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Application of Uphole Seismic Refraction Survey for Subsurface Investigation: A Case Study of Liso Field, Niger Delta, Nigeria

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Abstract: In this paper, an uphole refraction survey was carried out at the location of LISO Field in Niger Delta Nigeria in order to determine/estimate the thickness and velocities of the strata with a view to ascertaining the suitability of these layers for seismic reflection data acquisition and engineering structures. A hole drilled to a depth below the weathered layer contained hydrophones positioned at specific depths and dynamite charge as source of seismic energy. The uphole data were acquired using OYO McSeis seismograph. The time- distance plot obtained using IXsexsegy software was used for picking the first breaks arrivals of the signals. The depth of the weathered layer was obtained from these plots. The upsphere software was used to obtain the velocity of the different layers. The cuttings collected during the borehole drilling reveal sand, clay and gravel in which the sand sequence vary in sizes. Analyses of well-log show that the area of study is a two-layer model and the near surface geology is comparatively stable and inhomogeneous with moderate velocity contrast. The average thickness of the weathered layer to the top of the consolidated layer is 4.8m with an average velocity of 466m/s. The weathering thickness ranges from 2.9-8.9m and the velocity ranging from 362m/s to 689m/s. The consolidated layer velocities ranges from 1642m/s to 1884m/s with an average of 1746m/s sufficient enough to support engineering structures. In order to correct for weathering or statics a datum of about 6m deep would be required as this will eliminate the effect of the weathered layer on any proposed engineering structure to be developed in the area or its environs. This will also be suitable for the acquisition of good quality seismic data in the area. Also, mathematical linear regression models were generated relating the velocities of the layers and depth of the weathered layer which could be used for the prediction of one parameter in the absence of others provided they are within the same geologic environment.

Key words: Uphole survey · Weathered layer · First break · Hydrophones · Dynamite · Seismic energy source

INTRODUCTION

In recent years, there has been renewed interest in using the travel times of an uphole refracted seismic energy (first breaks) to compute velocity and thickness of the weathered layers prior to or during the processing of reflection seismic data. The near surface seismic waves refraction can provide useful information about the near surface for engineering and environmental purposes. The weathered layer velocity can be derived indirectly from surface seismic data and alternatively from shallow holes i.e. downhole surveys [1, 2] and uphole surveys where less work has been done [3, 4] is very essential to geoscientists and environmental engineers.

In seismic surveys employing surface energy sources, the seismic velocity of the surface layer is generally unknown, unless a separate uphole or refraction survey is carried out. Using an uphole method might have some implications on travel times of the signals i.e., it might result in a time delay due to variations in topography and weathering [5]. Time delays associated with unconsolidated weathering disrupt reflection continuity (i.e., trace -to-trace alignment) and pose a major obstacle to successful processing of seismic data [6].

The weathering layer which is usually the most variable of all layers in seismic processing is characterized by low transmission of seismic waves and shots taken in this layer tend to be of low frequencies because the

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layer is capable of absorbing high frequency signals. Datuming through an incorrect weathering model can introduce false structure into the deep reflectors [7]. Therefore, it becomes important to correct for the effect of variable thickness and lateral variation in velocities of the weathering layer. The weathering significantly modifies the wave propagation: reflected arrivals are attenuated and delayed, the layer serves as a waveguide for surface waves. In seismic surveys, traces are corrected for effect of weathering by the application of time shifts computed from weathering parameters of the layer.

An uphole survey provides a direct measurement of the seismic energy travel time in the low velocity layers as well as in the layer immediately below which is usually consolidated or unweathered [8]. Usually, a hole that penetrates below the weathering layer is drilled and geophones are placed at various known depths within the hole. It is therefore a good tool in taking decisions on drilled and charge depths prior to the commencement of any seismic reflection operation [9]. The use of this method overcomes the usually problem of weathering layer absorption of seismic waves during conventional seismic refraction investigation.

Apart from using uphole refraction method for investigations of the competence of the subsurface to withstand any engineering structure, other methods which have been applied or employed are surface refraction methods, ground penetrating radar [10] and electrical resistivity methods [11] to name a few. However, the merits of an uphole survey over some of the other geophysical methods cannot be over-emphasized. Besides providing a means of identifying and defining velocity inversions or reversals situations where a stratum has a lower velocity than that of the overlying material which may not be identified by surface refraction surveys [12], it also gives an insight to other subsurface conditions that would be obscured to an observer at the surface.

