Seasonal Impact on seismic Data Quality: A Case Study of Zaria Basement Complex, Nigeria

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Abstract

The impact on depths and P-wave velocities deduced from seismic data, due to subsurface water variation, resulting from the variation in the amount of annual rainfall, was investigated in this study in order to establish the best season for reliable seismic surveys in Zaria Area, Nigeria. A Terraloc MK6 Seismograph was used to collect the seismic refraction tomography data across a borehole of standard log with the centre of the spread situated at the borehole site. Using the same spread and parameters this procedure was repeated severally in a year for four years and the choice for each survey time depended on when there was significant change in rainfall data. The interpreted 2-D results suggested that the average P-wave velocities of the subsurface in the area were generally higher when the ground was wet than when it was dry. The calculated average seasonal changes in P-wave velocity is about 1.8 ms^{-1} for every millimeter change in the amount of rainfall between March and May when the subsurface was fairly saturated and about 1.3 ms^{-1} in August when it was most saturated. The velocities generated in this study for the interpreted rock types were compared with a standard velocity scale and the computed average error showed a little disparity of 3.8%, 3.0%, 8.7% and 7.3% between the standard velocities and the velocities for the tomograms generated from the seismic data collected when the average amount of rainfall was 0 mm, 44.8 mm, 322.1 and 62.8 mm respectively. The results also suggested that the overburden of about 9.0 m in thickness, the weathered basement of about 14.0 m in thickness and the fractured basement at a depth of about 23.0 m best fitted the borehole log. This best fit was consistently obtained in the months between March and May when the average total rainfall was about 44.8 mm in the area. The overall results of this study prompted a conclusion that for more detailed and reliable seismic studies in Zaria Area and its environs, with similar climatic condition, the surveys are best conducted between March and May.

Keywords: Seismic Survey, Seasonal Impact, Best Season, Data Quality, Zaria Area

Introduction

Geoscientists have long discovered that the seismic velocities of the subsurface of a given place differ when repeated readings are taken of the place at different times (Poupinet, *et al.,* 1984, Karageorgi, *et al.,* 1992, Kaoru, *et al.,* 2015 and Gassenmeier, *et al.,* 2016). It is known that the propagation velocities of seismic pulses are determined by the elastic moduli (i.e. bulk modulus K, shear modulus μ, axial modulus Ψ, and Young's modulus E) and densities of the materials through which they pass. Elastic modulus expresses the linear relationship between stress and strain in elastic field for any material. Hence, the linear relationship between stress and strain in the elastic field is specified for any material by its various elastic moduli, each of which expresses the ratio of a particular type of stress to the resultant strain.

The longitudinal body wave's velocity (or P-wave velocity, V_p) measured repeatedly in a location has been found to vary (Kaoru, *et al.,* 2015), sometimes significantly, even when the geological composition of the area remains constant. This has affected interpretation in seismic survey, sometimes leading to erroneous interpretation and deduction, especially in depths. One of the factors affecting the elastic moduli and density, and hence the measured P-wave velocity of any geologic formation is the amount of water saturation of the formation. It has been discovered that subsurface water saturation affects the time rate of propagation of seismic waves. Every geologic formation has a range of P-wave velocity which depends on the amount of water saturation (Kearey *et al.,* 2006, Osemeikhian and Asokhia, 1994, Hugh, 1995 and Salisbury et al, 2003). For example Hugh, 1995 gave the range of P-wave velocity for dry sand as 200 – 1000 ms^{-1} while the range for water saturated sand is about 1500 – 2000 ms^{-1} depending on the amount of water saturation.

Sometimes, the range of the velocity for one formation overlaps another. For example, the range of P-wave velocity for gneiss is 2000 – 5000 ms^{-1} and this overlaps the range for granite 4500 – 7000 ms^{-1} (Osemeikhian and Asokhia, 1994). This imposes difficulty in interpretation, and sometimes leads to erroneous deduction. In a place of complex geology like Zaria, measured P-wave velocity range of 4500 – 5000 ms^{-1} puts the Geophysicists into confusion on whether to classify the rock as gneiss or granite. The confusion becomes complex and sophisticated when additional information such as outcrop or/and borehole data is/are not available.

