

Delineation of Weathered Layer Using Uphole and Surface Seismic Refraction Methods in Parts of Niger Delta, Nigeria

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ABSTRACT: Uphole and surface seismic refraction surveys were carried out in parts of the Niger Delta, Nigeria, to delineate weathering thickness and velocity associated with a weathered layer. A total of twelve uphole and surface seismic refraction surveys were shot, computed and analyzed. The velocity of the uphole seismic refraction ranged from 344.8 to 680.3 m/s with a thickness of 5.45 to 13.35 m. Surface seismic refraction ranged from 326.6 to 670.2 m/s and 4.30 to 12.0 m, respectively. The average velocity and thickness ranged from 559.6 to 548.0 m/s and 9.43 to 8.63 m with differences of 11.6 m/s and 0.83 m respectively. The V_w/V_s ratios ranged from 0.955 to 1.059. This indicates that the uphole velocity is higher than the surface refraction velocity leading to low V_w/V_s values. This is a direct experimental proof of a low velocity zone, confirming the weathered nature of the area. The results of both refraction methods are reliable; the differences in surface refraction values are due to shot point offsets. Based on these findings, it is recommended that shots for seismic surveys should be located above 15.0 m in the area to delineate the effects associated with weathered layers to ensure that will be competent to withstand engineering structures.

Keywords: Niger Delta; Surface seismic refraction; Uphole and Weathered layers.

تفكيك طبقة مجففة باستخدام طرق الانكسار الزلزالي السطحي في أجزاء من دلتا النيجر ، نيجيريا

مافينيسو أكا، أوكيشوكو أجباسي، جونسون أيبوت و شوميمكا سامسون

المخلص: تم إجراء مسوحات الانكسار الزلزالي والسطحي في أجزاء من دلتا النيجر ، نيجيريا ، لتحديد سماكة التجوية والسرعة المرتبطة بالطبقة التي تعرضت للعوامل الجوية. تم تصوير ما مجموعه اثني عشر مسحًا انكسارًا زلزاليًا في قاع البئر والسطح وحسابها وتحليلها. تراوحت سرعة الانكسار الزلزالي في قاع البئر من 344.8 إلى 680.3 م / ث بسمك 5.45 إلى 13.35 م. تراوح الانكسار الزلزالي السطحي من 326.6 إلى 670.2 م / ث و 4.30 إلى 12.0 م على التوالي. تراوح متوسط السرعة والسماكة من 559.6 إلى 548.0 م / ث ومن 9.43 إلى 8.63 م بفارق 11.6 م / ث و 0.83 م على التوالي. تراوحت نسب V_w/V_s من 0.955 إلى 1.059 ، وهذا يوضح أن سرعة البئر أعلى من سرعة الانكسار السطحي مما يؤدي إلى انخفاض قيم V_w/V_s . هذا دليل تجريبي مباشر على منطقة سرعة منخفضة ، مما يؤكد الطبيعة المتجوية للمنطقة. ، نتائج كل من طريقتي الانكسار موثوقة ، والاختلافات في قيم الانكسار السطحي ترجع إلى إزاحة نقطة التسديد. بناءً على هذه النتائج ، يوصى بأن تكون لقطات المسوحات الزلزالية فوق 15.0 مترًا في المنطقة لتحديد التأثيرات المرتبطة بالطبقات التي تعرضت للعوامل الجوية ، والتي ستكون مؤهلة لتحمل الهياكل الهندسية.

الكلمات المفتاحية: دلتا النيجر؛ الانكسار الزلزالي السطحي تمسك طبقات مجوية.



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1. Introduction

The Niger Delta region of Nigeria comprises weathered layers of sedimentary materials and unconsolidated coastal plain underlain by, from bottom to top, Akata, Agbada and Benin formations [1]. Lack of proper understanding of the weathered layers' characteristics creates problems such as poor data quality and statics in seismic surveys [2]. The weathered layer problems are result of large disparities in the velocities and thicknesses of the weather layers and the underlying strata in seismic data acquisition. Small changes in the thickness of weathered layers make large differences in the arrival times of seismic data, which leads to false seismic imaging structures [3].

