Journal of Earth Sciences and Geotechnical Engineering, vol.7, no. 2, 2017, 91-102
ISSN: 1792-9040 (print version), 1792-9660 (online)
Scienpress Ltd, 2017

Seismic Refraction Investigation of Fracture Zones and Bedrock Configuration for Geohydrologic and Geotechnical Studies in part of Nigeria's Capital City, Abuja

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Abstract

Seismic refraction surveys have been in use for over 40 years in petroleum, geohydrology and geotechnical studies. The present survey was carried out to determine the subsurface nature (thickness, bedrock configuration and fracture zones), in Karshi part of Nigeria's Federal Capital City (FCT) Abuja, North Central Nigeria which lies between latitudes $8^{0}52^{1}$ – $8^{0}55^{1}$N and longitudes $7^{0}29^{1}$ - $7^{0}32^{1}$E and underlain by basement rocks that form part of the Nigerian Basement Complex. A 48 channel Geode^{TM} seismic system was used with a geophone spacing of 2m, giving a total spread length of about 96m. Elastically accelerated weight drop (50kg) energy source was used, with minimum of three number shots stacked per location. The quality of the recorded data was generally good, which shows clear direct arrival, 1st and 2nd refracted arrivals from the water bearing fractured basement and fresh basement interface. Analysis of the data revealed that, the layers are dipping and undulating with dip angles of -0.3 (down dip) and 0.79 (up dip) respectively. The results obtained suggests that, the upper slow velocity (283±0.16m/s) layer is loose overburden materials having a thickness ranges from 1.3m – 2.05m, the second layer (1572±0.004m/s) represent a water bearing fractured zones having a thickness ranges from 18.7m – 21.4m respectively, and finally the third layer (3385±0.002 m/s) represent the crystalline fresh basement rock. The thick fractured zones of the second layer are potential target for groundwater exploration and would require remediation treatment for engineering purpose.

Keywords*:* Seismic refraction, Bedrock configuration, Fracture zones, Geohydrology and Velocity

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1 Introduction

The seismic refraction survey is based on the times of arrival of energy at various geophone positions. The energy is initiated by a source, travels downwards and refracted at various interfaces, later arrivals which cause complications in the recorded ground motion are discarded. Thus the data set derived from refraction surveys consists of a series of times versus distances. These are then interpreted in terms of the depths to subsurface interfaces and the velocities at which sound travels through the subsurface within each layer. These speeds are controlled by a set of physical constants, called elastic parameters that describe the material. The method takes advantage of a common occurrence; seismic velocities (V) increase as a function of depth and age [1] In other words, the underlying strata, represented by V_2 and V_3 are assumed to provide a higher seismic velocity than the overlaying layer, represented by V_1 (i.e. $V_3>V_2>V_1$).

This is an important assumption when utilizing the seismic refraction method because "first arrivals," the fastest seismic velocity measured at each geophone, are the only ones considered when data are processed. If this assumption fails, then no critical refraction occurs at the V_1/V_2 or V_2/V_3 interfaces. This would lead to an overestimate of the thickness of the V_1 layer by including the thickness of the V_2 layer as "part" of the V_1 layer thickness. This dilemma is known as the "hidden layer" problem [2]. Since the velocity of the overburden and refractor are obtained from the slope of the line on the time-distance plot, therefore generalised reciprocal method (GRM) [3] would be required to detect the hidden zone.

The seismic refraction techniques is often used to map the depth to bedrock below an area of unconsolidated material and such information can be used to determine how the foundation of a structure should be constructed so that it lies on the bedrock. This technique has been successfully used for shallow fault and stratigraphic studies, static corrections in reflection surveys [4], mapping depth to base of backfilled quarries, depth of landfills, thickness of overburden and the topography of groundwater for civil engineering and environmental studies. In ideal refraction surveys interfaces should be shallow, roughly planar and dip at an angle of less than 15 degrees. The survey area is located in Karshi part of Nigeria's federal capital city (FCT) Abuja, North Central Nigeria between latitudes $8^0 52^1$ – $8^0 55^1$N and longitudes $7^0 29^1$--$7^0 32^1$E, having areal extent of $14400m^2$ and underlain by basement rocks that form part of the Nigerian Basement Complex; specifically they fall within the Basement Complex of North-Central Nigeria. Extensive applications of geo-electrical methods for near-surface studies have been reported as compared to the use of seismic refraction technique in the basement area. The present study is therefore aimed at evaluating the thickness of overburden materials, depth-to-bedrocks, bedrock topography, fracture zones and nature of the subsurface layers using refraction imaging technique. It is our hope that the results of this work will be found useful to the civil and geotechnical engineers as well as geohydrologist in this fast growing city of Abuja.