Similarly, sometimes, there has been much disparity in depth resolution of a given area in different geophysical studies (including seismic) conducted at different times. Hassan et al., (1991) had observed much depth disparities in Kubanni Basin in different previous geophysical studies which took place at different seasons. Some of the previous seismic geophysical studies of the basin which showed such disparities in depth resolution include Ogah (1990), Akaolisa (2006), Chiemeke and Osazuwa (2007), Ibe (2008), Egwuonwu (2008), Osazuwa, *et al.,* (2010), Ahmed, *et al.,* (2012), Ibe (2016) and Ibe and Anekwe (2016). These differences in depth resolution may have been due to seasonal variation in subsurface water saturation.

Combination of geophysical techniques and additional information such as borehole data, although, minimise ambiguity in Geophysics interpretation, they are not cost and time effective and sometimes the facilities/equipment are not readily available. When there are limited funds and time or unavailability of equipment for combination of Geophysical techniques and inaccessibility of additional information such as borehole data, there is need to employ other measures that minimise ambiguity in interpretation. One of such measures is to conduct the geophysical survey at the most appropriate season/time. Hence, there is need to investigate the effect of subsurface water variation arising from monthly variation in rainfall, on the p-wave velocity and depth resolution of geologic formations in a given area. This is necessary in order to establish the best time of the year to conduct seismic surveys for reliable results, especially, in a place with complex geology like Zaria. This study is therefore aimed at investigating the impact subsurface water variation, resulting from the variation in the amount of annual rainfall, has on depths and P-wave velocities deduced from seismic data, in order to establish the best season for reliable seismic surveys in Zaria Area, Nigeria.

The Study Area and Its Geology

Zaria Area, bounded approximately by longitudes 7˚ 12' to 7˚ 47' E and latitudes 11˚ 03' to 11˚ 11" N, is located at a height of about 670 m above sea level and more than 640 km away from the sea (Hore, 1970).

According to Hore (1970), Zaria area possesses a tropical continental climate. The continentality of its climate is more pronounced during the dry season, especially in December and January. Hore (1970) observed that the mean daily maximum temperature shows a major peak in April and a minor one in October. The daily maximum temperature rises gradually from January and attains its highest value in April. Then it drops to its lowest value in December. The records of the daily Meteorological observations obtained from the School of Aviation Technology, Zaria, show that in recent years, between 1998 and 2015, the mean maximum daily temperature of Zaria is about 31.75^{o}C while the mean minimum daily temperature is about 19.50^{o}C. The observations also show that within this period (1998 – 2015) the mean temperature of the soil at 30 cm below the surface is about 26.95^{o}C and it is about 27.75^{o}C at 100 cm below the surface.

Zaria Area lies within a region with distinct wet and dry seasons; the wet season occurring in the high-sun period. The year in Zaria, according to Hore (1970), can be divided into the following seasons:

Dry Season:

(Winter season and the season of harmattan)	:November to February
Season of Thunderstorms and Squalls	:March to June
Wet Season	:July to October.

October is really a transitional month when normally the wet season ends and the dry season begins. The mean annual rainfall is about 109.22 cm (Hore, 1970). However, the record of the daily meteorological observations obtained from the School of Aviation Technology, Zaria, shows that in recent years, between 1998 and 2015, the mean annual rainfall in Zaria is about 99.33cm.

The area has a tropical savannah climate; precisely, it lies within the Guinea Savannah supporting a tropical bush land vegetation of few scattered trees and shrub bushes. These are undergrown by a vegetation of tall herbs and grasses.

This study involved seismic refraction tomography across a borehole of standard log located in Kubanni Basin (Figure 1), Zaria, Nigeria. The borehole is located approximately on latitude 11° 09′ 11.0″N and longitude 7° 39″ 48.0″E.