Surface seismic refraction alone has been routinely used to delineate the effects of the weathered layer by previous researchers within the study area [1, 2]. This method has not provided a good definition of the weathered and consolidated layers, which has led to persistent cases of structural failure and environmental hazards encountered within the study area. The current research, therefore, combines both uphole and surface seismic refraction to better delineate the effects of weathered layers by taking advantage of the elevation and lithology of lateral formations coupled with the weathered layers' velocity and thickness. This is because differences in the elevation leads to differences in travel time of the geophone, which have an effect on the positioning of synclines, anticlines and fault formations. Therefore, the weathered layer data acquired during seismic prospecting is corrected to take care of these anomalies [4]. The uphole seismic refraction method is the measurement of the near surface seismic velocity by generating a seismic source on or close to the surface, adjacent to a drilled borehole, and recording the travel times of its first arrival at intervals down the hole using a geophone [5].

The uphole technique measures the vertical changes in seismic velocity by placing a source at the top of a borehole and measuring travel times at multiple intervals in the borehole [6]. The P and S wave travel times for each geophone are combined and plotted for the uphole as travel time versus depth curves, respectively. This gives total velocity profiles from which various elastic moduli can be calculated from the borehole, thereby producing a true picture of the subsurface. Weathered layers are characterized by high porosity, lack of cementation, low pressure and low bulk modulus, which are responsible for the low velocity encountered in them. Comparing measurements obtained by uphole techniques with the surface method, reveals shortfalls in the determination of weathered layers and provides a way of inaccuracy in surveys. This proves that the method is viable for the delineation of the thickness and velocity of the weathered layer.

2. Location and Geology of Study area

The area under study is the southern part of the Niger Delta, Nigeria. It lies between the latitudes $4^{\circ}33'$ and $4^{\circ}45'$ N and from the longitudes $7^{\circ}52'$ to $8^{\circ}02'$ E as shown in Figure 1. The sediments of the area are unconsolidated with a high variable thickness throughout the region [7]. The Niger Delta is characterized by fault-bounded sedimentation, extensive shale structures and weathered layers which are comprised of low velocity zones [8]. It is made up of fresh water swamps and mangrove swamps with relief that increases towards the north. It is composed of three sedimentary formations namely: Benin, Agbada and Akata formations as shown in Figure 2. The Benin formation consists of coarse-grained sandstones with minor intercalations of shale. The Agbada formation consists of alternating sandstones, marine shale and fluviomarine sandstone. The Akata formation consists of shale with local interbedding of sands and siltstones [9].

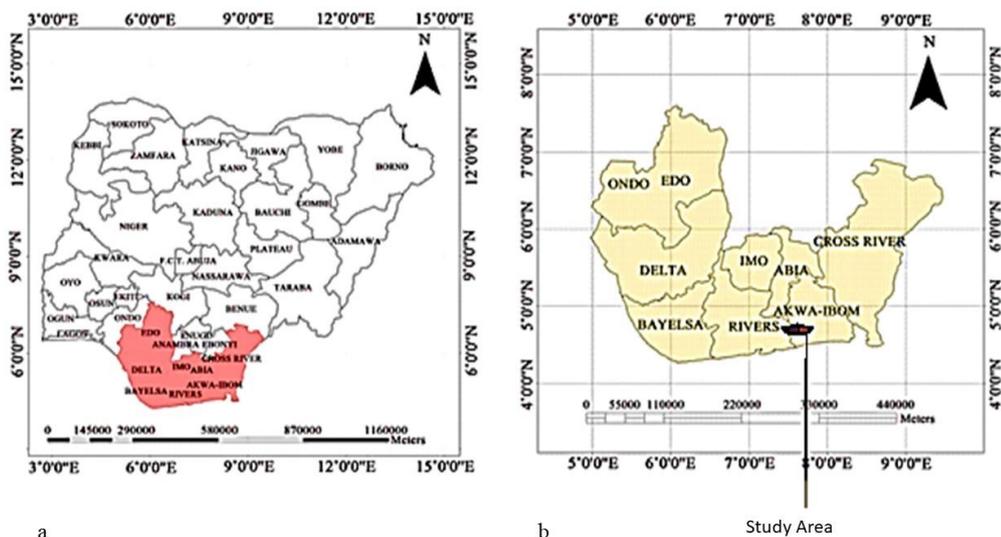


Figure 1. (a) Map of Nigeria showing the Niger Delta region and the study area (b) Niger Delta region showing the study area.

