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Integration of Seismic Velocities, Vp/Vs and Poisson Ratio Obtained from Seismic Refraction Analysis and Correlation with Borehole Lithologic Information to Reduce Ambiguity in Exploration for Clean Groundwater Aquifer in Yenagoa, Bayelsa State, South-South, Nigeria

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Abstract
A seismic refraction investigation has been conducted in this study to determine the presence of potable groundwater aquifer within the subsurface around Yenagoa, Bayelsa State, South-south, Nigeria. The analysis refraction results were correlated with the existing borehole information obtained from resistivity surveys carried out in the same study area. There was a good agreement between the seismic results and borehole information. To obtain the layer velocities used for the seismic interpretations, a t-x curve was plotted with the refraction data obtained from the seismic events (first breaks) picked using the ReflexW Version 3.5.7 Software. The p-wave layer velocities were then derived as the inverse of the slope of various segments of the curve while the downdip and updip thicknesses of the layers were computed using the time intercept equations. The s-wave layer velocities were calculated from a well-fitted regression model. The results obtained depicted a three-layer model, with layer velocities increasing with depth due to variation in lithology compositions. Based on the results and correlation with the borehole data, the aquifers in the study area were located in the third and fourth layers. The third layer, with p-wave velocity ranging from 370m/s to 560m/s, s-wave velocity ranging from 218m/s to 329m/s, Vp/Vs ratio lying between 1.6995 and 1.7 and Poisson ratio ranging from 0.235 to 0.24, was composed of consolidated water-saturated sand with intercalations of clay and was indicated as the first aquifer in the area. The average depth of this layer from the ground surface to the water table was about 12.8m. However, this aquifer may not yield potable water due to the poor texture of the aquifer, presence of clay, lack of coarse/gravelly sand filter and possible infiltration of surface contaminants. Correlation of the seismic model with the borehole lithologic model showed that there was an appreciable agreement between them, with the borehole information revealing the third layer as a contaminated aquifer. The fourth layer was found to be a better aquifer compared to the third layer given the increase of velocity with depth. Although this layer was not adequately penetrated by the refracted waves, correlation with the existing borehole information showed that the fourth layer was made up of weathered gravelly/coarse sand and could serve as a more reliable source of clean groundwater in the study area. Therefore, integrating velocity, Vp/Vs and Poisson ratio obtained from seismic refraction technique with borehole lithologic information can improve our success ratio in the search for clean groundwater.

Keywords: *Exploration, Clean, Groundwater, Aquifer, Seismic, Refraction, Borehole*

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I. Introduction

Exploration for groundwater aquifer and assessment of its productive potential have been extensively achieved around the world by the application of the electrical resistivity method of geophysical prospecting [eg 1, 2, 3, 4, 5]. However, the seismic refraction technique serves as another effective and complementary geophysical approach for distinctly delineating the subsurface lithological structure and depths of aquiferous strata. An integration of the seismic method with the vertical electrical sounding technique offers an additional advantage of comparing and correlating results from both the seismic and geoelectric surveys, giving more detailed information that can help in understanding the characteristics of subsurface lithologies in relation to groundwater potentials. A number of authors had utilized the seismic refraction technique to obtain a tomographic velocity structure of the subsurface as a tool for assessing the groundwater potential. George and Okwueze [6] carried out a seismic refraction investigation of groundwater in parts of the Oban Massif, Southeastern, Nigeria, using a portable MOD S79 3-channel digital signal seismograph. Their objectives were to determine the depth to the water table, the thickness of the saturated overburden and the depth to the basement for the purpose of groundwater development. By correlating the seismic interpretation with available borehole lithologic data, they found that good potential aquifers for groundwater abounded in the study area. Nwankwo et al. [7] in their seismic refraction study used a 12-channel digital signal enhancement Terraloc ABEM Seismograph in a continuous forward profiling to determine the depth to the aquifer in Rukpokwu area of Rivers State, South-south, Nigeria. From the analysis of the refraction data which revealed a three-layer model, they found that the aquifer was located in the third layer which was characterized by a p-wave velocity range of 275.0 m/s to 714.3 m/s and a depth range of 12.52m to 26.56 m. Comparison of their seismic results with the depths of existing water boreholes and geoelectric resistivity data showed that their result was reliable. They therefore concluded that the seismic refraction method is a useful tool in defining the depth to groundwater aquifer. Jagadeshan et al. [8] also conducted a seismic refraction survey in Secha Arba Minch Ethiopia using a 12-channel Oyo McSeis Seismograph for investigation and evaluation of the hydrogeological reservoirs in the area. The result of the seismic velocity distribution indicated three different subsurface lithologic layers, with the depth to the groundwater-saturated layer ranging from 36m to 50m from the ground surface. The result showed that the aquifer was a weathered basaltic layer with average thickness of about 23m. The seismic refraction interpretations in these studies were based on the use of seismic p-wave velocities only. However, some authors had reported that the use of seismic refraction p-wave velocities alone could lead to misleading results [9, 10]. Desper et al. [11] independently reported that higher velocities could be possible for deeper fully saturated layers, but in areas such as in the tropics some saturated layers might have much lower velocities due to the rapid rising of water levels from heavy rainfall. Due to the ambiguity in the use of Vp values alone, some authors had included secondary wave velocities (Vs) in the seismic acquisition and further validated the presence of groundwater aquifers using the Vp/Vs ratio [9,12]. Improvement in geophysical interpretation for the investigation of water saturation in subsurface layers using the combination of Vp and Vs is an idea that was also strongly supported by the long-established observations in the works of Garner and Harris [13], Domenico [14], and Tatham[15] in addition to the recent results of the studies conducted by Omudu and Ebeniro [16], Omudu [17] and Nwankwo [18]. However, their use of the discriminators (Vp/Vs and Poisson ratio) was limited to the search for hydrocarbon resources. The general results of these authors showed that Vp/Vs ratio for well consolidated water-saturated sands is less than 2.0, while high porosity water-saturated sandstones tend to have high Poisson ratio of 0.30 to 0.40. Poisson ratio tends to decrease as porosity decreases and sediments become more consolidated. The gas-saturated high porosity sandstones tend to have abnormally low Poisson's ratio in the order of 0.10 and Vp/Vs less than 1.4. Based on these observations, the Vp/Vs and Poisson ratios can thus be used complimentarily with Vp to reduce ambiguities in seismic interpretation for investigation of groundwater aquifer but this requires the vigorous acquisition of shear wave velocities Vs in addition to the Vp data.