2 Data Acquisition

The design for seismic refraction survey involves: location of survey site, geophone spacing, spread (cable) length, source strength and source type. The survey should be recorded on days with little wind, away from traffic and other sources of noise or vibrations. If unwanted energy present on site is minimal, the true waveform may be captured employing larger energy sources and filtering and/or stacking the received signals. In addition, since some of the noise travels as airwaves, covering the geophones with sound absorbing material (partially filled sandbag) may help dampen unwanted noise and enhance coupling of the geophones to the ground. In general, refraction spreads need to have a length at least three times the desired depth of investigation [5], if investigating to depths of 20m, it will require at least 60m spread length. If a 24 channel seismic system is used, a geophone spacing of 3m, giving a total spread length of about 70m, will be sufficient, and will also provide velocities for shallower bedrock layers. Both refractors depth and velocities can also be obtained from the spread length. Generally, geophones having a natural frequency of about 10Hz are commonly used for near-surface refraction investigations.

The equipment used for the acquisition exercise were: Seismograph (4X Geode™, 48 channels, 2m spread cable takeout interval), 10Hz vertical geophones and elastically accelerated weight drop (50kg), triggers cable, striker plate, battery charger, measuring tape and GPS. The 48 channel seismic system was used with 2m geophone spacing, giving a total spread length of about 96m, which is sufficient to provide velocities for shallower bedrock layers and refractors depth. Elastically accelerated weight drop energy source was used at two different shot point locations (X= 0m and X= 96m), with minimum of three number of shots stacked per location. The data were recorded in SEG-2 format with a total record length of about 0.4s at 0.2ms sample interval. The weather condition during the survey experiment was generally dry, sunny with light wind. The survey profile line elevations were determined using GPS at each geophone location along the survey line. The result shows small deviation in elevations, in which the Root Mean Square value is 0.22 m. This deviation is too small to affect the final results of the experiment. The station coordinate profile and elevation along the survey profile line are shown in Figure 1 & 2 respectively.

3 Data Processing

The first step in processing refraction seismic data is to pick the arrival times of the signal, called first break picking. A plot is then made showing the arrival times against distance between the shot and geophone positions. This is called a time-distance graph. The graph for the present work is shown in Figure 3. The first arrival times were picked manually using paper copies and also from the ‘onscreen’ display. The accuracy of picking ‘onscreen’ was a lot better than on the paper copies as the scale was only 0.4ms. However from ‘onscreen’ the first arrival times were picked to the nearest 0.2ms. Figure 3 displays the complete set of picks for direct arrival, first refracted arrival and second arrival from the Basement interface for both forward and reverse shots. The forward and reverse shots reciprocal times are about equal (good quality check).

4 Data Interpretation

The velocity of the refractors and overburden are obtained from the slope of the time-distance graphs (Figure 3). The graphs are symmetrical about the centre indicating there is little dip and undulations on the refractors. The depths to the refractors are determined using the Intercept Time Method (ITM) and Generalized Reciprocal Method (GRM). The T-X plot (Figure 3) reveals that, the interface are dipping (due to difference in intercept time) and undulating, therefore application of GRM is necessary for interpreting the subsurface layers. When a refractor dips, the slope of the travel time curve does not represent the "true" layer velocity. Shooting up dip, i.e. geophones are on updip side of shot, apparent refractor velocity is higher than shooting down dip, i.e. geophones are on down dip side of shot. To determine both the layer velocity and the interface dip, forward and reverse refraction profiles must be acquired as schematically shown in Figure 4. The travel times (**T**) are equal for forward and reverse directions for switched, reciprocal, source/receiver positions. The geometry is the same as flat 2-layer case, but rotated through **α,** with extra time delay at **D** (Figure 4). So travel time **T** is given in equation1.0.