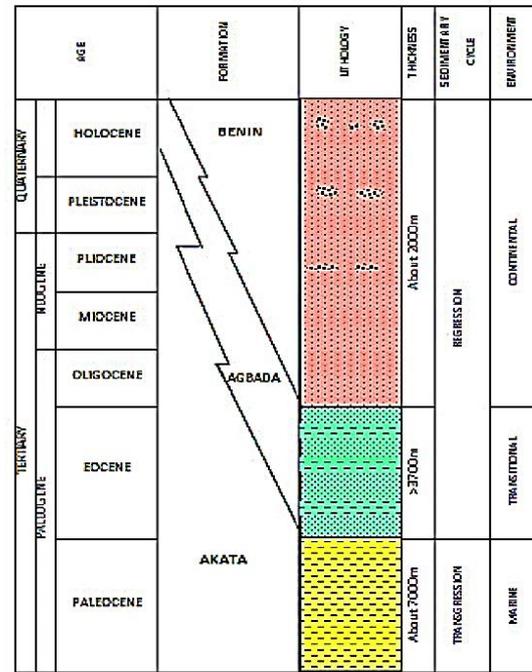


Figure 2. Stratigraphic chart of the Niger Delta region, Nigeria.

3.Theoretical Background

The seismic refraction method is a geophysical technique used to determine thickness of weathered layers, depth to bedrock, depth of the water table and other seismic velocity boundaries [10]. For the seismic refraction method to be used effectively, subsurface determination, the travel times of the generated wave and the offset distance must be determined. The uphole method of seismic refraction is a seismic field technique which uses receivers on the ground surface and an underground source to obtain information about the subsurface lithology. It requires a drilling rig, pulley, water tank and man power and takes some time for the drilling process. It measures the travel times of primary and secondary waves from the energy source to the receivers. It also provides near surface information at the point of survey about the lithology of lateral formations [11]. In uphole refraction, the survey is performed in a single borehole in that a hole is drilled to the required depth at the survey location and a vibrating source is created to determine the velocity for various soil layers [6].

A single wave source is located on the ground and underground surfaces, a multiple receiver is fixed at known depth and the output is measured as a function of time and depth as shown in Figure 3. The exact times of the source being produced and of the energy reaching the receivers need to be determined to analyze the first arrival times. The first arrival of seismic energy is always the direct wave or the refracted wave. The travel time versus depth and uphole survey time relationship are also shown in Figures 4 and 5, respectively. The velocity of the weathered layer can be calculated from the reciprocal of the gradient of the direct arrivals. However, the velocity of the second layer can be calculated from the reciprocal of the gradient of refracted arrivals. A good knowledge of the thickness distribution of the layer is often of immense advantage to engineering geophysical studies as well as in seismic refraction data acquisition ventures. Hence, the depth (thickness) of the interface can be calculated from the intercept of refracted arrivals along with the velocity [12], as shown in equations 1 and 2, respectively.

On the other hand, the surface seismic refraction technique is slightly different from the uphole method as it measures the travel time of P and S seismic waves refracted at the interfaces between surface layers of different velocity. It also provides information about the near surface over the length of the laid spread. It requires the use of hammer and plates, weight drops or small explosive charges as energy sources, geophones as detectors and a seismograph as a recording unit. Moreover, it is easy to accomplish, time efficient and more economical compared to uphole refraction. In surface seismic refraction, the survey is performed with a linear array of geophones connected to a seismograph at certain regular interval. Seismic energy generated by a source located on the surface, radiating out from the shot point, penetrating into the subsurface is refracted at various interfaces, corresponding to geological boundaries [13]. However, the travel time is measured and plotted with respect to depth. The velocity and thickness are calculated in a similar way as in the case of uphole refraction.

$$t = \frac{2z}{v_1 v_2} (v_2^2 - v_1^2)^{1/2} \tag{1}$$

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$$Z = \frac{t_1 V_1 V_2}{2 (V_2^2 - V_1^2)^{1/2}} \quad (2)$$

where Z = the depth of the thickness, t = total time along refracted path, t_1 = intercept time, V_1 = Velocity of the first layer and V_2 is the velocity of the second layer.