To obtain the seismic velocities of the overburden and basement layers, the conventional seismic refraction method utilizes dynamic low strain primary and secondary seismic waves. The waves can be generated by striking metal plates stuck to the ground vertically and horizontally with a sledge hammer. The generated waves propagate through the ground and are critically refracted at lithologic interfaces before returning to the ground surface where they are recorded by detectors. Whereas the refracted primary waves arrive at the ground surface vertically and are recorded by appropriate set of geophones, the secondary waves arrive horizontally at the ground surface and are recorded by another set of geophones. Plots of the arrival times of the waves against the geophone spacings (known as t-x curves) yield the seismic velocities which increase smoothly with vertical layer depths. The subsurface compressional velocity structure can help the geophysicist to draw the lithologic profile from which the number of layers, the associated lithology of each layer, the depth to the water table and the thickness of the weathered aquiferous bedrock can be inferred. The Vp data can be further combined with the Vs data to derive the discriminators (Vp/Vs and Poisson ratio) which are diagnostic of lithologies and water-saturated strata.

Yenagoa (the study area), located in the Niger Delta region of Nigeria, is a geologic environment which is composed of sediments of alluvial origin. Most geophysical surveys carried out in the area and its environs were predominantly based on the use of geoelectric and borehole techniques. In the other parts of Niger Delta with the same sedimentary compostion as the study area, the seismic refraction studies carried out to investigate the groundwater aquifer potential was based on the use of seismic p-wave velocity alone. This, however, can lead to ambiguity in interpretation of seismic refraction data owing to the effect of sediment compaction and differential pressure on the p-wave velocity as the depth of lithology increases. It is therefore necessary to apply an appropriate and more reliable geophysical approach that can reduce the ambiguities in seismic interpretation in locating clean aquiferous layers within the subsurface. However, up till today there is no known geophysical work that has been conducted in Yenagoa and its environs involving the integrated use of seismic p-wave velocities, Vp/Vs, Poisson ratio and borehole data to investigate the presence of potable groundwater in the study area. In this study therefore, the seismic refraction technique was used to obtain Vp, while Vs was calculated from the Vp data using a well-fitted regression model. With Vp and Vs known, the Vp/Vs and Poisson ratios were derived using the appropriate mathematical relationships. The Vp/Vs and Poisson ratios were then used complementarily with Vp in addition to existing borehole information to improve the seismic interpretation. Overall, lithologic distribution in the study area was obtained with more accuracy and the presence of potable groundwater-saturated strata was detected.

