

Weathered Layer Determination and Its Effects on Engineering Structures: Case Study of Parts of the Niger Delta

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Abstract Failures associated with civil engineering structures in the study area with specific reference to roads and buildings have been attributed to lack of proper understanding of the weathered layer characteristics. This study was therefore carried out using downhole seismic refraction data from twenty borehole locations within parts of PortHarcourt, Niger Delta, Nigeria to determine the weathered layer characteristics of the area. The survey was carried out with the Geometrics Stratavisor NZ11 instrument using a set of hydrophones arranged in a definite manner in each of the boreholes. The data was processed using Udysys software and analyzed graphically using the seismic refraction interpretation technique. Several contour and analytical maps were generated for the weathered and consolidated layers. Similarly, four interpretative cross sections namely NW-SE, NE-SW, N-S and E-W were used for the purpose of correlation. Results of the study revealed that the velocity of the weathered layer ranged between 144 and 996m/s with a regional average of 407 m/s. The results also revealed that the thickness of the weathered layer ranged between 3.0 and 9.6m with a regional average of 5.0m. Velocity of the consolidated layer varied between 1449 and 1812m/s with a regional average of 1738m/s which is adjudged sufficiently competent to withstand engineering structures. It is therefore recommended that construction of heavy buildings and roads especially bridges in the area should have their foundations laid to a minimum depth of 9.6m to enable the infrastructure sit on the consolidated layer.

Keywords: downhole survey, weathered layer, consolidated layer, seismic refraction, Niger delta

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1. Introduction

The weathered is the shallow subsurface layer composed of unconsolidated materials such as soil, sand and gravel. It is heterogeneous in composition and is characterized by low seismic velocity which account for the delay experienced in travel time of the seismic waves [19,20,32]. The weathered layer is also characterized by high porosity, lack of cementation, low pressure and low bulk modulus. All of these properties account for the very low compressional and shear wave velocities observed in the layer. The base of the weathered layer can be referred to as the interface between the weathered layer and consolidated layer.

The seismic refraction method including the downhole survey is used to investigate the properties of the subsurface. This is done by generating arrival time and offset distance information to determine the path and

velocity of the elastic disturbance in the ground. The theory is based on the fact that the rays are refracted across layer boundaries where there is a difference in the properties of the formation. The critically refracted signal travels down through the different layers before returning back to the surface to be successfully detected by the line of geophones [5].

Uphole and downhole seismic refraction studies are the most important and commonly used techniques for studying the features of the low velocity layer [2]. These two techniques are useful in delineating the near surface velocities, depths and thicknesses of the layers in the vertical direction [2,13]. The velocity information obtained from these techniques is used in determining the geology and seismic response of a particular site. The raw data acquired from a downhole study are the travel times of compressional and shear waves from the source to the geophones and the distance between the source and geophones [7]. In the case of a downhole survey, a seismic source is used to generate a seismic signal at or near the

ground surface and offset horizontally from the top of a cased borehole, while downhole receivers are used to detect the arrival of the seismic wave train. The receivers are usually placed at selected test depths in a borehole. The method involves connecting the source and the receivers to a data recording system that records the response of the downhole receivers when a seismic signal is initiated. The seismic signal could be created by explosives, hammer, weight drop, or some other equivalent methods for sending impulsive energy into the ground [4,6,18]. Detectors which are laid out at almost regular intervals are used to detect the first arrival of the energy and measures its time. The records are plotted in time-distance graphs from which the velocities of the different layers and their depths are estimated.

Geophysicists use these weathered layer parameters in the design of receiver source arrays for field filtering purposes [32]. These parameters are used in the analysis of soil behaviour under static and dynamic loads. The elastic constants obtained are input variables into the models defining the different states of deformations such as elastic, elasto-plastic and failure [9,33].

The area under study, which is located within the Niger Delta Basin, is a hydrocarbon province with a lot of civil engineering constructions going on. The problems of failure of engineering structures are common in the Niger Delta due to lack of proper understanding of the weathered layer characteristics of the area. Figure 1- Figure 2 below, shows typical failures of engineering structures in the study area which are most often associated with the characteristics of the weathered layer.



Figure 1. Collapsed four-storey building under construction at Akpajo, Old Refinery Road, Obio/Akpor, Rivers State believed to be foundational



Figure 2. Collapsed Niger Delta University lecture theatre under construction

heavy rainy season and very short dry season. The heaviest precipitation in the study area occurs during september with an average of 367mm of rain while december is the driest month of the year with an average rainfall of 20mm. Temperatures throughout the year in the area is relatively constant, showing little variation throughout the course of the year. Average temperatures are typically between 25°C - 28°C in the study area.

1.1.2. Geology of the Area

The Niger Delta, covering an area of about 200,000 square kilometers, is situated on the West African continental margin at the apex of the Gulf of Guinea, which formed the site of a triple junction during continental break-up in the Cretaceous. The delta sequence comprises an upward-coarsening regressive association of Tertiary clastics up to 12km thick [10]. It is divided into three lithostratigraphic units which includes:

- i) Marine claystones and shales of about 6.5km thick at the base (Akata formation);
- ii) Alternations of sandstones, siltstones and claystones of about 3.5km thick (Agbada formation); and
- iii) Alluvial sands of about 2km thick at the top (Benin formation) [10].

The Benin Formation, on which the study area sits, consists of predominantly massive, highly porous, fresh water-bearing sandstone, with local interbeds of shale. It is a continental deposit of Miocene to Recent age [11,35].