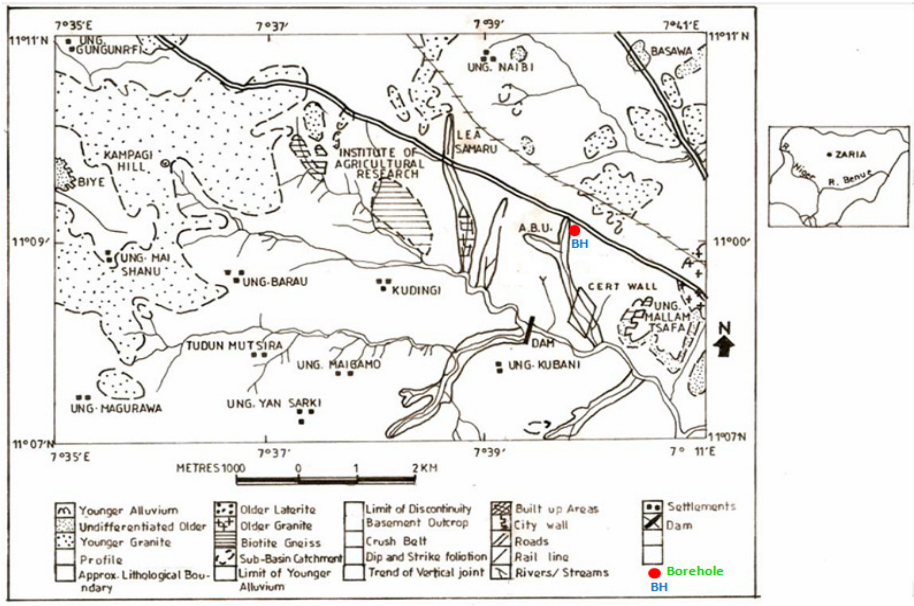

Fig. 1: Geology Map of Kubanni Basin, Zaria, Nigeria Showing the Location of the Borehole where Data were Collected (adopted from Geology Department, Ahmadu Bello University, Zaria).

Zaria Area belongs to the Precambrian basement complex of northern Nigeria which is composed of three rock types: gneiss, porphyritic granite and medium grained granite. The porphyritic granite and medium grained granite were intruded into the gneiss during the Pan African (McCurry, 1973; Garba and Schoeneich, 2003). The greater part of the area is covered with thick regolith mainly derived from in-situ weathering of the basement rocks.

According to Garba and Schoeneich (2003) and Ahmadu Bello University, Zaria (2008), there are two types of aquifers in the area: (a) the regolith (soft overburden) aquifer and (b) the fractured bedrock aquifer. The regolith aquifer is the main aquifer and the only available source of water to the majority of the population via hand-dug wells.

There are scarce distributions of rock outcrops except in the areas of inselberg clusters in the south of Zaria where outcrops are seen frequently.

Method of the Geophysical Investigation and Its Basic Theory

A two-dimensional (2D) seismic method involving refraction tomography technique was used in this study. This choice was made because it is one of the most recent methods with less ambiguity in interpretation.

The elastic moduli (bulk modulus K, shear modulus μ and the densities ρ) of the materials through which seismic wave travels are related to P-wave velocity, V_P by:

$$V_P = \left[\frac{K + {}^4/_3\,\mu}{\rho}\right]^{1/2}$$

Tomography is a technique of making an image of a slice. Series of such 2-D slices, when carefully studied, can give detailed information about the internal features of a three-dimensional (3-D) body. In seismic tomography travel time which is a function of the slowness or inverse of velocity along the ray path through the earth is measured (Kayal, 2003). Assuming a multiple layer earth and critically refracted ray paths, the traveltime t is related to the depth Z of the refractor by:

$$t = \frac{X}{V_n} + \sum_{j-1}^{n-1} \frac{2ZCosi_j}{V_j}$$

where X = the distance between the shot and geophone,

i = the angle of incidence when the wave strikes the refractor = the angle of refraction when the ray re-enters the first medium,

V_j = the velocity of the wave in the first layer

V_n = the velocity of the wave in the n^th layer and j denotes the layer.

The information obtained from any type of tomography is meant to infer the internal structure of the 3-D object after a sufficient interpretation.

Data Collection, Processing and Results

The 2-D seismic refraction tomography data were collected along a profile across the borehole of standard log (Figure 2) with the centre of the spread situated at the borehole site.