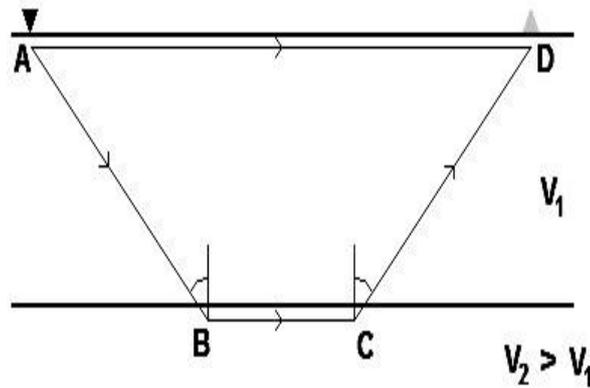


Figure 3. Direct and refracted waves in two layers.

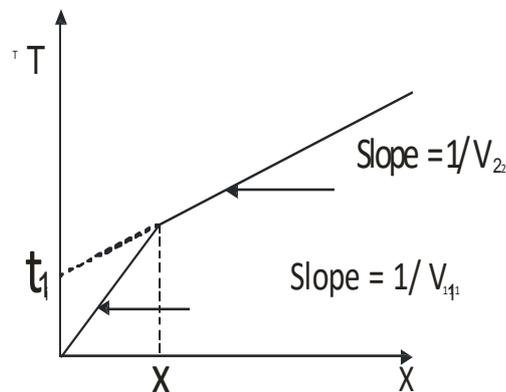


Figure 4. Travel time versus depth plot.

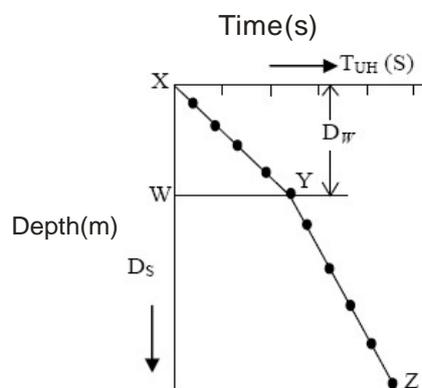


Figure 5. Uphole survey time depth relationship.

4. Materials and Method

Uphole refraction surveys were conducted at twelve different locations within the study area, using a TD500 top drive drilling machine, a twelve channels enhancement seismograph and 48 Hz geophones. During drilling, a deep hole was drilled at the intersection of the source and receiver line. Dynamic charges were laid successively in the hole at 5 m intervals, starting from the greatest depth of 60 m. Each charge extended to the surface with the depth written on it. The holes were tamped after each successful shot to prevent loss of energy at the hole during the shooting processes.

Twelve geophones were laid on the surface at 5 m intervals from the hole to receive the seismic signal to the seismographs. After explosion, a single geophone was planted close to the hole surface to obtain an uphole pre-trigger time, which is the time elapsed between the shot and the reception by the geophone.

Surface seismic refraction surveys were also carried out at twelve different locations, covered by five traverses namely A, B, C, D and E, respectively. Each of the traverses was 60 m long with an inter-geophone separation distance of 5 m. Shot points were recorded on each profile.

A twelve-channel enhancement seismograph was used to measure the refracted travel times of P and S waves along with the 48 Hz frequency geophones. The seismic wave signals received by the geophones were converted from mechanical to electrical. However, parts of the signals that were undesirable (noise) were attenuated by a frequency filter. The outputs of the arrival times after filtration were displayed on the monitor and selected as shown in Figure 6 and 7, respectively. In processing the data, the first break of arrival times were picked for various shots. The first break time is the first pick-up time recognized for any trace which is the parameter of interest in the interpretation of uphole data. The uphole data were normalized by subtracting the pre-trigger time from the first break time. By doing this, the pick-up time of the shot by each geophone was assumed to be the same [14]. Moreover, the differences were due to time delays introduced by weathered layers with different lithology sediments. The recorded travel times were then plotted against geophone offset for each uphole point. The parameters of interest, that is, velocity and thickness, were calculated from the slope of travel times versus offset distance as the reciprocal and intersection points for all the shots, which constitutes the data set as shown in table 1.