Major growth-fault trends cross the Delta from northwest to southeast, dividing it into a number of structural and Stratigraphic belts, called depobelts, which become younger towards the south. Hydrocarbons have been located in all of the depobelts of the Niger Delta, in good quality sandstone reservoirs belonging to the main deltaic sequence.

2. Theoretical Background

Downhole survey is one of the best methods of carrying out near surface investigation to determine the weathering and sub-weathering thicknesses and velocities. A downhole survey normally requires taking shots on or near the surface and at a distance from the borehole, and using geophones/hydrophones to measure the arrival times downhole giving information on static shifts to the surface from the source depth. Figure 5 below shows a typical downhole survey acquisition geometry. This method of survey involves the measuring of the near-surface velocity with geophones or hydrophones in a borehole and a source on or near the surface. Seismic energy is generated on the surface at a fixed distance from the top of the borehole. The travel times of the first-arrival seismic waves are measured at regular intervals down the hole using a string of hydrophones or, in the case of S-wave surveys, a single clamped triaxial geophone that is gradually moved down the hole. The P- and S-wave arrival times for each receiver location are combined to produce travel-time versus depth curves for the complete hole. These are then used to produce total velocity profiles from which interval velocities and the various elastic moduli can be calculated (in conjunction with density data from geophysical logging of the borehole)

P-wave energy is normally provided by a hammer and plate or weight drop similar to shallow seismic reflection and refraction profiling surveys. Polarized S-waves are generated using a shear wave hammer. This comprises two hammers connected to either end of a plank that is held to the ground using a vehicle or heavy weight. Collecting both positive and negative polarized (so called A and B) S-waves using the two hammers separately, enables the S-wave arrivals on the receiver shot records to be distinguished from those of P-waves and coherent noise.

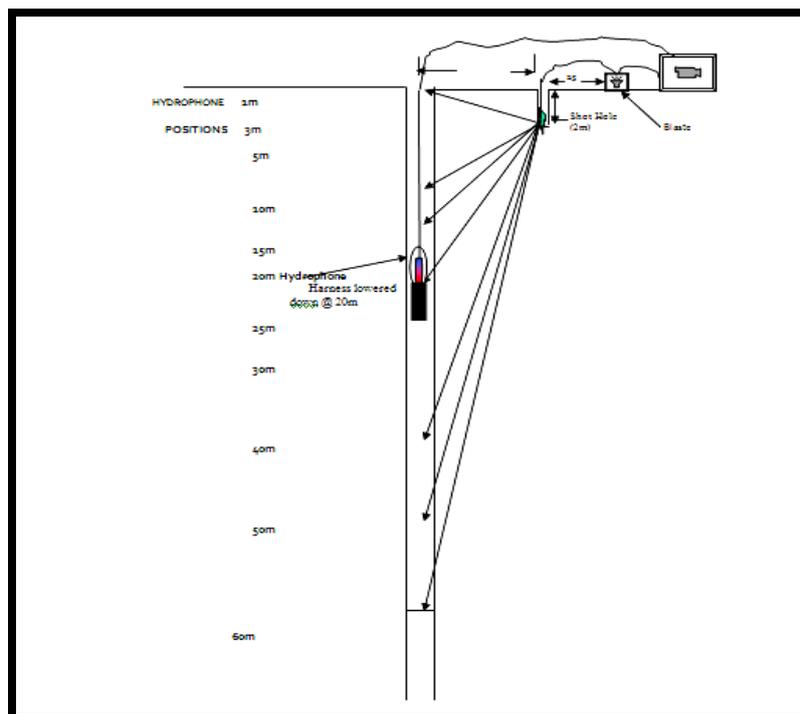


Figure 5. A typical acquisition geometry used for the downhole survey.

The arrival times measured by the sensors are plotted against detector depths. The downhole geophone plot will

change substantially where the shot enters the low velocity layer. The slope of the portion above the base of the low

velocity layer gives the weathering velocity while the break in slope defines weathering depth.

Processing of the downhole survey data involves picking the first break times from the monitor records. The picked times are first corrected for offset and surface.

Correction for offset and surface is given by:

$$t^1 = t^* \frac{D}{\sqrt{D^2 + X^2}} \quad (1)$$

Where D = downhole depth, X = source-borehole offset, t = Measured one-way time and t¹ = corrected time. These converted times are then plotted against receiver depths in a Time-Depth graph. The velocities and depths of the different layers are all determined from this plot.

3. Data Acquisition and Processing

Borehole depths of not less than 53m and not more than 66m was drilled for each downhole point. The holes were drilled using the flushing drill method. Water was used in drilling the hole which helps to soften the soil and acts as weight upon the drill bit as it rotates inside the ground and flushes out the cut sediments into the mud pit. Lithologic samples (from the drill cuttings) were collected at interval depths of 3m. The reason for the collection was to use them to reconstruct the vertical profile of the soil at the downhole point. This could be used to observe velocity changes with change in lithology with depth. The statistics of the different boreholes are presented in Table 1 below. The extra depths are to allow for possible back filling of the hole. The recording holes were cased with plastic casings and filled with water before logging. An energy source hole of 2m deep and 3 metres away from the recording hole was drilled to bury the explosive charges. Drilling was by semi-manual, engine powered rotary method. This involves rotating drilling stem by manual labour and pumping water through to flush out cuttings.

Drilling mud was formulated from drilling chemicals (bentonite and EZ mud) to provide borehole stability and transportation of cuttings to the surface.