Additionally, uphole survey allows for the construction of a detailed map of the thickness and velocity of the weathered layer. With this information, a statics model could be created and applied to the seismic data to remove the effects of the weathered zone. Closely related to the aforementioned merit of the uphole method is that with the detailed map of the weathered zone, it is possible to determine the optimum shot hole depth. Recently, [13] reported their results on low velocity layer using uphole refraction survey in preparation for 4D seismic reflection prospection. In a similar approach, analyzed the weathering layer characteristics of the North-Western Niger Delta with 29 Low Velocity Layer refraction lines and one uphole shot point. The results revealed an average regional thickness of 4.4 m. The average weathered layer compressional wave velocity was about 525 ms^{-1} while [14] have used refraction tomography to compute a multilayer near surface model, with an assumption that the velocity in the weathering layer was known.

This paper investigates the feasibility of identifying and determining both weathering layer velocity and depths on the basis of wave-front interpretation that must be avoided prior to the development of engineering structures as well as the estimation of the velocity of the consolidated layer using an uphole survey and the acquisition of quality seismic data in LISO Field, Niger Delta providence of Nigeria.

MATERIALS AND METHODS

Geological Settings: The geology of Nigeria is predominantly of both basement complex and sedimentary environments [15]. The basement complexes are the crystalline igneous and metamorphic rocks, while the sedimentary environment is largely made up of sedimentary rocks and sometimes of various earth materials. The regional geology map of the Niger delta basin where the study was carried out is shown in Figure 1 [16]. Sedimentary rocks predominantly composed of sands and sandstones, clay and limestone covers about half of the surface area of Nigeria [17]**.** The study area is characterized by fresh water and mangrove swamps with relief that increases towards the north of the studied area [18]. Three distinct facies belts have been identified in the Niger delta [19, 20]. These include:

- The Benin Formation (Miocene to Recent) consists of predominantly massive, highly porous fresh water-bearing sandstone, with local interbed of shale. The sand and sandstone which are due to continental deposition from Miocene to Younger age [21, 22].
- The Agbada Formation, between Lower/Middle Miocene to Pliocene, consists of alternating sandstones and shales of the delta front, distributary-channel and delta plain origin. The sandstones are medium to fine grained, fairly clean, locally calcareous, glauconitic and shelly with dominantly quartz and potash feldspar with subordinate amounts of plagioclase, kaolinite and elite [23].

