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Effect of Indiscriminate Hydrocarbon Exploration on Possible Occurrence of Earthquake in some parts of Niger delta, Nigeria

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Abstract

Seismic activities leading to tremors have been a subject of interest in geophysical survey. Here in, we reported the (seismic) tectonic activities of Langbodo field, an area where tremors have occurred in the Niger Delta, Nigeria. The seismic data used in this research work were analyzed using the CPillar® and the Plaxis 2D® seismic softwares. These softwares are based on sensitivity, probabilistic and finite element analyses. The variation in the depth of the exploration boreholes for the five identified locations, LCT A, LCT B, LCT C, LCT D and LCT E with respective values 7525 km, 7000 km, 8000 km, 7600 km and 9000 km showed the extent to which the underlying crust can be pressurized. The seismic information from the drilled wells revealed that the tensional force created through stress ranges from $5.517 \times 10^{13}\ N$ to $6.130 \times 10^{14}\ N$ and that of compression ranges from $3.065 \times 10^{14}\ N$ to $5\ 517 \times 10^{14}\ N$. The tectonic activities of each of the locations were recorded using the seismic reflection method. This study revealed that more than 50 % of the earth tremors experienced in the area were humanly triggered. Seismic records of the areas showed that human activities that result to rapid injection of fluid into the plates, if not controlled, can trigger tremors. The magnitudes of tremors that have occurred in the five identified locations LCT A, LCT B, LCT C, LCT D and LCT E are respectively 3.50 M_L, 3.20 M_L, 4.20 M_L, 4.00 M_L and 4.32 M_L. This research work however concluded that the study area is likely to witness earthquakes of about 7.0 M_L magnitude should explorations continue indiscriminately. Probable occurrence of earthquakes in this location can be nipped in the bud by setting up agencies that monitor and assess subsurface pressures, quantities of injected fluid, volume of extracted fluid, and the seismicity of vulnerable regions with time.

Keywords: Seismic Activities; Seismic Wave Velocity; Depth of Borehole; Compressional and Tensional Forces; Seismic Reflection Method.

I. Introduction

Nigeria has witnessed several incidents of earth tremor but due to lack of active observatory bodies to find out what might have caused them, records were not taken as at the times they occurred. Evidence from literatures revealed that only the five most recent incidents of tremor were recorded for research purposes [1]. However, with the establishment of agencies such as Centre for Geodesy and Geodynamic (CGG), Nigeria National Network of Seismographic Station (NNNSS) and the National Space Research and Development Agency (NASRDA), records of any noticeable seismic activities in the country can now be documented. Earthquake refers to the vibration and shaking of the crust as a result of plate tectonics which can occur on any known types of boundaries between plates in the subsurface. The release of tension from the crust results into movement of plates which build up pressure at a point known as the focus which is located below the epicentre [1]. Energies that cause earthquake are released from different seismically built up waves such as the primary (P) waves and the secondary (S) waves. These waves create tensional and compressional forces which initiate crustal movement or vibration leading to earthquakes [1]. Waves spread out from the focus but their strong effects are experienced at the epicentre. As the waves travel away from the epicentre, the effects of the quakes become less. Most of the most damaging earthquakes in the world occurred near or at the epicentre [2]. Evidence from literatures portrays earthquakes as disasters emanating from the lithospheric energy which create seismic disturbance leading to shaking and possibly rupturing of the earth's surface. Earthquakes can occur naturally and their occurrences can also be triggered by daily human activities [1]. Apart from common energy companies' activities resulting to the most humanly triggered earthquakes across so many countries in the world, other earthquakes triggering practices include research findings that examine faults stress, construction of building, geothermal operation, carbon capturing, quarrying, water boreholes drilling, carbon storage, nuclear explosions, enhanced oil recovery and oil and gas (hydrocarbon) exploration [2]. Scientific research works most times prompt researchers to embark on tectonic faults threatening research findings, such as induced hydrocarbon exploration, geothermal activities and chemical crustal injection: when this is done, block of rocks in the subsurface can slip relative to another especially when activities of researchers build up additional pressure in the crust [3]. Some of the disasters recorded around the world were due to erection of buildings in seismically active areas. Many of these buildings were erected without any proper geophysical surveys of the lands which could have given a comprehensive seismic histories of the areas before erection [4]. Apart from the occurrence of earthquake, erecting heavy building structures on seismically active areas can lead to other natural disasters such as tsunamis, landslides, avalanches and flood [5]. Geothermal operating stations embark on activities which result into injection of fluids of high pressure into the deeper parts of the well in order to collect heat from spacious rocks close to the core. Apart from the existing fractures on the rocks, new ones can be created due to the high pressure fluids and this can trigger the occurrence of earthquakes in the area [6]. Carbon capture and storage (CCS) is majorly carried out as an approach to reduce the emission of greenhouse gas but this can be done by massively sequestering over 3400000000 metric tons of carbon IV oxide every year. This activity is enough to build up pressure in the crust as the underlying faults can be pressured to slip. Continuous slipping of the underlying faults results to plate deformation and rupture which can later lead to earthquakes [7]. Quarrying activities can cause vibrations similar to the ones caused by earthquakes. Ground shaking that occur from quarrying can trigger serious seismic activities leading to earthquakes [8]. Injected chemical fluids during enhanced oil recovery (EOR), migrate into the hydrocarbon reservoirs and beyond the underlying porous rocks. Although these chemicals enhance the deliverability of reservoirs yet they induce pressure in the subsurface thereby causing plate deformation and rupture [9]. Indiscriminate sinking of water and exploration boreholes of varying depths is a common practice in the study area and Nigeria at large. Findings from literatures established that the processes involve in sinking these boreholes can cause very serious vibration in the subsurface let alone the infiltration of chemically active fluids into the plates [10]. Greater number of human-induced quakes are as a result of exploration activities. As drilling engineers drill to the depth below the rocks in order to explore hydrocarbon, spaces, holes and crevices abandoned behind result into instability which snowballs into collapses capable of triggering earthquakes [11]. The intensity of earthquakes – (the extent to which quakes shook the ground surface) can cause rupturing of gas pipelines, toppling of bridges and buildings, tsunamis, volcanoes and landslides [12]. All these are the reasons for injuries and death in the areas where earthquakes occurred. Almost all earthquakes result when the movement of two or more plates terminates at a point where fault lines exist [13]. Prevention of natural quakes is practically impossible but efforts can be made to mitigate their likely effects by hazards identification, erection of safer buildings and provision of adequate education on safety measures [14]. It is worthy to mention that the increase in the number of earthquakes around the world can be traced to the indiscriminate exploration activities and fracking activity during exploration on its own, does not usually result to earthquake; it is the forceful injection of fluid into the plates when disposing wastewater that most times infiltrates millions of tanks of brine into the subsurface during exploration [15]. While some tremors leading to earthquakes might have originated from tectonic activities which were natural, a handful of them have occurred as a result of the day-to-day human activities triggering their occurrences. Among the humanly triggered earthquakes that have occurred around the world include the Sichuan province earthquake in China which claimed almost 87,000 lives and a lot of researchers blamed this on the Zipingpu exploration reservoir because fluid may have migrated into the faults and made them to slip [16]. Although many debated that this might be natural. The Netherlands' earthquake in 2012 which was as a result of the Dutch Oil and Gas Company (Netherlands'

