Nigerian Journal of Environmental Sciences and Technology (NIJEST)
www.nijest.com
ISSN (Print): 2734-259X | ISSN (electronic): 2734-2603
Vol 5, No. 2 October 2021, pp 404 - 412

Effect of Confining Pressures on Dynamic Response Characteristics of Silty Soils in the Niger Delta

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https://doi.org/10.36263/nijest.2021.02.0258

ABSTRACT

The probability of earthquake occurrence in the Niger Delta region of Nigeria was studied in this research. The resonant column/bender element tests were used for the study. Series of analysis were carried out on compacted silt in subsoil strata obtained from various locations in Rivers, Bayelsa, Delta and Akwa Ibom States. The effects of confinement on frequency, shear modulus, shear velocity and damping ratio were studied. The tests results revealed that confinement has effects on the investigated parameters. Thus, frequency response increases with increase in confinement pressure. Also, the resonance column test at various confinements revealed changes in shear modulus, accelerometer output and damping ratio. Accordingly, there was high disparity in the tested parameters as confinement pressure was increased. Similarly, the bender element tests also showed that pressure has effect on shear wave-velocity, shear modulus and damping ratio confinement. The shear modulus and shear wave-velocity generally increased as confinement pressure was increased, while damping ratio decreases as confinement pressure was increased. The variations in Resonance Column/Bender Element test parameters showed that the silty soil in the Niger Delta region, an oil and gas rich area, is likely to experience earthquake in the future. Therefore, geological data should be collated for monitoring, especially as several geological activities take place in the region.

Keywords: Earthquake, Confinement Pressure, Seismic Properties

1.0. Introduction

The management and analysis of earthquake activities have been proposed as a good technique for understanding the susceptibility of earthquake event (Hudyma and Potvin, 2010). Thus, seismic responses contribute to the timing, location and magnitude of seismic hazard. So, establishing an understanding of spatial and temporal characteristics of seismicity is fundamental for the effective management of seismic risk (Hudyma and Potvin, 2010; Cho *et al.*, 2010). Spatial and temporal characteristics of seismic hazard impact on the effectiveness of strategic and tactical methods are used to manage risk associated with different sources of seismicity (Hudyma and Potvin, 2010; Potvin, 2009).

A theoretical foundation for time-dependent seismicity within mining environment is not definitive, and is tentatively addressed in some studies. Malek and Leslie (2006) suggested that the non-linear behaviour of rock mass failure is indicative of critical phenomena and is evidence of unstable conditions. This concept is discussed in detail by Mendecki and Lynch (2004), giving a theoretical basis for system excitability as a model of self-organized criticality. It is postulated that the criticality (or state of the rock mass) can be monitored by pulse tests, otherwise described as taps (blasting) or self-taps (seismic events). Furthermore, it is suggested that seismic responses to these tests contain information concerning rock mass stability. Other studies have shown that the spatial and temporal characteristics of mining-induced seismicity following large events are comparable to characteristics of earthquake main and aftershock responses (Hills and Penney, 2008; Kgarume *et al*., 2010; Vallejos and McKinnon, 2010).

One of the most important geotechnical parameters, which can be used to estimate earthquake factors, is the shear wave velocity. Shima (1978) found that the analytically calculated amplification factor is linearly related to the ratio of shear wave velocity of the surface layer to that of bedrock. When the bedrock shear wave velocity is found to be relatively constant over a wide area, the relative amplification in each locality can be obtained from the shear wave velocity of the surface layer. Various researchers (Borchedt *et al*., 1994; Chan and Jenu, 2014; Szilvágyi *et al*., 2016; Gluchowski *et al*., 2020) have shown the significance of shear wave velocity in the study of soil geotechnical analysis.