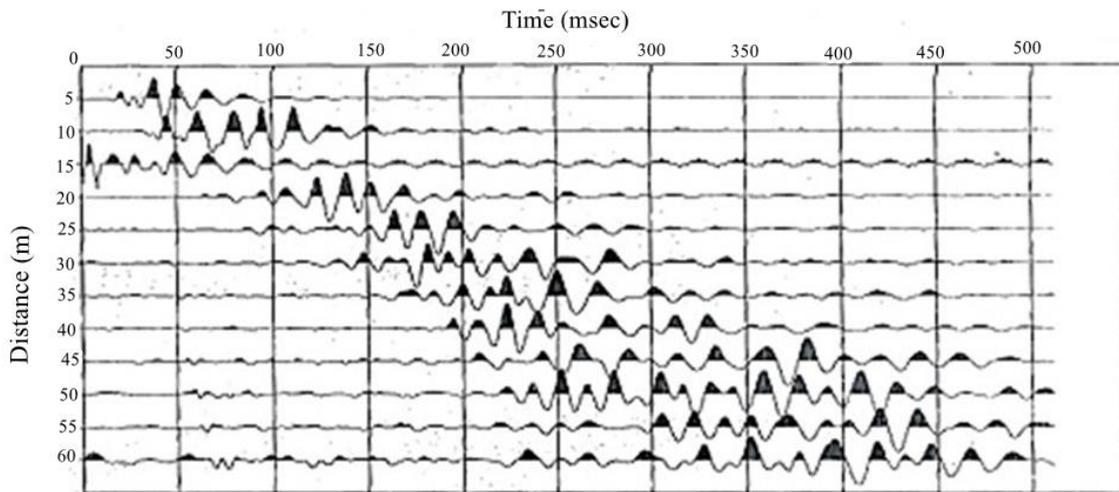


Figure 6. Surface monitor record in selected area.

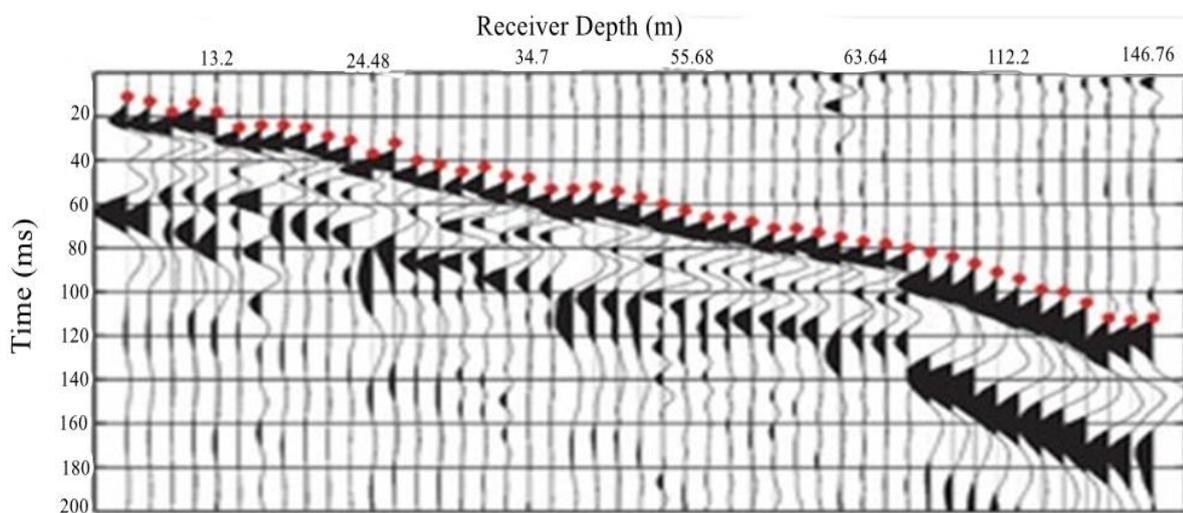


Figure 7. Uphole monitor record in selected area.

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Table 1. Summary of weather red layer velocity and thickness for uphole and surface seismic refraction from each location.