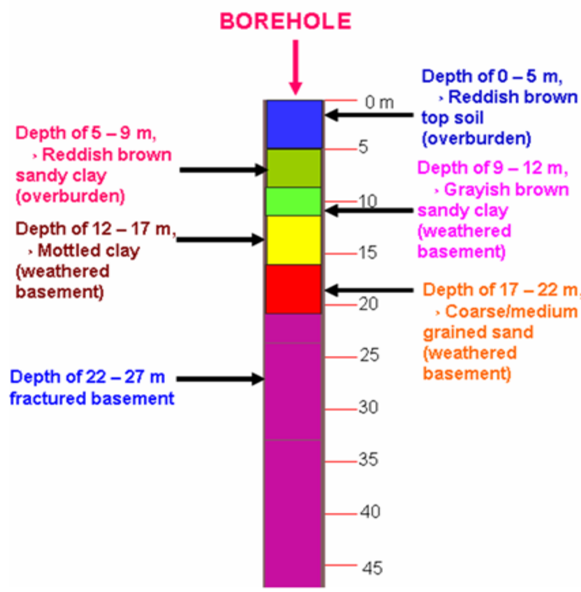

Fig.2: Geological Borehole Log Used as a Control Experiment (By Hydro-Skill and Engineering Services, Kaduna (2005))

An ABEM MK 6 Seismograph with 24 channels was used for the data collection. The geophones were spaced at 5 m intervals. Hence the length of the profile is 120 m. Seismic refraction tomography requires several shots along a profile line. Hence, in the acquisition of the tomography data, shots were taken at each geophone point. Using the same parameters, this procedure was repeated along the same spread and on the same shot points for at least once in a month for at least eight months in a year for four years.

The choice for each survey time depended on when there was significant variation on rainfall data as provided by the School of Aviation Technology, Zaria.

The data collected for each survey were subjected to different stages of processing using “REFLEXW” software (Sandmeier, 2003) to enhance signal to noise ratio. The filtered data were tomographically inverted.

The results of the interpreted data are the tomograms presented in Figures 3 – 6. Each figure is an example of the tomogram generated from the seismic data collected when the average total rainfall is or slightly different from the value shown on the figure.

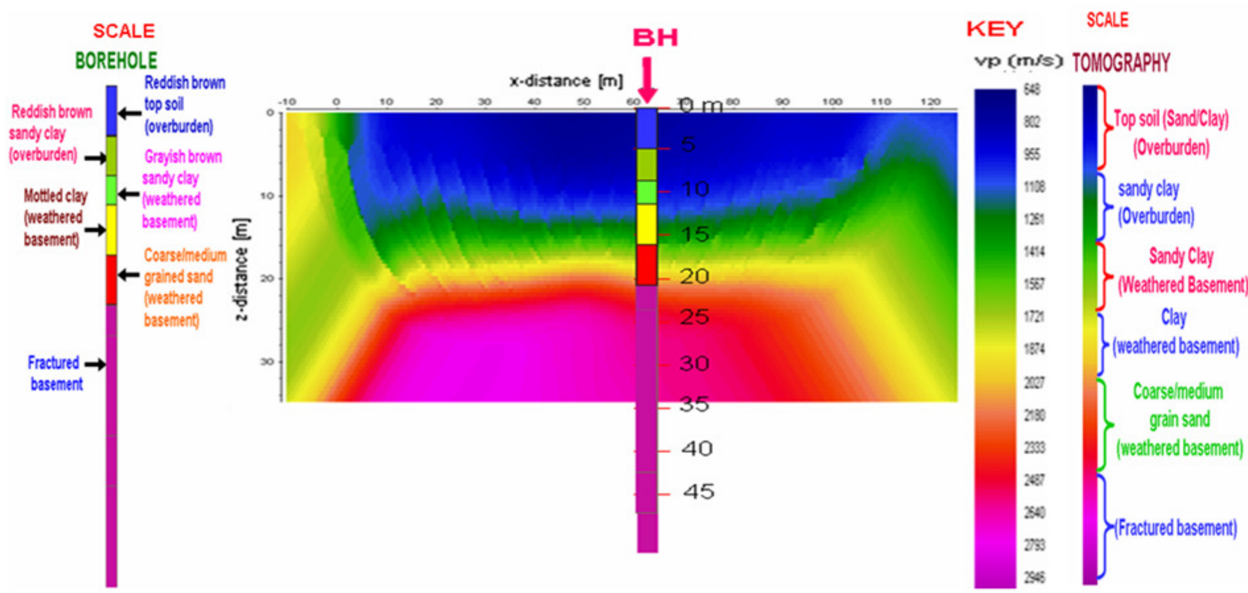

Fig.3: Geological Borehole Log Fitted into a Sample of Tomography Section of Seismic Data Collected Across the Borehole in the month of January (No Rainfall)