II. Materials And Method

2.1The Study Area

This study was carried out at Opolo, Yenagoa, Bayelsa State, South-South, Nigeria (Figure 1). Yenagoa is the capital city of Bayelsa State and is located within the Niger Delta Basin. It covers an area of 50km^2 and lies on longitudes 006^{0}10'307'' and 006^{0}25'10.53'' east of the prime meridian and latitudes 04^{0}51'39.73'' and 05^{0}2'25.53'' north of the equator [19]. Yenagoa lies within the freshwater and meander belt geomorphic unit of the Niger Delta Basin [20]. The Niger Delta itself is basically a sedimentary basin and tertiary delta situated in equatorial West Africa in the Gulf of Guinea. The delta extends throughout the Niger Delta Province and borders the Atlantic Ocean at the Southern end of Nigeria between latitudes 3^0 and 6° and longitudes 5° and 8° [21] (Figure 2). Reports on the stratigraphy of the Niger Delta show that its subsurface lithology is comprised of an upper sandy formation called the Benin Formation, an intermediary unit of alternating sandstone and shale known as the Agbada Formation and a lower shaly formation called the Akata Formation. The Benin Formation, with an estimated thickness of about 2km, is fluval in origin and is overlain by the Quaternary floodplain alluvial sediments which are composed mainly of clay, silt, sand and silty-clayey sand [22, 23, 24]. It is within the Benin Formation that the regional aquifer lies and it is known to be very porous and highly permeable [19]. Many of the groundwater boreholes in Yenagoa and its environs are drilled within these alluvial sediments of the Benin Formation.

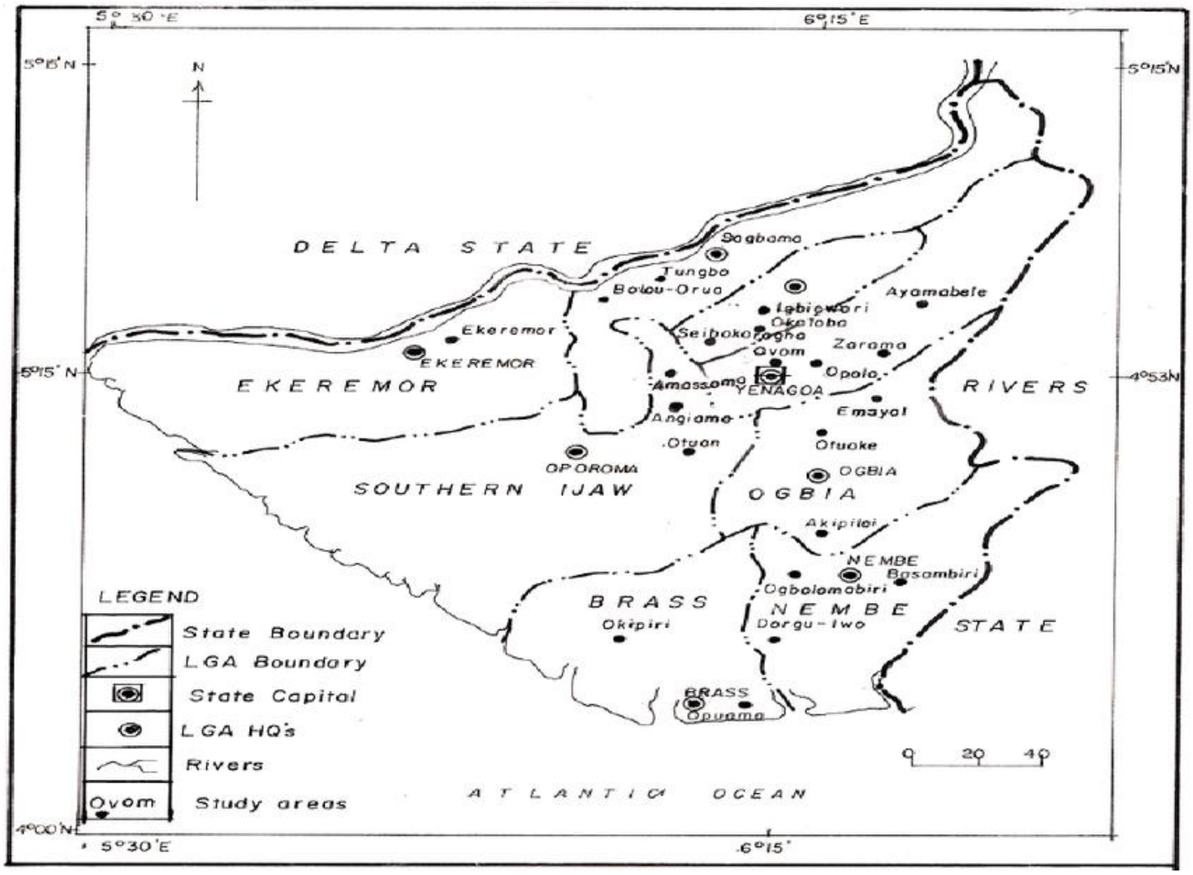


Figure 1: Map of Bayelsa State Showing Opolo, Yenagoa (the Study Area) (Source: [25]