$$T_{ABCD} = \frac{X \cos a}{V_2} + \frac{(Z_a + Z_b)\cos i_c}{V_1} \qquad (1)$$

The travel time for down dip and up dip shots are given in equation 2.0 and 3.0 respectively.

$$T_d = \frac{X \sin(\theta_c + a)}{V_1} + \frac{2Z_a \cos\theta_c}{V_1} = \frac{X}{V_d} + t_a \quad (2)$$

$$T_u = \frac{X \sin(\theta_c - a)}{V_1} + \frac{2Z_b \cos\theta_c}{V_1} = \frac{X}{V_u} + t_b \quad (3)$$

Where: V_u V_d is apparent refractor velocities for updip and downdip, t_u, t_d is the intercept times for updip and downdip, α is dip angle, θ_C is critical angle, V_1, V_2 is layer 1 & 2 velocities and Z_a, Z_b are depths. We can now solve for dip, critical angle, velocities and depth from equation 4.0, 5.0, 6.0 and 7.0 respectively:

$$a = \frac{1}{2}\left[\sin^{-1}\left(\frac{V_1}{V_d}\right) - \sin^{-1}\left(\frac{V_1}{V_u}\right)\right] \quad (4)$$

$$\theta_c = \frac{1}{2}\left[\sin^{-1}\left(\frac{V_1}{V_d}\right) + \sin^{-1}\left(\frac{V_1}{V_u}\right)\right] \quad (5)$$

$$V_2 = \frac{V_1}{\sin\theta_c} \quad (6)$$

$$Z_a = \frac{V_1 t_a}{2\cos\theta_c} \quad (7)$$

Therefore using the intercept time method (ITM) of computation the results obtained are presented in Table 1. The velocities obtained (Table 1) suggest that, the upper slow speed (283m/s) layer is loose overburden materials (top soil), the second layer with speed of 1572m/s is from water bearing fractured basement, and finally the third layer (3385m/s) is fresh crystalline Basement rock.

The Generalised Reciprocal Method (GRM) [6] is a technique for delineating undulating refractors at any depth from in-line seismic refraction data consisting of forward and reverse travel times. The method was first developed by [6]. The travel times at two geophones, separated by a variable distance XY, are used in refractor velocity analysis and time-depth calculations. At the optimum XY spacing, the upward travelling segments of the rays to each geophone emerge from near the same point on the refractor. This results in the refractor velocity analysis being the simplest and the time-depths showing the most detail. This method provides a means of recognizing and accommodating undetected layers provided an optimum XY value can be recovered from the travel time data, the refractor velocity and/or the time-depths. The presence of undetected layers can be inferred when the observed optimum XY value differs from the XY value calculated from the computed depth section. The undetected layers can be accommodated by using an average velocity based on the optimum XY value. This average velocity permits accurate depth calculations with commonly encountered velocity. In GRM two functions are usually computed; the refractors velocity analysis function, (t_v) and the time-depth function (t_g), which provide an analysis of travel time into predominantly vertical and horizontal components. The velocity of the refractor and overburden are immediately available from the slope of the time-distance lines (Table 1). The depth to the refractor can be quantitatively obtained using GRM. A full GRM interpretation provides more detail about depth to the refractor, velocity of the refractor, or refractors.

The main objective of GRM is to determine the depth to bedrock under geophone at *D* (Figure 6). This is done using the following calculations. The travel times from the shots at A and *G* to the geophone at *D* are added together *(T1)*. The travel time from the shot at *A* to the geophone at *G* is then subtracted from *T1*. Figure 7 shows the remaining waves path after the above calculations have been performed. These are the travel times from *C* to *D* added to the travel times from *E* to *D* subtracting the travel time from *C* to *E*. The sum of these travel times can be shown to be approximately the travel time from the bedrock at *H* to the geophone at *D*. Since the velocity of the overburden layer can be found from the time-distance graph, the distance from *H* to *D* can be found giving the bedrock depth. The results obtained from GRM analysis revealed the refractor depths and topography which is shown in Figure 8.0 and 9.0.