Gronigen gas field) extraction and exploration activities [4]. The Akenfa and Igbogene tremor in Bayelsa state, the Akinima, Akieoniso (Oruama) tremor and the One Man Country and Mbiama tremor in Rivers state which resulted to a wide spread panic among the inhabitants of the affected areas [17]. Humanly triggered tremors have skyrocketed from a usual twenty (20) plus quakes a calendar year to one hundred and eighty-seven (187) plus as recorded in 2011 by [18]. Right from the first time the first oil well was struck in Oloibiri (Bayelsa state, Nigeria), exploration of hydrocarbon by different authorities has been intense and indiscriminate with no realization of the debilitating effects on the communities from which the exploration took place [19]. These research findings aimed at determining the causes of the previous earth tremors in the Niger Delta, relating the previous tremors to various exploration activities some kilometers away from the borehole locations, if any and predicting possible occurrences of earthquakes in vulnerable communities, will help to reduce the risks associated with exploration in the study area. Results from this research is expected to help the appropriate agencies take informed decisions by educating the reservoirs explorationist on the likely effects of indiscriminate hydrocarbon exploration.

A. Study Area

The area studied is the Langbodo field in the Niger Delta region of Nigeria with respective latitudinal and longitudinal boundaries of $(6°40'\ N$ and $6°60'\ N)$ and $(7°50'\ E$ and $7°63')$. It is the delta of Niger River which is sitting directly on the Atlantic Ocean of the country and on the Gulf of Guinea. This region is located within nine southern states located in the coastal region. These include Akwa Ibom, Abia, Cross River, Bayelsa, Edo, Delta, Ondo, Imo and Rivers [20]. The Niger Delta region according to the 2006 conducted population census, has over 30 million people and population density of 265 people per square kilometre. It highly rich in petroleum which has attracted the attention of the government of Nigeria and other international countries [20]. One major concern in this region over the years has been the issue of pollution that has emanated majorly from oil spillage and poisoning of farmlands of people in the communities where explorations were being carried out [21]. About 70% or more of the wells drilled in the Niger Delta have reached a depth of 9,000 feet (2,743 metres) and 2% of the wells have penetrated a depth of more than 15,000 feet (4,572 metres) [21]. These depths have penetrated enough to stir up high seismic activities which can trigger tremors if not well controlled. The singular act of exploring hydrocarbon using the Sonde at many locations around a community can cause a very high tensional and compressional forces which can trigger vibration and infiltration of fluid into the plate boundaries causing them to slip and rupture [21]. Fig. 1 shows the seismic hazard map of the study area.

The folds depicted n Fig. 1 are as a result of compressional force which can gradually rupture the plate tectonics, thereby resulting to tremors and consequently heavy earthquakes if not controlled. The stratigraphic sequence of the Niger Delta provides the information about the differences in the pressure of each of the formation (Akata, Agbada and the Benin) [23]. These pressure differences are the reason for tremors noticed in the study area. As more exploration are carried out around the same locations, more pressures are exerted on the plates and heavy earthquakes can occur [23]. As movement of plates continues in the crust, a time is reached when two opposite block rocks meet and folding eventually occurs. The early stage of the folding leads to earthquake at the point where the fault is slipping due to wastewater disposal during exploration [24]. As time progresses, quakes are numerously brought about by rocks slipping layers on top and close to the location of faults as buckling of folds occurs under high pressure [24].

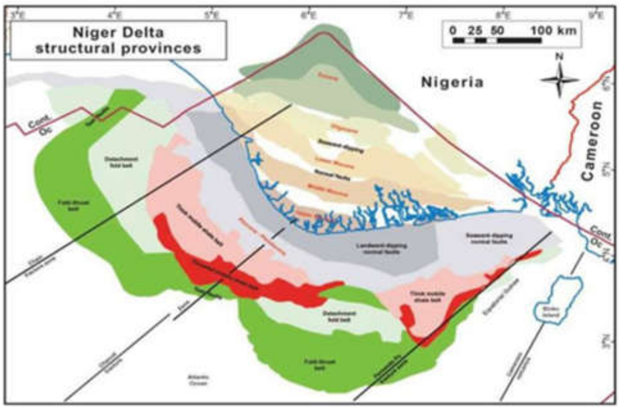

Fig. 1 Seismic Hazard Map of the Niger Delta [22]

Folding are geological activities built up when two or more crustal plates approached each other through the force of compression which leads to the bending away of the earth's crust from the usual flat surface to folds. An upward bent is known as the anticline while the downward bent is the syncline [25]. As folding results into bending of the crustal plates, the unbalanced seismic activities can lead to earthquakes that are capable of toppling buildings and other structures around the location [25]. Fig. 2 portrays the base map of the study location.