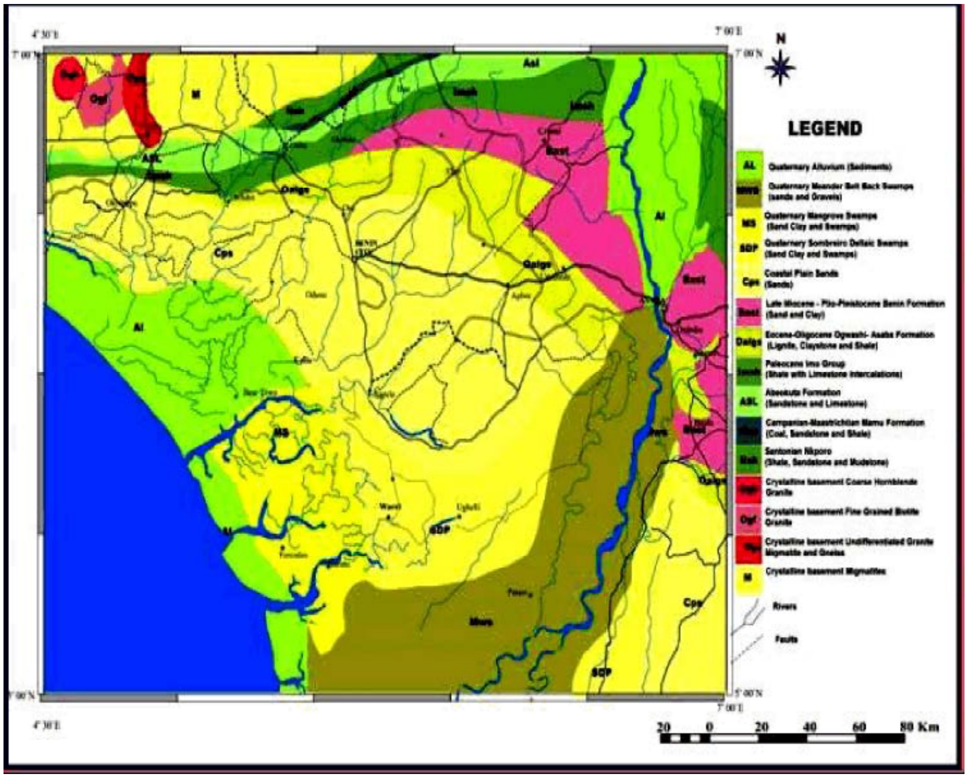

Fig. 1: Regional Geology Map of the Niger Delta Basin, Nigeria [16]

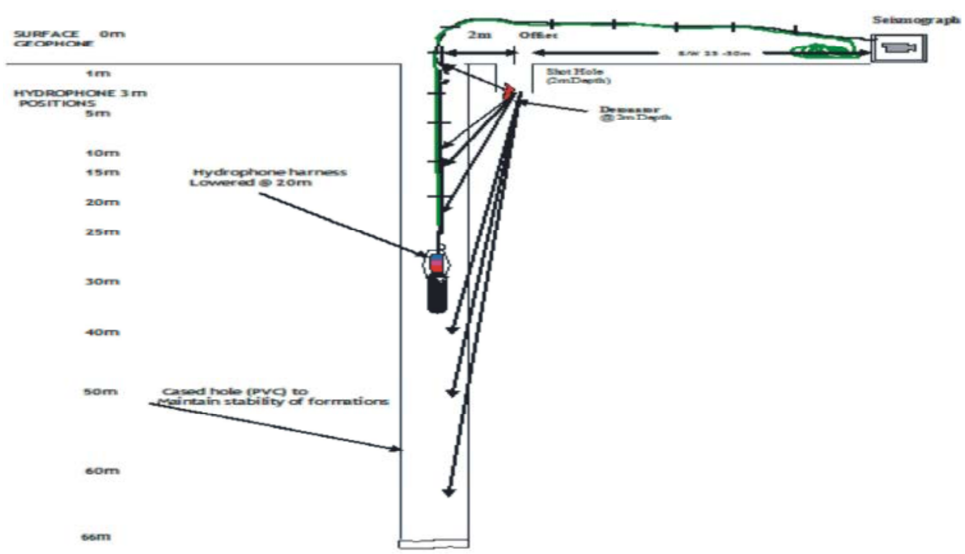

Fig. 2: Schematic of an uphole survey showing an array of hydrophones

- The Akata Formation aged Eocene to Recent is made up of a sequence of under-compacted marine clays with minor sandy and silty beds. The shales are dark grey, medium hard and may contain lenses of abnormally high-pressured siltstone or fine-grained sandstone. It is thought to be the main hydrocarbon kitchen of the Niger Delta [24].

Data Acquisition: The uphole design comprised a single hydrophone unit secured on a rope and weighted on the lower end by a heavy metal. The marine rope was pre-calibrated at each depth point and logged up to twelve channels as shown in Figure 2. In this study, the calibrated depths used were in the range of 1m to 66m. The upholes were located at established seismic lines.

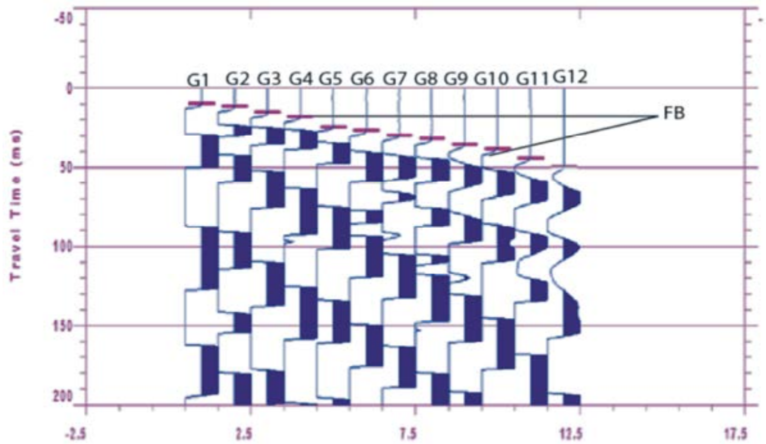

Fig. 3: Seismic trace showing first breaks (FB) with geophones positions (G)

