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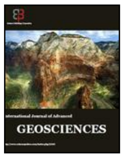

Determination of rock elastic parameters using VP/VS relationship for escravos area, Niger delta, Nigeria

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Abstract

The elastic properties of sedimentary rocks in the Escravos area, Niger delta, Nigeria, have been computed for six boreholes drilled to a maximum of 22 m. Compressional wave (Vp), Shear wave (Vs) velocities and density (ρ) values were computed for the lithologies at the six different boreholes. The elastic properties were estimated using the computed Vp, Vs and ρ values. Empirical relations between the derived elastic and physical properties of the subsurface lithologies encountered in the boreholes were established. The results show three distinctive layers comprising Sand, Sandy clay and Clayey sand existing in the boreholes. The computed values of the elastic properties show that the formation encountered in the wells are moderately dense and saturated with water. A distinct linear relationship existing between Vp / Vs was observed; while an exponential relationship was derived for σ/Vs. Empirical relationships derived from this study for Vp - Vs is given as Vs = 0.902Vp - 1164, and for Vs - Poisson's is given as $\sigma = -1E\text{-}07Vs^2 - 4E\text{-}05Vs + 0.502$. The values of allowable bearing capacity and the settlement suggest that the study area is able to support engineering construction. Empirical relations established for Vp - Vs and Vs - Poisson's is characteristics of sedimentary terrain, and can be used within the Escravos area, Niger Delta, Nigeria.

Keywords: *Allowable Bearing Capacity, Elastic Properties, Empirical Relations, Settlement.*

1. Introduction

For any engineering and geotechnical project, rock elastic constants provide valuable information about the subsurface rock. The involvement of geophysics in civil and environmental engineering has become a promising approach. The deformational characteristics of rocks are essential in the design and construction of any structure on the rock. The seismic method utilizes the propagation of waves through the earth. Wave propagation depends upon the elastic properties of rocks (Sheriff 1989). A body subjected to stress undergoes a change in shape and/or size known as strain. Elasticity of a body is defined by its ability to resist deformation and the tendency to restore itself back to its original shape and/or size when the stress applied is removed.

A Perfectly elastic body is one that recovers completely after being deformed. Many substances including rocks are considered to be perfectly elastic provided that the deformations are small as in a seismic survey.

The Hooke's law explains the concept of stress and strain. The borehole seismic method has been proven a useful tool for the delineation of seismic wave propagation properties near a well (Hardage 1985). Compressional wave and Shear wave velocities and densities have been acquired in six different wells from which the elastic properties have been obtained and the subsurface lithologies predicted; empirical relations were also established for the survey area, Niger Delta. It has been discovered that the determination of seismic velocities, elasticity modulus and structural properties of soils is not enough in the design of engineering projects. In design of engineering structures, one of the main factors related to soil is bearing capacity and other is settlement so that is subgrade reaction (Keceli 2012). Many investigators have extensively studied to obtain the relations between the various parameters of soil mechanics and seismic wave velocities. (Some of them are Hardin & Black 1968 and Ohkubo & Terasaki 1976). Few authors have published an empirical formula between seismic wave velocities and Standard Penetration Test (SPT) N- blow counts for the determination of bearing capacity, (Imai & Yoshimura 1972, Imai 1975, Parry 1977, Sternberg et al. 1990). Keçeli (1990, 2000) showed that the determination of the presumptive or allowable bearing capacity could be obtained by means of the Seismic Method.

2. Location and geology of the study area

Escravos is located in the Niger Delta about 100 kilometers (62 mi) southeast of Lagos. It is located precisely in Delta State, Nigeria at coordinates 5^0 36' 57''N and 5^0 12' 20''E (Fig. 1).The Niger Delta is the youngest sedimentary basin within the Benue Trough system. The Niger delta development began after the Eocene tectonic phase. Up to 12.0 km of deltaic and shallow marine sediments have been accumulated in the basin. The Niger and Benue Rivers is the main supplier of sediments. Three lithostratigraphic units are distinguished in the Tertiary Niger Delta.

The basal Akata Formation which is predominantly marine prodelta shale is overlain by the paralic sand/shale sequence of the Agbada Formation. The topmost section is the continental upper deltaic plain sands – the Benin Formation. Virtually all the hydrocarbon accumulations in the Niger Delta occur in the sands and sandstones of Agbada Formation where they are trapped by rollover anticlines related to growth fault Development (Ekweozor & Daukoru 1994, Michele et al. 1999, Uko 1996).

Fig. 1: The Point Location of Escravos on the Map of Nigeria.

3. Materials and methods

The basic data used for this work comprise a set of data from six wells from a Field drilled in the Niger Delta region precisely in Escravos. The data was acquired using borehole seismic method. Borehole seismic technique in geophysical exploration, involves measuring the in situ behavior of downgoing and upgoing seismic wavefields which propagate through a stratigraphic sequence near the well (Fig. 2).

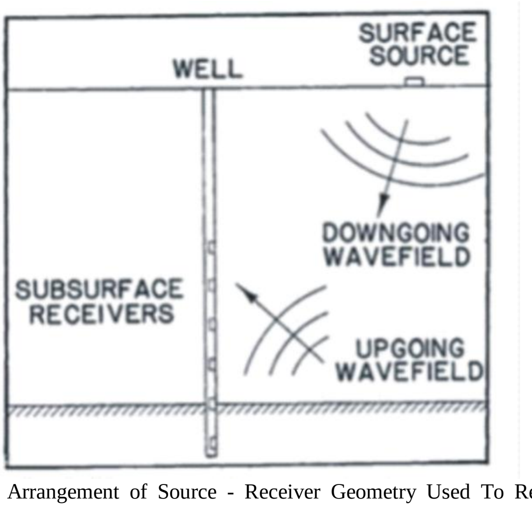

Fig. 2: Arrangement of Source - Receiver Geometry Used To Record Borehole Seismic Data (Hardage 1989).