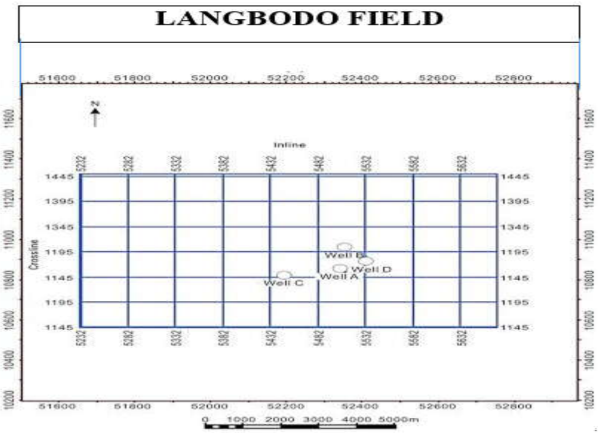

Fig. 2 Base Map of the Study Area

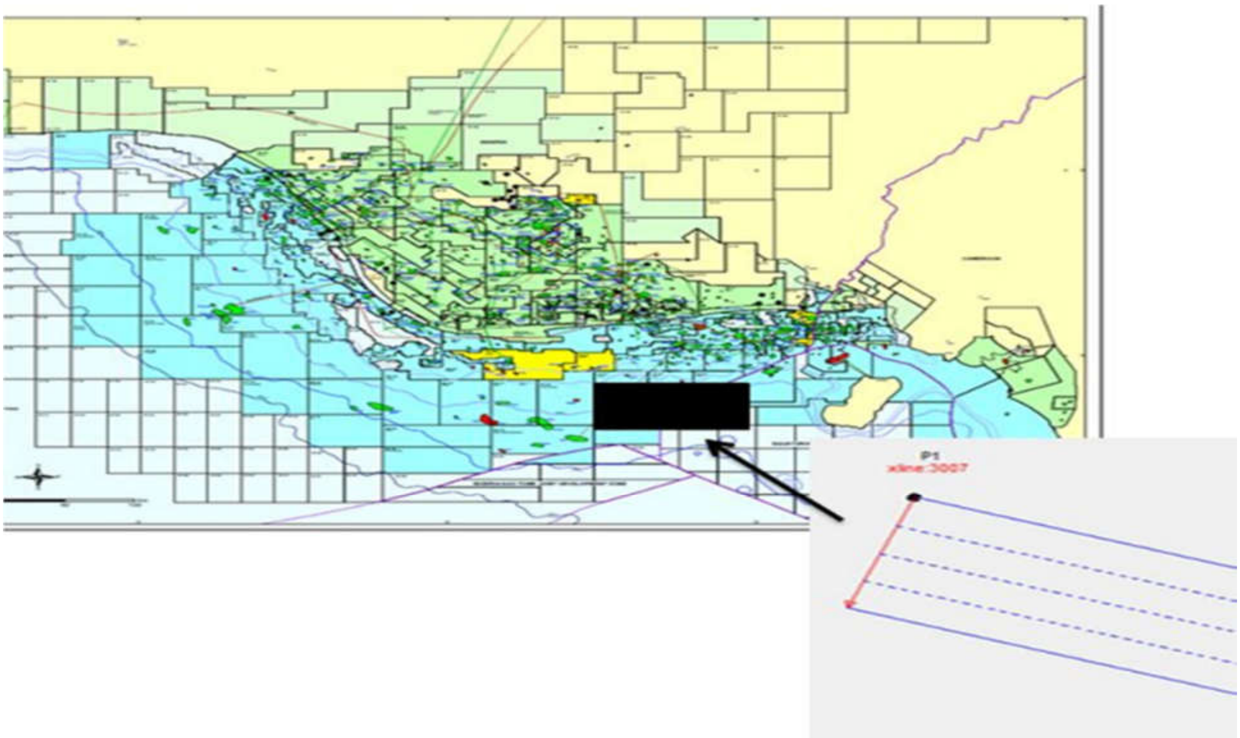

Fig. 3 Seismic Hazard Map of the Niger Delta Showing the Plate boundaries [22].

The faults in Fig. 3 can slip due to tensional force. It can be as a result of the infiltration of fluids when disposing wastewater. These fluids find their ways into the plate boundaries and cause them to slip. Slipping of the plates, if not massive may cause small tremors noticed in the study area. Massive slipping of the plates can lead to heavy earthquakes in the area [26]. During the drilling process, several millions of tanks of fluid, large quantity of sand and some chemicals are pumped at a very high pressure into the borehole. This is done to break the underlying rocks so as to access the oil and gas beneath. The gas comes up with the fracking liquid and salty brine [27]. These combinations are thereafter forcefully pumped below the underlying shale into rocks of high porosity for complete disposal. As one continues to inject more liquid into the wastewater, it builds up pressure on the underlying faults and this may eventually cause one of them to slip. The slipping of one fault in the subsurface may lead to heavy faults slipping which can cause earthquakes [27]. Wastewater injections are capable of altering stresses holding faults in place and allow them move away thereby resulting to earthquakes which may still continue even when water injections have stopped [28]. This is because the previous injections have resulted to change in pressure in the deep crust and this can continue for years as long as it is encountering the nearest possible faults. Faults are of varying lengths which can be measured in millimeters, kilometers or thousands of kilometers depending on their areas of coverage [28].

Fig. 4 A picture of the Drilling Environment in the Niger Delta [29].

The drilling environment shown in (Fig. 4) is made of heavy machines that can trigger tectonic movement. These machines penetrate into the plates, break some heavy rocks and cause faults within the boundaries. Several communities around the study area have faced environmental catastrophe such as the contamination of the air, land and water. The heaviness of the machine itself can cause vibrations which can do a lot of damages to the buildings around the locations [30].

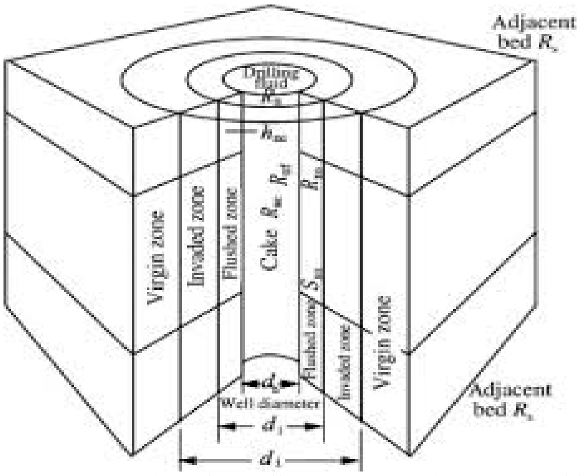

Fig. 5 Cross Section of a Well Bore, Penetrating a Permeable Formation [29].

Locations where holes are drilled into formations experienced alteration of rocks and fluid in the vicinity of the holes. Wells boreholes and the surrounding rocks are contaminated by the mud. The percentage of the contamination is function of the weight of the mud the mud filtrate loss [31]. In the process of filtering into the formation, the mud leaves a mud cake on the borehole wall. The environment of the borehole is divided into the (i) invaded and (ii) uninvaded zones. The invaded zone is the zone affected by filtrate from the mud. It is made up of the flushed and the transition zones. The zone near the borehole where the filtrate from the mud took over almost all the formation fluid is the flushed zone. The area between the uninvaded zone and the flushed zone is referred to as the transition zone. The area beyond the invaded zone where filtrate from the mud cannot contaminate the fluid in the formation is the uninvaded zone [31]. As drilling continues, disposal of brine takes place. This can cause infiltration of brine into the plate tectonics. The plate boundaries around the borehole vibrate and slip and as a result leads to earth tremors in the environment [15].

