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

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ABSTRACT

The study investigated the earthquake potential in Niger Delta region of Nigeria. A series of resonant column and bender element test was performed on compacted clay soil samples across the investigated Niger Delta States, which showed the influence of confinement on frequency, shear modulus, shear velocity and damping ratio. The confinement in clay was high. The frequency response increases with pressure increase. Also, the resonance column test at various confinements revealed changes in shear modulus, accelerometer output and damping ratio. Thus, there was high variation in the test 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. Although, unlike Resonance Column tests, the shear modulus and shear wave-velocity generally increased as confinement pressure was increased, while for damping ratio it decreases as confinement pressure was increased. The variations in resonance column/binder element test parameters showed that the Niger Delta region, as an oil and gas area, is susceptible to earthquake. Therefore, continuous monitoring of oil exploration activities must be put in place.

Keywords: Earthquake, Confinement pressure, Seismic properties

1.0. Introduction

An earthquake is a form of energy of wave motion, which originates in a limited region and then spreads out in all directions from the source of the disturbance. It usually lasts for a few seconds to a minute. The point within the earth where earthquake waves originate is called the focus, from where the vibrations spread in all directions. Earthquakes originate due to various reasons, which fall into two major categories viz, non-tectonic and tectonic. The origin of tectonic earthquakes is explained with the help of an 'elastic rebound theory'. Earthquakes are distributed unevenly on the globe. Seismicity induced by human activities related to energy technologies is caused by a change in pore pressure and/or change in stress taking place in the presence of faults with specific properties and orientations, human activity has been observed and documented since at least the 1920s (Pratt and Johnson, 1926). The quest for oil and gas exploration using explosives, filling of large oil wells and reservoirs, mining activities such as are river sand and crushed stone mining, blasting activities and fluid pumping and gas, in an extremely brief period that exerts sudden pressure on its surroundings (Dionne *et al*., 1986).

Niger Delta regions within the areas of the border between the states of Bayelsa and Rivers were on the 15th and 24th July, 2016, struck by earthquake and structures were seriously damaged in this case, but no loss of lives but left roads with cracks, structural failure of buildings, lifeline, degradation of various oil and gas facilities and other infrastructures seriously damaged, (magnitude was not recorded but effect was high). This recent event in Niger Delta region despite the Warri, 1933 event after reviewed and Nigerian seismologists all agreed that Nigeria is no longer an earthquake-free zone as previously thought following series of earth tremors in various parts of the country as of late and this is a sign that seismic exercises within the country are expanding and earnest measures should be embraced to avert shocking outcomes of vast quakes in the most crowded black country on the planet.

The use of explosives as a seismic exploration energy source in the Niger Delta over the years has generated fears and concerns to the inhabitants as to the effects on roads, buildings, and the entire environment. Seismic induced activities such as blast-induced ground vibrations have been studied by several researchers throughout the world; each study relates the geological formation and surface soil characteristics of the geographical location in which the study is carried out. For the most part, the seismic technique uses the proliferation of waves through the earth (Adeoti *et al*., 2012). These waves are often generated by the detonation of explosives such as dynamite. Eze and Okara (2014) noted that the guidelines applied to the use of explosives by the exploration companies were based on standards developed in countries whose soil types and geology are different from what obtains in the Niger Delta.

Seismic microzonation is the initial phase in quake hazard alleviation study and requires a multidisciplinary approach with significant commitments from the fields of geography, seismology, geophysics, geotechnical and basic designing (Adeoti *et al*., 2012). This is very important to identify the tectonic and geological formations in the study area which is essential for determining the seismic sources and also for establishing earthquake hazard models for the investigation. Based on this effect, the determination of geotechnical properties of soils arises as to investigate the causes of failures and sudden change in soil properties which resulted in the triggered actions of earth tremors.

The overall structure of the Delta field has 2 main fault blocks that area unit separated from each other by a serious traditional fault; the western block is that the wall that's born relative to the eastern bloc. Another fault exists within the North Eastern part of the sector and is characterized by a minor crust. The growth of faults within the northern delta province area unit principally movement, increase in slope seaward, and area unit equally spaced together with the expansion faults, change anticlines, sedimentary rock ridges, and sedimentary rock diapirs exist within the basin and may be seen within the schematic structural profile of the Niger Delta (Tuttle and Brownfield 1999). The ground of Niger Delta of African nation is formed within 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), and its subterranean profile consists of a high lateritic clay layer underlain by loose clays and sands that area unit successively succeeded by poorly stratified sand and gravel though all of the Niger Delta space is characterized by tropical rain conditions, annual rain ranges from 2000mm within the fresh zone to over 4000mm at the coast that additionally accounts for nearly 85% of the annual rain. Therefore, the coastal and Angiospermous tree zones contain nearly 70% of the many marshes and back swamps that occupy the maximum amount as 50% by space of the additionally they are sometimes submerged throughout the wet season (April to October).

