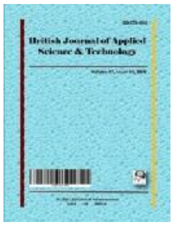

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Geological, Geophysical and Seismological Investigations for Siting of Seismic Stations in Minna and Abakaliki, Nigeria for Data Reliability

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Authors' contributions

This work was carried out in collaboration between all authors. Authors UKA, MST and COO designed the study. All authors participated in the field investigations and data collections. Authors UKA, MST, TAY, TSO and COO performed the seismological, geological and geophysical data acquisition, processing and analysis. Authors DD, COO, UKA and TAY were involved in setting up of field instruments and data processing. Authors UKA and MST wrote the protocol and the first draft of the manuscript. Authors JU and GO participated in field work and handled the GIS. Authors MST, TAY, UKA, PE, ME and OAA managed the analyses of the study. Authors UKA and MST managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The goal of this study is to adopt international standard criteria to carefully select sites to host seismic stations in Minna and Abakaliki, Nigeria, that can give reliable seismic data with high network detectability, monitor local seismicity and record local events with improved accuracy. By this, mistakes made during the construction of existing stations in Nigeria would be avoided systematically. To achieve these therefore, detailed field assessments were carried out to select most suitable site amongst the four potentials sites earlier proposed to host the sensitive seismic

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equipment for each area. These steps were later followed with detailed geological, geophysical and seismological investigations to ascertain the rock types at the sites; determine the depth of the bedrock where the sensor would be placed; and evaluate the signal to noise ratios and sources of possible noise to the pre-selected sites. Results from the various investigations have helped a team of seismologists, geologists, geophysicists and GIS experts drawn from the Centre for Geodesy and Geodynamics (CGG), Federal Ministry of Science and Technology and the National Emergency Management Agency (NEMA), to select most reliable sites for seismic stations in Minna and Abakaliki. As this is the first time these kind of investigations have been undertaken to select a site for seismic equipment in Nigeria, it is expected this study would set standard practices for future site selection for sensitive equipment in Nigeria and in the sub-region.

Keywords: Nigerian seismic network; seismic stations' site selection criteria; Minna and Abakaliki seismic stations; data quality.

1. INTRODUCTION

Nigeria is not located in regions that are famous for seismic activities; however, both historically observed and instrumentally recorded events have been witnessed in the country from 1933 till date [1,2]. Occurrence of earthquakes in Nigeria was one strong goal, amongst others, that informed the establishment of the Nigeria National Network of Seismographic Stations (NNNSS) in 2006. The network, comprising broadband seismic equipment, is shown in Fig. 1. While stations at Ile-Ife in South-West; Kaduna and Toro in the North-East and North-Central, and Nsukka and Awka in the South-Eastern parts of the country have been completed and operational, the planned stations in Ibadan, Oyo in the South-West; Minna and Abuja in the North-Central; and Abakaliki in South-East, were not operational.

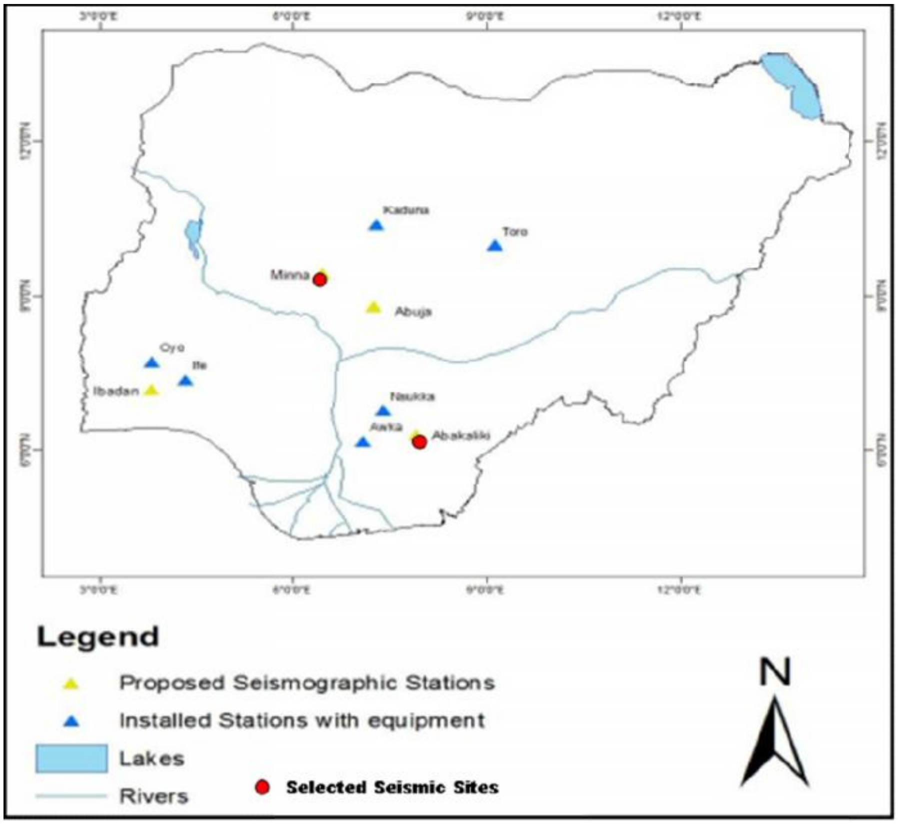


Fig. 1. Existing and proposed stations in Nigeria. The red solid dots are the selected sites in Minna and Abakaliki (Modified after [2])

Prior to the establishment of seismic stations at Nsukka, Awka, Ife, Oyo, Kaduna and Toro, there were no detailed seismological and geophysical investigations to ascertain or otherwise, the suitability of the respective sites to host sensitive seismic equipment. As a consequence of this, operators and users of products from the existing stations have to contend with impaired data with high noise level, especially from the Nsukka station, sited on a Sedimentary basin; water-logged vaults as witnessed at Oyo station where the sensors previously installed at different times, were completely submerged and damaged, amongst other challenges.