A downhole cable with a hydrophone positioned at different intervals was used for logging. The logging depths are 60m, 50m, 40m, 30m, 25m, 20m, 15m, 10m, 5m, 3m, 1m, and 0m. The cable/rope used is calibrated. The data for the downhole survey were acquired with Geometrics Stratavisor NZ11. This instrument is basically a signal enhancement seismograph that has a combination of features such as speed, accuracy, and light weight. Other instruments used include 2kg, 6mm cap explosive detonators as seismic source, a 10Hz hydrophone receiver, a calibrated downhole cable, and a 24-volt rechargeable battery. The data are recorded on data sheet and on diskette/tape for further play back. However a hard copy printout is done. The trace size and appearance can be easily adjusted to meet specific requirements for immediate display.

Table 1. Summary of downhole statistics in the study are

DNH. SN	DRILLED (m)	LOGGED (m)	ELEVATION
1	55	50	28.94
2	53	50	13.41
3	53	50	30.24
4	55	50	23.7
8	62	60	30.88
7	62	60	28.3
6	54	54	26.2
5	66	60	20.73
9	66	60	30.78
10	66	60	24.27
11	63	60	21.9
12	62	60	17.98
16	59	50	28.7
15	66	60	24.68
14	66	60	17.6
13	66	60	17.33
17	66	60	26.45
18	60	54	24.24
19	66	60	15.6
20	66	60	11.71

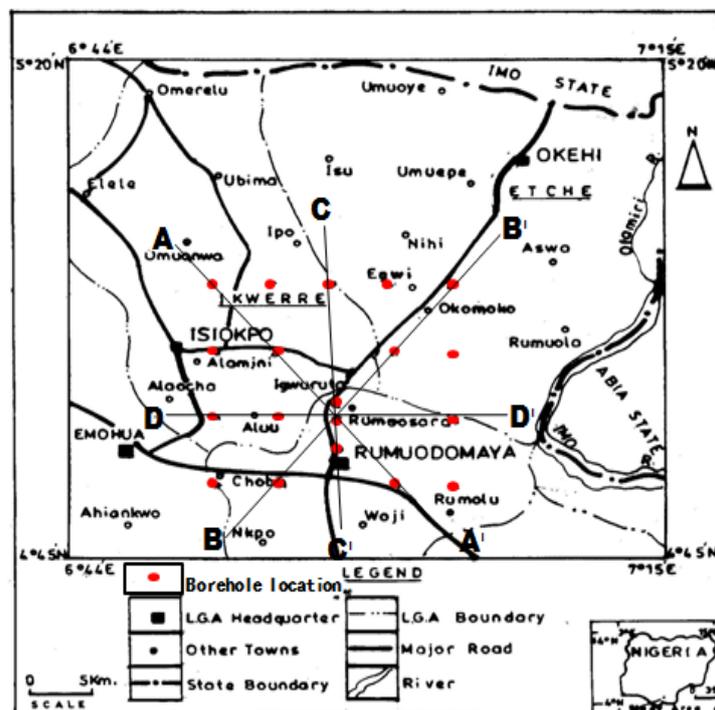


Figure 6. Location map of the study area showing the borehole locations and interpreted profiles

In processing the downhole data, first break arrival times are picked for various shots. First break time is the first pick up time recognized for any trace, and it is a parameter of interest in the interpretation of downhole data. Near surface depth models are computed from picked first break time, and to achieve this, the time is plotted against each hydrophone position in the hole [30]. Processing of the downhole survey data involves picking the first break times from the monitor records. The data was carefully processed using Udysys software to produce travel-time versus depth curves for all the boreholes. The curves were then further analyzed and interpreted. Informations extracted from the curves was used to generate accurate thickness and velocity contour maps and models for the weathered and consolidated layers of the study area using Surfer 10 software. Interpretative cross sections of NW-SE, NE-SW, N-S and E-W traverses of the project area showing the depths to the weathered layer

were then generated as shown in Figure 6. Also, elevation and weathering thickness values were plotted against the borehole locations for each of the traverses considered for the purpose of comparison.

4. Result Presentation, Interpretation and Discussion

The raw data of some of the downhole survey in the study area are shown in Table 2- Table 4 below. A total of twenty downhole points were logged. Qualitative interpretation was done using time-depth graph (intercept method) to obtain the weathering layer models with its calculated values. Some of these time- distance curves are shown in Figure 7 to Figure 9 below. The overall result shows a two (2) layer model as shown in Table 5 below.

Table 2. Raw data for Borehole 5 (Ts = offset and surface corrected time)

CHANNEL	1	2	3	4	5	6	7	8	9	10	11	12
DEPTH(m)	0	1	3	5	10	15	20	25	30	40	50	60
Ts(ms)	0	3.5	7.1	9.4	12.5	15.2	18.8	20.4	22.9	28.9	34.9	40.4

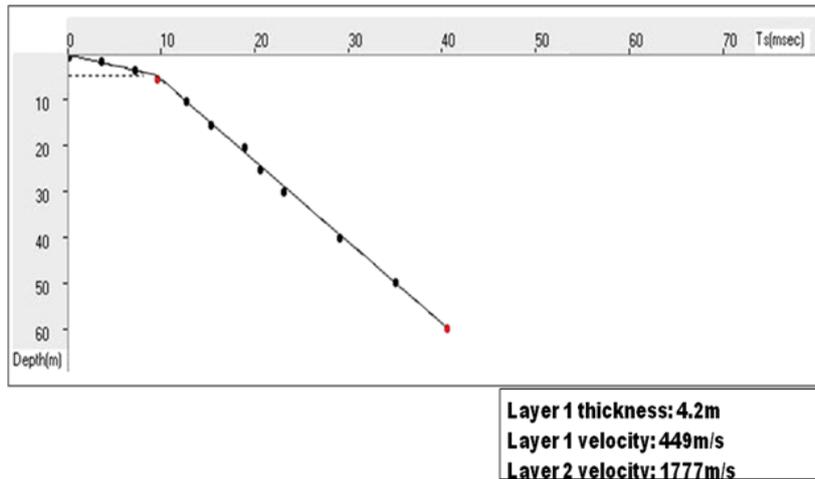


Figure 7. Travel-time versus Depth curve for borehole 5

Table 3. Raw data for Borehole 7 (Ts = offset and surface corrected time)