At every uphole location, a hole was drilled to 66m depth at an intersection point between source and receiver lines using rotary method and flushed continuously for 20 minutes to enhance stability for smooth and effective casing. Samples were collected at every 3m-depth interval. Hydrophone spreads consisting of 12 hydrophones at different positions were lowered into the drilled hole to a depth of about 66m (Figure 2). Plastic casings were installed in the hole to prevent the hole from collapsing and caving in. Before lowering the hydrophones string, a cylindrical weight of 5kg was attached to the end of the hydrophone spread to keep it upright and floating in the borehole. The data used in this work was generated at one shallow borehole in which uphole data were acquired (Figure 2). The seismic refraction energy source was generated by small explosions of a dynamite of mass 0.25kg inside the borehole buried to a depth of about 2m beneath the earth surface with an offset distance of 2m from the uphole position. The total depth of the borehole was about 66m. The uphole data was obtained in the borehole for receiver depths of 66m, 60m, 50m, 40m, 30m, 25m, 20m, 15m, 10m, 5m, 3m and 1m. The variations in depths of the dynamite shootings ensured that the shot and receiver points were not at the same datum so that the first breaks and an event with noticeable energy whose arrival time was less can be observed. Both first breaks and delayed events were also identified. Data recording was carried out using seismograph OYO McSeis equipment after the detonation of the charge.

Data Processing: After the shots were taken, the first breaks on the seismographs were picked from the recorded traces. The files were processed with seismic wave processing software (IXseg2segy). IXseg2segy (interpex limited seismic shot conversion) is seismic wave processing software that can handle digital waveform data obtained by seismographs. The main function of IXseg2segy was to pick the first arrivals as shown in Figure 3. The first and second layer velocities were filtered using velocity model function with a specified window length which was determined according to the degree of smoothness required. The picked travel times were corrected to account for the 2m offset distance from the seismic source to the borehole head. This correction approximates as though the data were recorded with the seismic source placed exactly at the borehole head. The recorded travel times were plotted against the source-receiver distance. The graphs were plotted for each uphole points and the layer velocities and thicknesses were obtained. The slopes of the two layers were automatically calculated and the reciprocal of the slopes gave the velocities of the weathered and consolidated layers. The depth to refractor (thickness) was also calculated from the point of intersection of the two slopes (point of inflexion). This was done for all the shot points. The classification of the different lithologic sediments into grain sizes was carried out using the standard proposed by Wentworth in Table 1. A sample of the plot of time-distance graph with well log reflecting lithology is shown in Figure 4.

The Microsoft excel was used to generate the plot velocity of the consolidated layer (V_b) against velocity weathered layer (V_w) and also the plot of velocity of weathered layer versus depth of the weathered layer to establish if subsurface information of one unavailable parameter can be predicted in the presence of another parameter within the same geologic settings.

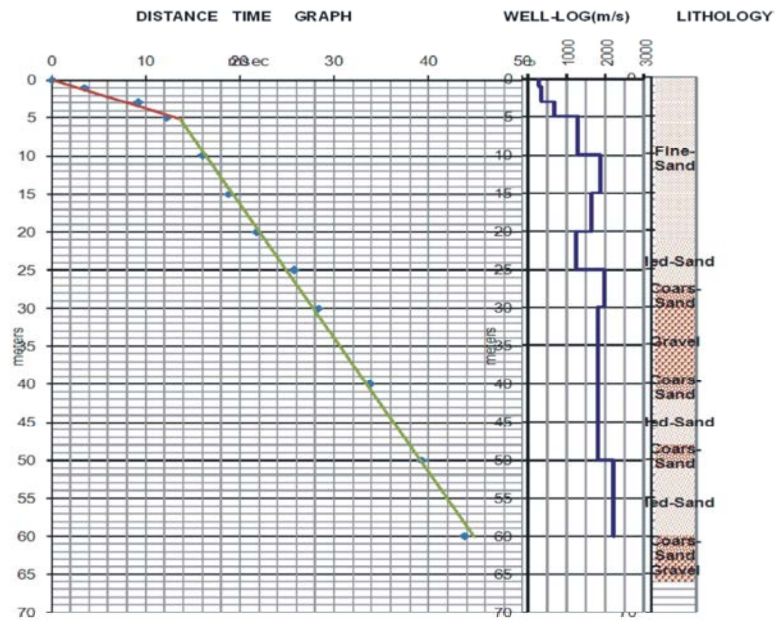

Fig. 4: Time - distance curve from an uphole location with well log data

Table 1: Grain size scale [25]

