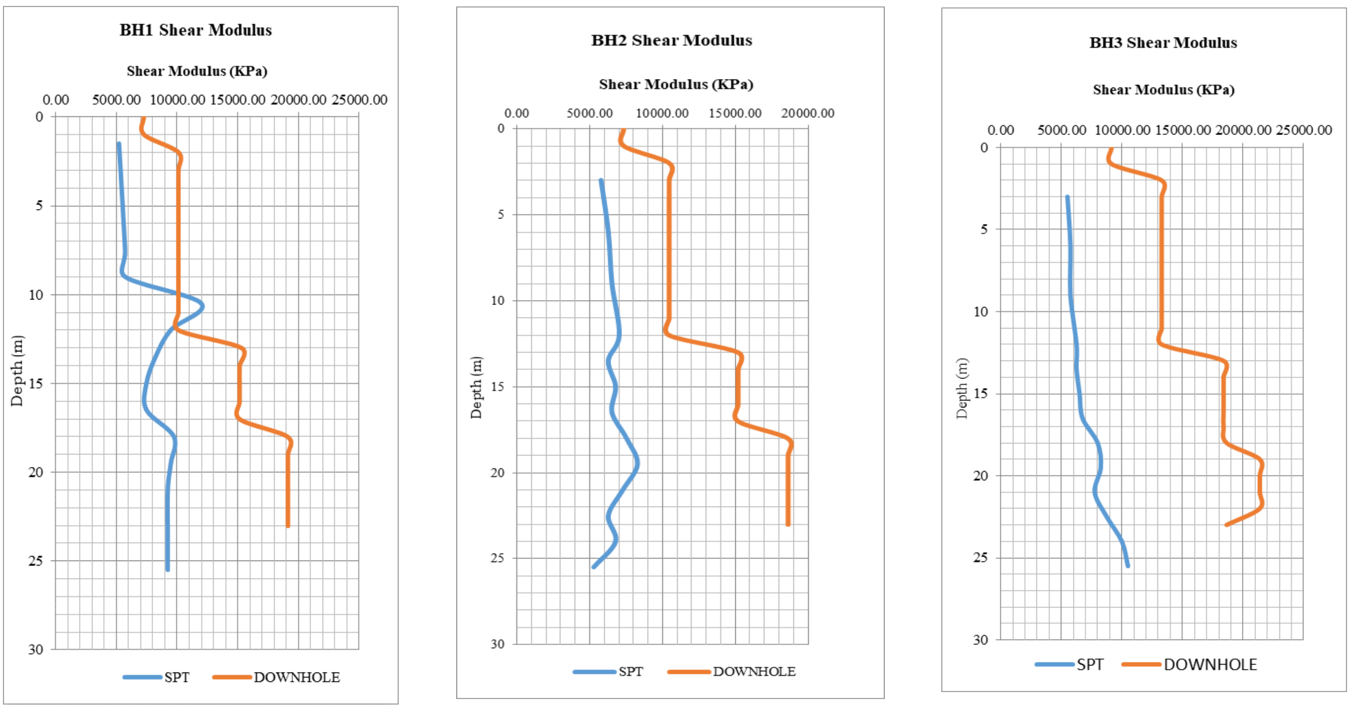

Figure 4: Results of Static and Dynamic Shear Modulus Plotted Against Depth in BH1, BH2 and BH3

Table 4: Results of Derived Static Soil Shear Modulus Obtained from SPT Geotechnical Survey Conducted in BH1, BH2 and BH3