An attempt is made to relate the results of present work with results of seismic refraction survey for ground water as carried out by [7] in parts of the Precambrian Basement Complex of Oban Massif of SE Nigeria. The result is shown schematically in Figure 10. From the Figure there is a fair comparison in velocities of the aquiferous and fresh basement zones of both terrains respectively. There is good comparison of depths to bedrock of ≈ 19m in study area and an average of 16.4m in Oban. The presence of a layer with velocity 969m/s between the upper and third layer in the Oban area whose lithologies are clay, gravel, laterite and sand, but its absence in the Abuja data can be explained thus: these lithologies are secondary lithologies produced by denudation processes in this area of heavy and prolonged annual rainfall.

5 Labels of figures and table

Table 1: Velocities and thicknesses for updip and downdip shots

FORWARD SHOT (FWS) X= 0m				REVERSE SHOT(RVS) X=96m		
Layers	Apparent Velocity(m/s)	Thickness (m)	True Velocity(m/s)	Apparent Velocity(m/s)	Thickness (m)	Dip
1	283	2.05	283±0.16	283	1.3	-0.3
2	1609	18.7	1572±0.004	1536	21.4	0.79
3	3450	∞	3385± 0.002	3320		

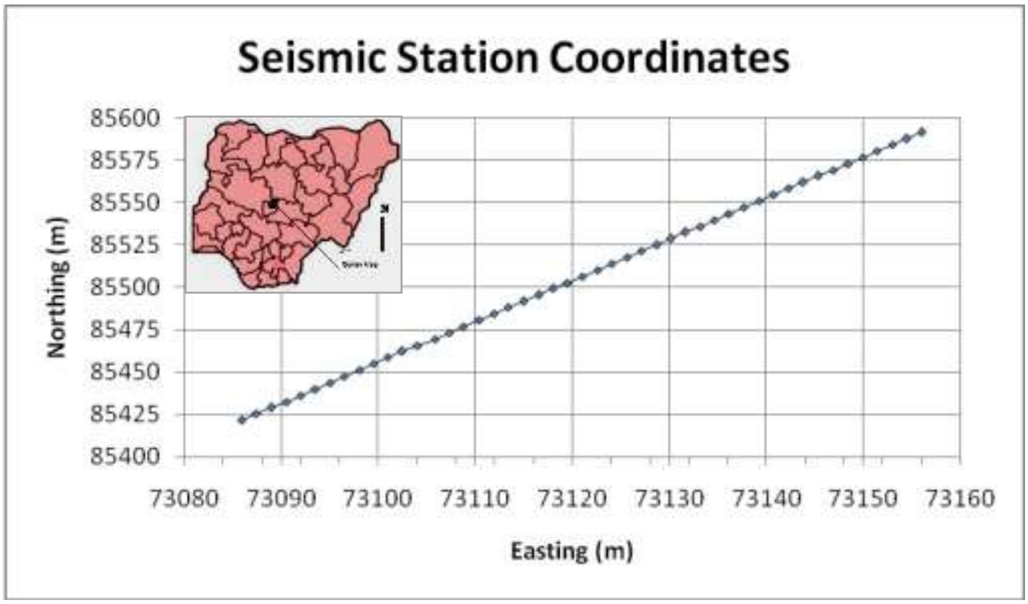

Figure 1: Location of survey area and profile for the station coordinates.