Prior to the selection of sites for seismic stations, it is required that detailed geological, geophysical and noise analysis are vigorously carried out. A station that is installed on soft soil, be it a Very Broadband (VBB) device, can be rendered useless, while the Short-Period (SP) signals may not the true representation of expected signals as a result of local ground effects [3,4,5,6,7]. In another scenario, supposing the seismic network layout is such that, it was unsuitable, this would unavoidably lead to inaccurate location of seismic events, most times systematically biased, or even impossible [3,8]. These are some of the challenges amongst others, faced by Operators of, and users of products from the Nigerian National Network of Seismographic Stations (NNNSS), that this study sought to avoid in choosing sites for its future seismic stations.

The main goal for the establishment of additional seismic stations therefore, was to densify the existing seismological infrastructure to boost their capability to monitor local seismic activities in Nigeria, thereby assisting the National Emergency Management Agency (NEMA) and to a large extent, and the entire country, in seismic hazards monitoring, prediction, disasters mitigation and management. Against this backdrop, the Centre for Geodesy and Geodynamic (CGG) in collaboration with NEMA and the Federal Ministry of Science and Technology, carried out detailed geological, seismological and geophysical investigations for the establishment of seismic stations at Minna and Abakaliki, in strict compliance with the recommendation in [3,9,8], and taking the peculiarities and characteristics of the targeted sites in to serious consideration too. Upon the completion of these stations, sensitive seismic equipment like the 120 sec. Digital Very Broadband Guralp Seismometer or the 100 sec, EP-105 Broadband Seismometer with DR-4050 Data acquisition system, are expected to be installed at both sites.

2. GEOLOGY OF THE RESPECTIVE AREAS

2.1 Geologic Setting of Ebonyi State University Sites

The early marine space of the Benue trough was generally believed to have started in the mid-Albian period with the deposition of the Asu River Group. Fig. 2 shows the distribution of the Asu River Group and other lithologic units in the lower (or southern) Benue trough, Southeastern Nigeria [10]. The Asu River group sediments are predominantly shales, commonly referred to as the ‘Abakaliki shale formation’ in and around the Abakaliki metropolis and localized occurrences of sandstone, siltstone and limestone intercalations [10].

The group has average thickness of about 2000 m and rests unconformably on the Precambrian Basement [11]. The Abakaliki shale formation, which has an average thickness of about 500 m, is dominantly shale, dark grey in colour, blocky, and non-micaceous in most locations. It is calcareous (calcite-cemented) and deeply weathered to brownish clay in the greater part of the formation [11].

2.2 Geologic Setting of Lunko Village (FUT Minna)

The surveyed area is underlain by rocks belonging to the Precambrian Basement Complex of Nigeria (Fig. 3). These are a group of crystalline (hard) rocks generally represented by Granites, Schist, Migmatite, Gneiss, Quartzite and a host of others. These rocks have undergone various stages of metamorphism, tectonism and weathering to produce secondary structures like jointing, fracturing, foliations and weathered zones that tend to modify their original form and structure.

The local geology of the area under study revealed that the site is underlies by Granite Gneiss, even though outcrops of the rocks are not immediately visible in the area exposures of the rock occur about 500 m from the site selected. Pegmatite veins with predominance of quartz (50%), muscovite mica (20%) and feldspar (10%) in hand specimen also abound in the area, these occur as intrusions into the gneisses trending in the NW-SE direction. Depth of weathering is shallow and is estimated to be between 2 – 10 m. Fig. 3A is the geological map of the area superimposed on the topographic map plotted from values obtained using the GPS.

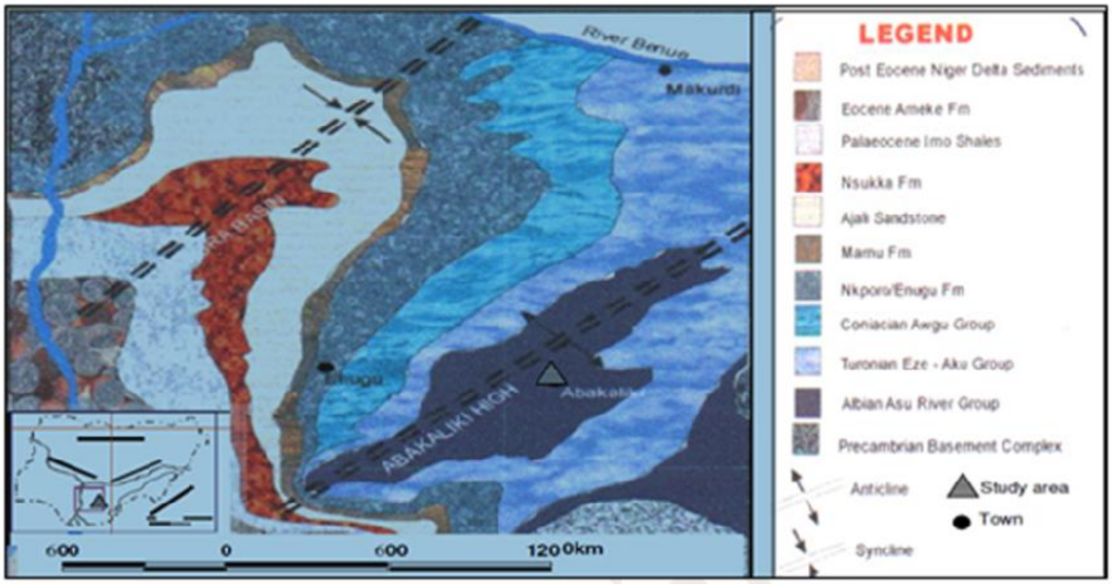


Fig. 2. The generalized geological map of south-eastern Nigeria showing the Abakaliki (Modified after [11])