BH1			BH2			BH3		
Depth	**SPT (N)**	**Shear Modulus**	**Depth**	**SPT (N)**	**Shear Modulus**	**Depth**	**SPT (N)**	**Shear Modulus**
(m)		(kPa)	(m)		(kPa)	(m)		(kPa)
1.50	6.00	5250.00	3.00	8.00	5750.00	3.00	7.00	5500.00
7.50	8.00	5750.00	6.00	10.00	6250.00	6.00	8.00	5750.00
9.00	8.00	5750.00	9.00	11.00	6500.00	9.00	8.00	5750.00
10.50	33.00	12000.00	12.00	13.00	7000.00	12.00	10.00	6250.00
12.00	23.00	9500.00	13.50	10.00	6250.00	13.50	10.00	6250.00
13.50	18.00	8250.00	15.00	12.00	6750.00	15.00	11.00	6500.00
15.00	15.00	7500.00	16.50	11.00	6500.00	16.50	12.00	6750.00
16.50	15.00	7500.00	18.00	15.00	7500.00	18.00	17.00	8000.00
18.00	24.00	9750.00	19.50	18.00	8250.00	19.50	18.00	8250.00
19.50	23.00	9500.00	21.00	14.00	7250.00	21.00	16.00	7750.00
21.00	22.00	9250.00	22.50	10.00	6250.00	22.50	20.00	8750.00
24.00	22.00	9250.00	24.00	12.00	6750.00	24.00	25.00	10000.00
25.50	22.00	9250.00	25.50	6.00	5250.00	25.50	27.00	10500.00
27.00	10.00	6250.00	27.00	5.00	5000.00	27.00	34.00	12250.00
28.50	9.00	6000.00	28.50	6.00	5250.00	28.50	22.00	9250.00
30.00	12.00	6750.00	30.00	6.00	5250.00	30.00	40.00	13750.00
31.50	11.00	6500.00	31.50	8.00	5750.00	31.50	16.00	7750.00
33.00	11.00	6500.00	33.00	11.00	6500.00	33.00	21.00	9000.00
34.50	11.00	6500.00	34.50	13.00	7000.00	34.50	25.00	10000.00
36.00	12.00	6750.00	36.00	14.00	7250.00	36.00	29.00	11000.00
37.50	20.00	8750.00	37.50	14.00	7250.00	37.50	25.00	10000.00
39.00	21.00	9000.00	39.00	16.00	7750.00	39.00	23.00	9500.00
40.50	21.00	9000.00	40.50	15.00	7500.00	40.50	27.00	10500.00
42.00	23.00	9500.00	42.00	17.00	8000.00	42.00	20.00	8750.00
43.50	23.00	9500.00	43.50	17.00	8000.00	43.50	13.00	7000.00
45.00	25.00	10000.00	45.00	19.00	8500.00	45.00	12.00	6750.00

Table 5: Comparison between Static and Dynamic Shear Modulus Derived for BH1, BH2 and BH3

Depth (m)	**BH1 Shear Modulus (KPa)**				**BH2 Shear Modulus (KPa)**				**BH3 Shear Modulus (KPa)**			
	Static	Dynamic	Difference	% Diff	Static	Dynamic	Difference	% Diff	Static	Dynamic	Difference	% Diff
2.00	5250.00	10250.00	5000.00	95.24	6000.00	10000.00	4000.00	66.67	5100.00	13000.00	7900.00	154.90
4.00	5500.00	10150.00	4650.00	84.55	6000.00	10500.00	4500.00	75.00	5500.00	13200.00	7700.00	140.00
6.00	5750.00	10150.00	4400.00	76.52	6200.00	10500.00	4300.00	69.35	5800.00	13200.00	7400.00	127.59
8.00	5750.00	10150.00	4400.00	76.52	6200.00	10500.00	4300.00	69.35	5800.00	13200.00	7400.00	127.59
10.00	1000.00	10150.00	9150.00	915.00	6800.00	10500.00	3700.00	54.41	5900.00	13200.00	7300.00	123.73
12.00	9500.00	10000.00	500.00	5.26	6900.00	10500.00	3600.00	52.17	6100.00	13000.00	6900.00	113.11
14.00	8000.00	15190.00	7190.00	89.88	6200.00	15200.00	9000.00	145.16	6200.00	18400.00	12200.00	196.77
16.00	8000.00	15190.00	7190.00	89.88	6200.00	15200.00	9000.00	145.16	6700.00	18400.00	11700.00	174.63
18.00	9750.00	19170.00	9420.00	96.62	7500.00	18000.00	10500.00	140.00	8000.00	18400.00	10400.00	130.00
20.00	9250.00	19170.00	9920.00	107.24	8000.00	18500.00	10500.00	131.25	8100.00	21300.00	13200.00	162.96
22.00	9250.00	19170.00	9920.00	107.24	6100.00	18500.00	12400.00	203.28	8800.00	21300.00	12500.00	142.05
24.00	9250.00	19170.00	9920.00	107.24	6800.00	18500.00	11700.00	172.06	10000.00	21000.00	11000.00	110.00
Minimum			500.00	5.26			3600.00	52.17			6900.00	110.00
Maximum			9920.00	915.00			12400.00	203.28			13200.00	196.77
Average			6805.00	154.27			7291.67	110.32			9633.33	141.94
St. Dev			3029.65	241.13			3503.36	51.54			2409.95	25.98