II. MATERIALS AND METHODS

If Seismic (earthquake) data collected were first checked to eliminate null values. Analysis of data was done with the CPillar® and the Plaxis 2D® seismic softwares. Data were thereafter inputted into the Microsoft excel environment and appropriate statistical relations were employed to evaluate the magnitude of each of the tremors that have occurred in the study area. The depths of the water bore boreholes and the drilled wells were obtained using the seismic reflection methods. Values obtained from the seismograph were digitized and converted to the Richter–Gutenberg scale (M_L). The magnitudes of the tremors were thereafter compared to the primary (P) waves and the secondary (S) waves within the study area. Quantitative analysis of data involved the use of empirical formulas to estimate parameters such depth of boreholes, compressional and tensional forces, frequency of P and S waves, seismic wave velocity and the magnitude of tremors. Calculation of these parameters helped to determine if tremors within the area studied were as result of oil and gas (hydrocarbon) exploration.

A. *Estimation of Seismic Wave Velocity*

Earthquake generate two types of waves which propagate through rocks. These are the primary (P) and the Secondary (S) waves.

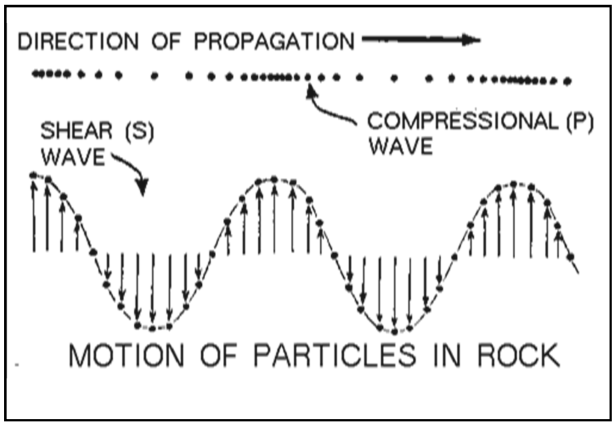

Fig. 6 Direction of Propagation of (P and S) waves

From Fig. 6, the primary, P-wave propagates in the direction of the rocks vibration. It has the highest velocity, as it travels faster than the S-wave. During minor or major earthquakes, the P-waves are the first to be noticed on the recording seismograph. The Secondary/Shear/S-wave travels with lower velocity when compared to the P-wave [32]. It has a speed of less than 60 % that of the P-wave [32]. This is the reason S-wave arrives some minutes after the P-wave records have been taken. The velocities of the primary (P) and the secondary (S) waves are estimated as a factor of the density and the coefficients of elasticity of the materials. Equations (1) and (2) show the relations for estimating the velocities of the P and S waves respectively.

$$V_{primary} = \sqrt{\frac{(K+\frac{4}{3G})}{\rho}} \quad (1)$$

$$V_{secondary} = \sqrt{\frac{G}{\rho}} \quad (2)$$

Where, K is the bulk modulus (Nm^{-2}), G is the modulus of rigidity (Nm^{-2}) and ρ the density(Kgm^{-3}).

If the values of the bulk modulus (K) and the modulus of rigidity (G) are always positive, it implies that the velocity of the P-wave is greater than that of the S-wave. S-wave cannot be propagated through fluid [32]. This can be seen when $G = 0$ for different liquids. In this case, the velocity of secondary, S-waves becomes zero. The determination of fluid in the core was done through this process. Fig. 7 shows the features of the primary and secondary waves.

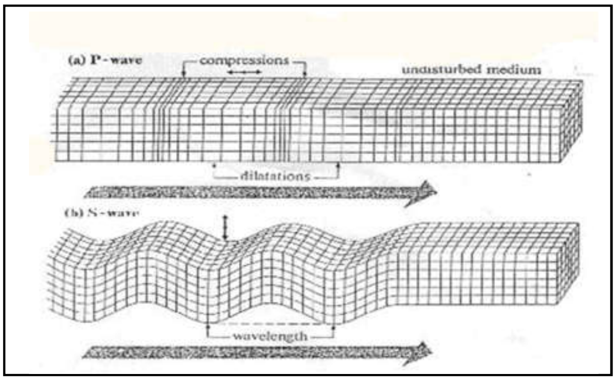

Fig. 7

B. Estimation of the frequency of seismic wave

The frequency of a wave can easily be estimated from its velocity. The linear velocity, V relates the angular velocity, ω with the amplitude, A of the wave. The frequencies of seismic (P and S) waves are estimated as a factor of the amplitude (A). The angular velocity (ω) obtained is then employed in estimating the frequency. Equation (3) enables one to determine the angular velocity when the amplitude (A) is known and the frequency (f) can then be determined from (4).

$$V = \omega \mathrm{A} \quad (3)$$

$$F = \frac{\omega}{2\pi} \quad (4)$$

C. Estimation of Compressional and Tensional Forces

The compressional and tensional forces are respectively estimated from the compressional and tensional stresses. The compressional stress makes the rocks in the earth's crust to push or squeeze against neighbouring rocks. The stress type targets the rocks centres and can result to either vertical or horizontal orientation. If the compression is vertical, the crust will become thin and cut off but if the compression is horizontal, the crust becomes thick and reduced [34]. The compressional force pushes rock against another rock, causing the edges of the plates to collide and rise. High impact compressional stress in the crust can result to a mountain after the collision of plates. Tensional stress caused the plates in the crust to pull apart. This type of stress either cause two plates to move far apart or make the end of each of the plates to move in separate directions. Literatures provide evidence that tensional stress might have been the reason behind the breaking of the heavy continent, Pangaea into the seven continents of the world [34]. The compressional and the tensional forces lead to stress within the plates. Stress, whether compressional or tensional is a function of the force and the cross sectional area in square kilometres. To calculate the compressional and tensional forces, the relations in (5) and (6) can be employed.

$$F_C = \delta_c \mathrm{A} \quad (5)$$

$$F_T = \delta_T \mathrm{A} \quad (6)$$

Where, F_C is the compressional force (N), F_T is the tensional force (N), δ_c is compressional stress (Nm^{-1}), δ_T is tensional stress (Nm^{-1}) and A the Cross sectional area of plate (m^2).