Various engineering parameters were calculated and used in interpretation: Young's Modulus (E), Shear Modulus (G), Bulk Modulus (K), Safety Factor (Fs), Bearing Capacity (Q) and Settlement (dz).
The universal relations among K, σ and G and among E, σ and G are given in the equations respectively (Dobrin & Savit 1988)

$$K = 2G\,\frac{1+\sigma}{3(1-2\sigma)} \qquad (1)$$

$$E = 2G\,[1+\sigma] \qquad (2)$$

If the Poisson's ratio is written with an equivalent based on Vp/Vs ratio

$$\sigma = \frac{(Vp/Vs)^2-2}{2(Vp/Vs)^2-2} \qquad (3)$$

Additionally, the existing relation between G and Vs is given in the Eqn. (4)

$$G=\rho Vs^2;\ \rho = \text{density of soil} \qquad (4)$$

The values of Vp/Vs and Fs depend on properties of soils and rocks increase from loose soil to hard rock. When Fs and Vp/Vs are used together in soil studies, better reliable the results may be achieved than when only one of Fs or Vp/Vs is used. Studies have shown that Vp/Vs is approximately twice of Fs.

$$Fs \approx \frac{Vp}{Vs} \quad Fs \leftrightarrow \frac{Vp}{Vs} \qquad (5)$$

For pre-consolidated soils, elastic settlement is predominant. Hook's Law defines the elasticity modulus, E, as

$$E = \frac{\text{longitudinal stress}}{\text{longitudinal strain}} \qquad (6)$$

E is also defined in terms of seismic velocities as

$$E = \rho Vs^2 \frac{3Vp^2-4Vs^2}{Vp^2-Vs^2} \qquad (7)$$

Hook's law may be expressed for the settlement of the soil medium with z depth in a vertical direction as follows:

$$d_Z = dZ = \frac{Qult}{E}\,z \qquad (8)$$

Where:
Q_{ult} = load per unit area is the stress value depending on the depth, z
d = settlement for unit value
d_Z = settlement value for the soil column with depth z
Z = active depth which is obtained
dZ = total elastic settlement for the active depth z
The set of equations 1 – 8 were used in estimating the various elastic parameters and the engineering properties.
The data obtained from the seismograph (seismogram) were processed using Pickwin.
Software to obtain the arrival time for P-wave and S-wave. With the geophone separations of 5 m interval, T-X graph were plotted for the different locations using Plotrefa software and the inverse of the slope were obtained as velocity for each of the layer penetrated. The Pick-win software helped in picking the arrival times while the Plotrefa software directly converted the slope into Velocity for the different layers and geologic models where generated.

4. Results and discussion

The computed elastic parameters of the sedimentary rocks in the Escravos area of Niger Delta are given in Table 1. The lithologies encountered are Sand, Sand clay and clayey sand. The depths of investigation vary from one well to the other. Generally, the P-wave and S-wave velocities obtained for the six wells range from 1498.4 m/s to 1669.8 m/s and from 187.8 m/s to 342.2 m/s respectively. The bulk moduli ranges between 3.779 GPa and 4.773 GPa while the density of the formation encountered in the wells varies from 1719.2 kg/cm^3 to 1824.8 kg/cm^3. The observed settlement varies from 0.083 m to 3.068 m with an increase in settlement with depth.
The Young's modulus which is a measure of the property of the rock to resist deformation ranges from 0.181 GPa to 0.628 GPa; the Young's moduli confirm the three lithologic layers encountered in the boreholes. The Poisson's ratios for the various wells vary between 0.478 and 0.492, which is high. The Safety Factor (i.e. Vp/Vs) ranges from 4.880 - 7.722. The shear moduli vary from 0.061 GPa to 0.212 GPa. The results confirm that the lithology in the area is sandy and contains some clay. The delineated porosity ranges from 26 % to 28 %. The allowable bearing capacity varies between 0.404 kg/cm^2 and 1.272 kg/cm^2. The computed values of the elastic properties show that the formation encountered in the wells are moderately dense and saturated with water.

4.1. Geologic models

The geologic models representing the subsurface lithologies were produced. Time-term inversion and tomographic inversion techniques were carried out to produce the models. The configuration used for the geologic models is as follows: receiver interval- 4, no of receivers- 21, no of sources- 4, no of layers- 3 or 2 as the time-distance curves specify. The geologic models show the topography of the subsurface and the number of layers. The depth was also shown in the geologic models representing the subsurface formations from each set.

4.1.1. P-wave geologic model of well 1

The P-wave geologic model generated for Well 1 (see Fig. 3) show that three distinct lithologies characterize the Well 1 viz: Sand, Sandy clay and Clayey sand. The P-wave velocity in the sand ranges from 1498.4 m/s to 1531.9 m/s and that of S-wave ranges 187.8 m/s to 191.8 m/s. The sandy clay layer is characterized by an average velocity of 1500 m/s. The model shows the number of layers and the thicknesses of the individual layers. Layer 1 has maximum thickness of 5.4 m, layer 2 has a maximum thickness of 11.5 m, layer 3 has a maximum thickness of 16.9 m and the total depth extent is about 26.0 m (Fig. 3).

4.1.2. P-wave geologic model of well 2

From Fig. 4, the geologic model shows that three distinct layers characterize Well 2 viz: Sand, Sandy clay and clayey sand. The P-wave velocity in the sand ranges from 1546.0 m/s to 1595.8 m/s and that of S-wave ranges 230.6 m/s to 275.5 m/s. The sandy clay layer is characterized by an average velocity of 1580 m/s. The model shows the number of layers and the thicknesses of the individual layers. Layer 1 has maximum thickness of 9.2 m, layer 2 has a maximum thickness of 12.3 m, layer 3 has a maximum thickness of 15.3 m and the total depth extent is about 32.0 m.

4.1.3. P-wave geologic model of well 3

From Fig. 5, the geologic model shows that three distinct layers characterize Well 3 viz: Sand, Sandy clay and Clayey sand. The P-wave velocity in the sand ranges from 1567.8 m/s to 1669.8 m/s and that of S-wave ranges 250.3 m/s to 342.2 m/s. The model shows the number of layers and the thicknesses of the individual layers. Layer 1 has maximum thickness of 6.2 m, layer 2 has a maximum thickness of 8.5 m, layer 3 has a maximum thickness of 20.8 m and the total depth extent is about 32.0 m.

4.1.4. P-wave geologic model of well 4

From Fig. 6, the geologic model shows that three distinct layers characterize Well 4 viz: Sand, Sandy clay and Clayey sand. The P-wave velocity in the sand ranges from 1506.6 m/s to 1569.3 m/s and that of S-wave ranges 195.1 m/s to 251.7 m/s. The model shows the number of layers and the thicknesses of the individual layers. Layer 1 has maximum thickness of 8.5 m, layer 2 has a maximum thickness of 20.8 m, layer 3 has a maximum thickness of 16.2 m and the total depth extent is about 35.5 m.

4.1.5. P-wave geologic model of well 5

From Fig. 7, the geologic model shows that two distinct layers characterize Well 5 viz: Sand, Sandy clay and Sand. The P-wave velocity in the sand ranges from 1528.9 m/s to 1545.4 m/s and that of S-wave ranges 214.6 m/s to 229.4 m/s. The model shows the number of layers and the thicknesses of the individual layers. In well 5, 2 layers were penetrated. Layer 1 has maximum thickness of 6.9 m layer 2 has a maximum thickness of 14.6 m and the total depth extent is about 21.6 m.

Table 1: Summary of Layer Parameters and the Elastic Properties of Escravos Area, Niger Delta.