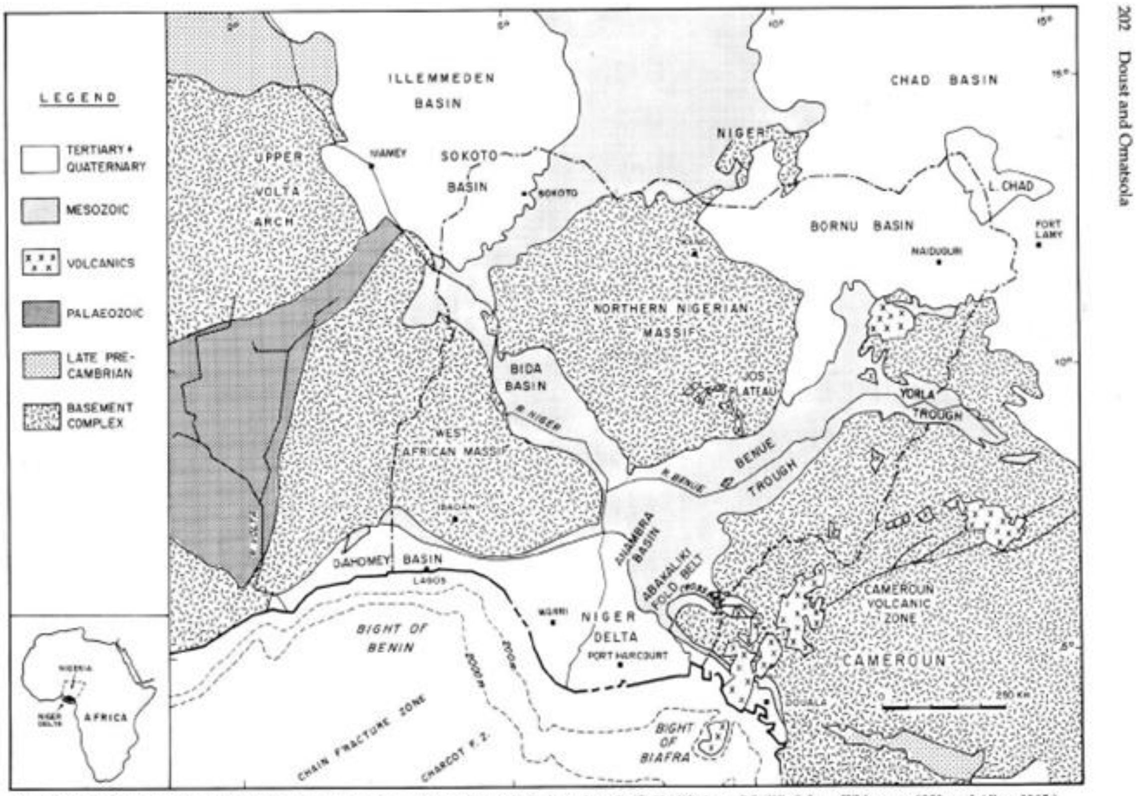


Figure 1—Simplified geologic map of Nigeria and surrounding areas showing main drainage into the Gulf of Guinea. (Modified from Whiteman, 1982, and Allen, 1965.)

Figure 2: Location Map of the Niger Delta (Modified from Whiteman [26] and Allen [27])

2.2 Instrumentations and Method

A dynamic low strain seismic refraction survey was carried out in order to investigate the presence of potable water in hydrogeological reservoirs within the subsurface. The profile line consisted of 12 geophones positioned along a straight line and covered a distance of 85m from the zero offset shot point. The first geophone was positioned at a distance of 30m from the shot point and a 5m spacing was maintained between the geophones. With the geophones cascaded to a 12-channel Terraloc ABEM Signal Seismograph, the first arrivals were detected and recorded as photographic traces in SEG-2 format. A 16kg sledgehammer and metal plates were used for generating the primary (p-) waves. To generate the waves, the metal plate was struck vertically with the sledge hammer. This strike orientation of the hammer-plate system was necessary because the direction of particle vibrations associated with the passage of p-wave is the same as the direction of the wave itself, and thus allows the geophones to detect and pick the p-arrivals. Forward and reverse shots were carried out along the profile in order to account for bed dipping, with 3-4 stacks recorded for every p-wave shot made.