D. Estimation of the Depth of Boreholes

The Common Depth Point (CDP) method is employed to obtain the depth of boreholes. The acoustic velocities of the sources and the time interval with which signals are obtained from the receivers are the major parameters necessary for determining the depth by the CDP method. The depth of the borehole is estimated using the seismic reflection method, also known as the CDP. Using (7), the distance of the incident ray path to the bottom of the borehole (D) can be determined when the incident speed (V) over a two-ways travel time (t) can be ascertained. All these information can be recorded on the receiving seismograph.

$$\mathrm{D} = \mathrm{V}\frac{t}{2} \quad (7)$$

Where, D is the depth to borehole bottom (m), V is the velocity of sound through the hole (ms^{-1}), and T the two-way travel time (s).

E. Estimation of the magnitude of Earth Tremors

An algorithm developed in 1935 by two American seismologists, Charles F. Richter and Beno Gutenberg was used to estimate the magnitude of the tremors [35]. The magnitude of the tremors is determine using an expression of the logarithm of the maximum displacement (amplitude) of the strongest calibrated seismic wave recorded by the seismograph. The algorithm relates the total numbers of earthquakes that have occurred in a lifetime to the magnitude of earthquakes in the region under study [35]. Equation (8) below represents the Richter-Gutenberg earthquakes magnitude assessment algorithm.

$$Log_{10}\mathrm{N} = \mathrm{a} - \mathrm{b}\,\mathrm{M} \quad (8)$$

Where, N is the total numbers of earthquakes that have occurred in a lifetime, M is the Magnitude of earthquakes in the region under study, while a and b are the constants of proportionality known as seismicity indices (parameters)

F. The Seismograph

The seismograph is an instrument used in seismology for the detection and recording of earthquakes as they occur. A seismograph is made up of an attached mass to the base. The mass remains fixed while the base moves during an earthquake. The base movement (motion) in relation to the mass can be converted to electrical potential difference (p.d). Records of the p.d. can be on magnetic tape, paper or other means. The motion of the mass is proportional to the p.d.

record and it can be converted mathematically to a complete ground motion. Fig. 8 shows the physical features of a seismograph.

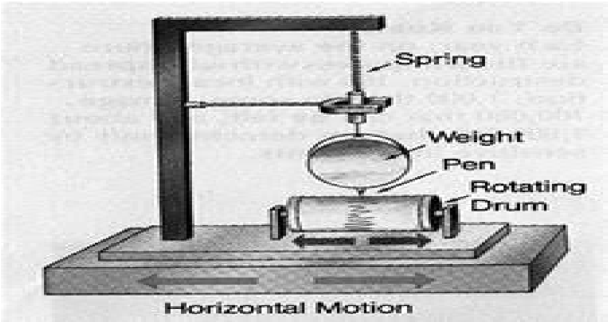

Fig. 8 Features of the Seismograph or Seismometer

III. RESULTS AND DISCUSSION

Five different locations, denoted by LCT A, LCT B, LCT C, LCT D and LCT E where exploration activities have been taking place were identified in the Niger Delta. The seismograph was used to determine the velocities of the seismic waves within the crust of the locations. The P-waves were found to travel in the crust of LCT A, LCT B, LCT C, LCT D and LCT E with average velocities of 4.5km/s, 4.0km/s, 5.5km/s, 5.0km/s and 6.0km/s respectively while the S-waves travel with lower velocities of 3.0 km/s, 2.0 km/s, 4.0 km/s, 3.5 km/s and 5.0 km/s through the same locations. The depth of the exploration boreholes within the five locations were also determine by sending to the bottoms of the holes, sound wave signals from a source over a two ways travel time and obtaining responses from the receiving seismograph on the surface. The varying depths of boreholes and the disposal of wastewater from various exploration activities in the Niger Delta caused some of the underlying plates in the crust to shift away from the boundaries [36].

A. *Quantitative Analysis of Seismic Wave Velocity*

Table I presents the velocities of seismic (P and S) waves at five different locations in the Niger Delta.

Table I. Velocities of P and S Waves across the boreholes locations

Location	P-wave Velocity(km/s)	S-wave Velocity(km/s)
LCT A	4.50	3.00
LCT B	4.00	2.00
LCT C	5.50	4.00
LCT D	5.00	3.50
LCT E	6.00	5.00

The two seismic waves (P and S) migrate outward from a tremor location within the earth's crust. These waves arrived separately at different times on the seismograph. At interval 5 minutes, the signals of the P and S waves were obtained on the seismograph. The P-wave was first noticed due to its higher velocity and amplitude [37]. The path of the Primary/Compressional/P-wave is through rocks of high densities which are deeply rooted into the crust from the five locations LCT A, LCT B, LCT C, LCT D and LCT E in the study area. The recorded P-wave velocities are 4,500 ms-1, 4,000 ms^{-1}, 5,500 ms^{-1}, 5,000 ms^{-1} and 6,000 ms^{-1} and that of the S-waves at 5 minutes' interval are respectively 2,000 ms^{-1}, 3,000 ms^{-1}, 4,000 ms^{-1}, 3,500 ms^{-1} and 5,000 ms^{-1}. The velocity of the wave is then used to determine the frequency as shown in Table II. Fig. 9 reveals the behaviours of P and S waves as they arrive on receiving seismograms.

Table II. Frequencies of p and s waves across the locations

Location	Frequency of P wave (Hz or s^{-1})	Frequency of S wave (Hz or s^{-1})
LCT A	354.05	238.70
LCT B	318.27	159.13
LCT C	437.61	318.26
LCT D	397.84	278.49

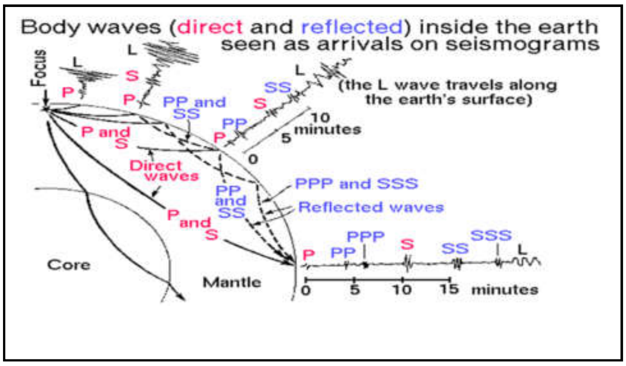

Fig. 9 P and S Waves As Arrived on the Receiving Seismograms [33].