CHANNEL	1	2	3	4	5	6	7	8	9	10	11	12
DEPTH(m)	0	1	3	5	10	15	20	25	30	40	50	60
Ts(ms)	0	2.2	8.7	13.3	17.7	21.1	23.3	26.4	29.4	35.5	41.5	47.5

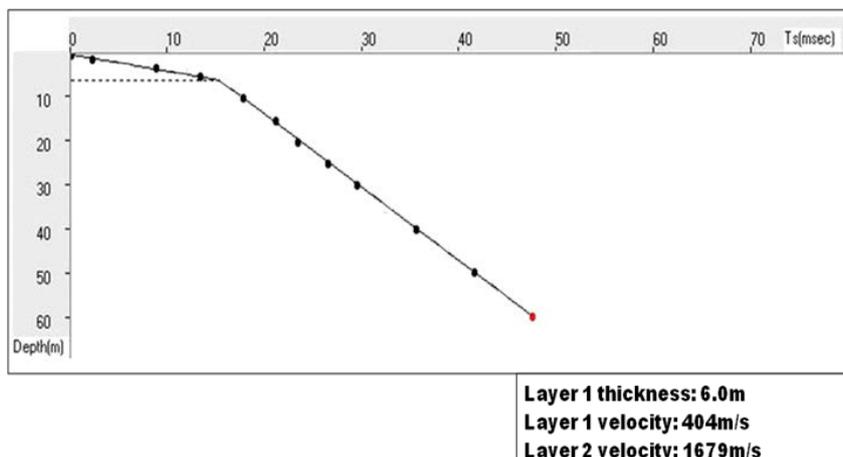


Figure 8. Travel-time versus Depth curve for borehole 7

Table 4. Raw data for Borehole 15 (Ts = offset and surface corrected time)

CHANNEL	1	2	3	4	5	6	7	8	9	10	11	12
DEPTH(m)	0	1	3	5	10	15	20	25	30	40	50	60
Ts(ms)	0	3.5	7.8	12.9	15.8	18.6	20.8	23.8	26.9	31.9	37.9	43.9

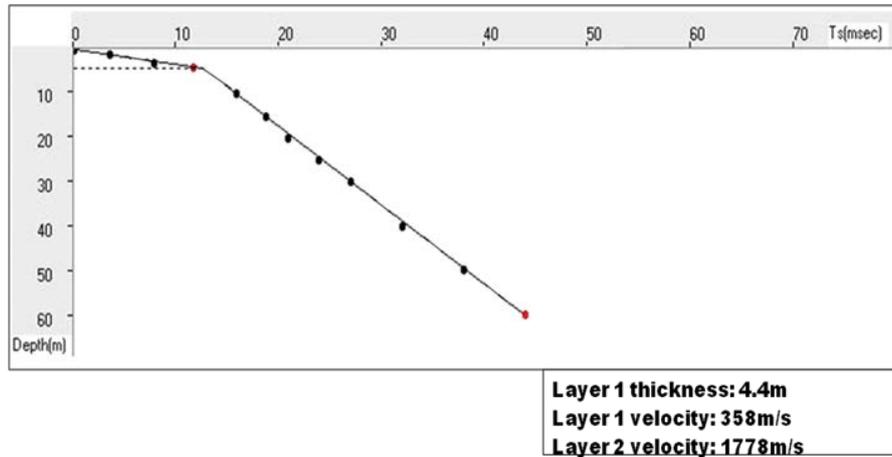


Figure 9. Travel-time versus Depth curve for borehole 15

Table 5. Summary of processed downhole data Results for all boreholes

DNH. SN	ELEVATION (m)	DEPTH OF WEATHERED LAYER (m)	WEATHERED LAYER VELOCITY (m/s)	CONSOLIDATED LAYER VELOCITY (m/s)
1	28.94	3.6	144	1812
2	13.41	5.5	167	1704
3	30.24	4.1	284	1723
4	23.70	4.1	178	1775
8	30.88	5.3	335	1762
7	28.30	6.0	404	1679
6	26.20	5.9	363	1449
5	20.73	4.2	449	1777
9	30.78	6.2	298	1742
10	24.27	5.7	500	1750
11	21.90	5.7	333	1755
12	17.98	5.1	588	1757
16	28.70	9.6	416	1751
15	24.68	4.4	358	1778
14	17.60	3.6	996	1760
13	17.33	4.1	287	1750
17	26.45	5.7	332	1748
18	24.24	5.3	315	1735
19	15.60	3.0	509	1768
20	11.71	3.3	887	1781