In the study by Balendra (2011) on the behaviour of long-distance travelling earthquake wave property, he observed that when high-frequency earthquake wave decay rapidly, the low-frequency waves have long-period waves, in which energy dissipation is very limited. This becomes amplified due to upward propagation and soft soil deposit whose frequency is very near to seismic wave frequency. Dynamic soil responses, such as frequency, shear wave velocity, shear modulus and damping ratio, have shown to be affected by soil confining pressure. Amini (1993), using transfer function estimators, showed that increase in confining pressure of Ottawa-sand also increased damping, but does not affect the shear modulus as there was no change in the frequency response. Hence, concluded that the shear modulus does not depend on confining pressure rather, on the frequency. However, the work by Asef and Najibi (2013) showed that both shear wave velocity and shear modulus increased with increase in confining pressure. These changes could result to earthquake occurrence at certain conferment, and studies have revealed that earthquake occurrence can be estimated by the values of shear wave velocity (Anbazhagan *et al*., 2009; UmaMaheshwari *et al.*, 2010).

In this study, the resonant column and bender elements tests were used to study silt soil samples in selected States of the Niger Delta region of Nigeria. The soil dynamic properties studied include frequency response, shear modulus, shear, damping ratio and accelerometer output.

2.0. Methodology

2.1. Description of study area

The Niger Delta is found in the Southern Nigeria, West African, and it is situated in the Gulf of Guinea between longitude 5.35°E to 8.45°E and latitude 4.5°N to 5.65°N and covers a distance of about 36,260 km^2. The region has the largest wetland in Africa and third in the world consisting of flat low lying swampy terrain that is criss-crossed by meandering and anatomising streams, rivers and creeks (Emoyan *et al*., 2008). The Niger Delta region constitutes 9 Sates out of the 36 States in Nigeria, which include Abia Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo and Rivers States, with its headquarters in Port Harcourt, the Capital of Rivers State. The region contributes immensely to the economic growth and development of the Nigeria, particularly for crude oil and gas production. The area lies lithostratigraphically within the traditional Benin, Agbada and Akata Formations. Sediments in the Benin Formation represent the subaerially exposed part of the delta, while Agbada Formation is a regressive offlap succession that is formed under shallow-marine conditions in active depobelts of the delta (Reijers, 2011). The stratigraphy of the Niger Delta is classy by clastic wedge syndepositional collapse that occurred because of the results of marine shales being mobilized (Doust and Omatsola, 1990). Together with the expansion faults, change anticlines, sedimentary rock ridges, and sedimentary rock diapers exist within the basin and may be seen within the schematic structural profile of the Niger Delta (Tuttle *et al*., 1999). The ground of Niger Delta of African nation is formed of 3 geomorphological zones as well as the coastal or Lower Delta zone, Transition or Angiospermous tree zone and the fresh zone consists of dry flatlands and plains (Akpokodje, 1989; Teme, 2002). The Niger Delta region is characterized by tropical rain forest, with average annual rainfall from 2000mm within the fresh zone to over 4000mm at the coast that accounts for nearly 85% of the annual rainfall; the coastal and Angiospermous tree zones contain nearly 70% of marshes and swamps that occupy, which are sometimes submerged throughout the wet season (April to October). Figure 1 shows the Map of the Niger Delta region.