B. *Force in the Crust*

The forces generated within the crust in each of the locations were recorded with seismic sensors. This is done by converting the force due to stress in the crust, into electronic signals observable on a seismic recorder. A seismic sensor with a force gauge graduated in newton (N) and kilonewton (kN) was positioned on each of the locations. The compressional forces across the locations were noticed to be higher than the tensional force. This may be as a result of greater force required to push a plate towards another plate in the crust [38]. This alone can result to tremor in the area. Table III gives the values of the forces generated by different kind of stress within the earth's crust while Plate 1 depicts the drifting apart of plates due to tensional stress.

Table III. Tensional and Compressional Forces at the Locations

Location	Tensional force (N)	Compressional force (N)
LCT A	5.517×10^{13}	3.065×10^{14}
LCT B	1.226×10^{14}	3.678×10^{14}
LCT C	1.839×10^{14}	4.291×10^{14}
LCT D	2.452×10^{14}	4.904×10^{14}
LCT E	6.130×10^{14}	5.517×10^{14}

Plate I. Picture of plates drifting apart due to tensional stress.

The spreading out of waves occurred at the focus but the strong effects of the earthquake are felt at the epicentre. Whatever we experience as effects of earthquake have their source from the focus. The plate's movement depicted in Fig. 10 may be due to infiltration of water into the faults and crevices of rocks. This movement can eventually rupture the ground surface, thereby destroying physical structures in the environment [39]. Despite the solidity of the ground around the study area, the subsurface still experience uniform interval motion which could not be seen but records from the seismograph proved its existence. A probe into the subsurface of the study area shows that the crust is divided into segmental pieces suspected to be the plate tectonics emanating from several gravity combination and heat within the core. Seven major different crustal plates were observed to be moving relative to numerous minor ones. These plates exist in the mantle and crust of the lithosphere in the study area. Disposal of wastewater initiate movement of plates in the subsurface of Langbodo field. Seismic history and information of the study area showed that the plates sometimes get stuck and this lack of movement may build up pressure which can cause the plates to slip. As shown in Fig. 10, the point in the interior from which earthquake originated is the focus. The epicentre on the ground surface receives the highest impact of the seismic waves originating from the focus [39]. The energy release from the focus migrates in different direction and stresses are built up in the process causing seismic waves to travel at different velocities resulting to the disturbances that people feel when earthquakes occur [40].

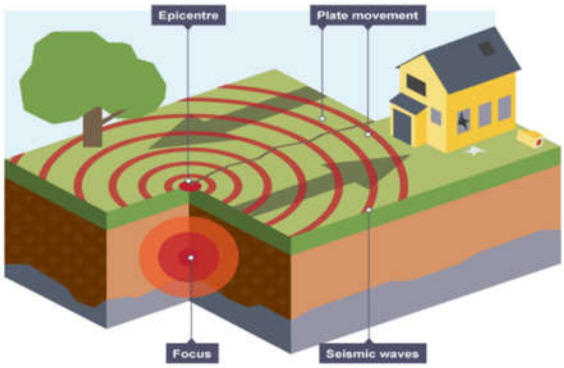

Fig. 10 Features of a Typical Earthquake Environment [33].

C. *Seismic Reflection Method*

The Common Depth Point (CDP) method shown in Fig. 11 was employed in determining the depths of the exploration boreholes in the study area. This CDP approach is also known as the common midpoint method [39]. When the locations of all the receivers are utilized as shot targets. The complexity of data on one point in the subsurface known as ½ (recording channel's number). The seismograph used for this study has 24 channels which recorded 12-fold data. Each of the shots is matched to each of the receivers which positions were shots into maximum wideness. Every point in the subsurface has 12 differently added traces, after the normal shifting, to replace the point. The depths of each of the boreholes were obtained from the velocities of the incident sources and the two ways travel times from the source to the receiver. Table IV shows the depths of each of the boreholes and the magnitude of tremor in the locations LCT A, LCT B, LCT C, LCT D and LCT.

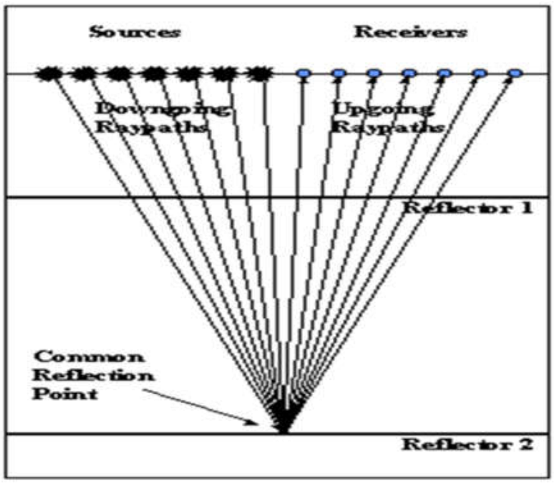

Fig. 11 Common Depth Point Reflection method

Table IV. Depths of the boreholes in the locations

Borehole location	Depths of borehole in the Location	Magnitude (M_L)
LCT A	7,525	3.50
LCT B	7,000	3.20
LCT C	8,000	4.20
LCT D	7,600	4.00

D. Magnitude of Tremors in Study Area

The Richter- Gutenberg recurrence law [36], was employed to determine the probability of the occurrence of heavy earthquakes in the study area. Results obtained from this law revealed that the study area is likely to experience earthquake up to a magnitude of 7.0 M_L in future as the exploration activities continue without deliberate action to control the processes [40]. The Magnitude of the tremors that have occurred in the marked locations are shown in Table IV. Records of the magnitude of tremor in each of the locations were taken by the seismograph placed on strategic points in the study area. Fig. 12 shows the behaviours of P and S waves passing through the earth's interior.

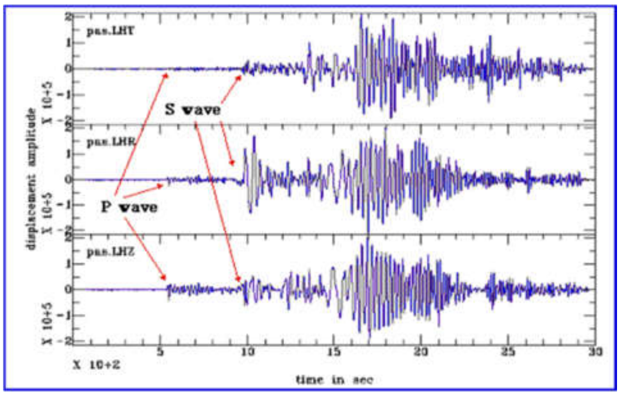

Fig. 12 Behaviours of P and S waves when passing through the earth's interior.