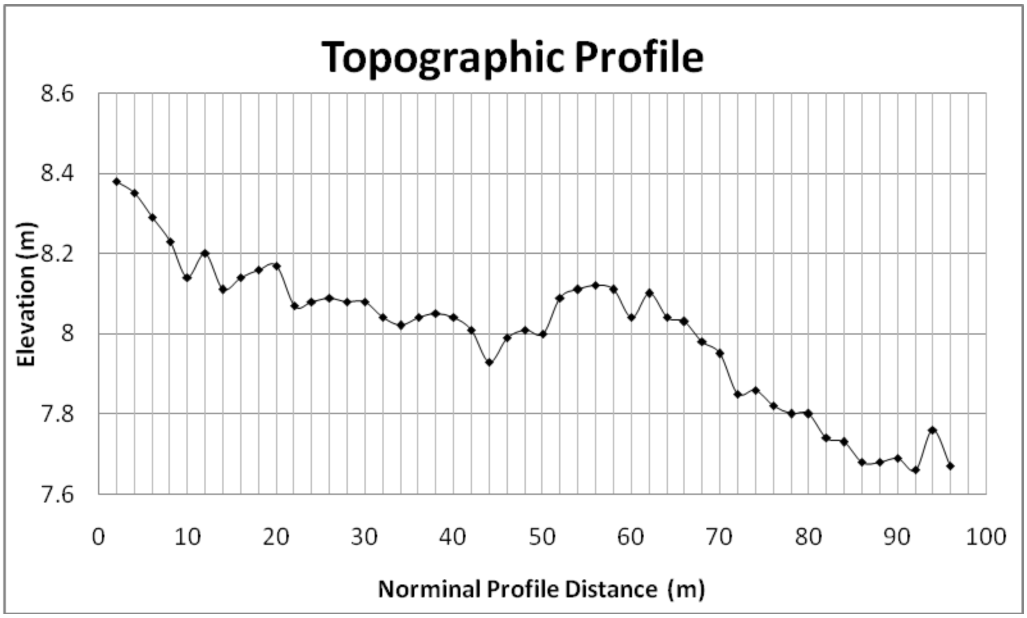

Figure 2: Deviations in elevation along survey profile line.

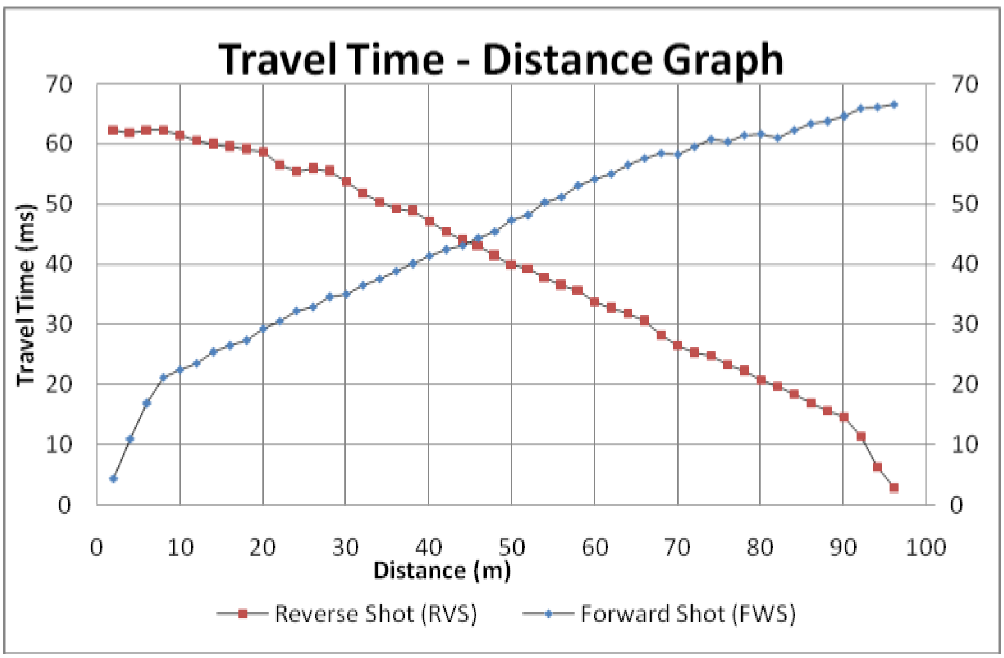

Figure 3: Travel Time – Distance (T-X) plot for the forward and reverse shots

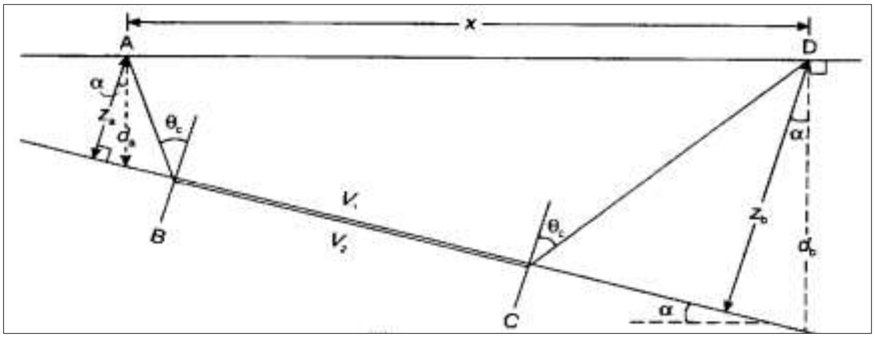

Figure 4: Schematic example of dipping interface and concepts of forward and reverse shooting.