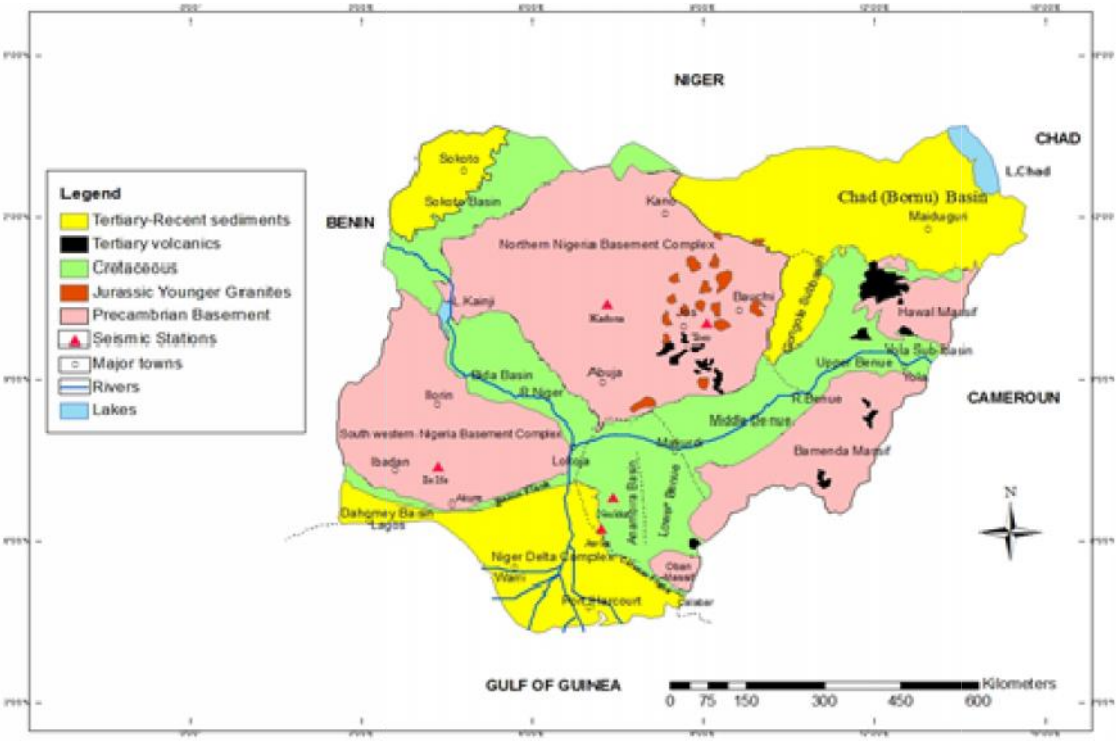


Fig. 3. The generalized geological map of Nigeria (Modified after [1])

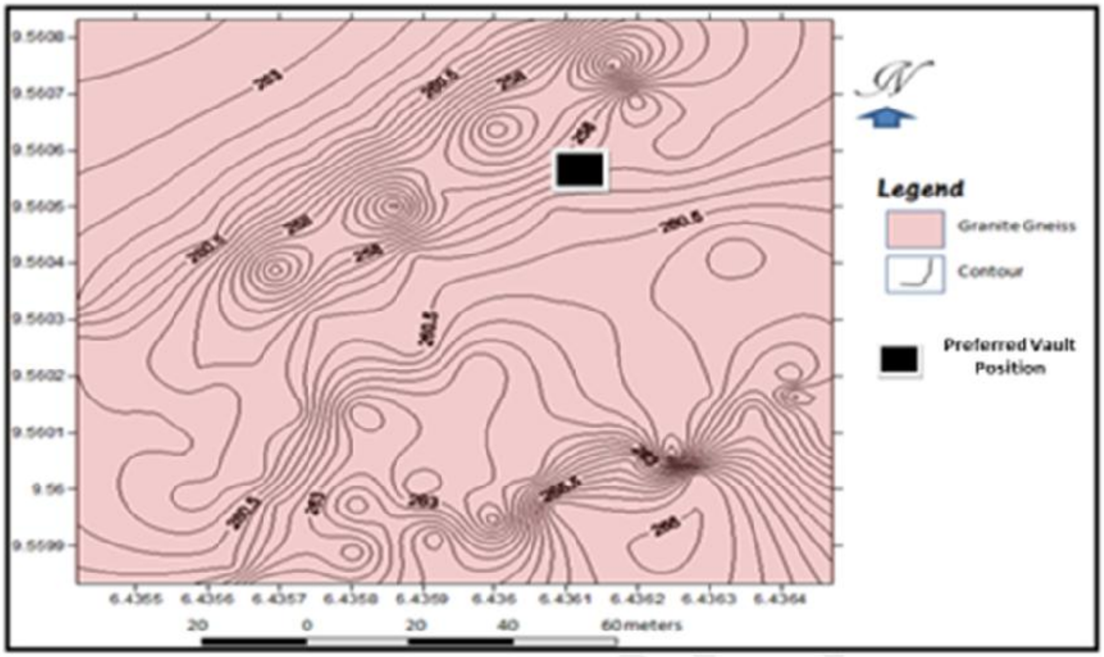


Fig. 3A. Geological map of the Minna site superimposed on the topographic map

3. SITES SELECTION FOR SEISMIC INFRASTRUCTURE AT MINNA AND ABAKALIKI

The sites proposed for both the Minna and Abakaliki stations are located within the University communities, far away from the busy and densely populated Minna and Abakaliki towns. The closest paved roads to Minna and Abakaliki sites are about 3km and 1.5km respectively. There have been unpublished reports of unconfirmed seismic activities in Minna in the past, which may be linked to suspected faults in the region [2,1]. However, there is no reliable history of seismic activities in Abakaliki region.