Lat/Long (m)	Elevation (m)	Locations	Uphole Velocity V_W (m/s)	Surface Velocity V_S (m/s)	$V_W /$ V_S (m/s)	Uphole Thickness D_W (m)	Surface Thickness D_S (m)	$D_W /$ D_S (m)
565568.5754/ 365103.2278	74.2054	A	680.3	670.2	1.015	13.35	12.00	1.113
570539.5123/ 360423.0335	85.2058	B	625.0	620.8	1.007	11.45	10.56	1.084
568627.2088/ 383721.0295	103.2058	C	588.2	568.6	1.034	10.60	10.00	1.060
557803.227/ 380138.3493	62.1058	D	531.0	525.0	1.011	9.90	9.20	1.076
514800.8760/ 386376.0214	24.4717	E	602.4	589.0	1.023	10.80	10.00	1.080
510781.3888/ 381888.5125	38.9448	F	549.5	537.5	1.022	9.25	8.20	1.128
573641.8600/ 381331.4300	0.0000	G	500.0	480.0	1.042	8.80	8.25	1.067
575130.5077/ 383323.1428	40.9058	H	476.1	448.0	1.063	7.25	6.95	1.043
565568.5754/ 365103.2278	74.2054	I	450.0	425.0	1.059	6.10	6.05	1.008
570539.5123/ 360423.0335	85.2058	J	672.0	703.5	0.955	12.95	12.10	1.070
568627.2088/ 383721.0295	103.2058	K	696.0	682.0	1.021	7.30	6.00	1.217
557803.227/ 380138.3493	62.1058	L	344.8	326.6	1.056	5.45	4.30	1.267
Averages			559.6	548.0		9.43	8.63	

5. Results and Discussion

The results of the analyses are presented in table 1 and Figures 8-12. The geophysical properties of interest are the seismic velocity and thickness variation competency of the weathered layer. Uphole and surface seismic refraction survey data were collected from twelve different locations and analyzed. Both methods show similar variations in velocity with uphole refraction having a slightly higher value for velocity than that of the surface refraction. These changes in velocity are the result of changes in lithology, cementation, fluid content and compaction of the formation, which determine the mechanical properties of the materials through which the seismic waves were propagated.

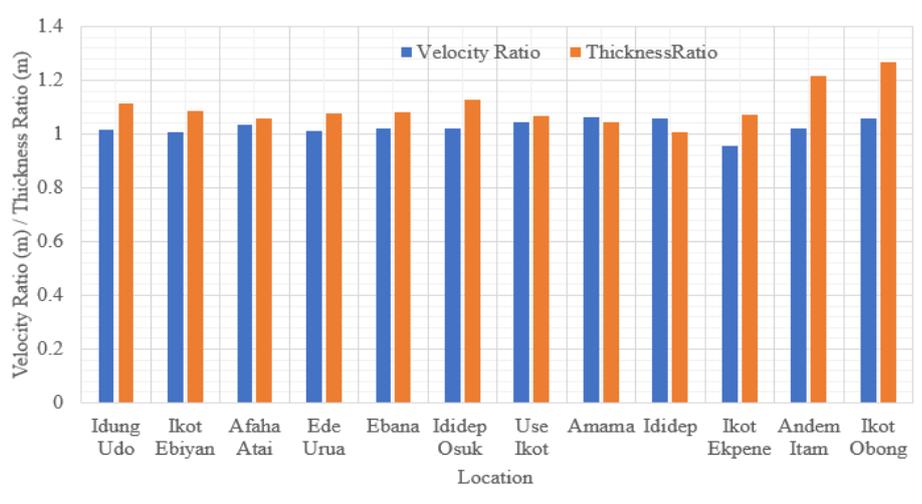


Figure 8. Velocity and thickness ratio of the study area.

The uphole velocity ranges from 344.8 to 680.3 m/s with an average velocity of 559.6 m/s. It is worthnoting that a reliable value of the uphole data is made only from shots taken well within the weatheredlayer. This is due to the fact

that the ray crosses the weathered layer twice, giving a more accurate representation of the ray path in the weathered layer than that of the surface data. For surface seismic refraction, the velocity ranged from 326.6 to 670.2 m/s with an average velocity of 548.0 m/s.