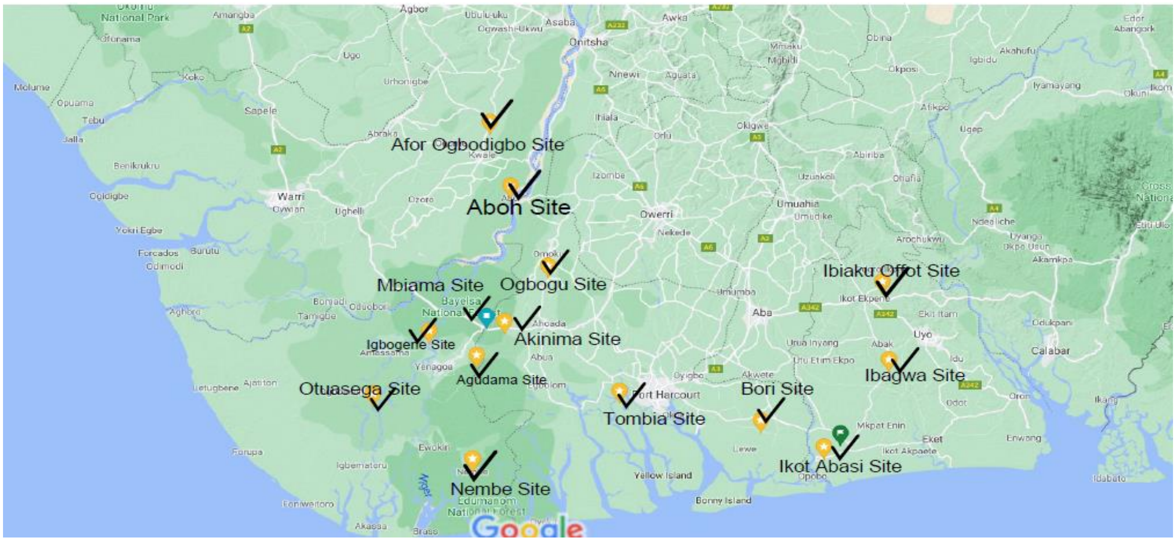

Figure 1: Study areas of Niger Delta

2.2. Soil sample collection

The soil samples for this study were collected from 4 states out of the 6 South-South states of the Niger Delta Region of Nigeria namely Rivers, delta, Akwa-Ibom and Bayelsa States. Five sites were located Rivers State (Akinima, Mbiama, Obite, Tombia and Bori Towns), Four sites in Bayelsa State (Igbogene, Agudama, Otuasega and Nembe Towns), Three sites in Akwa Ibom State (Ikot Abasi, Ikot, Ibagwa and Ibiaku Offot Towns) and Two sites in Delta State (Aboh and Afor Ogbodigbo Towns). The sites are tabulated in Table 1. The soil samples were collected from the subsurface at the sites by drilling and boring using the standard penetration test (SPT). Some analyses were performed right in the field (in-situ tests) and in the laboratory. The tests were conducted for estimation of dynamic soil properties. The soil samples were dried, crushed and sieved on sieve No 4(4.75mm).

Table 1: Test samples and their locations

State	Location	Sample
Rivers	Akinima	SILT-A12
	Mbiama	SILT-B18
	Obite	SILT-C2
	Tombia	SILT-D12
	Bori	SILT-E5
Bayelsa	Igbogene	SILT-F11
	Agudama	SILT-G6
	Otuasega	SILT-H17
	Nembe	SILT-I6
Akwa-Ibom	Ikot-Abasi	SILT-J14
	Ibagwa	SILT-K13
	Ibiaku Offot	SILT-L5
Delta	Aboh	SILT-M6
	Afor Ogbodigbo	SILT-N16

Soil samples were remoulded to field density and natural moisture content stage. Samples were prepared with specimen standard measurements of 20 mm height and 70 mm diameter, placed in membrane of rubber, mounted on bottom plate of cyclic direct simple shear machine of confined rings of control lateral deformation at consolidation stages.

2.3. Resonant column test

Resonant Column Test is a laboratory test commonly applied in geotechnical engineering practice to determine the shear elastic modulus and damping properties of soils. The damping can be determined either from the frequency response function by evaluating the bandwidth of the resonance peak, or from the decay of the free vibration. The bottom end is often fixed and the top end is capable of exciting the specimen by torsional or longitudinal vibration and also of measuring the soil response. The test commences by vibrating the cylindrical soil specimen at the top end while the sample is restrained at the bottom. The frequency of vibration is increased gradually until reaching the fundamental frequency in the first-mode of vibration of the sample. At this frequency, measurements are made of the resonance frequency and amplitude of vibration. With the known geometry and end constraints of the sample, the measured resonance frequency is then used to calculate the wave propagation velocity using the wave propagation and directly from the derived velocity and the density of the sample. The RC equipment used is of a bottom-fixed and top-free configuration. It is equipped with associate magnetic driving head with accuracy wound coils and internally mounted, counter balanced accelerometers. It accommodates soil specimen up to 50mm in diameter and 100mm tall, with cell pressure capability of 1MPa. The axial deformation of the specimen is measured by an interior high-resolution LVDT.