The seismic history of the study area was considered to determine the a and b values in the Richter-Gutenberg recurrence law. The frequency of tremors was thereafter used to determine the corresponding magnitude in Richter-Gutenberg scale (M_L).

When $N = 10$

$$\log_{10} 10 = 0.70 - 0.50M$$

$$1 = 0.2\,M$$

$$M = 5\,M_L$$

At the point when the number of tremor hits 10 in Nigeria, probable magnitude of tremor have reached 5 M_L.

When $N = 100$

$$\log_{10} 100 = 0.80 - 0.60M$$

$$2 = 0.2\,M$$

$$M = 10\,M_L$$

If the number of tremors become 100, probable magnitude of the resulting quakes would have reached 10 M_L.

When $N = 1000$

$$\log_{10} 1000 = 0.90 - 0.65M$$

$$3 = 0.25\,M$$

$$M = 12\,M_L$$

If the number of tremors become 1000, probable magnitude of the resulting quakes would have reached 12 M_L.

When $N = 10000$

$$\log_{10} 10000 = 0.90 - 0.65M$$

$$4 = 0.2\,M$$

$$M = 20\,M_L$$

If the number of tremors become 10000, probable magnitude of the resulting quakes would have reached 20 M_L.

When $N = 1000000$

$$\log_{10} 1000000 = 1.00 - 0.80M$$

$$6 = 0.24\,M$$

$$M = 25\,M_L$$

If the number of tremors become 1000000, probable magnitude of the resulting quakes would have reached 25 M_L.

This clearly shows that as injection of fluid continues, pressure created in the crust can still continue for years leading to increasing number of quakes and as the number of quakes increases, there is tendency for the magnitude to increase. This is because, the R-G recurrence law shows that M increases with increase in N. This is shown in the graph (Fig. 13) below. It is normal to argue that the number of tremors may likely not be up to the projected figures in Table V but bearing in mind the daily increase in indiscriminate sinking of water and exploration boreholes and other seismic activating practices around the country, one can settle for the figures if not higher because the R-G law only predict earthquake occurrence based on the number of quakes that have occurred or the ones projected, which are likely to occur over a stated period of time.

Table V. Proposed Values of a and b Based on the R-G Recurrence Law

Number (N)	a-value	b-value
10	0.70	0.50
100	0.80	0.60
1000	0.90	0.65
10000	1.00	0.80
1000000	1.10	0.86

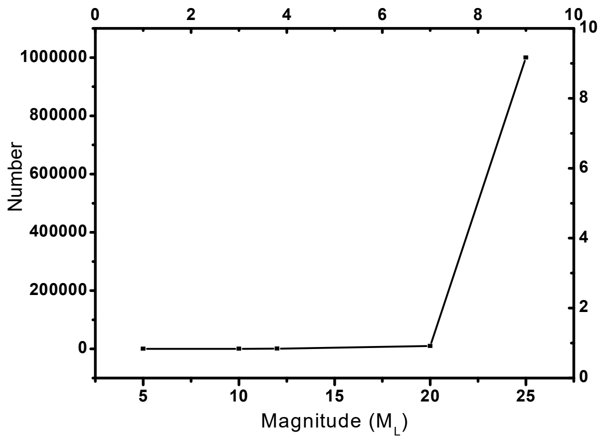

Fig. 13 Variation of Magnitude with the frequency of Earthquakes

Fig. 13 shows a gradual increase in the magnitude of tremors as the frequency increases. A normal increase in magnitude from 5 M_L to 10 M_L is shown for locations A and B with frequency 10 and 100. This trend however changed when the number of tremor is 1000 as the magnitude falls below the expected value. This may be due to the seismic activities which is evident from the seismic history of the study area. The usual trend shows when the predicted frequency hits 10000 and 1000000 as the magnitudes become 20 M_L and 25 M_L. This is similar to the work of [40] where observations of the seismic histories of areas in Nigeria where tremors have occurred were made and conclusion were drawn based on the R-G recurrence law that Nigeria is likely to witness tremors of up to 7.1 M_L some years to come. Research done by [40] did not state what might have been responsible for the previous tremors in Nigeria but this has been taken care of by the findings of this research.

It is evident from Fig. 14(a) that the velocity of P-wave is higher than that of the S-wave. The velocity of P-wave ranges from 4.0 m/s to 6.0 m/s while that of the S-wave ranges from 2.0 m/s to 5.0 m/s. This is due to the higher amplitude and wavelength of the P-wave. However, Fig. 12 and 14(a) also showed fluctuations in the velocities of both P and S waves in some of the locations with the same magnitude of tremor. Reference [41] opined that variation in seismic velocities may be influenced by type of stress, pressure in the pores, saturation, porosity and temperature. As frequency of a wave is directly proportional to its velocity, it is worthy to note that the frequency may likely behave the same way as the velocity.

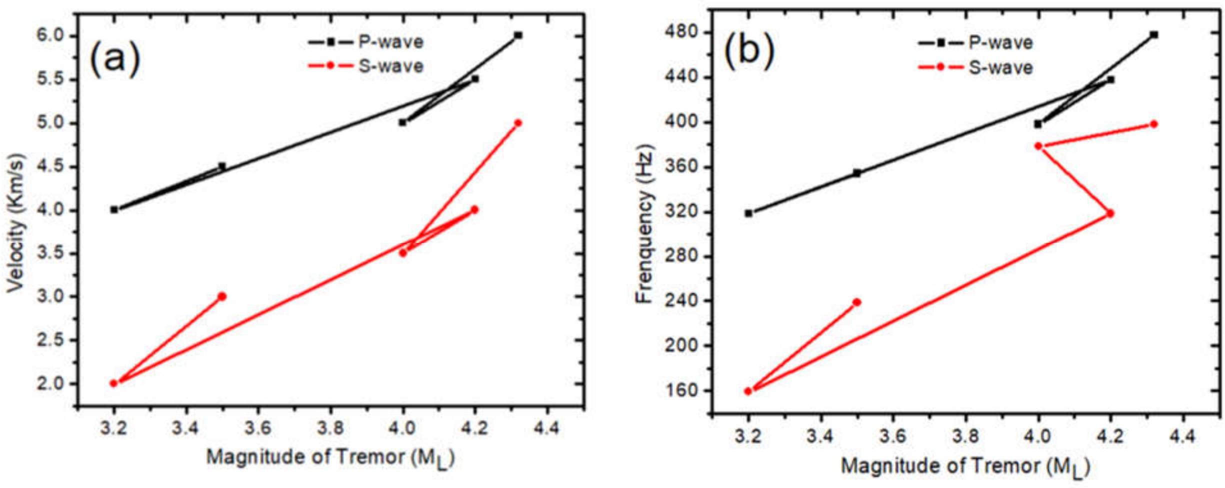

Fig. 14 Variation of Velocities and Frequencies of P and S Waves with the Magnitude of Tremor