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, 260km^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 onshore area is bordered by the geology of southern Nigeria and southwestern Cameroon, the northern margin of Niger Delta is the Benin flank and east northwest-trending hinge line south of the West Africa basement massif. The stratigraphy of the Niger Delta is complicated by clastic wedge syndepositional collapse that occurred as the result of marine shales being mobilized (Doust and Omatsola, 1990). 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 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.

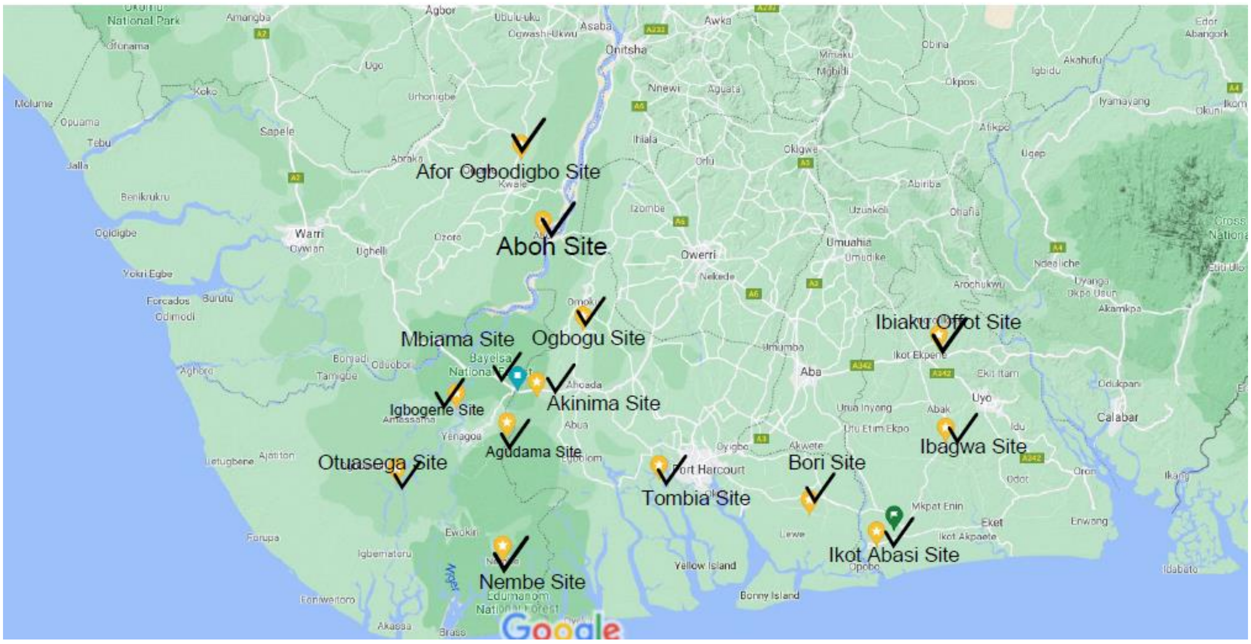

Figure 1: Study areas of Niger Delta

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. All soil samples were collected by subsurface exploration activities at the sites which included drilling and deep boring by standard penetration test (SPT). *In situ* field test and laboratory test were adopted in this research work.

Table 1: Test samples and their locations

State	Location	Sample
Rivers	Akinima	CLAY-A7
	Mbiama	CLAY-B4
	Tombia	CLAY-D3
	Obite	CLAY-C9
	Bori	CLAY-E10
Bayelsa	Igbogene	CLAY-F3
	Agudama	CLAY-G13
	Otuasega	CLAY-H3
	Nembe	CLAY-I2
Akwa-Ibom		
	Ikot-Abasi	CLAY-J6
	Ibagwa	CLAY-K6
	Ibiaku Offot	CLAY-L4
Delta	Abo	CLAY-M3
	Afor Ogbodigbo	CLAY-N7

The tests were conducted to estimate the dynamic soil properties. The soil samples were dried, crushed and sieved on sieve No. 4(4.75mm) with standard and known weights taken, mixed with amount water which represented natural water content state. Soil samples were remoulded to field density and natural moisture content stage. Samples were prepared with specimen standard measurements of 20mm height and 70mm 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 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 height, 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 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 is typically fitted in an exceedingly normal resonant column (RC) equipment.