2.4. Bender element test

The bender Element (BE) technique is globally used methodology to acquire, generate and receive P- and S-waves in soil specimens that propagate from one stop to the opposite. The Bender Element (BE) measures the peak (maximum) shear modulus (G_{max}) of a soil sample. This data is used to verify the stiffness of a soil. It is a key parameter in tiny/small strain dynamic analysis, like those to predict soil behaviour or soil structure interaction within and during earthquakes, explosion or machine and traffic induced vibrations. The bender element system contains piezoceramic transmitter. The receiver receives the electrical signal. The time period of the shear wave from the transmitter to the receiver is set exploitation proprietary software package that allows the operator to speedily calculate the shear wave speed. The bender element is used with tri-axial started for advanced applications. The bender element area unit typically fitted in an exceedingly normal resonant column (RC) equipment.

3.0. Results and Discussion

The effects of confinement pressure on frequency, shear modulus G_{max}, shear velocity and damping ratio D_{min} of silt samples was studied in selected States of the Niger Delta region of Nigeria using the resonant column and bender elements (RC/BE) tests. The test samples in Table 1 were simultaneously compacted for the analysis.

3.1. Frequency variation with confinement in the soils

Figure 2 shows the profiles of frequency versus confinement pressure induced in silt layer across the respective sites in Rivers, Bayelsa, Akwa-Ibom and Delta States. The confined pressures ranged from 11 to 225 kPa. As pressure was increased, frequency response equally increased. Thus, at confinement of 11 kPa, frequency response ranged from sand 39.93 – 48.83 Hz, while at the highest confinement of 225 kPa, it ranged from sand 59.10 – 66.14 Hz.

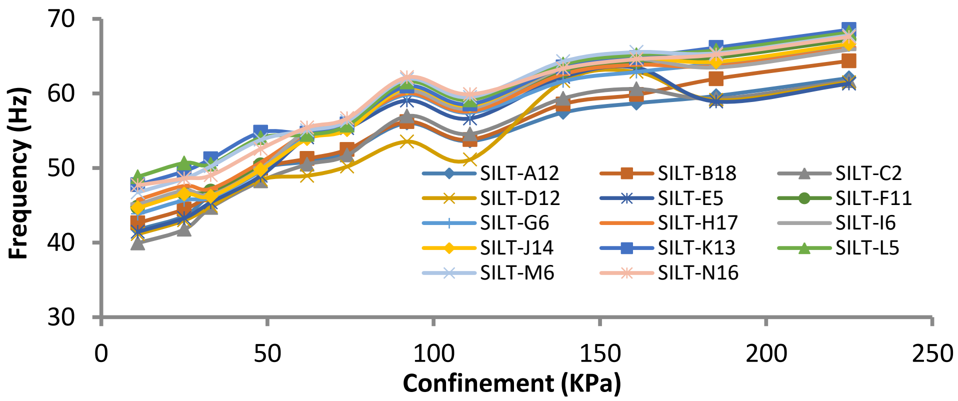

Figure 2: Variation of frequency with confinement

3.2. Variation of parameters for resonance column analysis

The shear modulus (G_{max}), accelerometer output (V_{rms}) and damping ratio (D_{min}) results from Resonance Column (RC) test are shown below. Figures 3 to 5 show the V_{rms}, G_{max} and D_{min} versus confinement pressure. From Figure 3, V_{rms} initially increases when the confinement increased from 11 kPa to 61 kPa across all the sites, which then decreased slightly to 225 kPa in all the sites. On the other hand, the G_{max} initially increased at pressure increase of 11 to 25 kPa, and the decreases as confinement pressure increased from 11 to 33 kPa across all the sites. However, from pressure increase of 33 kPa to 225 kPa, G_{max} increases slowly across all the sites. Also, the variation in minimum damping ratio (D_{min}) across the sites as confinement was increased can be described as a wavy like function, which increases at some pressures, and at other pressures, it then decreases.