Diameter	Particle	Sediment	Rock type
<0.0002	Clay	Mud	Claystone, Mudstone, Shale
0.0002 to 0.002	Silt	Mud	Siltstone
0.002 to 0.08	Sand	Sand	Sandstone
0.08 to 2.5	Pebble	Gravel	
2.5 to 11.8	Cobble	Gravel	Breccia (angular)
>11.8	Boulder	Gravel	Conglomerate (rounded)

RESULTS AND DISCUSSION

The result of lithology cross plot of uphole points is presented in Figure 5. A summary of uphole data for two layer model parameter is presented in Table 2. Contoured maps of weathered layer thickness, weathered layer velocity and consolidated layer velocity are presented in Figures 6-8 respectively. The regression plot of velocity of the consolidated layer (V_b) versus velocity weathered layer (V_w) and the regression plot of velocity of weathered layer against depth of the weathered layer are shown in Figures 9 (a and b) respectively.

The analysis of the result (Figure 5) shows the vertical and lateral extent of the lithologies collected during borehole drilling in the study area which are composed of gravel, sand (fine, medium and coarse), sandy clay, silt and clay using the classification standard in Table 1.

The Table 2 shows a substantial variation of the weathered thickness in the survey area. The variations in the thickness of the weathered layer are shown in Figure 6. The layer thickness ranges from 2.9m around shot locations 5571892 (profile 16) and 5651892 (profile 17) to 8.9m on shot location 5571688 (profile 21) with a marginal average thickness of 4.43m. This variation underscores the need to carry out statics correction of this layer through uphole survey prior to conducting reflection seismic survey or structural developments in the area. The map reveals that the weathered layer thickness increases towards the end of the south western flanks. A zone of fairly uniform thickness traverses across the central of the study. All the uphole plots have thickness ranging from 2.9m to 5.9m with exception of station number 5571688 (profile 21) and 5781928 (profile 18) with thickness of 8.9m and 6.1m respectively. This means that the weathered layer of the whole profile is very shallow and under favorable conditions suggests that it could be good or favorable for engineering constructions.

The uphole seismic refraction map showing variations of velocity of the weathered layer is shown in Figure 7. It shows that the velocity ranges from 362 m/s (minimum) on shot location 54711012 (profile 12) to 689 m/s (maximum) on shot location 56711012 (profile 14) with