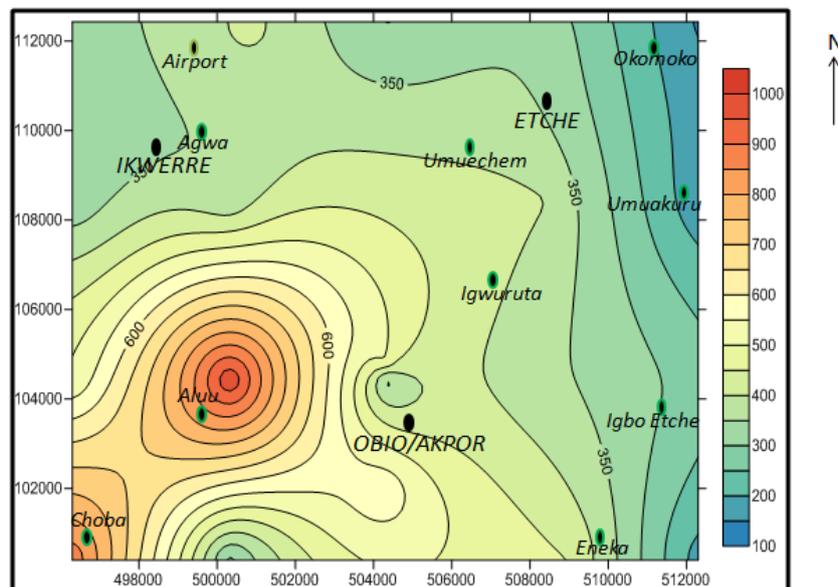


Figure 10. Weathered layer velocity contour map of the study area

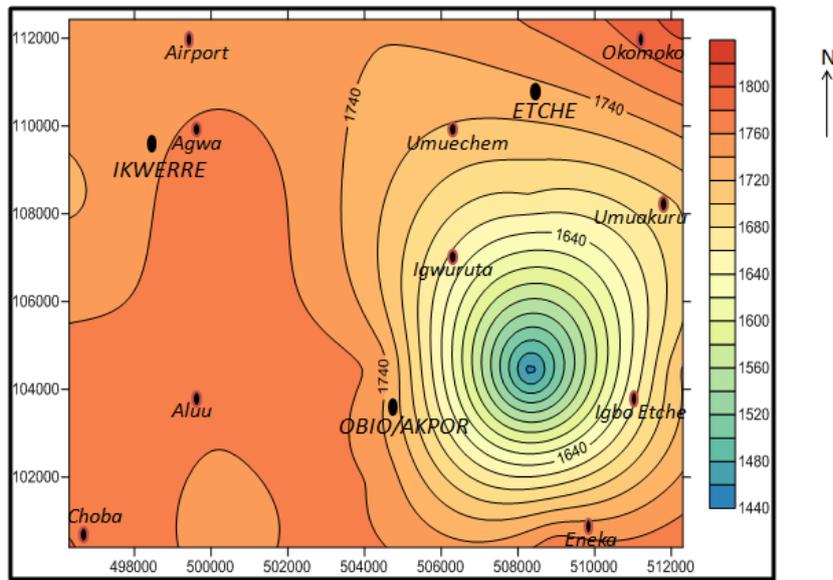


Figure 11. Consolidated layer velocity contour map of the study area

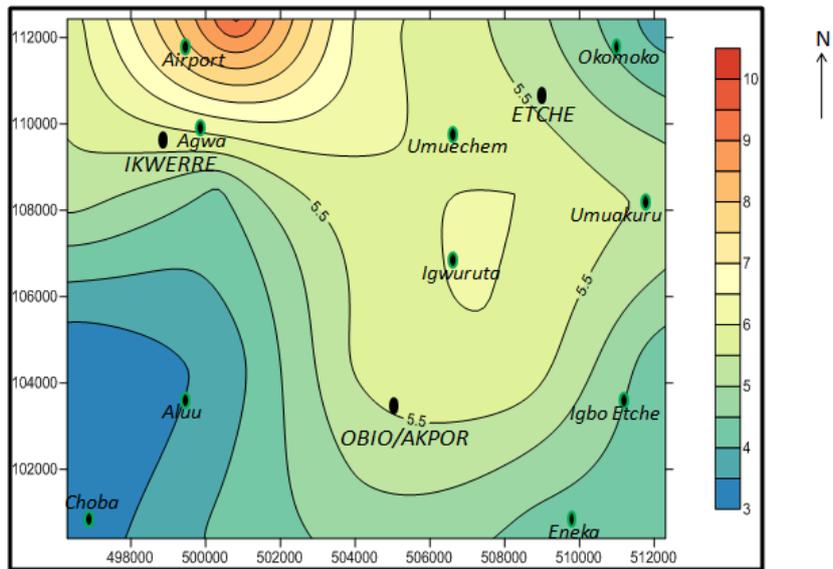


Figure 12. Weathered layer thickness contour map of the study area.