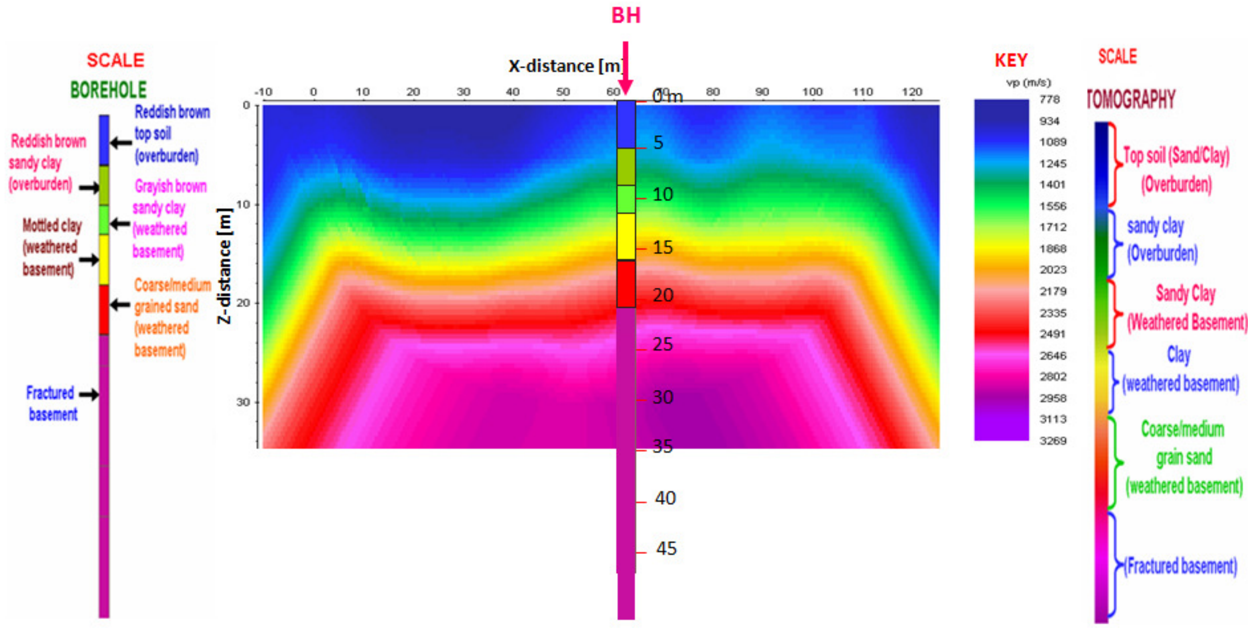

Fig.4: Geological Borehole Log Fitted into a Sample of Tomography Section of Seismic Data Collected Across the Borehole in the month of April (Average Total Rainfall = 44.8 mm)