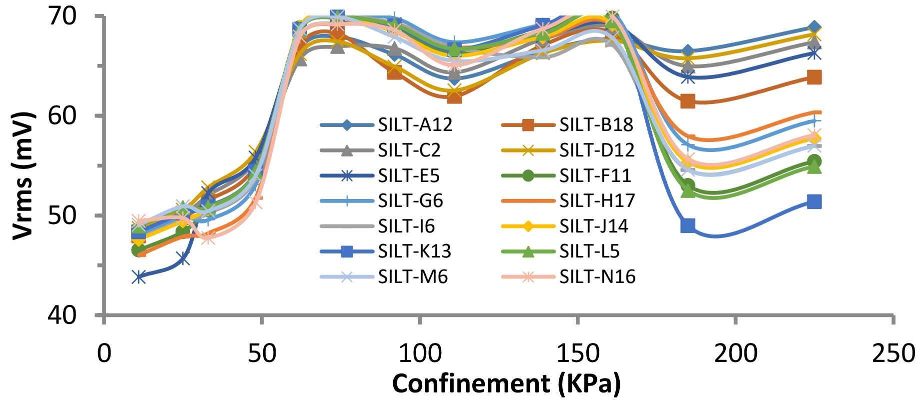

Figure 3: Variation of V_{rms} with confinement

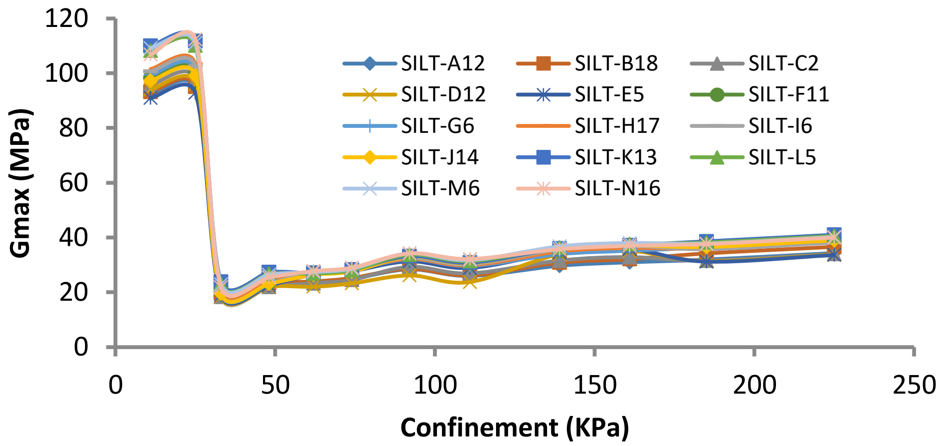

Figure 4: Variation of G_{max} with confinement

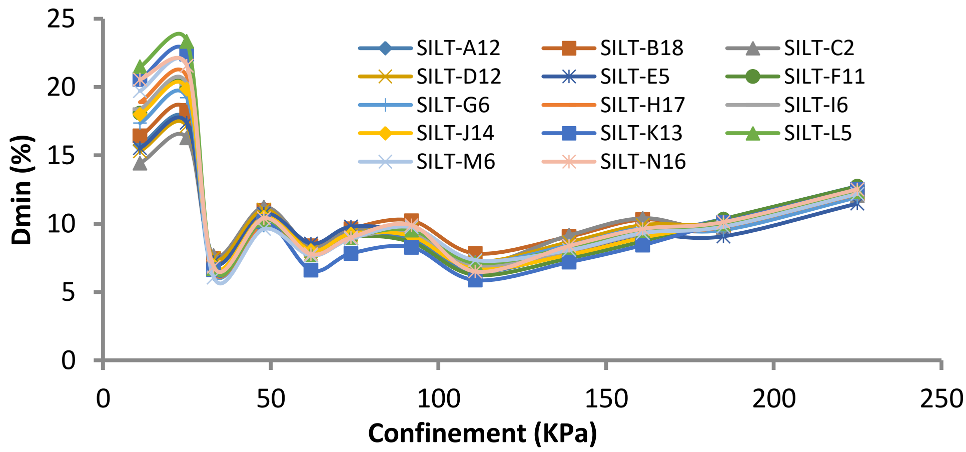

Figure 5: Variation of D_{min} with confinement

However, from confinement of 33 kPa to 225 kPa, D_{min} generally increase with confinement. This behaviour was said to be due to moisture content variation in soil strata (Thevanayagam, 1998; Anbazhagan *et al*., 2009; Tsai *et al*., 2009; Ige *et al*., 2016).