Well	Depth (m)	Avg Vp (m/s)	Avg Vs (m/s)	Avg Density (kg/m^3)	Avg Vp/Vs	Avg σ	Avg Φ	Avg G (Gpa)	Avg E (Gpa)	Avg K (Gpa)	Avg Qa (kg/cm^2)	Avg dZ(cm)
1	16	1507.3	195.8	1800	7.7	0.49	0.279	0.067	0.201	3.89	0.446	0.959
2	18	1576.4	258.0	1811	6.12	0.48	0.271	0.121	0.359	4.34	0.767	0.838
3	16	1617.5	295.1	1767	5.51	0.48	0.267	0.155	0.460	4.42	0.956	0.624
4	22	1542.5	227.5	1801	6.81	0.49	0.275	0.094	0.279	4.16	0.606	1.144
5	7	1535.0	220.2	1799	6.98	0.49	0.276	0.087	0.260	4.12	0.569	0.399
6	22	1601.8	280.9	1820	5.71	0.48	0.269	0.144	0.427	4.48	0.897	0.928

NOTE: Avg- Average, Vp- Primary Wave Velocity, Vs- Secondary Wave Velocity, σ- Poisson's ratio, Φ- Porosity, G- Shear Modulus, E- Young's Modulus, K- Bulk Modulus, Qa- Allowable Bearing Capacity (Ultimate Bearing Capacity/ Safety Factor), dZ- Settlement

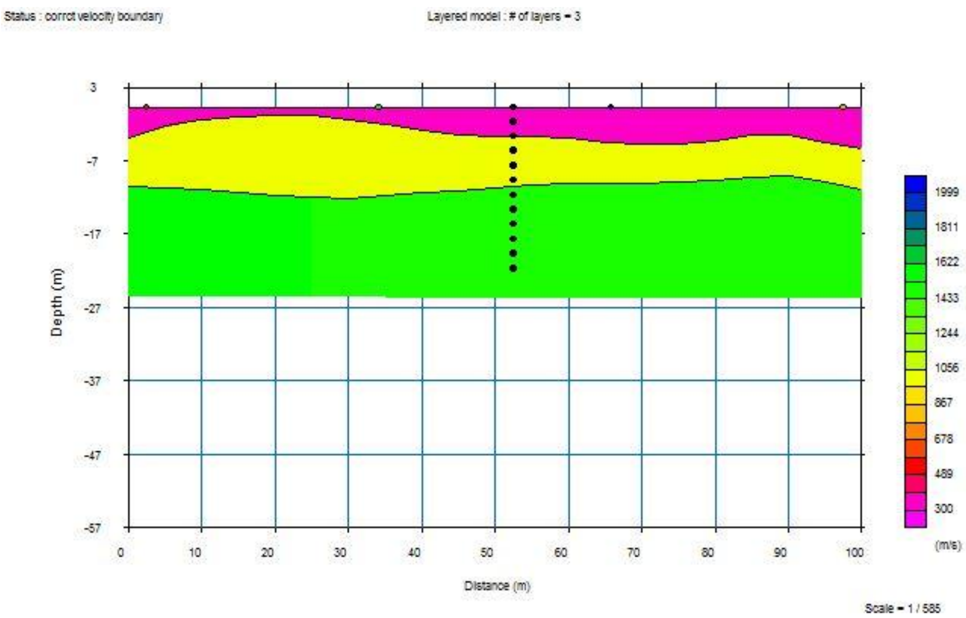

Fig. 3: Geologic Model of Well 1.

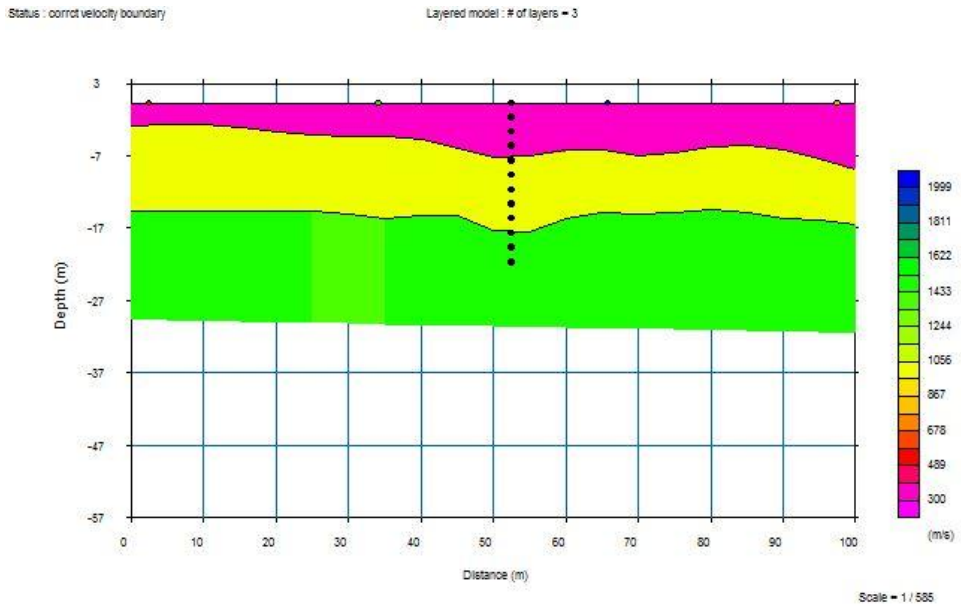

Fig. 4: Geologic Model of Well 2.

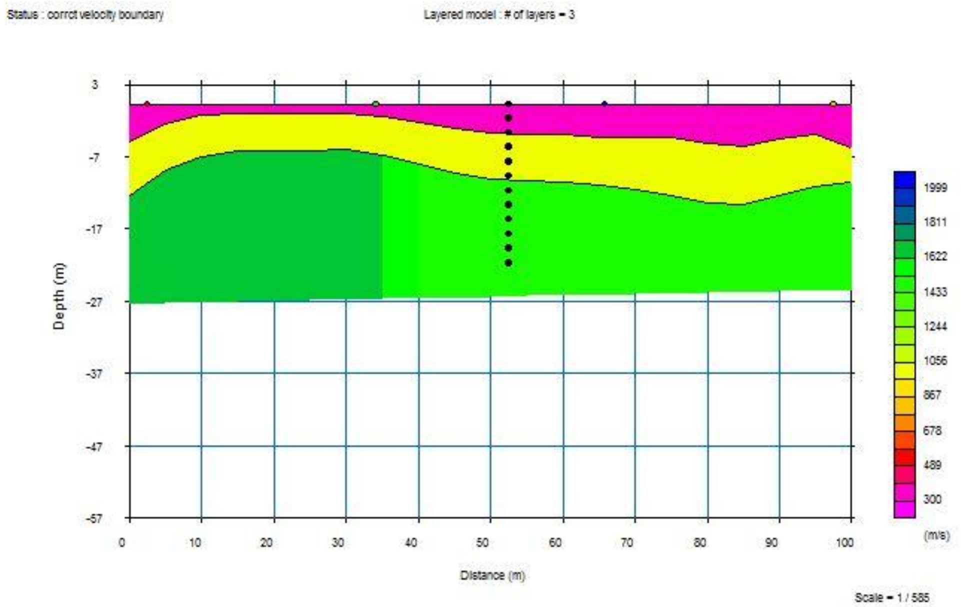

Fig. 5: Geologic Model of Well 3.