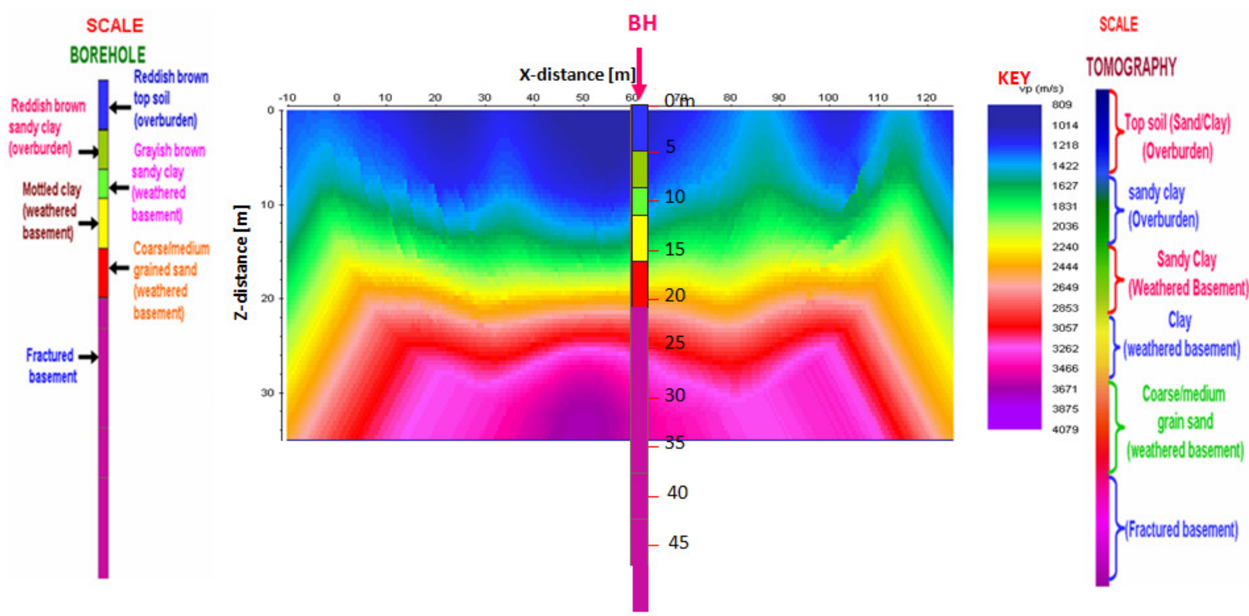

Fig.5: Geological Borehole Log Fitted into a Sample of Tomography Section of Seismic Data Collected Across the Borehole in the month of August (Average Total Rainfall = 322.1 mm)

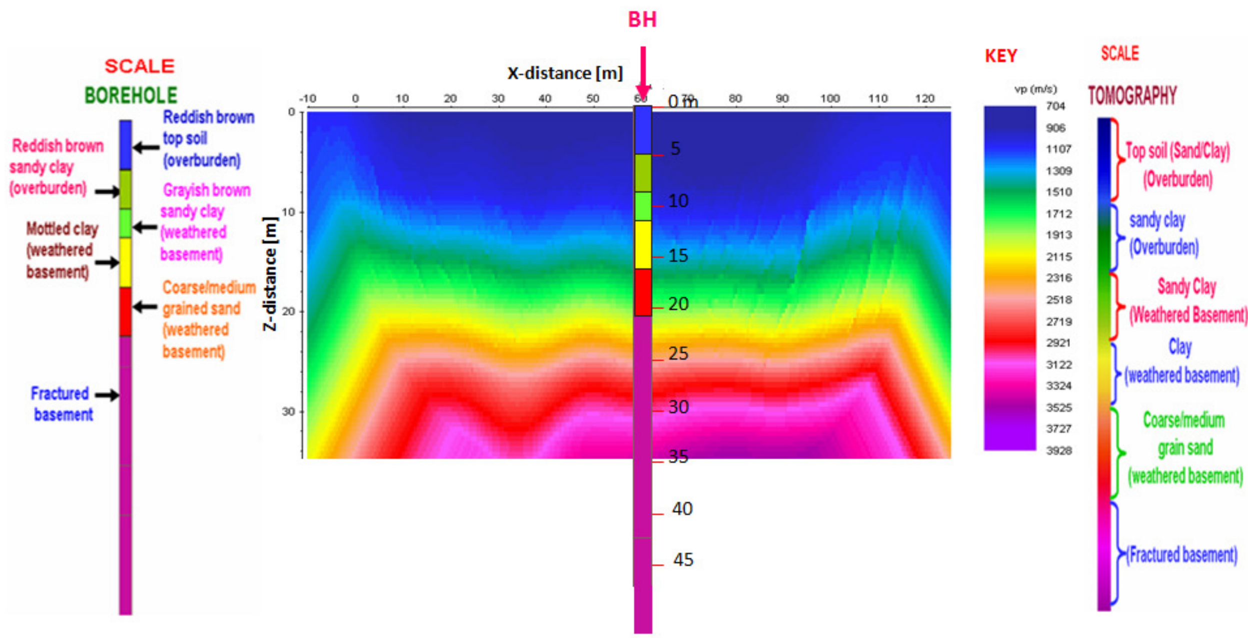

Fig.6: Geological Borehole Log Fitted into a Sample of Tomography Section of Seismic Data Collected Across the Borehole in the month of October (Average Total Rainfall = 62.8 mm)

The tomograms suggest that the p-wave velocities (V_p) associated with the subsurface across the borehole at shallow depth range from about 648 m/s (Figure 3) to 4079 m/s (Figure 5). Generally, the tomograms suggest that the P-wave velocities deduced from the seismic data when the ground was saturated are higher than those when the ground was dry.