Table 6: Results of Shear Modulus Derived from SPT Compared with Shear Modulus Derived from Regression Model

Depth (m)	BH1 Shear Modulus (KPa)				BH2 Shear Modulus (KPa)				BH3 Shear Modulus (KPa)				
	Static	Static (from Regression model)	Diff	% Diff	Static	Static (from Regression model)	Diff	% Diff	Static	Dynamic	Static (from Regression model)	Diff	% Diff
2.00	5250.00	3679.88	1570.12	29.91	6000.00	3503.91	2496.09	41.60	5100.00	13000.00	5615.54	-515.54	-10.11
4.00	5500.00	3609.49	1890.51	34.37	6000.00	3855.85	2144.15	35.74	5500.00	13200.00	5756.32	-256.32	-4.66
6.00	5750.00	3609.49	2140.51	37.23	6200.00	3855.85	2344.15	37.81	5800.00	13200.00	5756.32	43.68	0.75
8.00	5750.00	3609.49	2140.51	37.23	6200.00	3855.85	2344.15	37.81	5800.00	13200.00	5756.32	43.68	0.75
10.00	1000.00	3609.49	-2609.49	-260.95	6800.00	3855.85	2944.15	43.30	5900.00	13200.00	5756.32	143.68	2.44
12.00	9500.00	3503.91	5996.09	63.12	6900.00	3855.85	3044.15	44.12	6100.00	13000.00	5615.54	484.46	7.94
14.00	8000.00	7157.04	842.96	10.54	6200.00	7164.07	-964.07	-15.55	6200.00	18400.00	9416.48	-3216.48	-51.88
16.00	8000.00	7157.04	842.96	10.54	6200.00	7164.07	-964.07	-15.55	6700.00	18400.00	9416.48	-2716.48	-40.54
18.00	9750.00	9958.47	-208.47	-2.14	7500.00	9134.93	-1634.93	-21.80	8000.00	18400.00	9416.48	-1416.48	-17.71
20.00	9250.00	9958.47	-708.47	-7.66	8000.00	9486.87	-1486.87	-18.59	8100.00	21300.00	11457.73	-3357.73	-41.45
22.00	9250.00	9958.47	-708.47	-7.66	6100.00	9486.87	-3386.87	-55.52	8800.00	21300.00	11457.73	-2657.73	-30.20
24.00	9250.00	9958.47	-708.47	-7.66	6800.00	9486.87	-2686.87	-39.51	10000.00	21000.00	11246.57	-1246.57	-12.47
Minimum			-208.41	-2.14			-964.07	-15.55				43.68	0.75
Maximum			5996.09	-260.95			3044.15	-55.52				-3357.73	-41.45
Average			873.36	-5.26			349.43	6.15				-1222.32	-16.43
St. Dev			2169.68	83.66			2406.82	37.15				1423.35	19.98

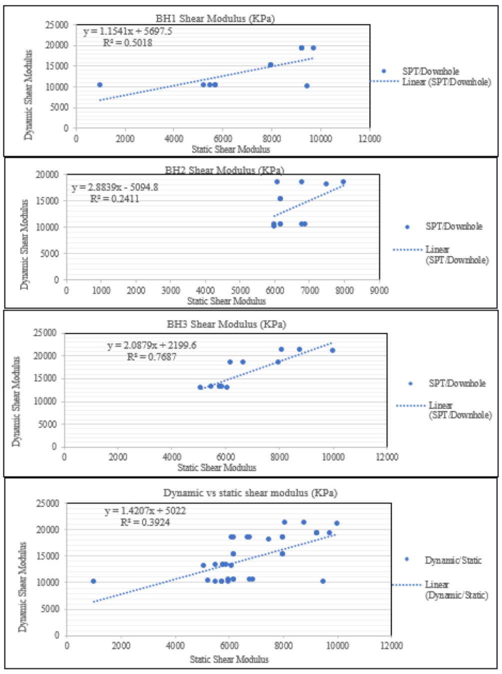

Figure 5: Cross Plot of Static Versus Dynamic Static Shear Modulus (a) BH1 (b) BH2 (c) BH3 (d) all three Boreholes Combine