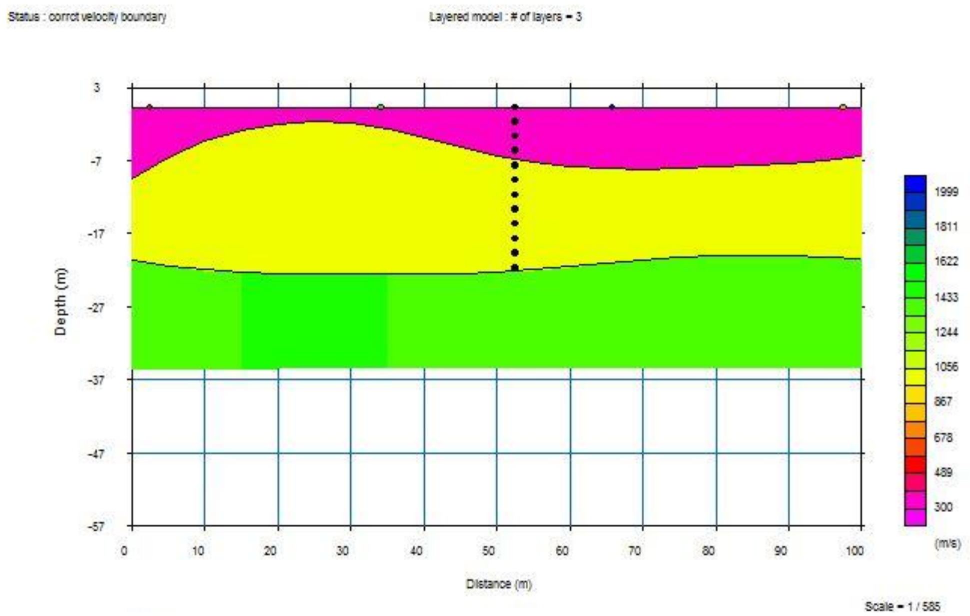

Fig. 6: Geologic Model of Well 4.

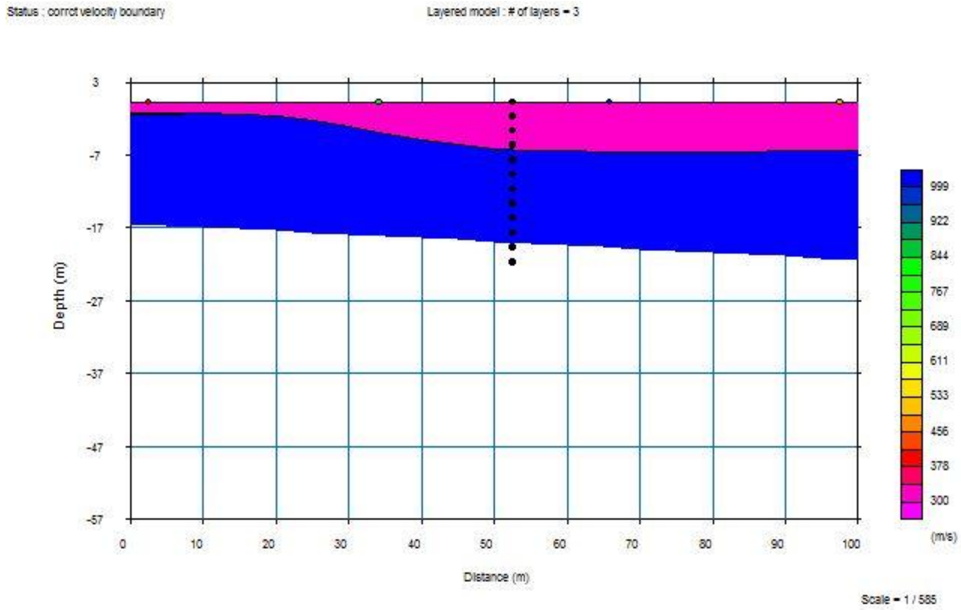

Fig. 7: Geologic Model of Well 5.

4.1.6. P-wave geologic model of well 6

From Fig. 8, the geologic model shows that three distinct layers characterize Well 6 viz: Sand, Sandy clay and clayey sand. The P-wave velocity in the sand ranges from 1528.9 m/s to 1545.4 m/s and that of S-wave ranges 214.6 m/s to 229.4 m/s. The model shows the number of layers and the thicknesses of the individual layers. In well 6, 3 layers were penetrated. Layer 1 has maximum thickness of 3.8 m, layer 2 has a maximum thickness of 7.1 m, layer 3 has a maximum thickness of 14.5 m and the total depth extent is about 27 m.

4.2. S-wave velocity models

Using WaveEq module, S-wave velocity models showing the S-wave velocity variation with depth within the subsurface geology penetrated by the well was produced. Using the dispersion curves that were generated and an initial model was generated by the program after which iteration was carried out. For each of the models, iteration curves were plotted, some of which converge at zero. This approves the accuracy of the S-wave velocity models. With careful observation of the S-wave velocity models, it is observed that at some depths in each of the wells, there appear to be a decrease in both P-wave and S-wave velocities, due to the presence of little clay materials within the sand unit. At these particular depths, it is observed that there is also a decrease in shear modulus. At these depths also, there is a reduction in bearing capacity and subsequently ultimate bearing capacity.

The S-wave velocity models show that the unit change in velocity at some specific intervals. In generating all the S-wave velocity models, inversion was carried out using Least Square Smoothening Method. The Root Mean Square (RMS) error in percentage was plotted against the number of iterations. The iteration curve converges to zero (Figs. 9 to 20).

4.2.1. S-wave velocity model and iteration curve of well 1

The S-wave velocity model obtained shows secondary wave velocity variation with depth (Fig. 9). Up to about 3.0 m, the velocity increases gradually and then it begins to reduce to about 7.9 m at which depth the S-wave velocity increases again. The decrease in S-wave velocity between 3.0 m and 7.9 m is due to the presence of little clay materials within the sand unit. At these depths also, there is a decrease in shear modulus. At these depths also, there is a reduction in bearing capacity and subsequently, ultimate bearing capacity.

4.2.2. S-wave velocity model and iteration curve of well 2

The S-wave velocity model shows secondary waves velocity variation with depth (Fig. 11). Up to about 4.5 m, peaks at 5.0 m, the velocity increases gradually and then it begins to decrease to about 10.4 m from which the S-wave velocity increases again and decreases at 11.9 m. The decrease in S-wave velocity between 5.0 m and 10.4 m is due to the presence of clay within the sand unit. At these particular depths, it is observed that there is a corresponding decrease in shear modulus. At these depths also, there is a decrease in bearing capacity and subsequently, ultimate bearing capacity.