The depth to the fractured basement underlying the profiles ranges from about 22.0 m (Figure 3) to 25.0 m (Figure 6).

Discussion

The tomographic inversion of all the seismic refraction data across the borehole, collected at different seasons/times each year for four years, have suggested that the P-wave velocities consistently have higher values when the ground was wet than when it was dry. These results agree well with the results of previous works in seismic. For example, it is known that the range of P-wave velocity for dry sand is about 200 – 1000 ms^{-1} while the range for water saturated sand is about 1500 – 2000 ms^{-1} (Hugh, 1995). In this study the calculated average seasonal changes in seismic P-wave velocity caused by subsurface water saturation is about 1.8 ms^{-1} for every millimeter change in the amount of rainfall between March and May when the subsurface was fairly saturated and about 1.3 ms^{-1} in August when the subsurface was most saturated. However, the tomograms show that the P-wave velocity ranges deduced in this work agree well with the ranges associated with the rock types as presented in the borehole log (Figure 2). For example, the interpreted result (Figure 3) has shown that the weathered basement comprises sandy clay, clay and coarse/medium grain sand; this is in agreement with the borehole log (Figure 2). Figure 4 shows that the P-wave velocity ranges for the interpreted weathered basement are about 1400 – 1700 ms^{-1} for sandy clay, 1750 – 2000 ms^{-1} for clay and 2000 – 2700 ms^{-1} for coarse/medium grain sand. These agree fairly well with the ranges, 1000 – 1500 ms^{-1} (Kearey *et al.,* 2006), 1000 – 2500 ms^{-1} (Hugh, 1995) and 2000 – 2200 ms^{-1} (Kearey *et al.,* 2006) usually associated with sandy clay, clay and coarse/medium grain sand respectively (Table 1).

Table 1: Standard P-wave Velocity Scale for Some Rock Types (Compiled from Telford, *et, al.,* 1976, *Mooney,*1977, Osemeikhian and Asokhia, 1994, Hugh, 1995 and Kearey *et al.,* 2006)

ROCK TYPE	STANDARD P-WAVE VELOCITY (ms^{-1})
Dry sand	200 – 1000
Water saturated sand	1500 – 2000
Sandy clay	1000 – 1500
Clay	1000 – 2500
Sand (coarse/medium grain)	2000 – 2200
Gneiss	2000 – 5000
Granite	4500 – 7000

The P-wave velocities generated in this study for the interpreted rock types were compared with a standard velocity scale (Table 1) and the percentage errors were computed (Table 2). The results suggest that the average error in the P-wave velocity ranges for the tomograms generated from the seismic data collected between November and February when the total amount of rainfall was almost zero and the subsurface was dry is about 3.8%. The average error in the P-wave velocity ranges for the tomograms generated from the seismic data collected between March and May when the total amount of rainfall was about 44.8 mm and the subsurface was fairly wet is about 3.0%. The average error in the P-wave velocity ranges for the tomograms generated from the seismic data collected between June and August when the total amount of rainfall was about 322.1 mm and the subsurface was very wet is about 8.7% and the tomograms generated from the seismic data collected between September and October when the total amount of rainfall was about 62.8 mm is about 7.3%.