The seismic refraction data was processed using the ReflexW Version 3.5.7 Software. First, the software was used to pick the first arrivals consisting of direct arrivals and refracted arrivals. The direct waves from the first layer/topsoil and headwaves from the deeper layers arrived at the geophones at times that varied depending on paths traveled and layer velocities. After picking the first breaks for all the seismic events, a t-x curve (showing a graph of the arrival times against the geophone positions) was plotted. The velocities (Vp) of the homogeneous and isotropic layers were obtained as the inverse of the slope of segments of the curve, while the layer depths/thicknesses were obtained from the intercepts of the seismic plots. The s-wave velocities Vs were not acquired from the survey but were rather computed from the Vp using a well-fitted regression model. The p-wave, s-wave velocities, Vp/Vs, Poisson ratio and the layer thicknesses were used in conjunction with the interface dips (which were also considered in the refraction modeling) to facilitate the seismic interpretation.

For a multi-layer case with n layers, the thickness Z_i of an ith layer can be determined using the travel time intercept for any ray critically refracted along the top surface of the (i+1)th layer. This is given by

$$t_n = \frac{X}{V_n} + \sum_{i=1}^{n=1} 2\,Z_i \frac{\sqrt{Vn^2 - V_i^2}}{V_n V_i} \qquad (1)$$

where x is the geophone distance and V_n, V_i are the appropriate input velocities.

The Vs was calculated from Vp using the well-fitted regression equation given by Adewoyin et al. [28] as

$$Vp = 1.7Vs \qquad (2)$$

To further improve the seismic interpretation, the Vp/Vs and Poisson ratio σ were used complementarily with the Vp. The model-calculated Vs was combined with the acquired Vp to mathematically derive Vp/Vs and σ for the layers. As pointed out earlier, the Vp/Vs and Poisson ratio are not only used as lithology discriminators but are also sensitive to fluid types in formations. Besides, unlike the p-wave velocity Vp, they are not affected by sediment compaction with depth [13, 14, 17, 18, 29]. The Poisson ratio σ was calculated from its relationship with Vp/Vs given by:

$$\sigma = 0.5\,\frac{\left(\frac{Vp}{Vs}\right)^{2} - 1}{\left(\frac{Vp}{Vs}\right)^{2} - 1} \qquad (3)$$

Equation (3) thus gives Vp/Vs ratio as

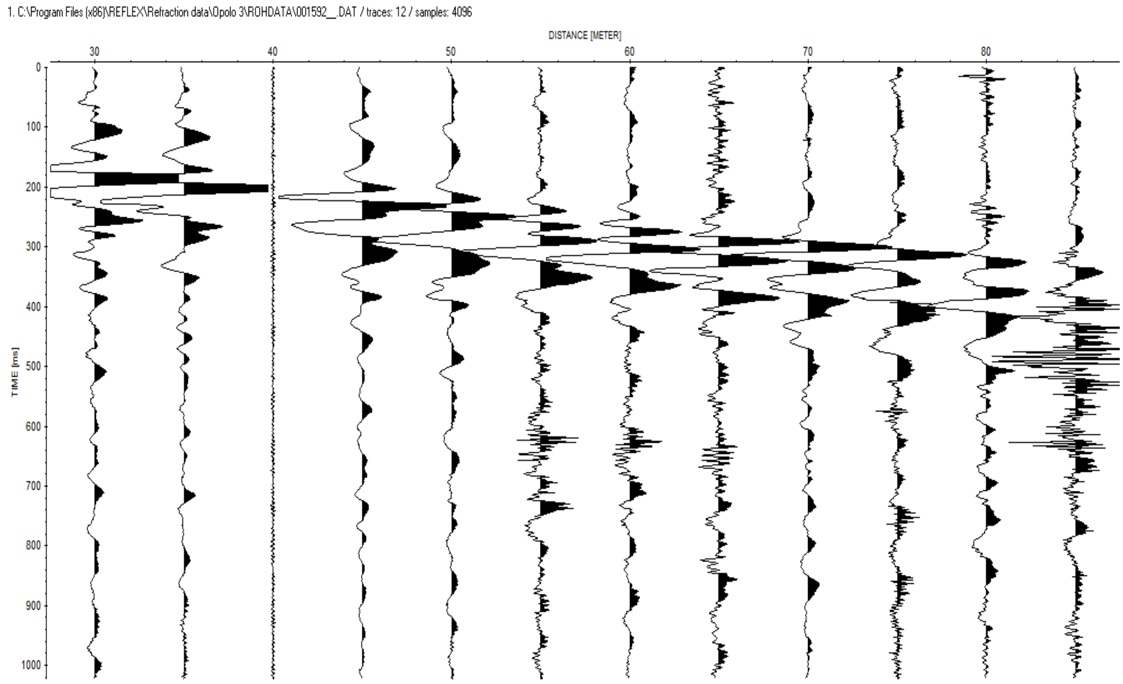
$$\frac{Vp}{Vs} = \left(\frac{2(1-\sigma)}{(1-2\sigma)}\right)^{\frac{1}{2}} \qquad (4)$$