3.3. Variation of parameters for bender element analysis

Figures 6, 7 and 8 show the bender element (BE) tests for the shear wave-velocity (V_s), shear modulus (G_{max}) and damping ratio (D_{min}) versus confinement, respectively. Thus, while V_s and G_{max} generally increased as confinement pressure increases, the damping ratio (D_{min}) decreases with increase in confinement pressure. Though, there was initial increase in D_{min} as pressure was increased from 11 to 48 kPa before decreasing again as confinement increased to 139 kPa.

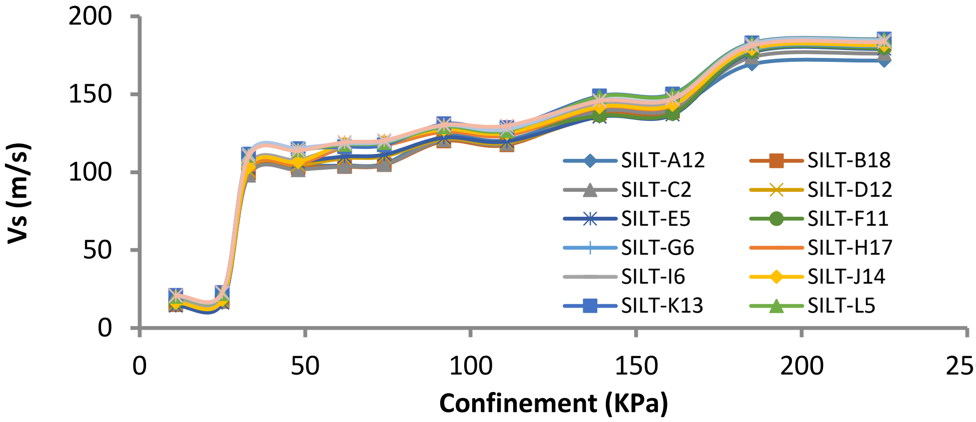

Figure 6: Variation of V_s with confinement

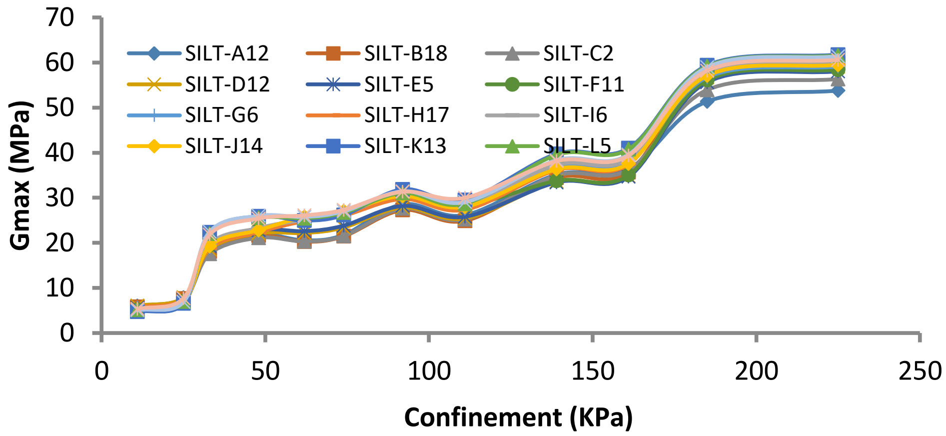

Figure 7: Variation of G_{max} with confinement

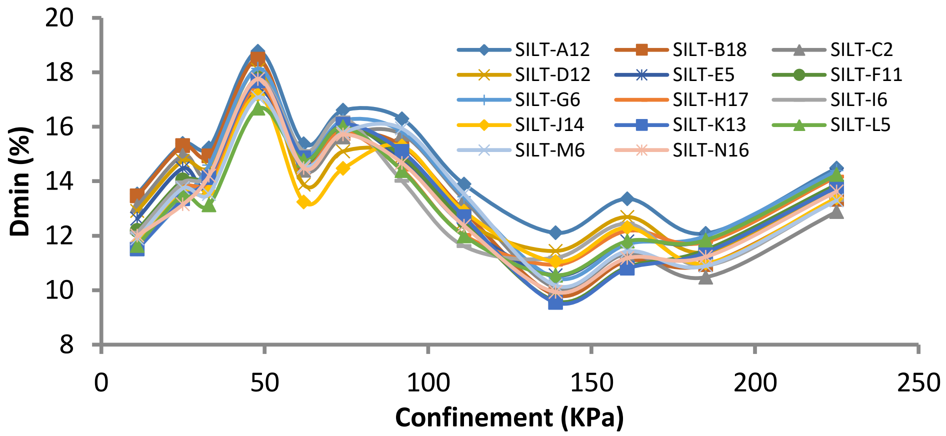

Figure 8: Variation of D_{min} with confinement

The minimum value of V_{rms} recorded across the sites for the RC test ranged between 43.85 mV and 49.45 mV, while the maximum value was between 68.16 mV and 70.39 mV. Also, the shear wave-velocity (V_s) measured from the BE test across the sites has minimum value between 14.32 m/s and 20.94 m/s, while the maximum value was between 171.69 m/s and 185.37 m/s at confinement range of 11 to 225 kPa. It can be deduced that accelerometer decreases with confined pressure, while shear wave-velocity (V_s) generally increase with confinement pressure. This observation agreed with the work of Asef and Najibi (2013) which also reported increase in shear wave velocity as confine pressure was increased. According to this study, initial increase in shear wave velocity represents a poroelastic regime, which becomes linear above the critical pressure.

Similarly, the minimum value of G_{max} recorded across the sites ranged between 18.36 Mpa and 23.79 Mpa with RC test and 4.70 Mpa and 6.03 Mpa with BE test, while the maximum value was between 92.82 Mpa and 112.33 Mpa with RC test and 53.77 Mpa and 61.75 Mpa with BE test. Finally, the minimum value of D_{min} recorded across the sites ranged between 5.87% and 7.44% with RC test and 9.55% and 12.10% with BE test, while the maximum value was between 16.28% and 23.34% with RC test and 16.68% and 18.77% with BE test. It was observed that the values of shear modulus and damping ratio obtained from the RC test were higher than those from the BE test at all confinement. Variations of results obtained via BE tests as compared to RC tests are reported by some authors (Chan and Jenu, 2014; Szilvágyi *et al*., 2016; Gluchowski *et al*., 2020).