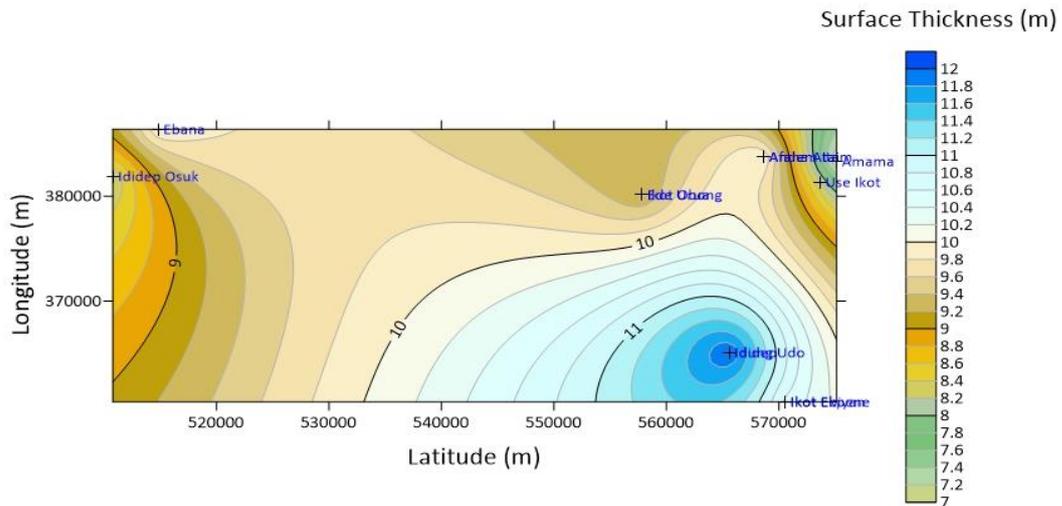


Figure 9. 2D contour map for surface thickness.

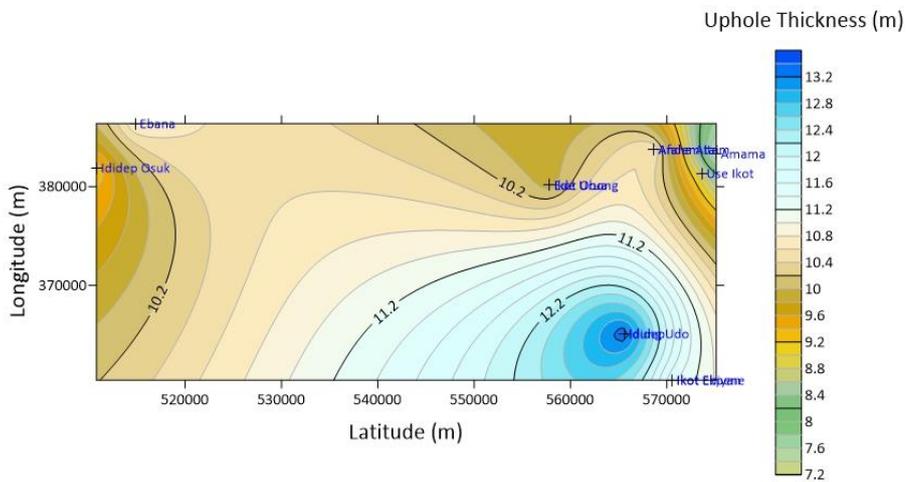


Figure 10. 2D contour map for uphole thickness.

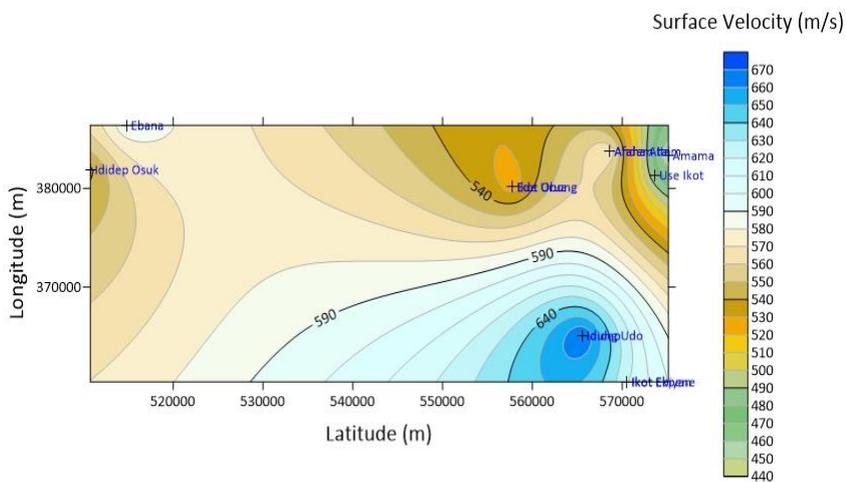


Figure 11. 2D contour map for surface velocity.