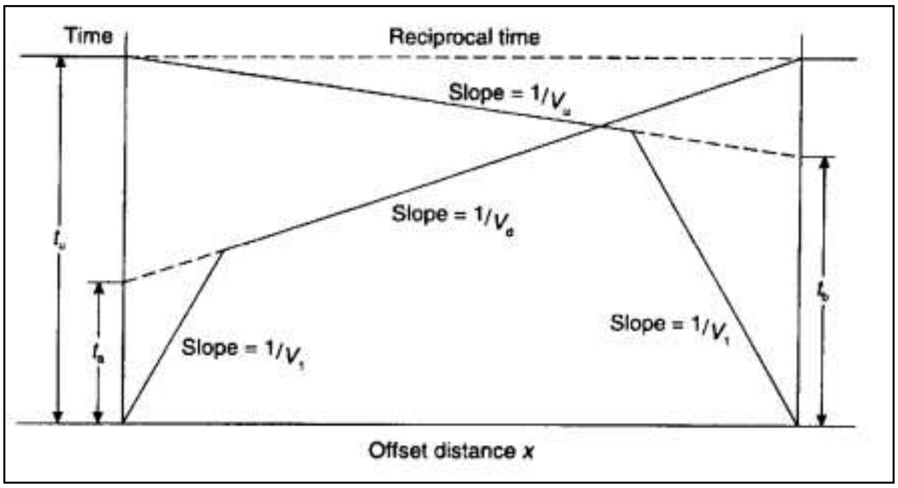

Figure 5: Schematic travel time – distance (T-X) plot for the forward and reverse shots.

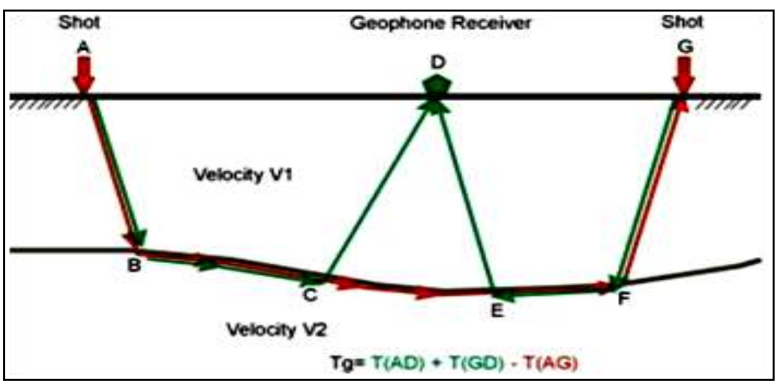

Figure 6: Basic Generalized Reciprocal Method Interpretation (adapted from Palmer, 1981).

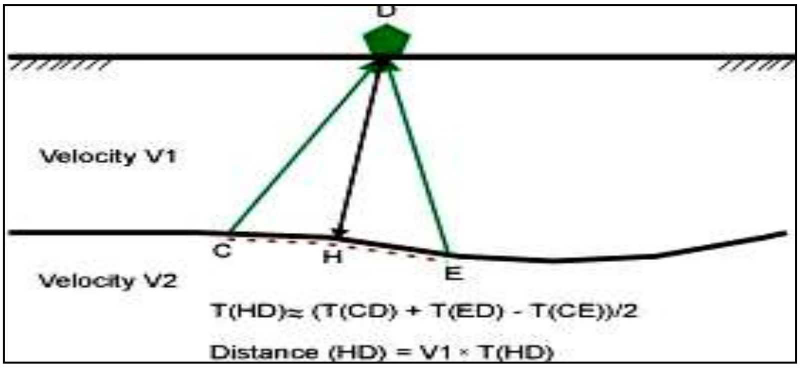

Figure 7: Basic Generalized Reciprocal Method Interpretation (adapted from Palmer, 1981).