Earlier study had reported a distinct behaviour of shear modulus of sand obtained from the BE and RC tests at varying particle size for confinement pressure of 0 – 400 kPa (Souto and Ozudogru, 1994). Thus at 0-2 mm, there was no significant difference between the shear modulus obtained via the BE test from RC test, but at 0-8 mm the shear modulus for BE tests was higher than that of RC test, and higher than that of RC tests at 0-18 mm crushed till. The deviation of BE tests from the RC tests was attributed to shear strain amplitudes (Chan and Jenu, 2014), but with precise source and receiver signals, accurate sampling interval and frequency, improvement on consistency and compatibility of BE tests with RC test could be achieved , especially for multiple measurements (Szilvágyi *et al*., 2016). Analysis of G_{max} and D_{min} is vital for accurate interpretation of soil dynamics, calculation of ground movements and interaction between soil and structures, especially during foundation or when subjected to cyclic and dynamic loading (Kalioghlou *et al*., 2008).

4.0. Conclusions

Resonant column and bender element test performance analysis on compacted silt samples in Niger Delta States showed that confinement has influence on frequency response, shear modulus, shear velocity and damping ratio in silt soil. Thus, while some parameters increased with pressure increase, others decreased with increase in confinement pressure. The variations in the test parameters showed that the silty soil in the Niger Delta region is likely to experience earthquake in the future, especially as several geological activities are carried out in the region. Hence, adequate monitoring of the different soil strata in the region, through the evaluation of soil dynamic properties will help for accurate interpretation of soil dynamics, calculation of ground movements and interaction between soil and structures when subjected to cyclic and dynamic loading. This will also assist in proper understanding of the soil properties as influenced by load or oil exploration activities.

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Cite this article as:
Okovido J. O. and Kennedy C., 2021. Effect of Confining Pressures on Dynamic Response Characteristics of Silty Soils in the Niger Delta. *Nigerian Journal of Environmental Sciences and Technology*, 5(2), pp. 404-412. https://doi.org/10.36263/nijest.2021.02.0258