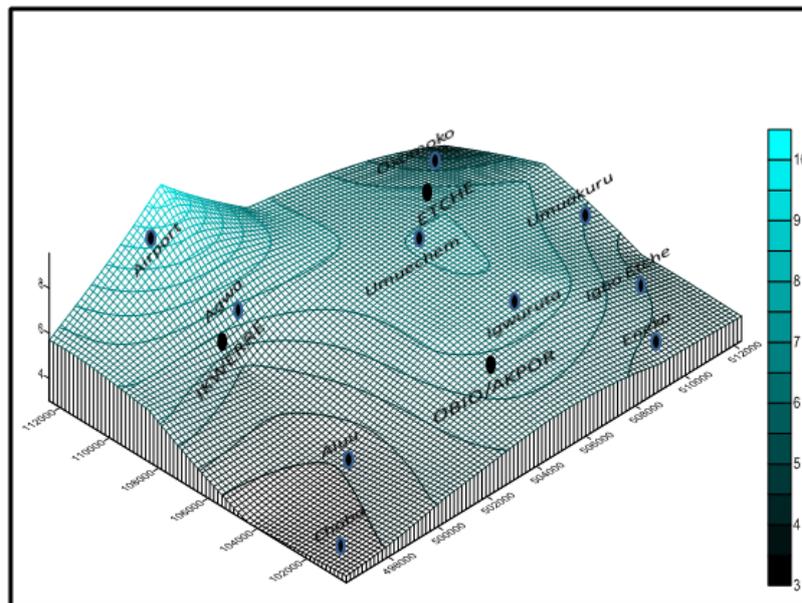


Figure 13. Thickness model of the weathered layer presented as wire frame map

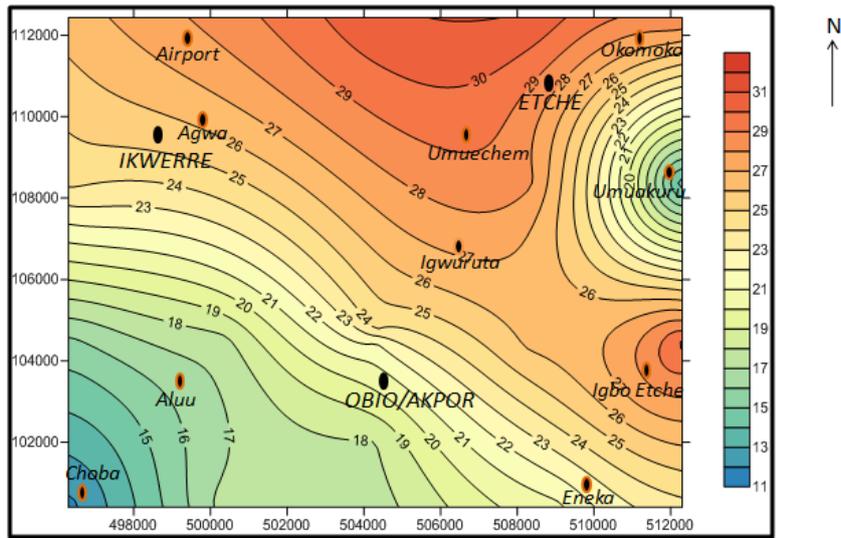


Figure 14. Surface elevation contour map of the study area

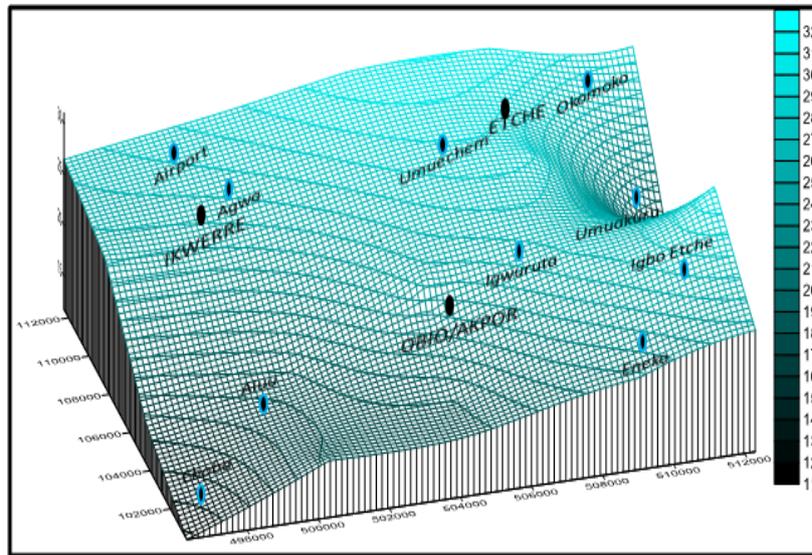


Figure 15. Surface elevation model presented as wire frame map

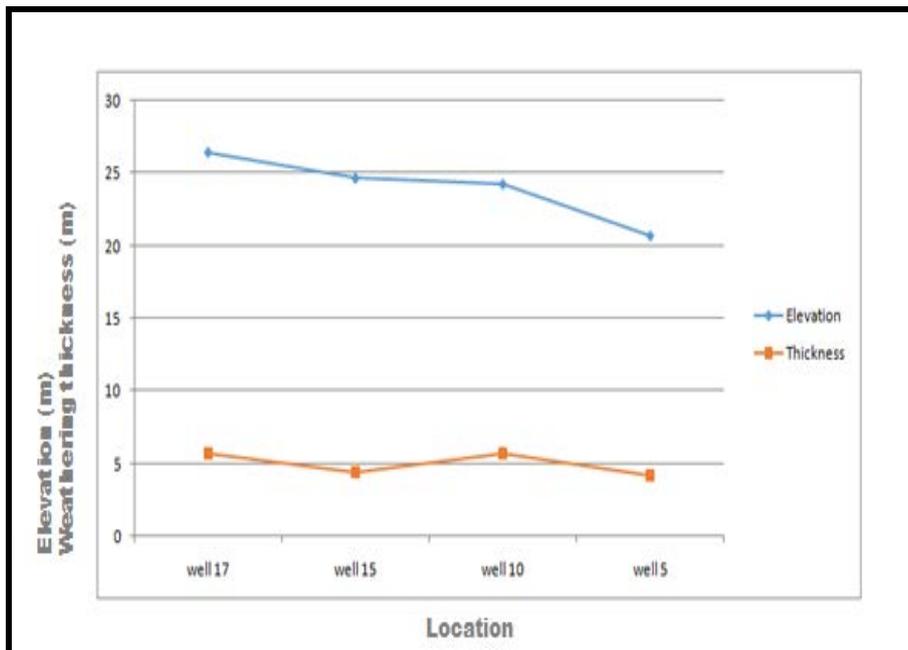


Figure 16. Comparison of elevation and weathering thickness for A-A¹ (NW-SE) profile of the study area