4.2.3. S-wave velocity model and iteration curve of well 3

The S-wave velocity model shows secondary wave velocity variation with depth (Fig. 13). Up to about 3.0 m, the velocity increases gradually and it is observed to be constant from 3.0 m to 5.9 m from which it then begins to decrease to about 6.7 m from which the S-wave velocity increases again to 13 m. The decrease in S-wave velocity between 3.0 m and 9.0 m is due to the presence of little clay materials within the sand unit. At these particular depths, it is observed that there is a corresponding decrease in shear modulus. At these particular depths, there is a decrease in bearing capacity and subsequently, ultimate bearing capacity.

4.2.4. S-wave velocity model and iteration curve of well 4

The S-wave velocity model shows secondary wave velocity variation with depth (Fig. 15). In this model, velocity is increases gradually and peaks at 5.3 m; it then gradually decreases to about 12.5 m from which the S-wave velocity increases again. The decrease in S-wave velocity

Between 5.3 m and 12.5 m is due to the presence of little clay materials within the sand unit. At these particular depths, there is a corresponding decrease in shear modulus and in bearing capacity and subsequently, ultimate bearing capacity.

4.2.5. S-wave velocity model and iteration curve of well 5

The S-wave velocity model shows secondary wave velocity variation with depth (Fig. 17). At 0.2 m, velocity increases

And decreases immediately, it then increases to 1.1 m. From 1.1 m to 2.6 m, velocity decreases gradually from which the S-wave velocity increases again to 6 m. The decrease in S-wave velocity between 1.1 m and 2.6 m is due to the presence of little clay materials within the sand unit. At these particular depths, there is a corresponding decrease in shear modulus and in bearing capacity and subsequently, ultimate bearing capacity.

4.2.6. S-wave velocity model and iteration curve of well 6

The S-wave velocity model shows secondary wave velocity variation with depth (Fig. 19). Up to about 4.2 m, the velocity increases gradually and then it begins to reduce to about 14.2 m from which the S-wave velocity increases again. The decrease in S-wave velocity between 4.2 m and 14.2 m is due to the presence of little clay materials within the sand unit. At these particular depths, there is a corresponding decrease in shear modulus and in bearing capacity and subsequently, ultimate bearing capacity.

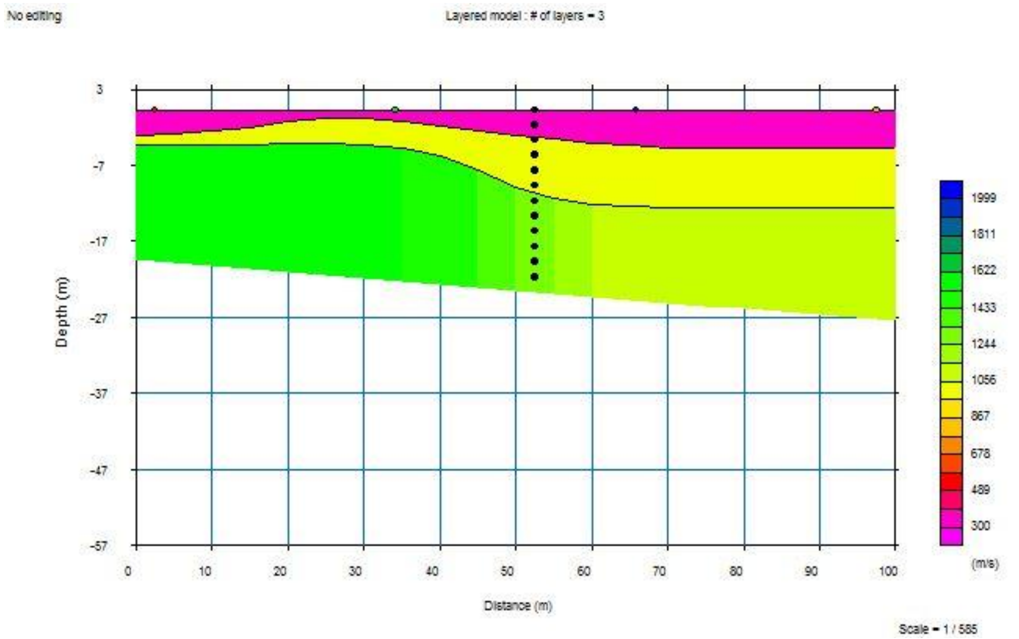

Fig. 8: Geologic Model of Well 6.

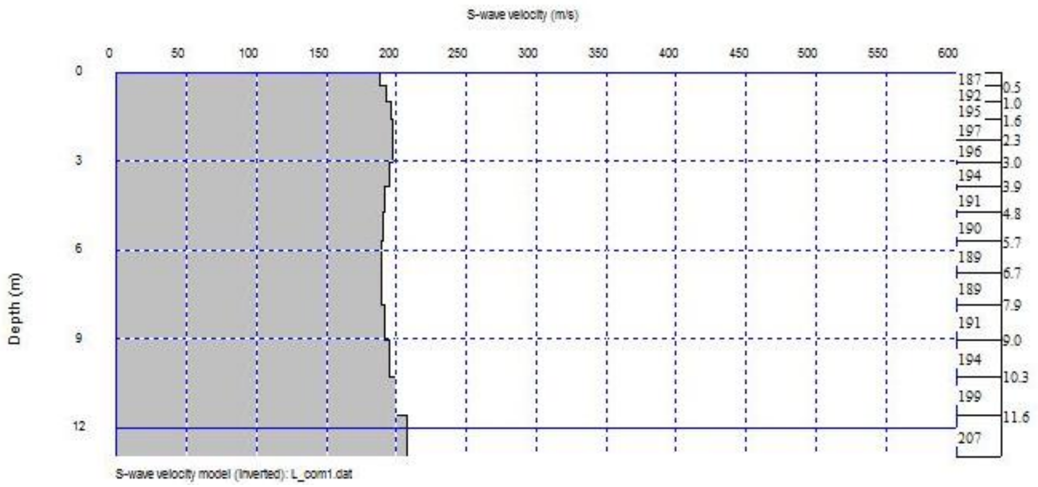

Fig. 9: S-Wave Velocity Model of Well 1.