Prior to selection of site to host a seismic station, a detailed geological, geophysical and noise analysis are required among other site's selection requirements. The capacity of a new seismic station and the Nigeria's seismological network setup to detect Earthquakes or Earth tremor and to record symbolic and subsequent event waveforms is ruled by the signal and noise physical characteristics of its sites and other seismo-geological conditions [12,8,13]. It was as result of this, that detailed investigations were carried out so as to obtain basic and relevant information at Minna and Abakaliki sites where the seismic equipment are to be installed.

Customarily, the process of site selection begins with choosing, more than one site; at least, two or three times as many potential sites as will be studied and finally narrowed to the best sites after considering many factors that can give a better detectability [3,8]. In selecting most appropriate sites to host a seismic station in Minna and Abakaliki respectively, the Seismo-geological conditions, topographic conditions, accessibility, Seismic noise sources in the region, data transmission and power considerations, Land ownership and future land use issues and security were taken into serious considerations.

Since the proposed sites at Minna and Abakaliki are not located in regions associated with harsh climatic conditions and severe rainfalls and proximity to oceans/seas, the following guidelines were aptly applied in selecting the respective sites and in line with recommendations in [3]: (1) Consideration for the station to be sited away from noise sources especially man-made and environmental sources, (2) avoidance of sloppy areas to evade horizontal tilt from gravitational, pressure and temperature effects on the horizontal (E) component of the sensor, (3) Keeping a reasonable distance from any water body, (4) Ensuring adequate security, (5) Ensuring that there is a good access to the station, (6) Taking measures to ensure the station should not be sited at areas of humid conditions, extreme cold or warm areas as well as areas with high probability of lightning, (7) Avoidance of areas of rough topography, (8) Adopting measures to ensure the station is not sited in areas of soft ground, that is, it should be located on a bedrock (Minna) or consolidated sandstone (Abakaliki), (9) Ensuring that the proposed site would not be susceptible to water-log, (10) setting up of a temporary station set up with the DR 4050 recorder and EP-105 sensor at each of the locations to run for at least 6 hours to determine the noise levels at the respective sites, (11) Taking necessary steps to choose a site that is not close to magnetic properties, (12) The station should be fenced to avoid access to straying/grazing animals, (13) At least 3 sites should be selected for further investigations.

4. MATERIALS AND METHODS

4.1 Field Studies

The field investigations were carried out in Minna and Abakaliki separately. The host institutions (Federal University of Minna and Ebonyi State University) of the proposed stations made efforts to provide four potential sites each. The team from Centre for Geodesy and Geodynamics (CGG), Toro, Bauchi State, Nigeria, comprises a seismologist, geologist, geophysicist and supporting team from CGG, Federal Ministry of Science and Technology and the National Emergency Management Agency, carried out the detailed investigations in Minna and Abakaliki. Three days were spent per site to accomplish the fieldwork.

All relevant maps and information about the sites and areas were prepared in advance for guidance. In general, the experts visited the sites to: verify the ease of access to the site; search and verify proximity of seismic noise sources the area under investigation; perform seismic noise measurements; study the local seismo-geological conditions; investigate the underground geological structures beneath the proposed seismic station; and verify availability of power and security etc.

The various techniques and equipment used in carrying out the field investigations include:

- **(a) Geological mapping:** Basic geological field equipment and materials, for example, a sledge hammer, chisel, compass, hand-held Global Positioning Systems (GPS), relevant chemicals, base maps, photo camera, sample bags etc.
- **(b) Geophysical Survey:** The equipment used in geophysical investigation are: ABEM Terrameter (SAS 1000) for Electrical resistivity using Vertical Electrical Sounding (VES) using the Schlumberger configuration. The Lund Imaging systems (Terameters SAS 1000 and a selector) were also used during the field work for assurance purposes.
- **(c) Noise Measurements and Analysis:** *EP-105* Seismometer and DR 4050 Recorder connected to a laptop, were used to measure noise at different sites in Minna and Abakaliki.

4.2 Noise Measurements and Analysis for Siting a Seismographic Station at Minna and Abakaliki

Seismic noise were the main data used for analysis in this part of the study, after the selection of four potential sites at Minna and Abakaliki respectively. Relevant seismic noise processing software like the Seisan software [14, 15] and PQL, were used for the noise analysis, using merged hour-long data windows, using almost 24-hour collected noise data. Using the approximate relationships in equations 1 and 2 [8], it was possible to calculate the noise power density N(dB) given in dB and the ground displacement d in meters [16,8].

$$d = f-1.5/39 * 10N/20 \ (3.17) \qquad (1)$$

$$N = 20\log(d) + 30\log(f)+32 \qquad (2)$$

Where f is the average frequency of the filter, dB (Decibel) is relative to 1 (ms-2)2/Hz [8].

Chart A shows procedures taken to process the seismic data, which include assessing sources of seismic noise and noise level determinations and computing the Signal to Noise Ratio (SNR) using noise recordings at both sites.

4.3 Noise Measurements and Analysis at Minna Sites

The properties of one of the sites on which noise measurements were taken and analyzed at Minna is on Latitude: 9.556N, Longitude: 6.435E, Altitude: 265 m above sea level, with average Temperature that did not exceed 33º C. Typical noise recordings at Minna site is shown in Fig. 4, and the noise power density in Fig. 5, respectively.