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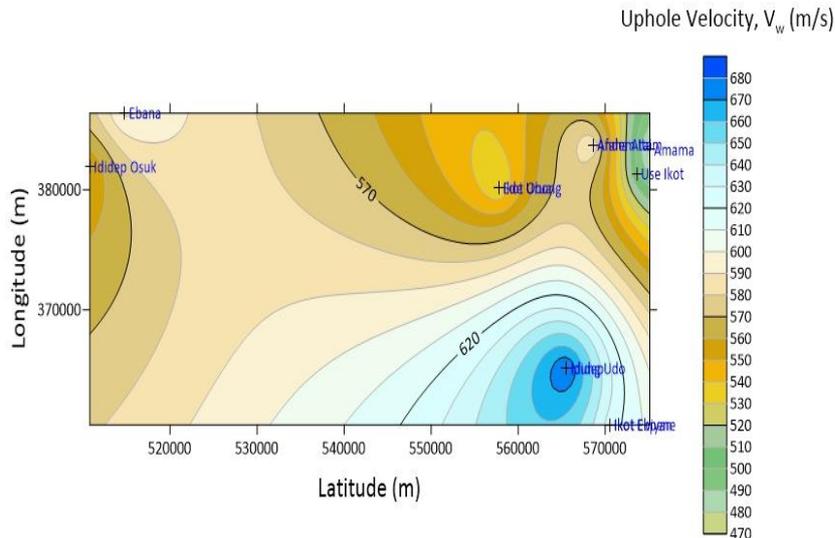


Figure 12. 2D contour map for uphole thickness.

The marginal variations in surface velocity are indicative of the high degree of homogeneity of the layer and data acquired in the study area. The differences in velocity of uphole and surface seismic refraction were 11.6 m/s, V_w/V_s ratios and <1.4142 indicating a negative Poisson ratio which can occur only in the weathered layer formation [15]. Hence, these results can be applied in near surface construction by removing the weathered organic layer of the top soil of the ground until finding V_w/V_s ratios that are >1.5 [12]. On the other hand, the thicknesses by uphole and surface seismic refraction are fairly uniformly thin in the area, ranging from 5.45 to 13.55 m, 4.30 to 12.0 m with an average of 9.43 and 8.63m, respectively. The disparity in the thickness values could be a result of shot point offset correction which could be caused by delayed arrival or low velocity formation, as observed in the surface seismic refraction which gives lower values than the uphole method. Similarly, it is observed that the uphole thickness is slightly higher than that of surface refraction, by 0.83 m. This is because the uphole drilling process changes the lithology in the vicinity of the borehole due to the formation of mud cake, which affects the speed of seismic wave propagation in rock.

6. Conclusion

Uphole and surface seismic refraction methods characterize the weathered layer by taking advantage of the lithology of the lateral formation, which can be used in comparison with drilled rock formations for better delineation of the weathered surface layer within the study area. The analysis is hinged on the determination of seismic velocity and thickness of the weathered layer as well as the elevation. The results show mainly a two-layer model in almost all the interpreted weathered layer data. The weathered layer velocity ranges from 344.8 to 680.3 m/s for uphole and 326.6 to 670.2 m/s for surface seismic refraction. Thickness ranges from 5.45 to 13.35 m for uphole and 4.30 to 12.0 m for surface seismic refraction, respectively. Comparatively, the average uphole velocity of 559.6 m/s is higher than the average surface velocity of 548.0 m/s. Also, the average uphole thickness of 9.43 m is higher than 8.63 m of the surface refraction across twelve locations. However, seismic refraction work within the study area required substantial static corrections, due to high variability of the weathered layer seismic velocity and thickness. Hence, uphole refraction is the better alternative. On the other hand, information obtained from both methods on weathered velocity, thickness and elevation will be of interest in determining the location of civil engineering structures and for the determination of the level of bedrock competence in the study area.

Conflict of interest

The authors declare no conflict of interest.

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