3.0. Results and Discussion

Resonant column and bender elements (RC/BE) device is useful for the investigation of key factors such as confine pressure, strain stiffness properties of unsaturated soil and how they affect the shear modulus and damping ratio of soils influenced by seismic activities. A series of resonant column and bender element test were simultaneously performed on compacted samples of clay. Thus, the effect of confinement (pressure) on frequency, shear modulus G_{max}, shear velocity and damping ratio D_{min} of clay samples was studied across selected States of the Niger Delta region of Nigeria.

The influence of shear strain on shear stress performed via the resonance column and bender element test was studied via the hysteresis loop triangle shown in Figure 2, with a triangle drawn opposite and adjacent sides labeled S and L. The loop was used to determine the shear strain modulus and damping ratio as shown in Table 3. Experimental results leading to the calculation of data in Table 3 is presented in Table 2.

3.1. Frequency variation with confinement in the soils

The frequency response of clay samples test subjected to confined pressure across the respective site locations in Rivers, Bayelsa, Akwa-Ibom and Delta States is shown in Figure 3. The number of cycles induced was 5 in each case.

Table 2: Tabulation for shear stress and shear strain values

Time (sec)	Lateral Lvdt	Lateral force	Sample area (mm^2)	Shear Stress = (F/A)*10^3 MPa	Shear strain =(disp./19.6)	$(\tau_i-\tau_{i+1})*(\gamma_i+\gamma_{i+1})$
0.00000	0.00000	0.07355	3850.85	0.01783	0.00030	-0.00010
0.02450	0.05146	0.08725	3850.85	0.02139	0.00243	-0.00015
0.04350	0.11783	0.11412	3850.85	0.02837	0.00582	-0.00018
0.06250	0.17488	0.13693	3850.85	0.03430	0.00873	-0.00018
0.08150	0.22092	0.15494	3850.85	0.03898	0.01108	-0.00025
0.10050	0.27817	0.17994	3850.85	0.04548	0.01400	-0.00028
0.11950	0.32506	0.20377	3850.85	0.05167	0.01639	-0.00026
0.13850	0.35953	0.22284	3850.85	0.05662	0.01815	-0.00032
0.15750	0.39684	0.24592	3850.85	0.06262	0.02005	-0.00032
0.17650	0.43747	0.26712	3850.85	0.06813	0.02213	-0.00022
0.19550	0.46204	0.27837	3850.85	0.07105	0.02338	-0.00019
0.21450	0.47738	0.28653	3850.85	0.07317	0.02416	-0.00018
0.23350	0.48971	0.33214	3850.85	0.08503	0.02479	-0.00041
0.25250	0.50147	0.35651	3850.85	0.09236	0.02539	0.00070
0.27150	0.50599	0.29705	3850.85	0.07591	0.02521	-0.00003
0.29050	0.50633	0.29260	3850.85	0.07475	0.02538	-0.00003
0.30950	0.50562	0.28819	3850.85	0.07360	0.02502	0.00081
0.32850	0.47881	0.21864	3850.85	0.05553	0.02423	0.00080
0.34750	0.43747	0.14470	3850.85	0.03632	0.02213	0.00050
0.36650	0.38769	0.08987	3850.85	0.02207	0.01959	0.00012
0.38550	0.36405	0.06830	3850.85	0.01647	0.01838	0.00023
0.40450	0.30537	0.03171	3850.85	0.00696	0.01539	0.00009
0.42350	0.21508	0.01852	3850.85	0.00353	0.01078	-0.00005
0.44250	0.19909	0.01130	3850.85	0.00166	0.00996	0.00001
0.46150	0.11520	-0.01398	3850.85	-0.00491	0.00568	-0.00006
0.48050	0.07343	-0.02827	3850.85	-0.00862	0.00355	-0.00006
0.49950	0.01581	-0.05296	3850.85	-0.01503	0.00061	-0.00011
0.51850	-0.07660	-0.07481	3850.85	-0.02072	-0.00410	-0.00012
0.53750	-0.09710	-0.08714	3850.85	-0.02392	-0.00515	-0.00022
0.55650	-0.18310	-0.12095	3850.85	-0.03271	-0.00954	-0.00016
0.57550	-0.22450	-0.13430	3850.85	-0.03618	-0.01165	-0.00026
0.59450	-0.26550	-0.15969	3850.85	-0.04277	-0.01374	-0.00039
0.61350	-0.33940	-0.19695	3850.85	-0.05245	-0.01752	-0.00016
0.63250	-0.35700	-0.20453	3850.85	-0.05442	-0.01841	-0.00043
0.65150	-0.39900	-0.23753	3850.85	-0.06300	-0.02055	-0.00036
0.67050	-0.44250	-0.26150	3850.85	-0.06923	-0.02277	-0.00014
0.68950	-0.45070	-0.26588	3850.85	-0.07037	-0.02319	-0.00039
0.70850	-0.47620	-0.30898	3850.85	-0.08157	-0.02449	0.00045
0.72750	-0.49470	-0.35050	3850.85	-0.09236	-0.02544	0.00848
0.74650	-0.49610	-0.28946	3850.85	-0.07649	-0.02501	-0.00005
0.76550	-0.49630	-0.28644	3850.85	-0.07571	-0.02512	-0.00005
0.78450	-0.49590	-0.28309	3850.85	-0.07484	-0.02525	-0.00002
0.80350	-0.49460	-0.27748	3850.85	-0.07338	-0.02543	0.00035
0.82250	-0.48220	-0.24355	3850.85	-0.06456	-0.02480	0.00050
0.84150	-0.46130	-0.19693	3850.85	-0.05245	-0.02373	0.00063
0.86050	-0.42830	-0.13628	3850.85	-0.03669	-0.02205	0.00058
0.87950	-0.38410	-0.07446	3850.85	-0.02063	-0.01979	0.00040
0.89850	-0.33150	-0.02307	3850.85	-0.00727	-0.01711	0.00018
0.91750	-0.26610	0.01098	3850.85	0.00157	-0.01377	-0.00003
0.93650	-0.19560	0.02070	3850.85	0.00410	-0.01018	0.00005