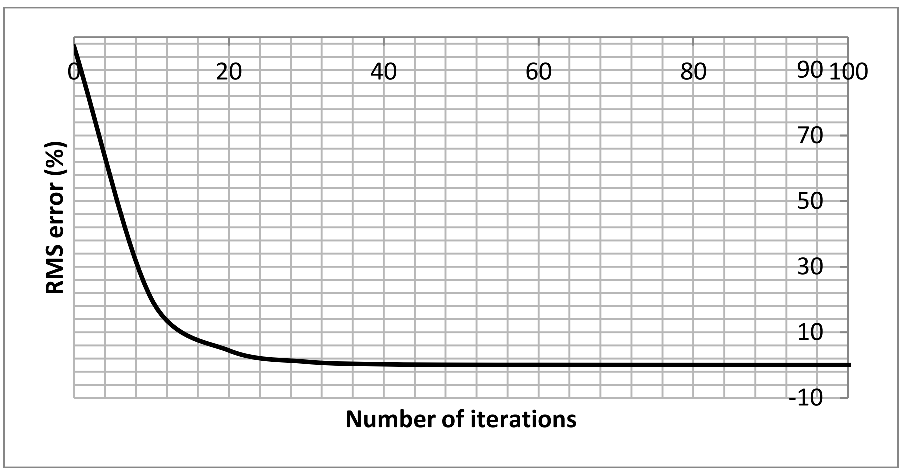

Fig. 10: Iteration Curve of Well 1.

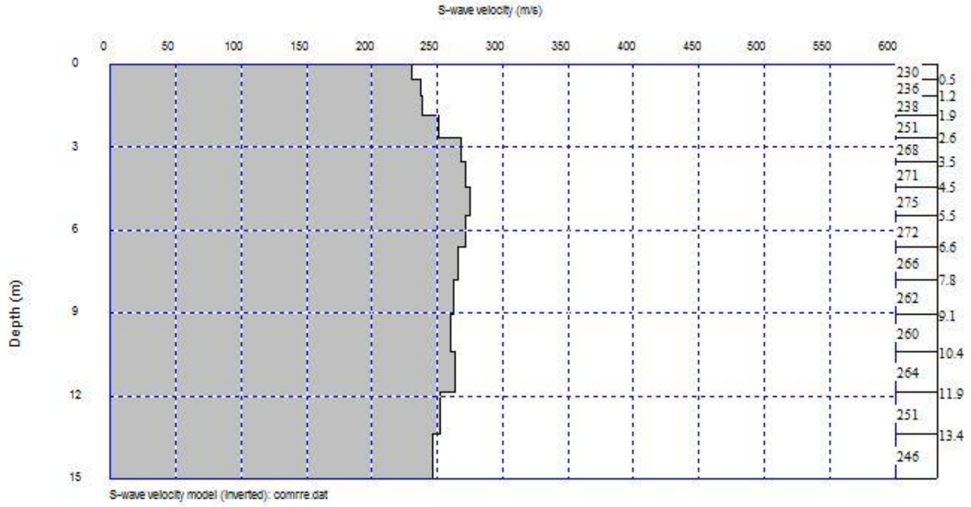

Fig. 11: S-Wave Velocity Model of Well 2.

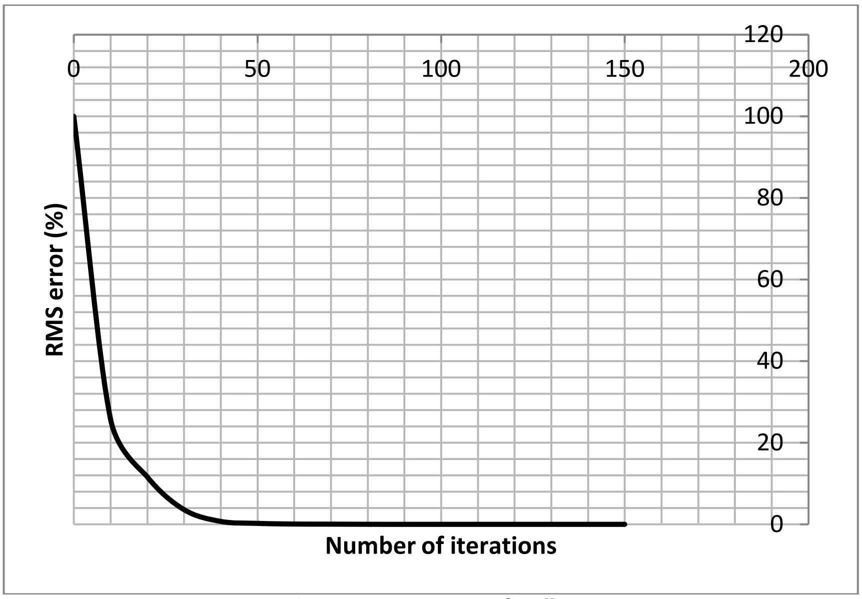

Fig. 12: Iteration Curve of Well 2.

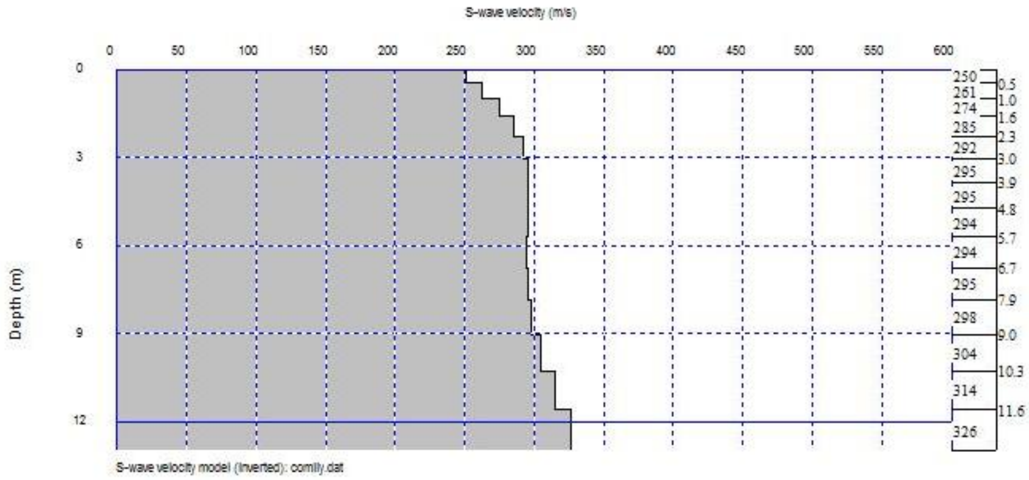

Fig. 13: S-Wave Velocity Model of Well 3.