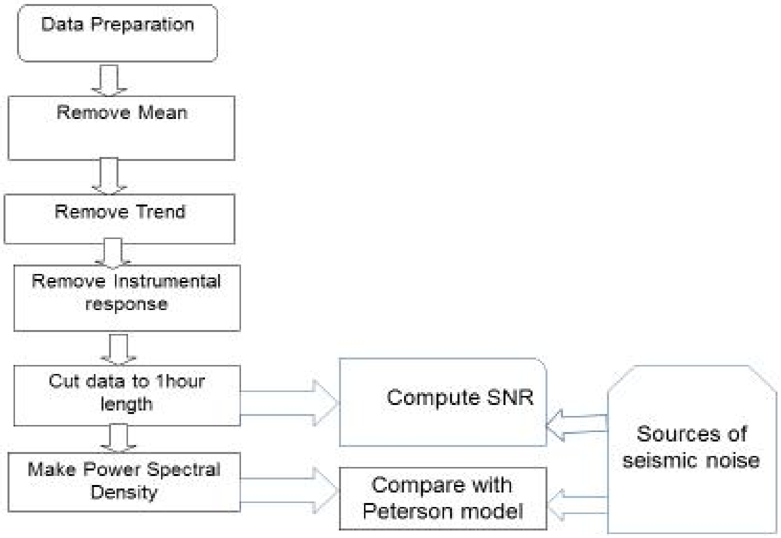


Chart A. Seismic noise data processing procedures

The noise data covered quiet and expected peak periods of anthropogenic noise [17]. At quiet periods (early hours of the day or late in the evening), the noise levels were very low (lower than -220 dB), which is considered ordinarily very good for seismic data recording. In order words, the contribution of noise at lower frequency bands (0.01-1.0Hz) is significantly low with distinct first and second microseismic peaks at frequencies 0.3 and 0.7 respectively. Plate 1 shows seismic equipment used in noise recordings at Minna and Abakaliki sites respectively.

Nonetheless, presence of high microseisms were observed in the raw data before the noise spectra were computed and analyzed. Since from field visitation, there were no fast running streams, oceans, seas, water bombarding coastal shores, the likely source of the high microseismic noise is wind on vegetation that are readily transmitted to ground and picked by a sensitive sensor, as explained in [18,19,20,8]. Anyway, this is not much of a problem to the recording efficiency of a sensor. Fig. 4 shows raw noise data recorded on the three components while Fig. 5 is the Fast Fourier Transform (FFT) of the noise, showing low noise level at Minna site.

Fig. 5a was determined for Minna site using all available information to help understand noise characteristics at the site, possible sources of natural and anthropogenic noise using the [21].

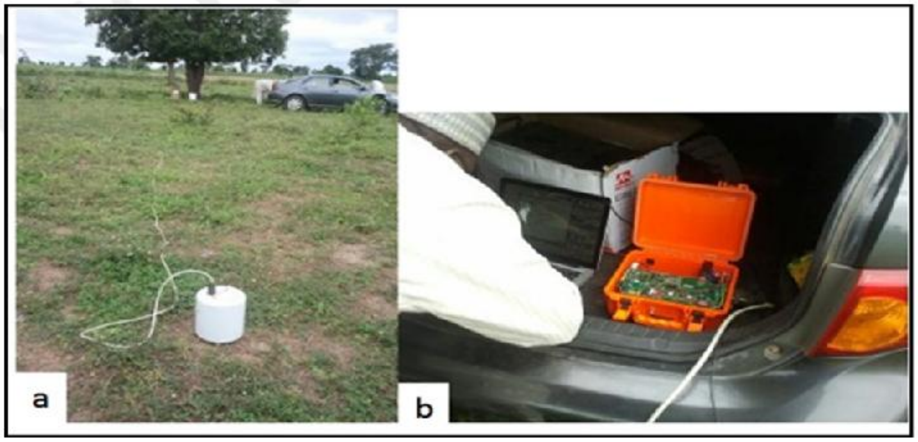


Plate 1. Noise Measurement instrumentation at selected site near Lunko village (a) Sensor and (b) Recorder