III. Results And Discussion

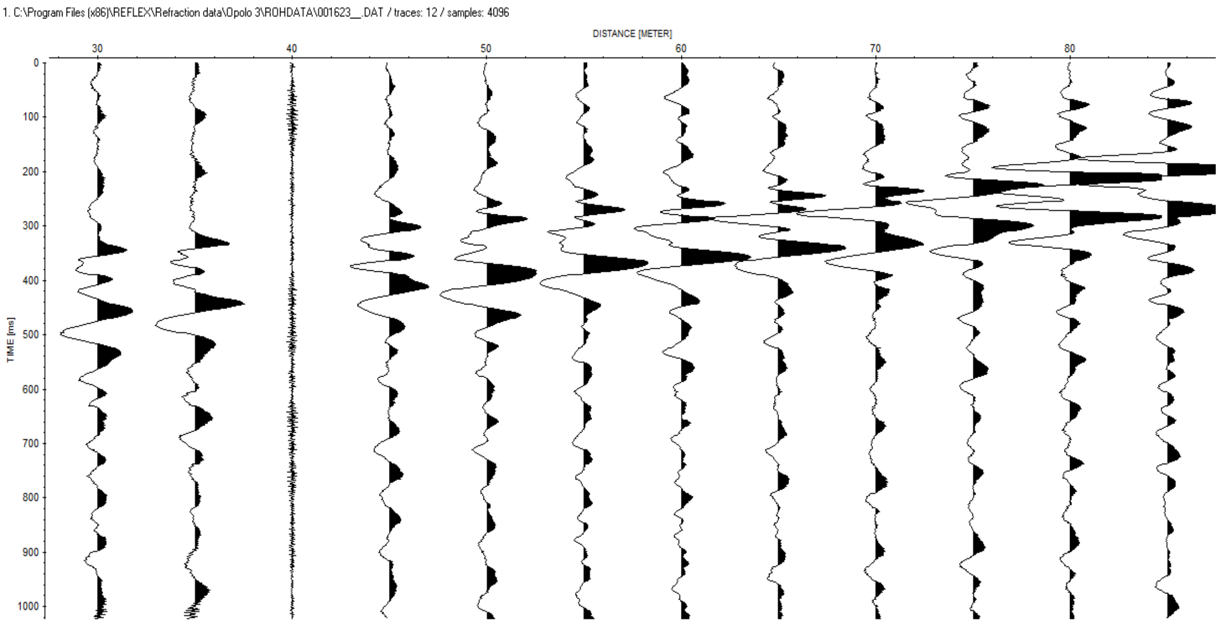
Figure 3 shows the seismograms for the forward and reverse shots for the profile in the study area.The first arrivals were picked from the seismograms using the ReflexW Version 3.5.7 Software. Fig.4 is the t-x curve plotted with the data obtained from the picked seismic events. The layer velocities were obtained as the inverse of the slope of various segments of the curve while the downdip and updip thicknesses of the layers were computed from the time intercept equations. The plot depicts a three-layer model, with layer velocities increasing with depth due to variation in lithology compositions. The topmost layer had the lowest seismic velocities with the p-wave velocity ranging from 93m/s to 106m/s with an average velocity of 100m/s, and s-wave velocity ranging from 55m/s to 62m/s, with a mean s-wave velocity of 59m/s. The Vp/Vs ratio for this layer ranged between 1.669 and 1.7 and the Poisson ratio correspondingly ranged between 0.235 and 0.24. Given these values of Vp, Vp/Vs and Poisson ratio, the first layer was found to correspond to the topsoil consisting mainly of consolidated wet clay. The thickness of this layer had values between 3m and 7.9m with an average of 5.5m**.** The second layer had the p-wave seismic velocity ranging from 184m/s to 253m/s with an average of 219m/s and s-wave velocity lying between 108m/s and 149m/s with an average of 129m/s. The Vp/Vs ratio fell within the 1.7 range while the Poisson ratio correspondingly was within the 0.24 range. The thickness of the layer ranged from 5.0m to 9.5m with an average of 7.3m. These quantitative results of Vp, Vp/Vs and Poisson ratio indicated that the second layer sediments were comprised mainly of consolidated water-saturated clayey sand. Therefore, wells dug into this layer would produce water but the water would be unfit for drinking because of the vulnerability of the layer to surface and clay impurities. These results obtained for the first and second layers were correlated with the existing borehole lithologic information obtained from a resistivity/borehole survey carried out around the same study area by Oboriel et al. [25] (Figures 5a and b). The results were found to be in agreement. In this area, the results from the survey covering twenty (20) VES stations depicted a four-layer system or lithological units within the depths probed, with the top layer having a thickness lying between 0.5 and 1.5 m and consisted of clay. The thickness of the second layer ranged from 4.7 to 11.2 m with an average thickness of 7.95m and was composed mainly of clayey sand. The borehole information showed that many of the hand-dug wells existing in the area were located in the second layer. Comparing the results of the borehole survey in the area with the seismic results for the first and second layers therefore clearly showed that they were in agreement. Slight differences in thicknesses between the seismic model and the borehole lithologic model arose from the interface dipping that was factored into the seismic model but was not included in the borehole model.