Figure 3 shows the profiles of frequency versus confinement induced in clay soil across the respective site locations. The confined pressures ranged from 115 to 2045kPa. However, as pressure was increased, frequency response was observed to equally increase. Thus, at the lowest confinement of 115kPa, frequency response across the respective sites ranged from 41.42 – 47.12Hz, while at the highest confinement of 2045kPa, it ranged from 82.49 – 88.01Hz. Frequency responses in the clay soil obtained from the site locations in Rivers, Bayelsa, Akwa-Ibom and Delta States are relatively similar as highlighted by the profiles in the figure.

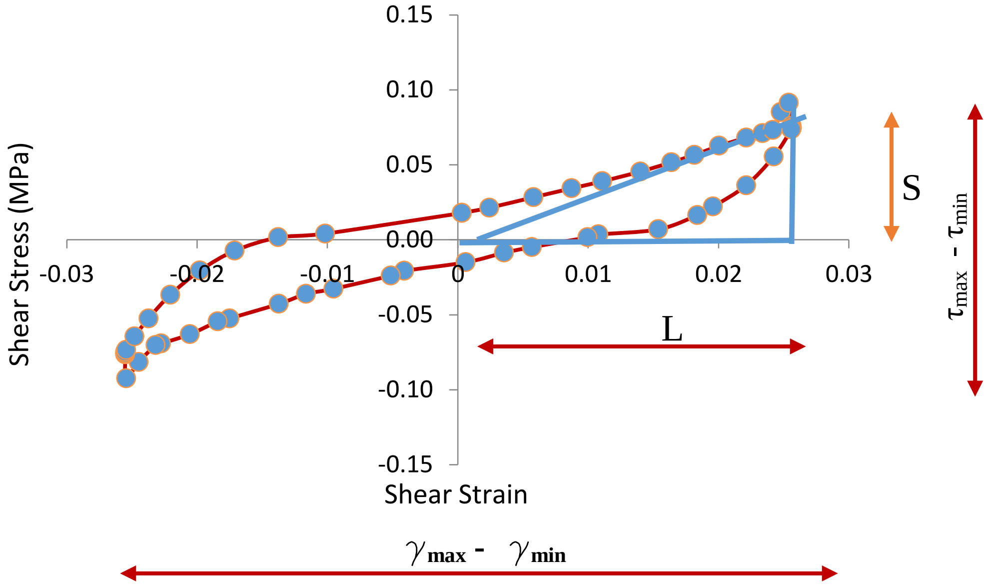

Figure 2: Hysteresis loop triangle for shear stress variation with shear strain

Table 3: Calculations for shear modulus and damping ratio with the aid of figure 1