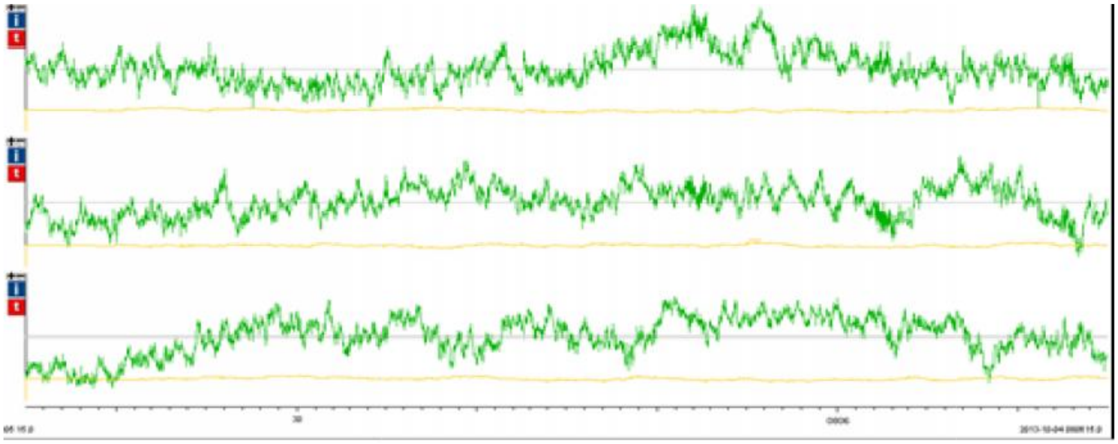


Fig. 4. Noise measurement at Minna site, recorded by 3-component sensor

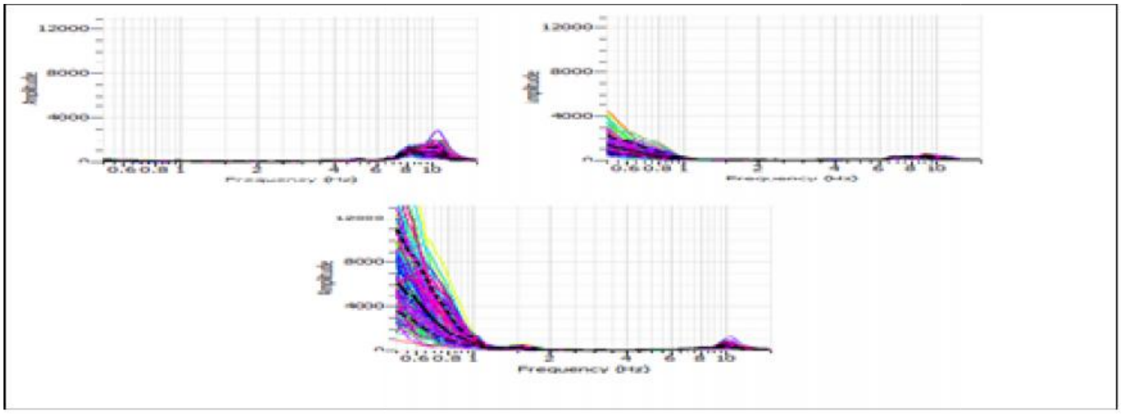


Fig. 5. Low noise level obtained from fast Fourier transform of the raw noise recordings at Minna site

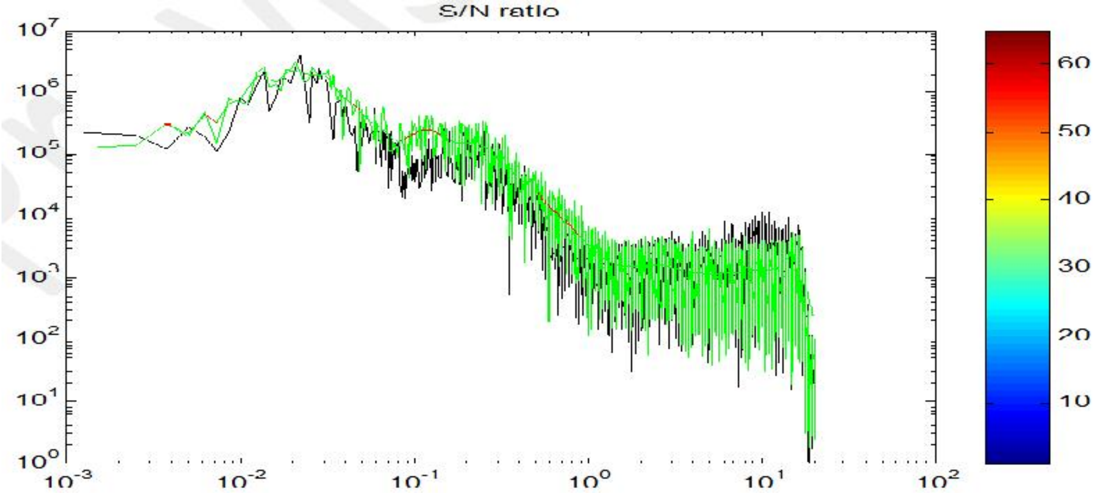


Fig. 5a. Signal to noise ratio at site in Minna

Green colour= Signal; black colour= Noise

At higher frequencies (1.0-10Hz), anthropogenic or cultural noise was introduced to the noise spectrum, especially during the peak period of human activities, the noise pattern jumped to between -200 and -180 and this noise characteristic was consistent for up to three hours. The good news is that the increase in noise levels fell within the globally accepted noise model, the Peterson low and high noise level models [22].

Also at high frequency bands, some not too visible spikes were noticed on the seismograms at regular intervals and it was difficult to ascertain the sources of the observed spikes that were not visible in the raw noise data. However, the unwanted spikes could easily be filtered out by cutting them off at desired frequency band during processing. The horizontal component of the sensor did not suffer from tilt, hence moderate noise level was observed on this component; even though the noise was slightly higher than that observed on the Z and N components.

4.4 Noise Measurements and Analysis in Abakaliki Sites

From geology and peculiarity of the Abakaliki, it was indeed a herculean task selecting four possible sites. Site one which is the old site earlier selected within the institution, was done away with because the vault was water-logged, difficult access to the site and for security concerns, as the investigating team met with a visibly hostile host community on their visit to the site.

4.4.1 Sites two and three

Sites Two and Three were treated as one site because they are within 300-meter circumference and could as well assume they would the same radius, albeit, different topography. Noise variation within this range will almost add up to zero. The parameters of the site is located on Latitude - 6.24236N, Longitude - 8.008070E, Altitude - 00083 m above sea level, and Temperature Variation was from 23.8-43.3ºC. Fig. 6 shows noise recordings from Abakaliki site and Fig. 7 is the noise power density.

High microseisms were observed at sites 2, 3 and 4 respectively. These likely came from wind on vegetation, slow running streams. In fact, microseisms dominated the noise waveforms. Specifically, at sites 2 and 3, the noise spectrum showed a clear decay with respect to amplitude and frequency. At low frequency bands (0.0100-0.316Hz), it was difficult for the instrument to resolve the noise, which may be due unavoidable geologic condition or weather condition or even site amplification. However, the noise level was not shot out of the acceptable range. The noise spectrum was almost outside the global model at frequency range (0.0100-1.0Hz) which was not likely due to the noise characteristics of the site but site amplification. Fig. 6 shows raw noise recordings at Abakaliki site while Fig. 7 is the Fourier transform, indicating high noise level at the site.