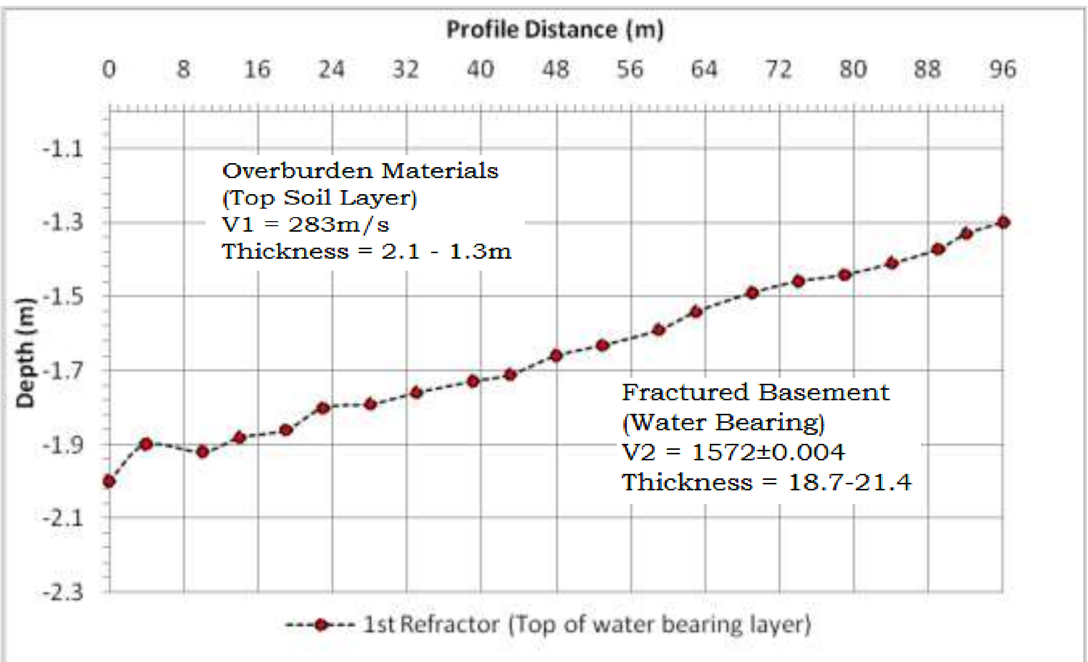

Figure 8: Velocity - Depth Model for First Refractor.

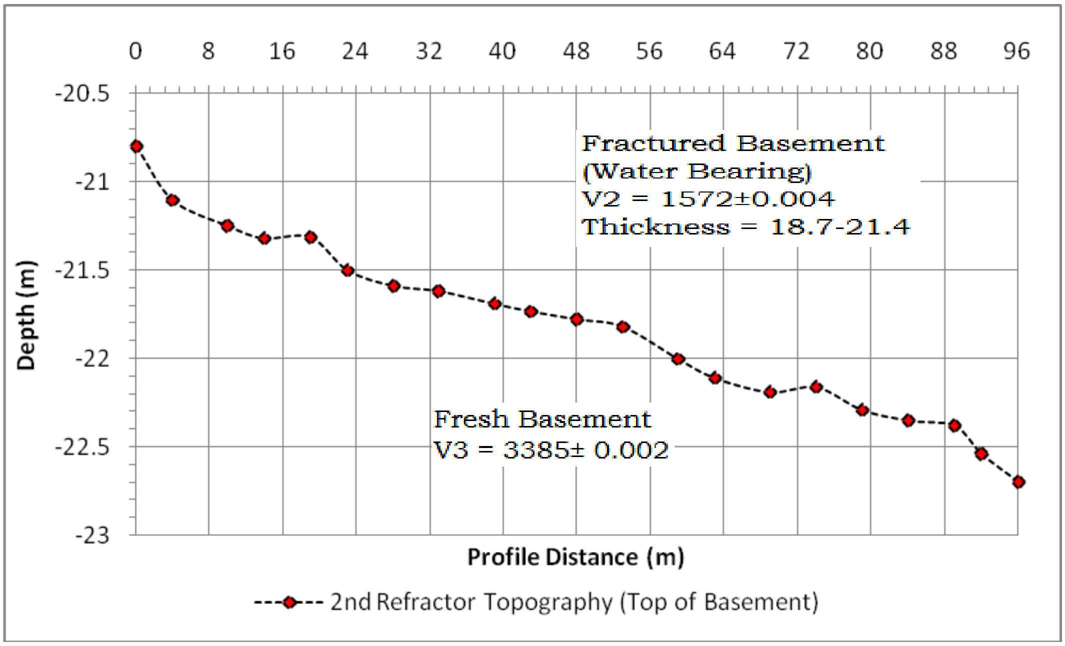

Figure 9: Velocity - Depth Model for Second Refractor.