Shear Modulus (MPa)	Specific Value (MPa)	Damping Ratio (%)	Specific Value (%)
τ_{max}	0.09236	Area of Hysteresis Loop $= 0.5\sum(\tau_i - \tau_{i+1})(\gamma_i + \gamma_{i+1})$	0.0043705
τ_{min}	-0.09236		
$\tau_{max} - \tau_{min} = 2S$	0.18472	Area of Triangle = $0.5 \times S \times L$	0.0011725
γ_{max}	0.02539		
γ_{min}	-0.02544		
$\gamma_{max} - \gamma_{min} = 2L$	0.05083	$D = \dfrac{\text{Area of Loop}}{4\pi \text{ Area of Triangle}} \times 100\%$	29.25
$G = \dfrac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}}$	3.6341		

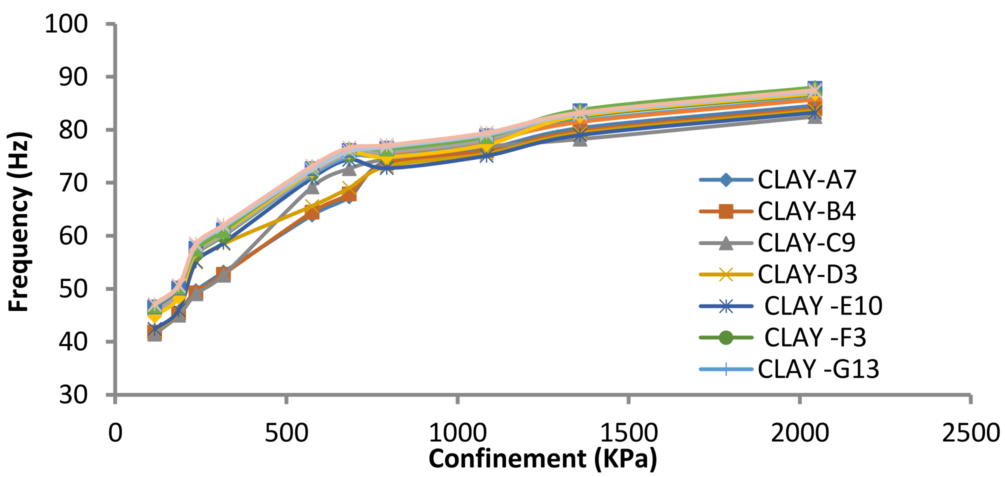

Figure 3: Variation of frequency with confinement

This indicates that the region shared similar clay characteristics, hence, an occurrence of any earthquake disaster in one of the States, implies there would be high potential of such disaster occurrence in the other States induced with same magnitude of confined pressure.

3.2. Variation of parameters for resonance column analysis

The shear modulus (G_{max}), accelerometer output (V_{rms}) and minimum damping ratio (D_{min}) obtained from Resonance Column (RC) test in clay soil is shown in the figures below.