Fig. 7a was determined for Abakaliki site using all available information to help understand noise characteristics at the site, possible sources of natural and anthropogenic noise using the [21].

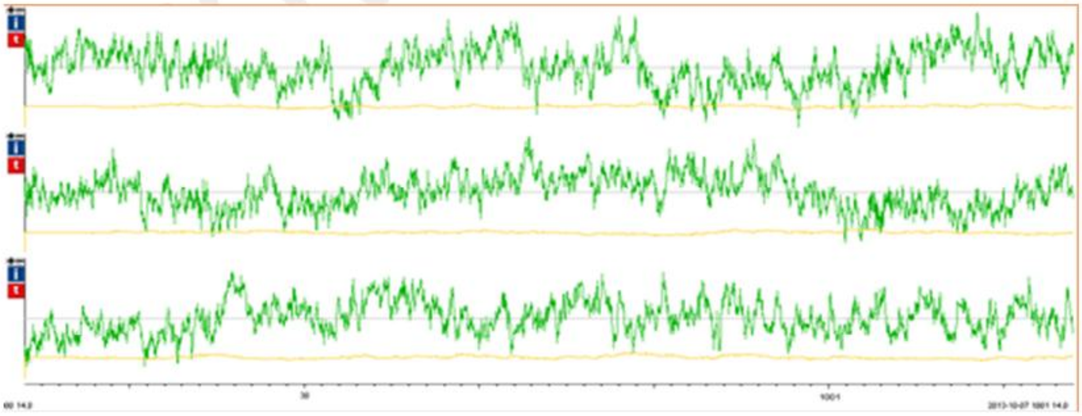


Fig. 6. Three-component noise measurements at Abakaliki site

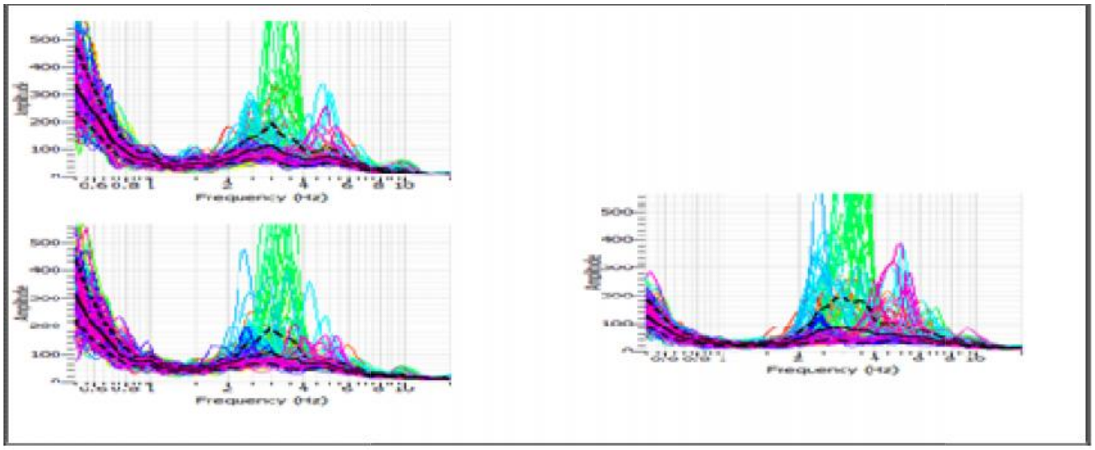


Fig. 7. Noise power density at Abakaliki. The spectra show high level of noise on the three components recorded in this vicinity

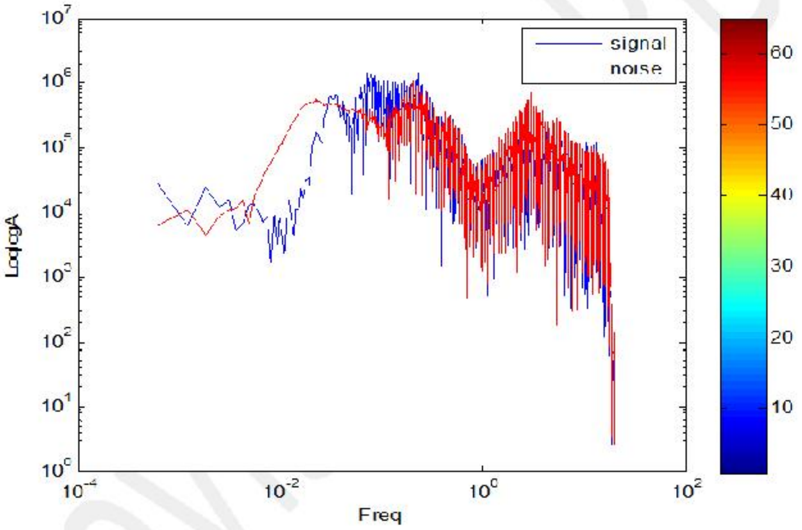


Fig. 7a. Signal to noise ratio at Abakaliki site

Red colour= Noise, Blue colour= Signal

At quiet periods, the noise levels were significantly low at all frequencies, even at 10z. But the situation was reversed during the peak noise periods especially in the afternoon and at frequencies (1-10Hz). Interestingly, the deviation was not more than -10 dB from global noise model. This is acceptable for a site under consideration provided other factors are favourable. Though, it is difficult to obtain 100% perfection in applying site selection criteria to measure and analyze noise, necessary measures are taken to select a site that would guarantee low noise. Some visible spikes were observed in the raw data and the noise spectrum which may likely be introduced from nearby human activities, like hitting the hammer on the nail, water dropping on the floor, stamping of foot on the ground, that are occurring at regular and defined intervals.