Results as revealed in Fig. 14(b) portray the fluctuation of the frequency of the P and S waves even at the same level of magnitude in the mapped out locations of the study area. The frequency of the P-wave ranges 320 Hz to 480 Hz while that of the S wave is from 160 Hz to 400 Hz. This can be as a result of chemical composition of the rocks in the crust. Research done on the fluctuation of frequency and distance by [42] showed that waves with frequencies higher that the range of 3 to 5 Hz experience variation of amplitudes of earth tremors characterized by patterns that are isotropic in nature. Despite the fluctuations noticed in the velocity and frequency, it remains clear from Fig. 14 (a) and (b) that both the velocity and frequency of waves (whether S or P) increase as the magnitude of tremor increases in the study area.

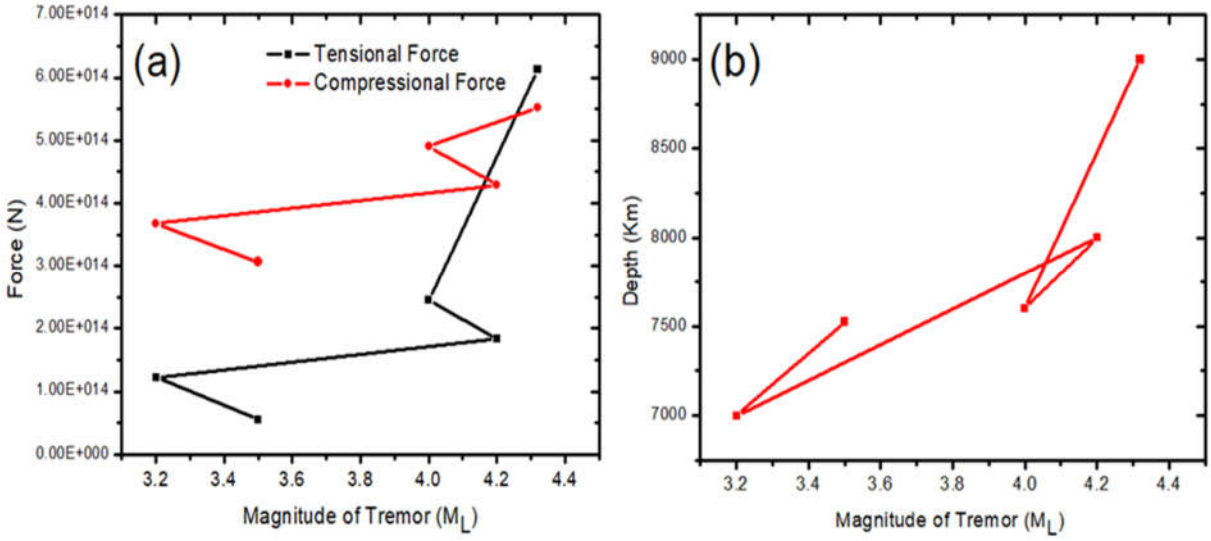

Fig. 15 Variation of Depth and Force with the Magnitude of Tremor

Fig. 15 (a) revealed the variation of the force of tension and that compression with the magnitude of tremor in LCT A, LCT B, LCT C, LCT D and LCT E. The tensional force is higher in value than four of the values of the compressional force. This is because some gorges indicating active tensional force in four of the mapped out location. This means that so many of the underlying plates are drifting away from their usual locations thereby causing a physical breakage on the ground. It is important to note that the compressional force at LCT E is higher than that of all the tensional forces. This can be attributed to the elevated upland around the location LCT E. The upland may be as a result of convergence of plates in the crust, leading to building of mountains in the location. This is the reason the magnitude of tremor at LCT E is higher than that of the other points for both tensional and compressional forces. Despite the fact that the force of tension is higher than that of compression for almost all the locations, the magnitude of tremor for locations LCT A, LCT B, LCT C and LCT D still remains the same for both tensional and compressional forces. Forces exerted on the crust in the study area are capable of slipping or converging the underlying plates and if this continues, an earthquake can occur.

Fig. 15 (b) showed that the depths of exploration boreholes in all the five locations is also a determining factor whether or not earthquakes will occur in the study area. Exploration boreholes in the Niger Delta comes with depths, depending on how many meters or Kilometres away from the surface, the hydrocarbon is located. The extent to which the drilling of exploration boreholes affects tremor in the study area is determined. Thorough comparison of each of the five locations showed, (LCT A, 7525 km, 3.50 M_L), (LCT B, 7000 km, 3.20 M_L), (LCT C, 8000 km, 4.20 M_L), (LCT D, 7600 km, 4.00 M_L) and (LCT E, 9000 km, 4.32 M_L). This implies that that the magnitude of tremor in the five locations increases with increase in the depth of the boreholes. This agrees with [15], that the disposal of wastewater results into infiltration of fluid into the plates. This caused slipping of plates and thereafter an earthquake in the location. Wastewater coming from the bottom of the deepest of the holes has the ability to penetrate from the deepest to the surface plates [15]. If exploration activities continue without control, earthquake may occur and this will put the lives of people around the location at risk.

IV. CONCLUSION

A careful comparison of the velocities of the body waves (P and S), frequencies of P and S waves, forces of tension and compression, depth of exploration boreholes and the magnitude of tremor in the five mapped out locations from the Niger Delta shows that the magnitude of tremor in the locations changes with the aforementioned. Based on the findings of this study, the velocities and frequencies of body waves, forces in the crust and the depth of exploration boreholes in the Niger Delta are the reasons for the previous tremors in the study area. The Richter-Gutenberg recurrence law [35] showed that the Niger Delta is likely to experience an earthquake of about 7.0 M_L, if exploration activities are not controlled. Hence, exploration activities in the Niger Delta should be well monitored and controlled by the appropriate authorities, as this will guide against future occurrence of earthquake.

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