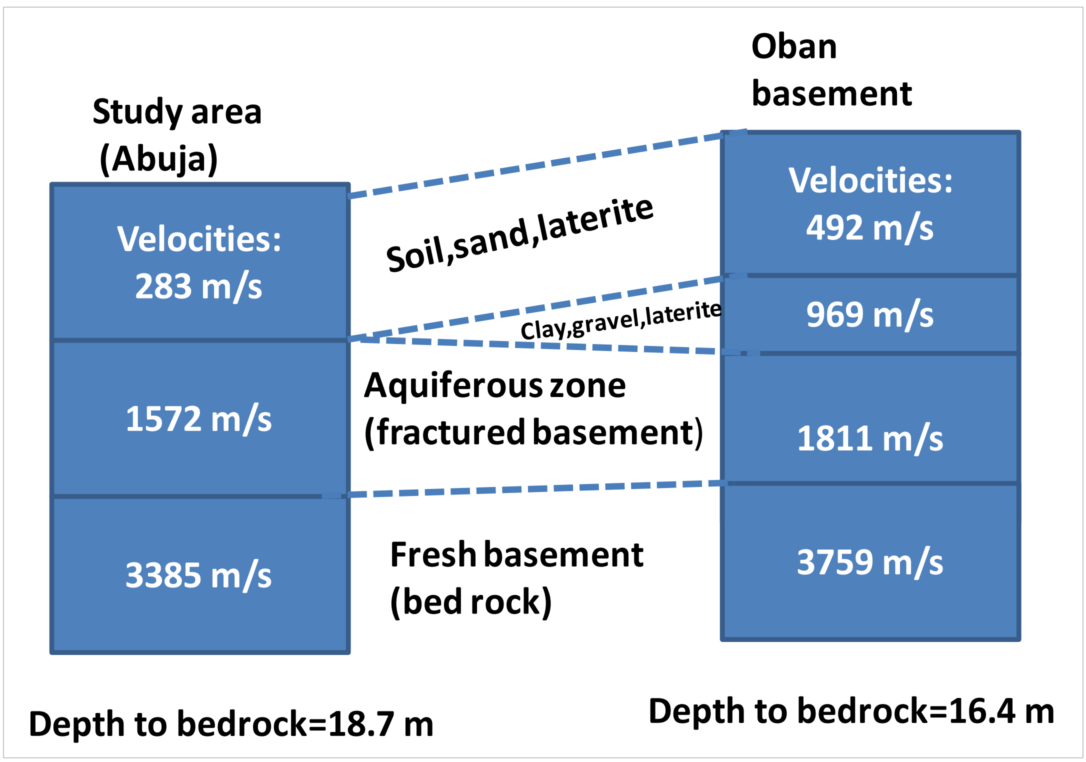

Figure 10: Seismic refraction model correlation between study area and Oban basement of SE Nigeria. Oban area data are adapted from [7], their velocities are averages.

6 Conclusions

This work has presented seismic refraction data over a part of Abuja. The work yield three lithoseismic layers based on intercept time and generalized reciprocal methods of interpretation. The methods have yielded velocities of 283m/s for the upper layer, interpreted as top soil with thickness of 2.05m. The middle layer has a thickness of 18.7m and velocity of 1572m/s and is interpreted as fractured aquiferous zone. Third layer's velocity is 3385m/s and is interpreted as bedrock with indefinite vertical extension. The second layer will present challenges to geotechnical engineers for foundation purpose in this fast growing capital city and would require remediation. Data correlation with seismic refraction survey of parts of Oban Massif SE Nigeria for geohydrologic purpose shows a good comparison. Refraction surveys can be used in conjunction with geoelectric surveys for geohydrologic or geotechnical purposes in order to minimize ambiguity in analyses of results.

Acknowledgement

The authors acknowledged the assistance and support of Eng, Solomon Ajayi for provision of the dataset.

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