Furthermore from the seismic results obtained, the third layer had the p-wave velocity ranging from 370m/s to 560m/s with an average of 465m/s and s-wave velocity ranging from 218m/s to 329m/s with a mean of 274m/s. The Vp/Vs ratio for the layer fell between 1.6995 and 1.7 while the Poisson ratio correspondingly ranged from 0.235 to 0.24. Given the Vp, Vp/Vs and Poisson ratio values obtained, the third layer was interpreted as a unit composed of water-saturated sand with clay intercalations. The third layer was thus indicated as the first aquifer in the area with an average depth of about 12.8m from the ground surface.

However, this aquifer may not yield potable water due to the poor texture of the lithology, presence of clay, lack of coarse/gravelly sand filter and possible infiltration of surface contaminants. Again, the seismic model obtained (Figure 5a) was correlated with the existing borehole lithologic section in the study area (Figure 5b) and there was an appreciable agreement and consistency between both models. Like the seismic model results, the borehole lithologic model revealed the third layer as the first aquifer consisting of fine medium sand with clay lenses. It showed the average depth of this third aquiferous layer to be about 9.5m from the ground surface, with its thickness varying between 23m and 59m. The difference in the average depth to this first aquifer reported from both models can be accounted for by the bed dipping which was considered in the seismic refraction model but was not included in the borehole model. In the final analysis, given the smooth increase of velocity with depth in the seismic analysis results, the fourth layer was found to be the second aquiferous layer with clean freshwater saturation. Although this layer was not adequately penetrated by the refracted waves, correlation with the existing borehole information showed the fourth layer to be made up of weathered gravelly/coarse sand and occurred at an average depth of 50.5m from the ground surface. Oboriel et al.[25] reported from their resistivity/borehole survey results in the area that the fourth aquiferous layer possessed better indices for clean groundwater yield due to its texture and lesser vulnerability to infiltration of surface contaminants. The fourth layer could therefore serve as a more reliable source of clean groundwater in the study area.



(a)



(b)

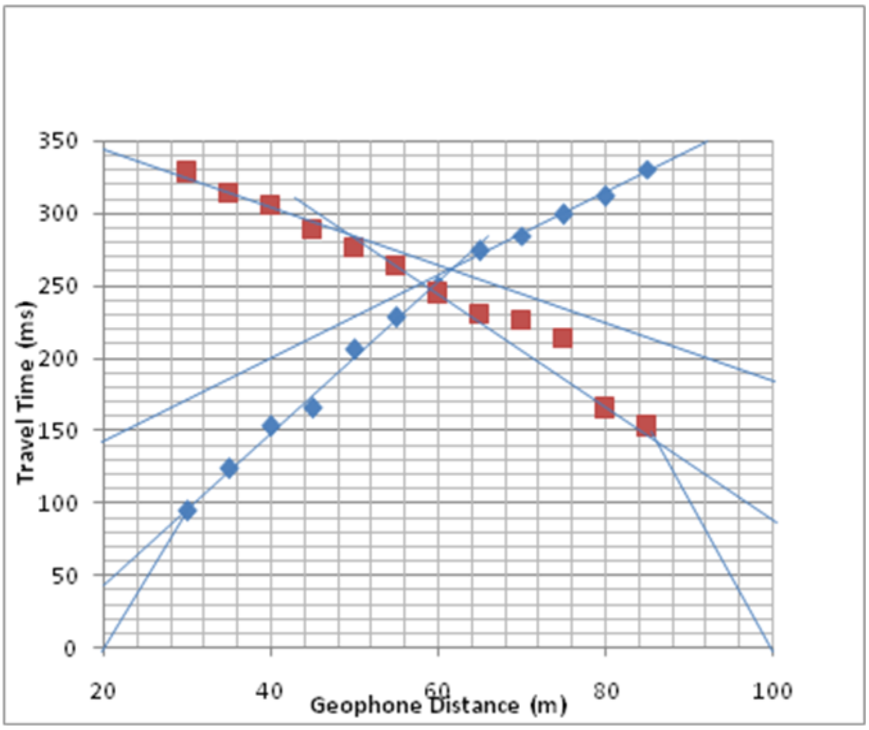


Figure 4: The travel time versus geophone distance (t-x) plot. Blue points are plotted points from the forward profile data; red points are plotted points from the reverse profile data.