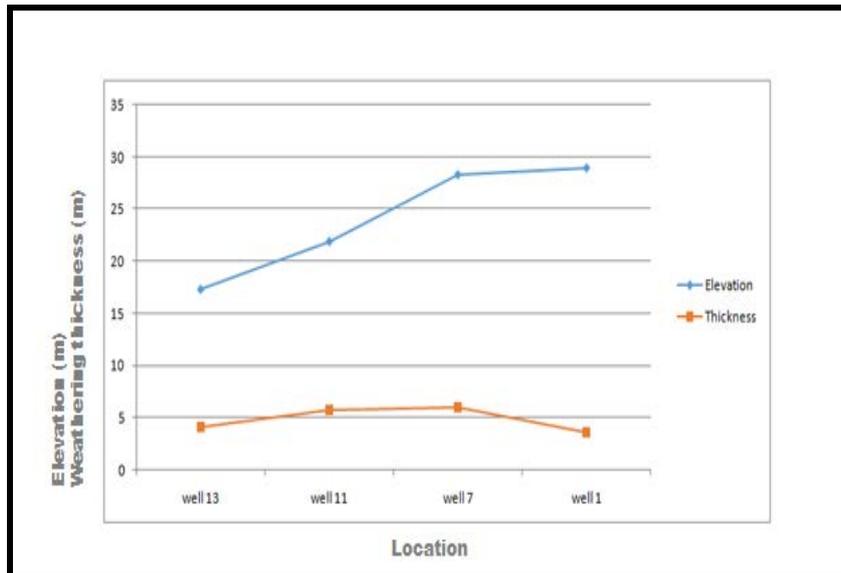


Figure 17. Comparison of elevation and weathering thickness for B-B¹ (NE-SW) profile of the study area

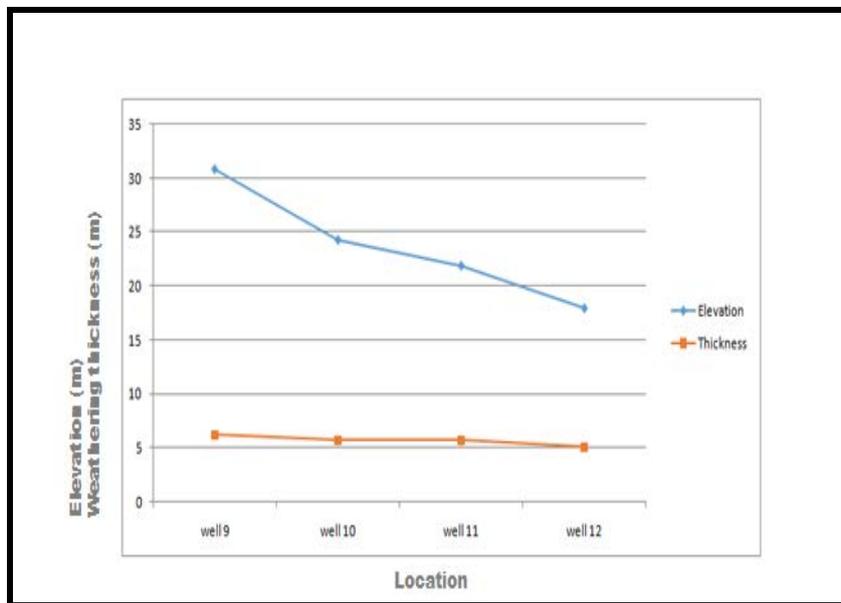


Figure 18. Comparison of elevation and weathering thickness for C-C¹ (N-S) profile of the study area

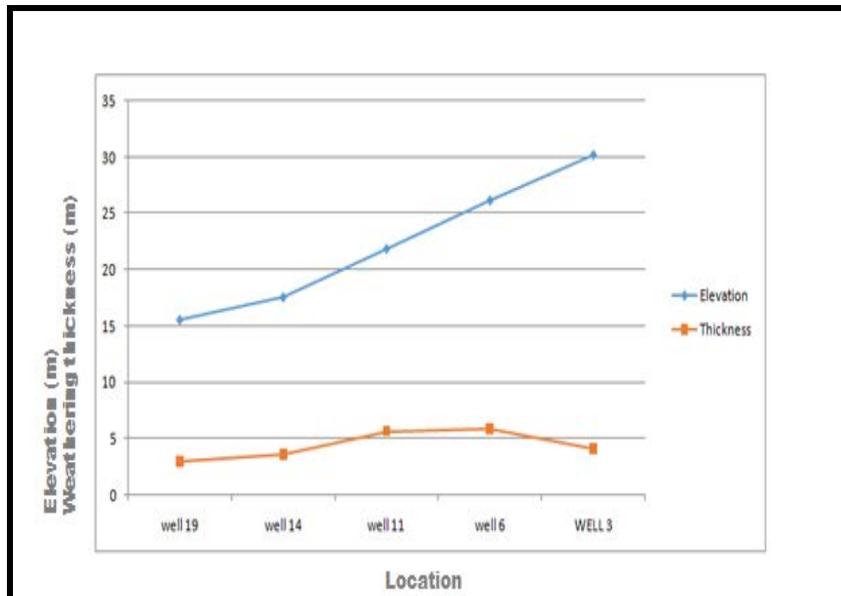


Figure 19. Comparison of elevation and weathering thickness for D-D¹ (E-W) profile of the study area