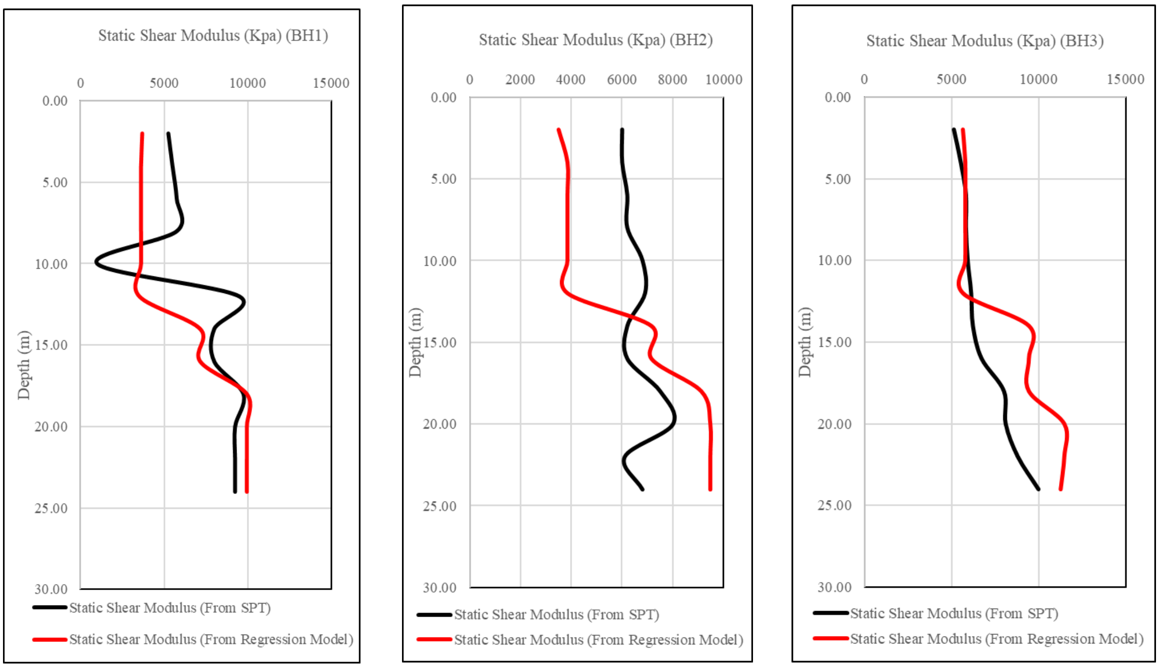

Figure 6: A Comparative Plot for Shear Modulus Derived from SPT against Shear Modulus Derived from Regression Model

Table 7: Results of Static Shear Modulus Derived from Empirical Model Compared with Staic Shear Modulus and Dynamic Shear Modulus

Depth (m)	**BH1 Shear Modulus (KPa)**			**BH2 Shear Modulus (KPa)**			**BH3 Shear Modulus (KPa)**		
	Static	Static Results from Empirical Model	Dynamic	Static	Static Results from Empirical Model	Dynamic	Static	Static Results from Empirical Model	Dynamic
2	5250	12480.675	10250	6000	13546.2	10000	5100	12267.57	13000
4	5500	12835.85	10150	6000	13546.2	10500	5500	12835.85	13200
6	5750	13191.025	10150	6200	13830.34	10500	5800	13262.06	13200
8	5750	13191.025	10150	6200	13830.34	10500	5800	13262.06	13200
10	1000	6442.7	10150	6800	14682.76	10500	5900	13404.13	13200
12	9500	18518.65	10000	6900	14824.83	10500	6100	13688.27	13000
14	8000	16387.6	15190	6200	13830.34	15200	6200	13830.34	18400
16	8000	16387.6	15190	6200	13830.34	15200	6700	14540.69	18400
18	9750	18873.825	19170	7500	15677.25	18000	8000	16387.6	18400
20	9250	18163.475	19170	8000	16387.6	18500	8100	16529.67	21300
22	9250	18163.475	19170	6100	13688.27	18500	8800	17524.16	21300
24	9250	18163.475	19170	6800	14682.76	18500	10000	19229	21000