Table 1: Values of layer Velocities, Thicknesses and Depths from the Seismic Refraction Data

Layers	Vp (m/s)			Vs (m/s)			Thickness (m)			Depth from Surface (m)		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Layer 1	93	106	100	55	62	59	3.0	7.9	5.5	0.0	0.0	0.0
Layer 2	184	253	219	108	149	129	5.0	9.5	7.3	3.0	7.9	5.5
Layer 3	370	560	465	218	329	274	-	-	-	8.0	17.4	12.8

Table 2: Values of Vp/Vs and Poisson Ratio from the Seismic Analysis

Layers	Vp/Vs			Poisson Ratio σ		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
Layer 1	1.699	1.7	1.6995	0.235	0.24	0.24
Layer 2	1.7	1.7	1.7	0.24	0.24	0.24
Layer 3	1.6995	1.7	1.6995	0.235	0.24	0.24

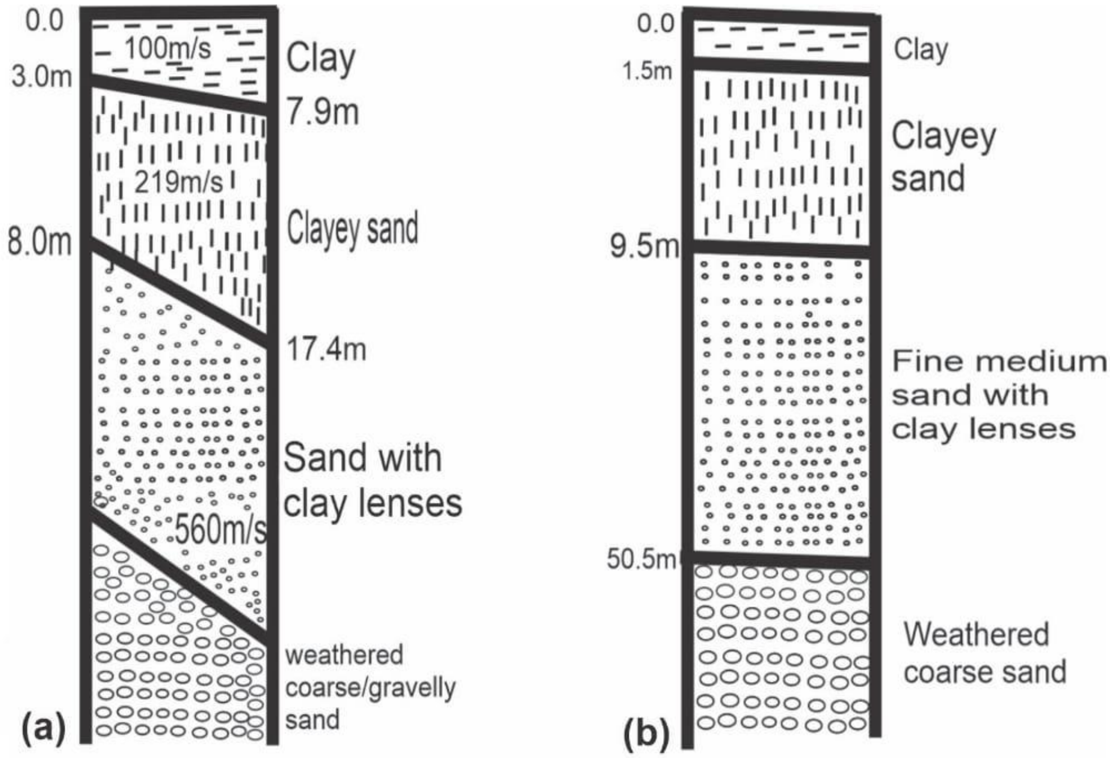


Figure 5: (a) and (b) respectively show the seismic refraction model and borehole lithologic section used for the correlation

IV. Conclusion

The results of the seismic refraction investigation in this study had shown the Yenagoa area of Bayelsa State to be underlain by two aquiferous layers, comprised of the third layer and promisingly the fourth layer. The third layer, made up of water-saturated sand with clay lenses, was delineated as a possible aquifer but may not yield potable groundwater due to clay presence in the aquifer, a fairly poor texture, lack of fine gravelly sand filter and possible migration of surface contaminants into the aquifer due to its shallow depth from the ground surface. The fourth layer, made up of weathered coarse/gravelly sand, could serve as a more reliable source of clean groundwater as it was found to possess better indices for clean groundwater yield due to its texture and lesser vulnerability to infiltration of surface contaminants.Overall, it has been shown in this study that integrating seismic velocity, Vp/Vs and Poisson ratio obtained from seismic refraction technique with borehole lithologic information can improve our success ratio in the search for clean groundwater.

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