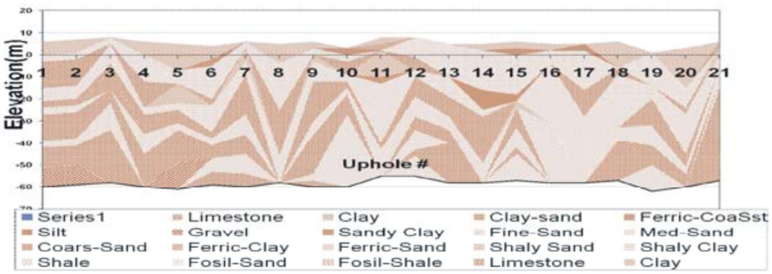

Fig. 5: Lithology cross section plot for upholes points

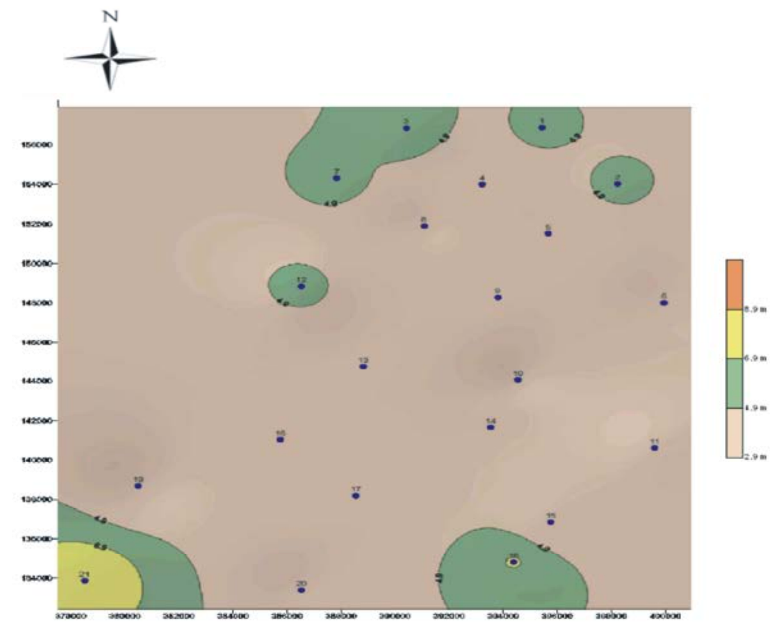

Fig. 6: Weathered layer thickness contoured map

Table 2: Summary of uphole data for two layers model parameters

S/N	Uphole Number	Coordinate (UTM) Eastings	Northings	Elevation (m)	Depth (Dw) Weathered	Velocity (m/s) Weathered	Velocity (m/s) Of Bedrock
1	55611252	395440.6	156863.2	6	5.2	396	1764
2	55611252	398242.4	154011.8	6.5	5.2	390	1781
3	54111180	390419.7	156836.7	7.7	5.6	423	1788
4	54911180	393222.6	153984.1	6	3.3	456	1732
5	55611180	395675.9	151487.5	5.4	3.6	498	1728
6	55711192	399958.6	147985.7	4.2	3.7	473	1826
7	54111108	387852.1	154313.1	6.4	5.2	415	1731
8	54911120	391083.3	151883	4.8	3.9	530	1884
9	55811108	393807.9	148250.8	5.8	3.7	381	1711
10	56511060	394551.4	144071.1	2.8	4.5	403	1798
11	57711084	399613.6	140632.3	7.8	3.1	419	1704
12	54711012	386531	148809.2	8.3	5.1	362	1700
13	5561988	388831.6	144760.4	5.4	4.4	422	1747
14	56711012	393542.7	141674.8	4.5	4.6	689	1727
15	5771976	395761	136848.4	6.4	3.1	545	1709
16	5571892	385756.3	141037.3	4.9	2.9	422	1752
17	5651892	388560	138183.8	5.3	2.9	422	1752
18	5781928	394399.5	134809.9	6.1	7	412	1642
19	5531784	380503	138678.8	1.2	3.4	683	1713
20	5691796	386539.7	133393.4	3.2	3.7	646	1690
21	5571688	378516.2	133852.2	5.5	8.9	390	1790