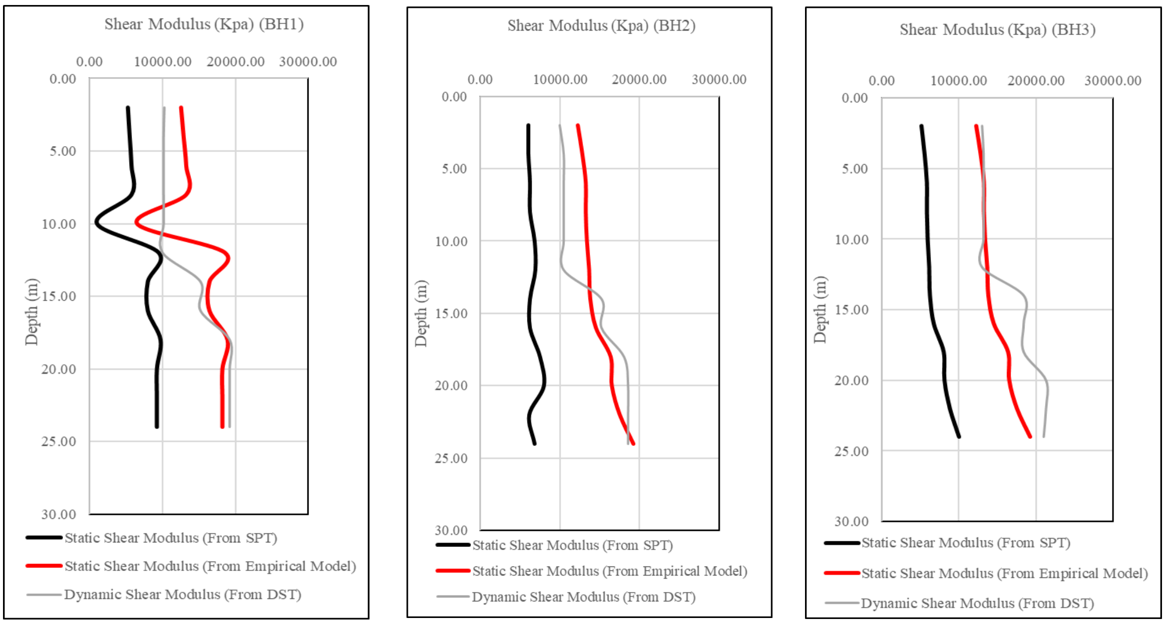

Figure 7: A Comparative Plot of Results of Shear Modulus derived from Empirical Model, SPT and DST

5.2 DISCUSSION

The results of soil dynamic shear modulus recorded from down-hole geophysical investigations conducted in BH1 ranges from 7300 KPa at the surface (0.0 m depth) to 19170 KPa at 23 m depth, 7350 at the surface (0.0 m depth) to 18620 KPa at 23 m depth in BH2, and 9150 at the surface (0.0 m depth) to 18620 KPa at 23 m depth in BH3. Meanwhile, soil static shear modulus recorded from geotechnical investigations conducted in BH1, BH2 and BH3 ranges from 5250 at 1.50 m depth to 10000 KPa at 45.0 m depth, 5000 at 27.0 m depth to 8500 KPa at 45.0 m depth and 5500 at 3.0 m depth to 13750 KPa at 30.0 m depth respectively. The results of dynamic shear modulus show a relative increasing trend from the surface to the total probed depth of 23.0 m in BH1, BH2 and BH3 respectively. Although the results of static shear modulus have some significant highs and low values at shallow depths in-between, it revealed a somewhat increasing trend generally with depth.

Generally, the results of soil dynamic shear modulus are significantly higher than the static shear modulus values recorded in this study. At shallow depths the results of static and dynamic shear modulus are fairly comparable, but the difference significantly increases with increasing depth. At shallow depths from 0.0 to 12.0 m depth the difference between the static and dynamic shear modulus ranged from 500 to 9150 KPa and from 7190 to 9920 KPa from 14 to 24.0 m depth in BH1. This accounts for about 5.26 to 91.5% difference at shallow depths and 89.88 to 107.24 % at deeper depths. In BH2, the percentage difference between static and dynamic shear modulus at shallow depths (depths ≤12.0 m) ranges from 54.41% to 75% and from 131.25 to 203.28% at deeper depths (> 12 to 24 m depth). In BH3, the percentage difference ranges from 110.00 to 196.77% from the from 2 to 24 m depth.