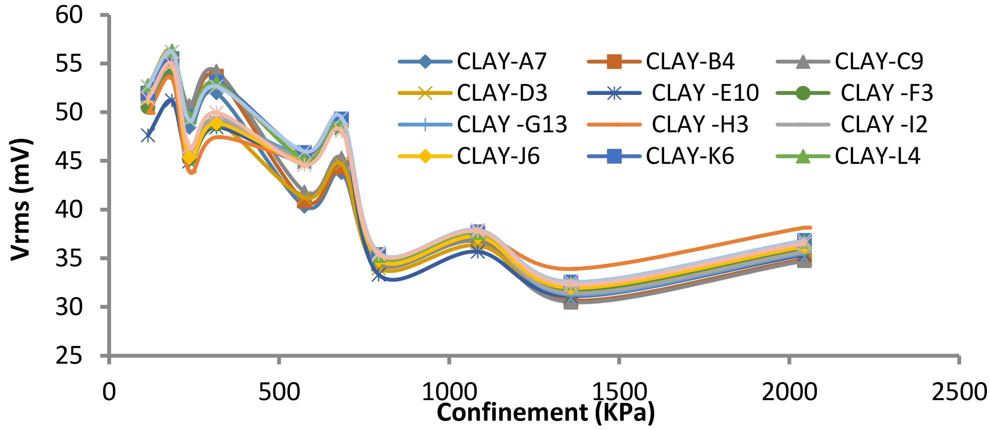

Figure 4: Variation of V_{rms} with confinement for RC test

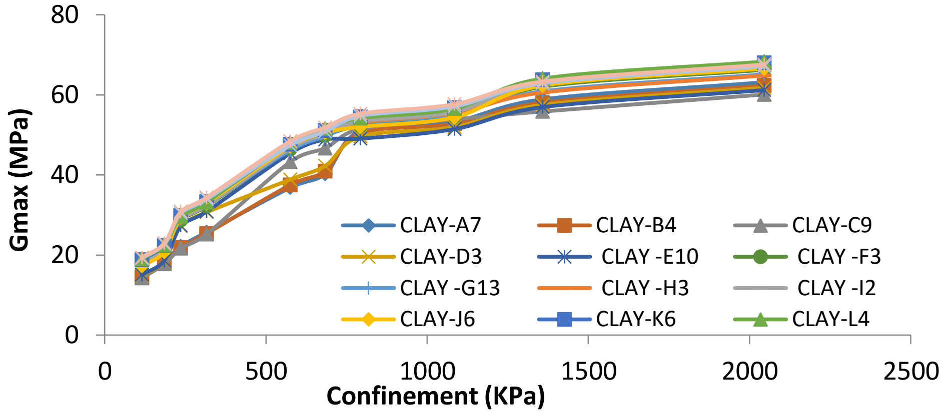

Figure 5: Variation of G_{max} with confinement for RC test

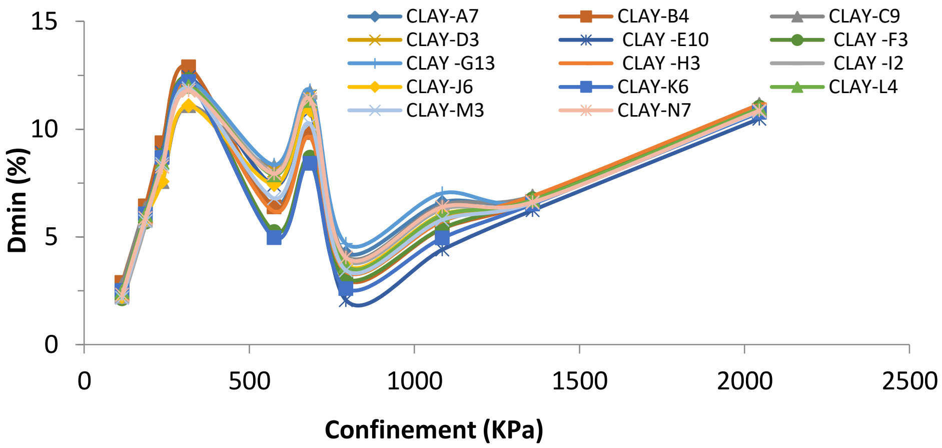

Figure 6: Variation of D_{min} with confinement for RC test

Figures 4, 5 and 6 show the V_{rms}, G_{max} and D_{min} relationship with confinement pressure in clay soil as obtained from the resonance column (RC) test. There was variation in RC test parameters. Thus, the V_{rms} values decreased generally with confined pressure across the sites, while the reverse was the case for G_{max} as it increases uniformly with increase in confinement in all the sites. However, minimum damping ratio (D_{min}) across the sites shows a sinusoidal characteristic response to confinement. This may be due to moisture content variation in the soil (10 – 32.50%). According research, moisture content affects the damping ratio (Thevanayagam, 1998; Anbazhagan and Sitharam, 2009; Tsai *et al*., 2010; Ige *et al*., 2016).

3.3. Variation of parameters for bender element analysis

Like RC test, the shear modulus (G_{max}), shear wave velocity (V_s) and damping ratio (D_{min}) were analyzed with Bender Element (BE), and the test results shown in the figures below.