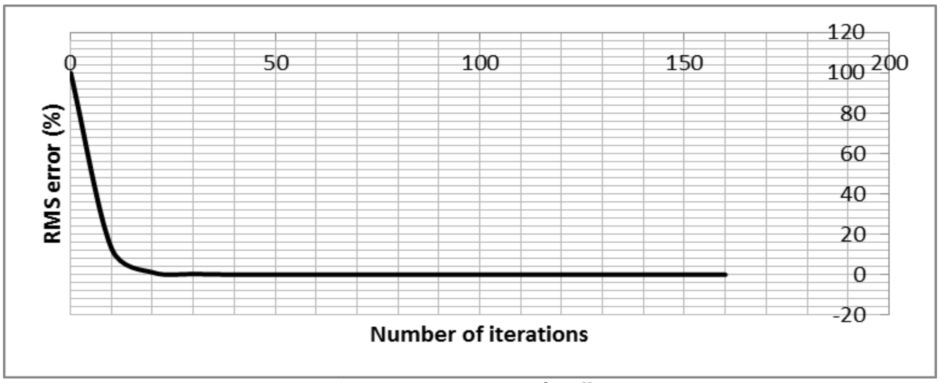

Fig. 14: Iteration Curve of Well 3.

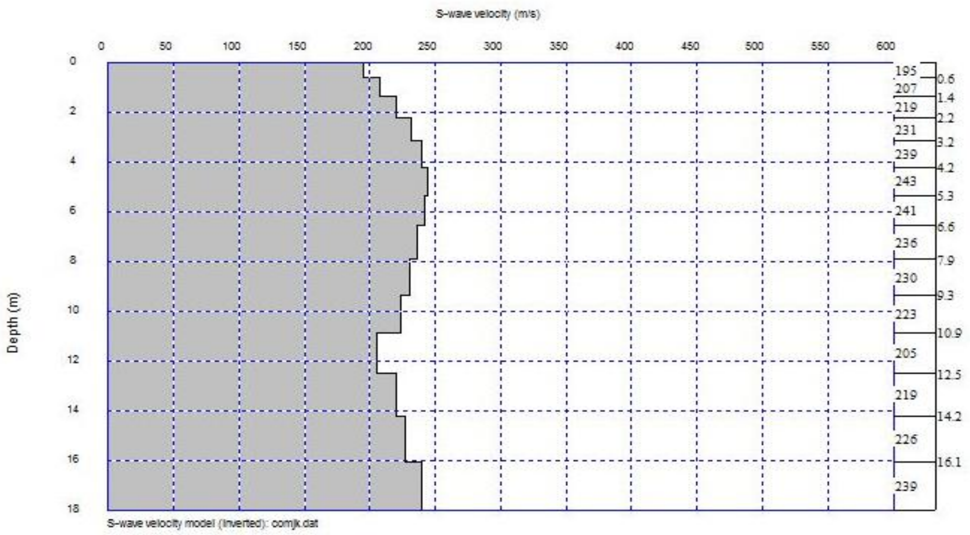

Fig. 15: S-Wave Velocity Model of Well 4.

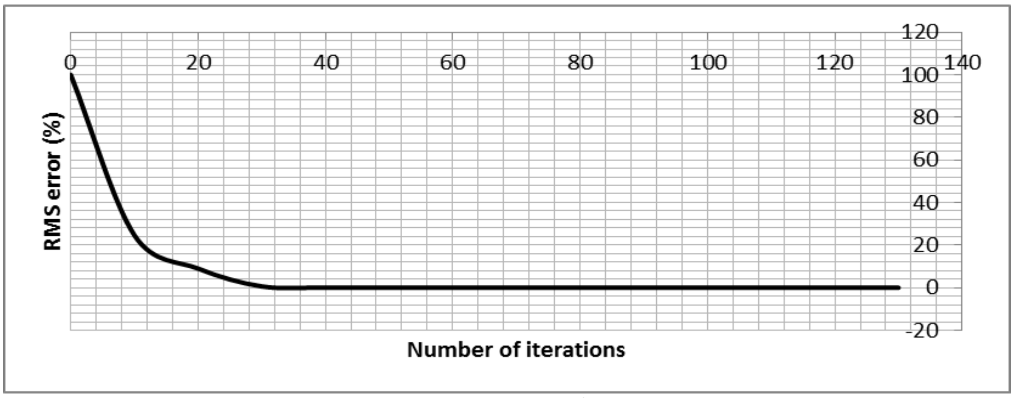

Fig. 16: Iteration Curve of Well 4.

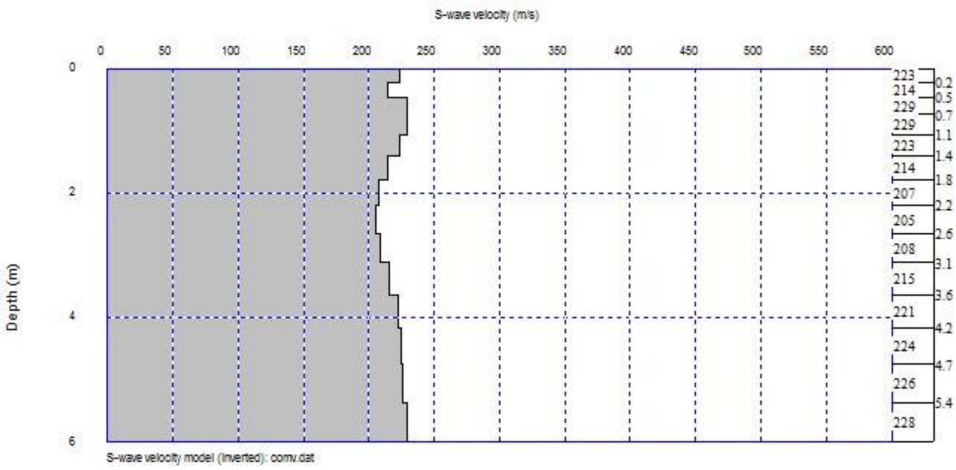

Fig. 17: S-Wave Velocity Model of Well 5.

Fig. 18: Iteration Curve of Well 5.

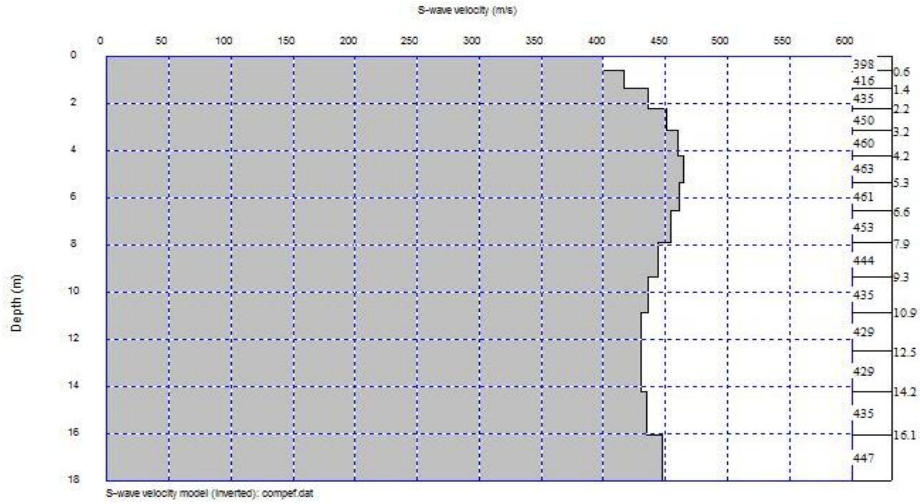

Fig. 19: S-Wave Velocity Model of Well 6.