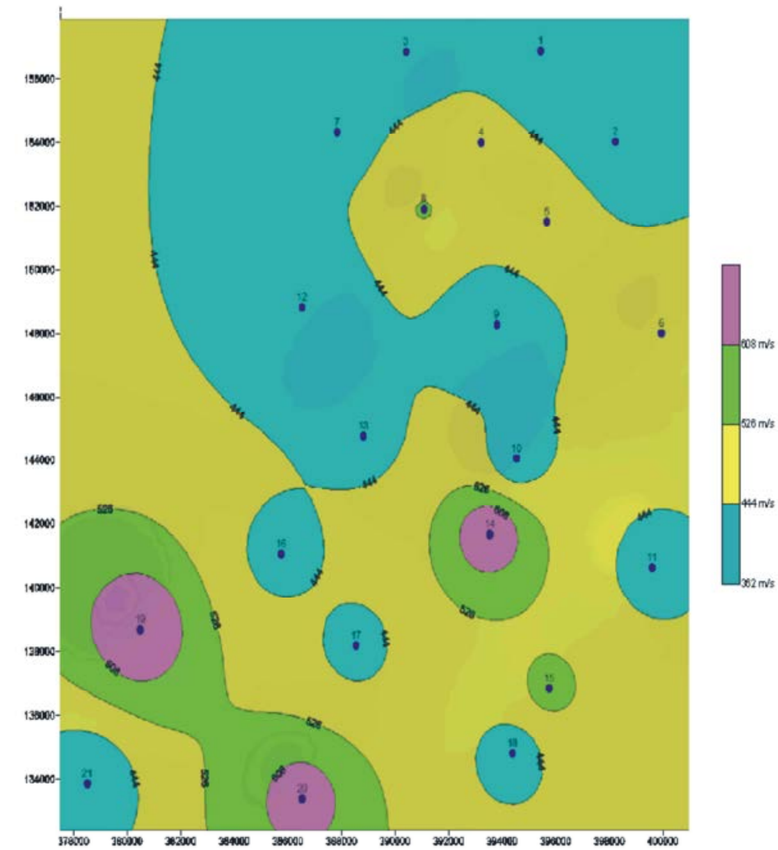

Fig. 7: Weathered layer velocity contoured map

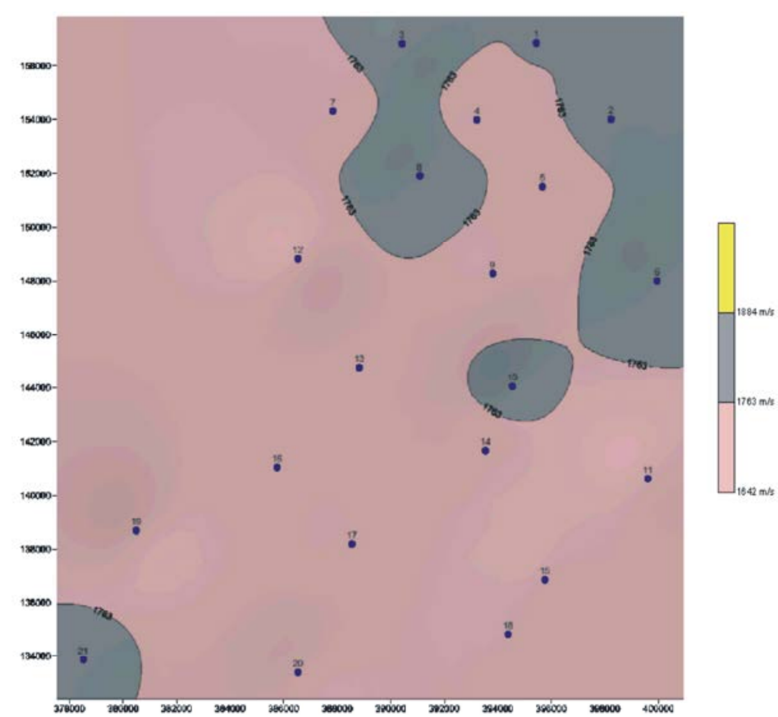

Fig. 8: Consolidated layer velocity contoured map

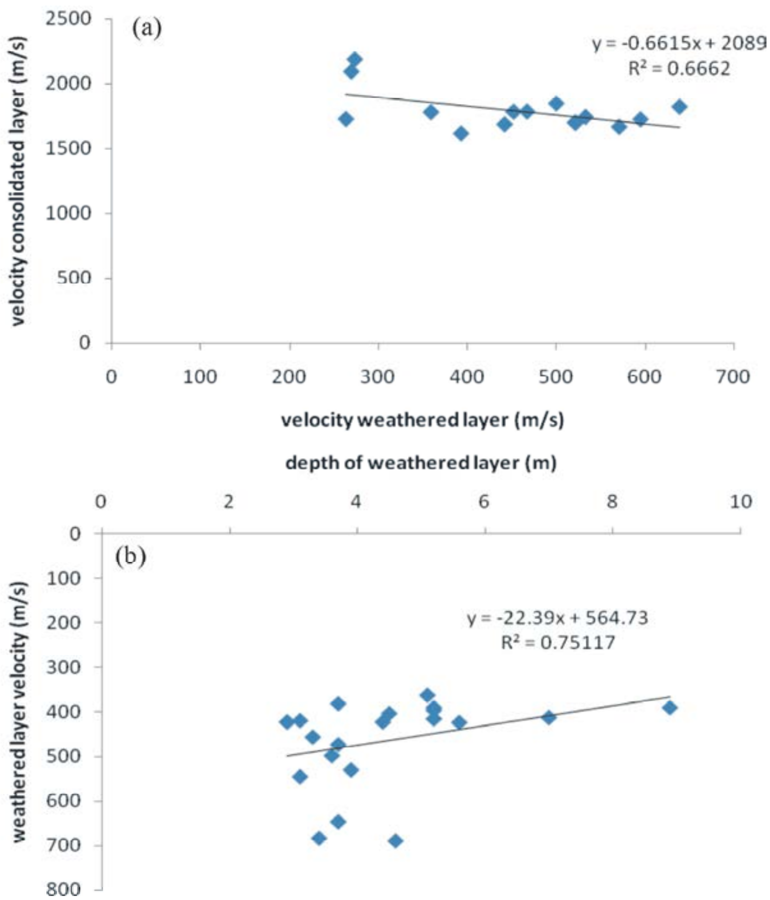

Fig. 9: Regression plots (a) V_b against V_w (b) V_w against D_w

an average velocity of 466m/s. Furthermore, along the south western flank, the velocity varies from 444 m/s (min) to about 649 m/s (max) on the down east central portion. For uphole shots 5, 6, 8 and 15 the velocity ranges from 471m/s (min) to 580m/s (max) while uphole shots 14, 19 and 20 have velocity values ranging from 580m/s to 689m/s with the rest uphole shots having velocities between 362m/s and 471m/s. The variations in velocity of the weathered layer are an attestation to the high degree of inhomogeneity of this layer and an indication of the possibility of a smooth statics behavior.

The pattern of the distribution of seismic velocity in the consolidated layer is shown in Figure 8**.** It is observed that towards the south-eastern portion of the studied area, the velocity is between 1642m/s (min) and 1884m/s (max) with an average of 1746m/s. The north eastern part of the area has velocity which ranges from 1763m/s (min) to 1884m/s (max) signifying the competence of the layer. For uphole shots 1,2,3 as well as 6,8, 10 and 21, the velocity ranges from 1764m/s to 1884m/s while the rest of the shot points fall between 1642m/s and 1763m/s. The velocity of the consolidated layer tends to be lower than the average towards the south-eastern part and remarkably higher towards the north indicating a general increase in the velocity with the amount of consolidation of the bedrock as well as underscoring the competence of the layer.

The result of the plot of the velocity of the consolidated layer versus the velocity of the weathered layer as shown in Figure 9a reveals a mathematical model of Equation 1 while the plot of the velocity of the weathered layer against the depth of the weathered layer as presented in Figure 9b shows a mathematical model of Equation 2. The square of correlation coefficient (R^2) of 0.66 and 0.75 obtained for plots of V_b versus V_w and V_w versus D_w respectively show that the variables are fairly fitted. The combination of Equation 1 and 2 presents a mathematical model which relates the velocity of the consolidated layer to the depth of the weathered layer (Equation 3) on the assumption that the average velocity of the weathered layer is uniform.

$$y = 2089 - 0.6615x \quad (1)$$

$$y = 564.73 - 22.39x \quad (2)$$