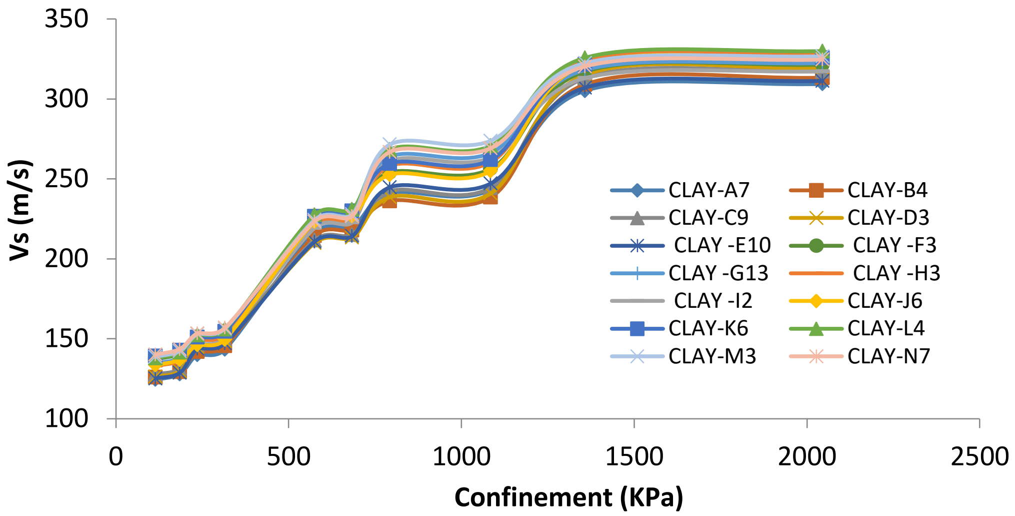

Figure 7: Variation of V_s with confinement for BE test

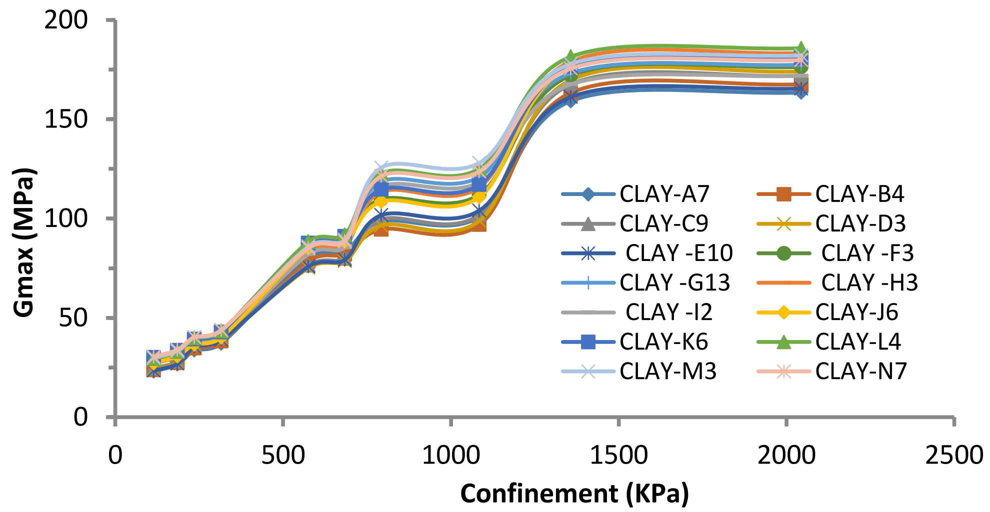

Figure 8: Variation of G_{max} with confinement for BE test

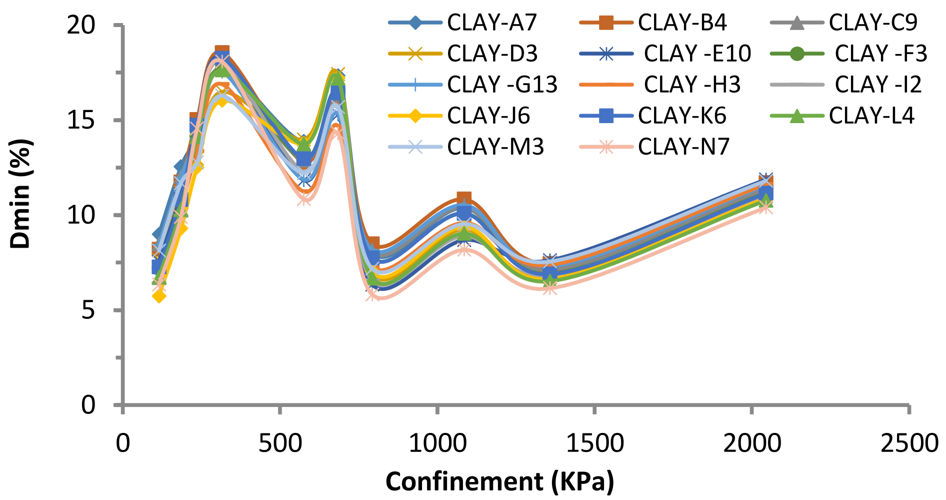

Figure 9: Variation of D_{min} with confinement for BE test

The bender element (BE) tests are shown in Figure 7, 8 and 9. Unlike RC tests, shear modulus (G_{max}) and shear wave-velocity (V_s) for BE test generally increased as confinement pressure was increased.

However, this was not so for damping ratio (D_{min}) as increase in confinement pressure resulted to decrease in damping ratio. It was also observed that moisture content influenced the variation in BE test parameters. Again, it was observed that higher confinement pressure amounted to more consolidation of the samples, which also makes the samples more rigid.

The minimum value of V_{rms} recorded across the sites at confinement of 115 to 3045kPa ranged between 30.49mV and 32.58mV, while the maximum value was between 51.19mV and 56.29mV. However, the shear wave-velocity (V_s), the equivalent of accelerometer output (V_{rms}) measured from the RC test, across the sites has minimum value ranged between 124.40m/s and 140.04m/s, while the maximum value was between 309.39m/s and 329.98m/s at confinement range of 115 to 3045kPa. Thus, it can be deduced that while the accelerometer output was decreasing with confined pressure, shear wave-velocity (V_s) obtained from the BE test generally increase with confinement pressure.

Similarly, the minimum value of G_{max} recorded across the sites ranged between 14.23Mpa and 19.40Mpa with RC test and 23.03Mpa and 30.42Mpa with BE test, while the maximum value was between 60.10Mpa and 68.03Mpa with RC test and 163.45Mpa and 185.77Mpa with BE test. Finally, the minimum value of D_{min} recorded across the sites ranged between 1.98% and 2.51% with RC test and 5.73% and 7.45% with BE test, while the maximum value was between 11.09% and 12.89% with RC test and 16.03% and 18.54% with BE test. Again, the values of shear modulus and damping ratio obtained from the BE test were higher than those from the RC test at all confinement. Gluchowski *et al*. (2020) equally observed these scenarios, though, at