Results of the velocities of the weathered and consolidated layers as well as the thickness of the weathered layer are presented as contour maps and 3-D maps as shown in Figure 10 -Figure 15. Also, the surface elevation contour map and 3-D model of the study area are presented in Figure 15 and Figure 16. Similarly, four interpretative cross sections which include A- A¹ (NW-SE), B- B¹ (NE-SW), C- C¹ (N-S), and D- D¹ (E-W) profiles were taken for the purpose of correlation and comparison. The aim of these cross sections is to establish the relationship between weathering thickness and depth in the study area. To achieve this, several bivariate plots were taken to establish this relationship as shown in Figure 16-Figure 19.

Results of the downhole survey carried out in the study area revealed that the area is dominated by a two (2) layer velocity model. Weathering thicknesses ranged from 3.0m to 9.6m with a regional average of 5.0m, while weathered layer velocities varies from 144m/s to 996m/s with a regional average of 407m/s. Similarly, the consolidated layer velocities varied from 1449m/s to 1812m/s with a regional average of 1738m/s. The velocity contour map of the weathered zone shows a sharp velocity increment while the weathered layer thickness map and model shows a decrease in weathering depth around the southwestern part of the study area (Aluu and Choba axes of Obio/Akpor) compared to other areas. This may be due to the presence of extensive compacted sand material in the area. The lowest velocity recorded in the weathered zone is observed within the northeastern part of the study area around Okomoko and Umuakuru axes of Etche. This is possibly because the areas are part of the basins of the Imo and Otamiri Rivers.

Similarly, a sudden increase in weathering depth and low weathering velocity was recorded around the northwestern part of the study area (Airport axis of Ikwerre) and this possibly suggests relatively high porosity and permeability in this area. Since porous and permeable rocks have greater ability to hold water, this results in low seismic velocity and explains why seismic wave velocity are markedly attenuated in some areas. The sharp consolidated layer velocity decrement recorded around the southeastern part of the study area (between Igwuruta area of Ikwerre and Igbo Etche area of Etche) suggests that the area might likely be undercompacted compared to other areas.

Finally, from the interpreted cross sections generated, the weathering depth did not vary much along the A - A¹ traverse except for a little decrease around well 15. Along the B - B¹ traverse, the weathering depth increased gently from well 13 down to well 7 before it began to decrease towards well 1. The weathering depth along the C - C¹ traverse increased slightly from well 9 before it started decreasing gently down to well 10 and 11, and a further slight decrement down to well 12. An increment in the weathering depth was observed along the D - D¹ traverse from well 19 to well 6 and a little decrement towards well 3. A comparison was also carried out between the total weathering thickness and elevation for A- A¹ (NW-SE), B- B¹ (NE-SW), C- C¹ (N-S), and D- D¹ (E-W) traverses of the study area. There seems to be a variation in the thickness of the weathered layer with elevation. This proves that elevation has an effect on the thickness of the weathered layer.

5. Summary, and Conclusion And Recommendation

In this work, downhole seismic geophysical method has been used to study the weathered layer geophysical characteristics of the study area. These include the weathered layer thickness, weathered layer velocity, and consolidated layer velocity. A total of 20 borehole locations were covered and results showed that the weathered layer thickness in the area ranged between 3.0 and 9.6m with a regional average weathered Layer thickness of 5.0m. The study also revealed that the weathered layer velocity in the area ranged between 144 and 996m/s with a regional average value of 407m/s. The consolidated layer velocity ranged between 1449 to 1812m/s with a regional average of 1738m/s, adjudged sufficiently competent to withstand engineering structures.

A sharp velocity increment and a decrease in weathering depth was observed around the southwestern part of the study area (Aluu and Choba axes of Obio/Akpor) compared to other areas. This may be due to the presence of extensive compacted sand material in the area. Also, a sudden increase in weathering depth and low weathering velocity was recorded around the northwestern part of the study area (Airport axis of Ikwerre) and this may suggest relatively high porosity and permeability in the area. From the comparison carried out between the total weathering thickness and elevation for the considered traverses, there seems to be a variation in the thickness of the weathered layer with elevation. This proves that elevation has an effect on the thickness of the weathered layer.

In conclusion, the result of the analyses was able to identify clearly the weathering and velocity profiles which show that the area is dominated by two layer models. The top of the consolidated layer and weathered zones were defined by the interpretative cross sections.

It can be concluded from the findings that downhole geophysical survey method is a very useful tool for studying the weathered layer characteristics of a given area. The method provides subsurface information over large areas at reasonable cost. Information obtained from downhole geophysical surveys are very useful in analyzing soil behaviour under static and dynamic loads and are helpful to civil engineers. Also, the information provided by the method can be used to infer the presence of subsurface structures in a given area.

Based on these findings, it is therefore recommended that:

1. Construction of high rising buildings and roads especially bridges in the study area should have their foundations laid to a minimum depth of 9.6m to enable the infrastructure sit on the consolidated layer.
2. In the future, data points on the acquisition grid should be established at a closer interval in order to obtain a better subsurface definition.
3. The study however could not draw up a relationship between downhole seismic refraction and surface seismic refraction to arrive at a more conclusive analysis. A surface seismic refraction survey should therefore be carried out in the area to draw far reaching conclusions on the weathered layer properties of the study area.

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