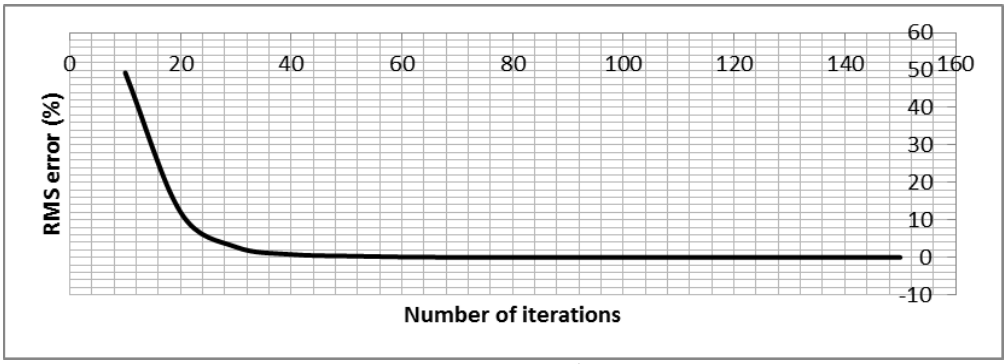

Fig. 20: Iteration Curve of Well 6.

4.3. Empirical relations

In other to derive the empirical relations for the investigated area from the data, the values of various elastic parameters calculated were plotted against one another. (VS – VP and σ – VS, Figs. 21 and 23 respectively). Empirical relations derived from them represent the characteristics of the study area, Escravos, Niger Delta.

4.3.1. VP - VS relations

When Vp is plotted against Vs, they follow a remarkably narrow trend. Variations in porosity, caly and pressure simply move the points up and down the trend (Gary Mavko 2009). From the equation in Fig. 21, the line of best fit defines the empirical relations as:

Vs = 0.902Vp - 1164.

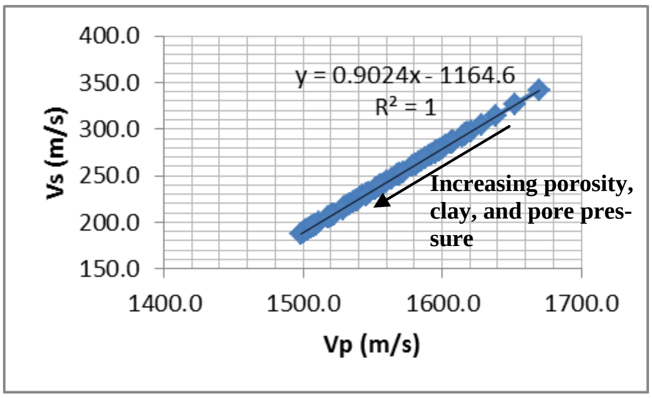

Fig. 21: Vs versus Vp.

The equation represents the empirical relation between Vs and Vp in the study area at Escravos.

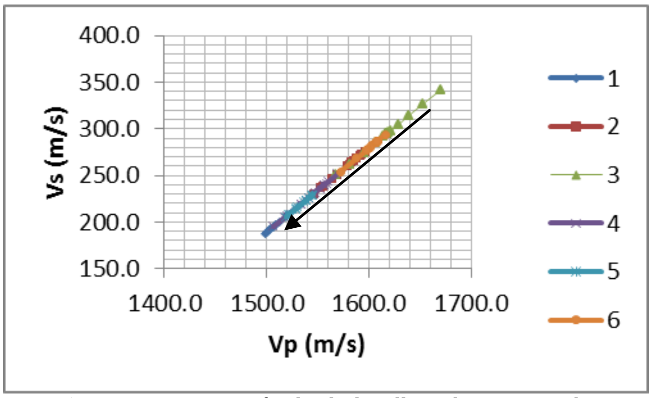

Fig. 22: Vs versus Vp of Individual Wells on the Same Graph

The arrow showing increase in porosity, clay and pore pressure also shows from Fig. 22 that porosity, clay, and pore pressure is lowest at Well 3 and increases as we move to Well 6 and is highest at Well 1.

4.3.2. VS - poisson's ratio relations

From this study, it is observed that a plot of Vp/Vs versus Vs is inversely proportional to a plot of Vp/Vs versus Poisson's ratio. That is:

$$\frac{Vp/Vs}{Vs} = \frac{1}{\frac{Vp}{Vs} \Big/ \text{Poisson's ratio}} \qquad (15)$$

Which becomes:

$$\frac{Vp/Vs}{Vs} = \frac{\text{Poisson's ratio}}{Vp/Vs} \qquad (16)$$

$$= \frac{\text{Poisson's ratio}}{Vs} \qquad (17)$$

Therefore, an attempt was made to plot Poisson's ratio against Vs.

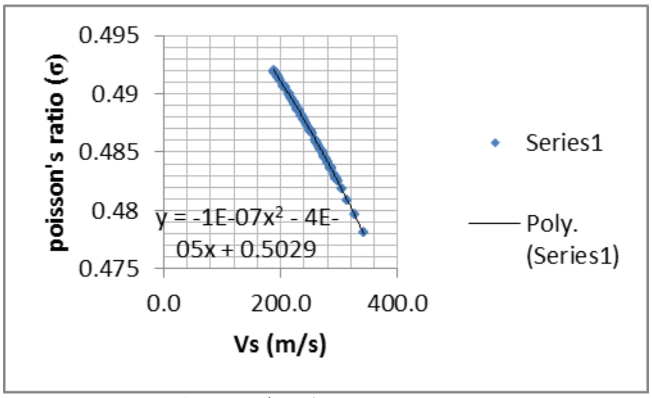

Fig. 23: Poisson's Ratio Versus Vs

The equation becomes σ = -1E-07Vs^2 - 4E-05Vs + 0.502. The equation shows the empirical relations between Poison's ratio and Vs.

5. Conclusion

This study has shown the relevance of borehole seismic Geophysical investigation in the characterization of the subsurface geology prior to civil engineering construction. The importance of seismic velocities in providing valuable information about the bulk physical properties of rocks was also established. This type of information can be invaluable during the design and construction phases of engineering projects. Empirical relations established for Vp - Vs and Vs - Poisson's is characteristics of sedimentary terrain, and can be used in any study area within the Escravos area, Niger Delta, Nigeria. The computed values of the elastic properties show that the formation encountered in the wells are moderately dense and saturated with water. This is in conformity with the fact that the major formations encountered in the wells are the Benin Formation. The Benin Formation consists of predominantly massive, highly porous, freshwater–bearing sandstones, with local thin shale interbeds. The values of allowable bearing capacity and the settlement suggest that the area of study is able to support engineering construction.

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