where abscissa x is the velocity of the weathered layer (V_w) and ordinate y is the velocity of the consolidated layer (V_b) in Equation 1 while Equation 2 ordinate y is the velocity of the weathered layer (V_w) and abscissa x is the depth of the weathered layer (D_w).

$$V_b = 1715.43 + 14.81D_w \quad (3)$$

The study infers that the regression models could be used to predict the velocity of the consolidated layer if the parameters of the weathered layer are known for the study area and its environs provided they have similar geologic settings.

CONCLUSION

Uphole survey was used to determine the velocities of both the weathered and consolidated layers as well as the thickness or depth of the weathering layer in this study area. The use of this method has proven to be an invaluable geophysical tool in addressing the low velocity effect of the weathered layer. The analysis of the sample of the cuttings collected during the borehole drilling shows that the area is made up mainly of sand, clay and gravel. For the weathered layer which is fairly uniformly thin, the average velocity and thickness are 466m/s and 4.43m respectively. Also, for the consolidated layer adjudged to be sufficiently competent to support engineering structures, the average velocity is 1746m/s. The regression plots of the relationships between velocities of the two layers and depth show that there is fair goodness of fit between the variables. This would allow for prediction of the velocity of the consolidated layer when the parameters of the weathered layer are known. It follows that a datum of 6m deep is required to eliminate the effect of the weathered layer on 3D/4D seismic reflection data acquisition in the area, areas greater than 6m (station number 5781928 and 5571688) which are 7m and 8.9m respectively should be considered for skip or diversion or prepare for extra cost of excavating more 3m. Further investigation should be carried out using other geophysical methods. This will provide further guidance as regards the suitability of the area for proposed engineering structures, planning and development of the area. In spite of the fact that the top surface is undulating (nearly flat), the same is not true of the subsurface. The depth of the weathered layer varies enormously. Thus, the near-surface weathered layer can be thought of as having a flat top but a highly irregular internal structure. Finally, asides the estimation of the velocities for the weathered and consolidated layers using the proposed method, we also obtained mathematical regression models for the study area.

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