different confinements. According to Szilvágyi *et al*. (2016), deviation of BE from the Standard RC test could be due to some parameters that were not accounted for in the triaxial confinement process and the orientation of stress state and wave direction, while Chan and Jenu (2014) noted that factors such as coupling of bender element with the soil could also be responsible for the deviation. G also experienced difficulties in obtaining consistent results with BE tests as compared with RC tests. However, with precise definition of source and receiver signals as well as accurate sampling interval and optimum set of frequencies to necessary perform multiple measurements could improve consistency and compatibility of BE tests (Szilvágyi *et al*. 2016).

It is worthy of note that the accurate determination of G_{max} and D_{min} are important for description of soil dynamics, as well as for the calculation of ground movements and soil-structure interaction system, especially when a soil is subjected to cyclic and dynamic loads such as machines and vehicles' vibration, earthquake and other kinds of shocks (Kalioghlou *et al*., 2008).

4.0. Conclusion

A series of resonant column and bender element test performed on compacted clay samples across the investigated Niger Delta States showed the influence of confinement on frequency, shear modulus, shear velocity and damping ratio of clay. The confinement in clay was high. The frequency response increases with pressure increase. Also, the resonance column test at various confinements revealed changes in shear modulus, accelerometer output and damping ratio. There was variation in the test parameters as confinement pressure was increased.

Similarly, the bender element tests for shear wave-velocity, shear modulus and damping ratio was influenced by confinement pressure. Although, unlike RC tests, the shear modulus and shear wave-velocity generally increased as confinement pressure was increased, while for damping ratio it decreases as confinement pressure was increased. The variations in RC/BE test parameters was influenced moisture content, and higher confinement pressures bring about soil consolidation, which makes them more rigid.

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