Table 2: Error in Generated P-wave Velocity Ranges

ROCK TYPE		Average Depth Range (m)				Average P-wave Velocity Range (ms^{-1})				Approximate Error in P-wave Velocity Range (%)			
		Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 3	Fig. 4	Fig. 5	Fig. 6	Fig. 3 (Dry)	Fig. 4 (wet)	Fig. 5 (wet)	Fig. 6 (wet)
Overburden	Sand/Clay	0 - 12	0 - 5	0 - 10	0 - 14	648 - 1130	778 - 1240	809 - 1450	704 - 1300	7	0	0	0
	Sandy clay	12 - 15	5 - 9	10 -14	14 - 16	1130 - 1300	1240 - 1400	1450 - 1700	1300 - 1500	0	0	7	0
Weathered basement	Sandy clay	15 - 17	9 -12	14 - 18	16 - 21	1300 - 1770	1400 - 1700	1700 - 1850	1500 - 2050	9	7	18	18
	clay	17 - 22	12 - 17	18 - 20	21 - 25	1770 - 2050	1750 - 2000	1850 - 2400	2050 - 2500	0	0	0	0
	Sand (coarse/medium grain)	22 - 24	17 - 23	20 - 25	25 - 30	2050 - 2500	2000- 2700	2400 - 3180	2500 - 3050	7	11	27	26
Fractured basement	Gneiss	>24	>23	>25	>30	2500 - 2946	2700 - 3269	3180 - 4079	3050 - 3928	0	0	0	0

These results suggest that the average error in the P-wave velocity ranges for the tomograms generated from the seismic data collected in all the seasons do not differ significantly. The errors showed a little disparity between the standard velocities and the velocities for the tomograms. They are not high and therefore are within tolerance. However, the results suggest that the average error in the P-wave velocities for the tomograms generated from the seismic data collected between March and May when the total amount of rainfall was about 44.8 mm is fairly more reliable than others.

The results of the tomographic inversion of the seismic data across the borehole suggest that the depths deduced in this study agree fairly well with the borehole log. Table 3 summarises the depths deduced from the tomograms and their comparison with the borehole depths. The comparison presented in the table suggests that the depths that agree most with the borehole depths are those shown in the tomogram of Figure 4. The figure is one of the samples of the tomograms for the seismic data collected between March and May when the average rainfall was about 44.8 mm. This further suggests that the seismic data collected within this time most likely gave more reliable results than those collected outside this time range. The table suggests that the least reliable data was collected within August and October.

Table 3: Summary of the Depths Deduced from the Tomograms and Comparison with the Borehole Depths

Source	DEPTH ESTIMATE (m)							Percentage Error in Thickness/Depth (%)		
	Overburden			Weathered basement			Basement			
	From	To	Thickness	From	To	Thickness		Overburden	Weathered basement	Basement
Figure 3	0.0	15.0	15.0	15.0	24.0	9.0	24.0	66.7	9.1	9.1

Figure 4	0.0	9.0	9.0	9.0	23.0	14.0	23.0	0.0	4.5	4.5
Figure 5	0.0	14.0	14.0	14.0	25.0	11.0	27.0	55.6	13.6	13.6
Figure 6	0.0	16.0	16.0	16.0	30.0	14.0	30.0	77.8	36.4	36.4
Bore-hole	0.0	9.0	9.0	9.0	22.0	13.0	22.0	Control Depths		

Conclusion

This study was carried out to determine the best time of the year, in terms of season, to conduct seismic survey in Zaria Area, Nigeria for most reliable results. Series of data collected at various times across a borehole of standard log for four years were interpreted and their results were compared with the log of the borehole and a standard P-wave velocity scale.

The tomograms generated in this study (Figures 3 – 6) had shown that the velocities of the interpreted formations generally increase with increasing subsurface water saturation. The calculated average seasonal changes in seismic P-wave velocity caused by subsurface water saturation is about 1.8 ms^{-1} for every millimeter change in the amount of rainfall between March and May when the subsurface was fairly saturated and about 1.3 ms^{-1} in August when the subsurface was most saturated. However, the results had shown that the velocity ranges in both dry and wet formations fairly fall within the standard ranges as provided in literature. The P-wave velocities generated in this study for the interpreted rock types were compared with a standard velocity scale and the computed average error showed a little disparity of 3.8%, 3.0%, 8.7% and 7.3% between the standard velocities and the velocities for the tomograms generated from the seismic data collected when the average amount of rainfall was 0 mm, 44.8 mm, 322.1 and 62.8 mm respectively.

The results suggested that the tomographic inversion of all the data collected within March and May when the average amount of rainfall was about 44.8 mm for the four years best fitted the depths of the borehole log.

These results suggested that for more reliable results, seismic surveys are best conducted in Zaria Area, Nigeria and its environs, with similar climatic condition, when the average amount of rainfall is about 44.8 mm. Records over the years had shown that this average amount of rainfall is obtainable between the months of March and May each year. Outside this time range the results of the seismic data may be used for preliminary studies only.

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