On average, the difference and percent differences between the static and dynamic shear modulus in BH1, BH2 and BH3 are 6805 ± 3029.65 KPa (154.27 ± 241.13%), 7291.67 ± 3503.36 KPa (110.32 ± 51.54%) and 9633.33 ± 2409.95 (141.94 ± 25.98%) respectively. In all three boreholes, the average difference in static and dynamic shear modulus > 100 %, with the highest difference in BH1 and lowest in BH2. The high standard deviation value recorded in BH1 is as a result of the high difference between the static and dynamic shear modulus recorded at 10.0 m depth, and very low difference recorded at 12.0 m depth. Cross plot analysis between static shear modulus and dynamic shear modulus revealed a positive correlation trend. This shows that an increase in the dynamic shear modulus will correspondingly lead to an increase in the static shear modulus and vice versa. The regression coefficient (R2) is 0.50 in BH1, 0.2411 in BH2 and 0.7687 in BH3.

The BH2 showed the strongest positive correlation (r = 0.88), while BH1 showed the weakest positive correlation (r = 0.50). Based on Pearson's correlation strength, values ≥ 0.50 are regarded as strong correlations (be it positive or negative). The closer the value to 1, the stronger the correlation existing between the given pairs. Generally, the correlation between the static and dynamic shear modulus for BH1, BH2 and BH3 all combined gave rise to Equation 4.1 below, with a regression coefficient value (R2) of 0.1611 and a strong positive correlation strength of 0.63. Based on the given equation, dynamic shear modulus can be derived from static shear modulus and vice vera.

$$Dynamic\ Shear\ Modulus = (1.4207 \times static\ Shear\ modulus) + 5022$$

Eq. 1

The regression model generated was used to convert the acquired dynamic shear modulus to static shear modulus. The results gotten were quite impressive results. Apart from an outlier in BH1 at a depth of 10.0 m, the percentage difference between SPT derived static shear modulus and static shear modulus derived from the regression model are significantly low, ranging from -2.14 to 63.12%. Similar trends were recognized in BH2 and BH3 having a percentage difference ranging from 15.55 to 55.52% and 0.75 to 51.88%. The plot of static shear modulus derived from SPT against static shear modulus derived from regression model all revealed fairly close match between them when plotted with depth. BH1 revealed a better match between static shear modulus and static shear modulus derived from the regression model, closely followed by BH3 and B2.

6. Conclusion

Geophysical and geotechnical methods are widely used for investigating the geomechanical properties of subsurface materials. The advantage of the geotechnical investigation method over the geophysical is mainly because actual soil samples are obtained for analysis in the lab as opposed to geophysical methods which usually do not involve sample collection. Analyzing soil samples in the laboratory is cost effective, depending on the number of samples and geotechnical properties to be evaluated. Hence, the major limitation in geotechnical investigations lies in the method of sampling and number of samples, bearing in mind that soils are anisotropic, and much information can be missed within intervals not analyzed. Hence, geophysical methods offer a complimentary tool for geotechnical subsurface investigations. Downhole seismic test (DST) geophysical investigations and standard penetration test (SPT) geotechnical investigations were conducted on three boreholes within the study area (BH1, BH2, BH3). Compressional and shear velocities were obtained from geophysical investigation which were used to determine shear modulus.

SPT was used to also determine the Shear Modulus and the results were compared with the geophysical method. The results of this study have shown that there is a wide variation between geomechanical properties derived from geotechnical investigations (static properties) and downhole geophysical investigations (dynamic properties). Based on depth trend analysis, the dynamic and static soil elastic properties all increases with depth. Generally, the dynamic soil properties were significantly higher than the static elastic properties. At shallow depths (<12.0 m), the difference between static and dynamic shear modulus was relatively small but increased with increasing depth. Correlation between the derived static and dynamic properties revealed positive correlation trends with the strength of the correlation for shear modulus being (r=0.63). The regression models generated from this study were used to derive static elastic properties and compared with the static properties obtained from geotechnical investigation. The results showed fairly good match between static (geotechnical) shear modulus and static (from regression model) shear modulus.

7. Recommendation

The results obtained from this study has shown that geomechanical properties of soil obtained from geophysical investigations and geotechnical investigations are of different results at same depth and location, therefore the study suggests the following:

i. That geophysical investigation should be adopted as standard investigation for acquiring geomechanical properties of soil because it is prone to less error and minimum destructive effect when compared with geotechnical investigation

ii. That geotechnical investigations should be used as a complementary tool to geophysical investigation when acquiring geomechanical soil properties.

iii. Further research to be carried out in different location to validate the wide applicability of the empirical model developed in this research.

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