4.4.2 Site four

Site 4 is a stand-alone site and was treated independent of sites 2 and 3. The site is located on Latitude - 6.240380N, Longitude - 8.006123E, Altitude - 00081 m, with Temperature Variation - 25.3-42.1°C.

Site 4 almost exhibited the same noise characteristics as observed on sites 2 and 3. While the noise levels at quiet periods are moderately high, the instrument could not resolve noise pattern at frequencies 0.0100Hz to 0.316Hz due to site effects. At peak noise periods, a strange high noise was observed at higher frequencies even above 10Hz, and this was consistent for a long period. The noise levels were higher than the global noise model at frequency range (3-10Hz) and this persisted for more than 3 hours. Consistent spikes were also observed in the raw data and the noise spectrum.

5. GEOPHYSICAL SURVEYS IN MINNA AND ABAKALIKI

Geophysical survey was conducted using the Electrical Resistivity method and also Resistivity Lund Imaging. Electrical Resistivity imaging measurements determine the average resistance of the soil materials in a given area by inducing a current into the ground between two electrodes and measuring voltage changes between two other electrodes. Typical Schlumberger array arrangement is shown in Fig. 8.

Thus, the current, voltage, and appropriate distances can be measured from Fig. 7 and therefore solve for apparent resistivity, using equation 3. After obtaining the resulting resistance of each VES point, the resulting apparent resistivity ρ_a were calculated respectively, using equation 3 [23].

$$\rho_a = \frac{2\pi\Delta V_{P_1-P_2}}{i}\left(\frac{1}{\frac{1}{r_1}-\frac{1}{r_2}-\frac{1}{r_3}+\frac{1}{r_4}}\right) \tag{3}$$

where ρ_a is the apparent resistivity, i is the current, $\Delta V_{P_1-P_2}$ is the potential difference across the electrodes, r_1, r_2, r_3, r_4, spacing between the first current electrode and potential electrode, spacing from the first potential electrode and the second current electrode, spacing of the first current electrode to the second potential electrode, and spacing between second potential electrode and second current electrode respectively. The electrical resistivity method involves generating a current field in the ground and then measuring voltage potential within that induced field. The method measures the electrical resistance of the subsurface materials within the current field. The resistance of the materials is a function of the material type, porosity, degree of saturation, and the electrical properties of the pore fluids. With this method, 2-D images reflecting changes in the material type, pore fluids, or porosity can be generated [24].

Vertical Electrical Soundings (VES) using Schlumberger array were carried out at Ten (10) stations in Minna. A regular direction of N-S azimuth was maintained in the orientation of the profiles. Overburden in the basement area is not as thick as to warrant large current electrode spacing for deeper penetration, therefore the largest Current electrode spacing C_1C_2 used was 144m, that is, ½(C_1C_2)=72m.

5.1 Equipment Used

The principal instrument used for this survey is the ABEM Terrameter (SAS 1000). The resistance readings at every VES point were automatically displayed on the digital readout screen and then written down on the field note book (Plate 2). The Global Positioning System (GPS) Garmin 76CSx instrument was also used to determine the geographic coordinates and altitudes of the VES stations.

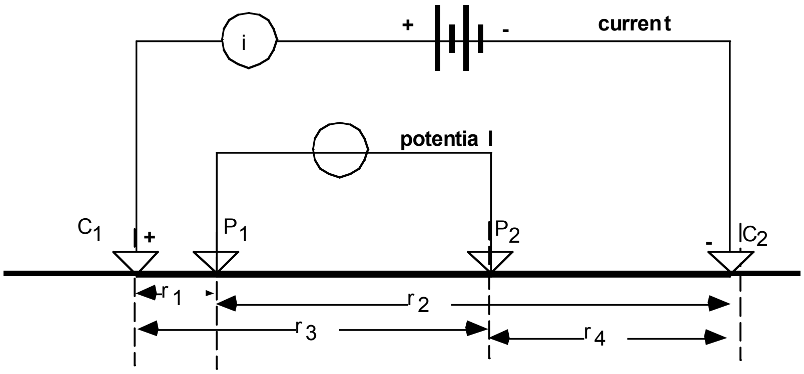


Fig. 8. Schlumberger array arrangement used in this study (After [23])

Plate 2. The geophysical instrumentation using resistivity technique at Lunko village (FUT Minna)

Choosing a location to set up the seismic station, and more importantly, where to place the seismometers require a detailed investigation and careful considerations of some basic parameters. Ideally, the seismometer is expected to be placed on a concrete slab which is in direct contact with the bedrock. The sensor can also be placed directly on bedrock.

The Electrical resistivity method was conducted at the permanent site (Gidan Kwano), Federal University of Technology, Minna. This method was selected to obtain subsurface information on the location. These information include; especially the depth to bedrock, faults, fractures and their orientation which probably control the geologic features in the area.

5.2 The Work Plan for Minna Geophysical Survey

The geophysical work plan sketch at Site 2 (Lunko village, Minna) and the establishments of VES stations along three profiles of about 35 m intervals (Fig. 9).

5.3 Data Acquisition

Three profiles of 90m long at intervals of 35m were established. At Profile1 (P1), Four (4) stations P12, P12, P13 and P14 at station interval of 30m were occupied, at profile P2, three stations P21, P22 and P23 were occupied and at profile P3 three stations P31, P32 and P33 were also occupied. A total numbers of 10 VES stations were occupied on the three profiles, shown in the Figs. 10 – 12.2. The Schlumberger configuration was adopted for the surveys. The inter-electrode spacing was varied from 1.5 to 72, 55, 55, 55, 55, 55, 55, 55, 72 and 55m at P11, P12, P13, P14, P21 P22, P23, P31, P32 and P33 respectively with total spread length of 105 to 144 m.

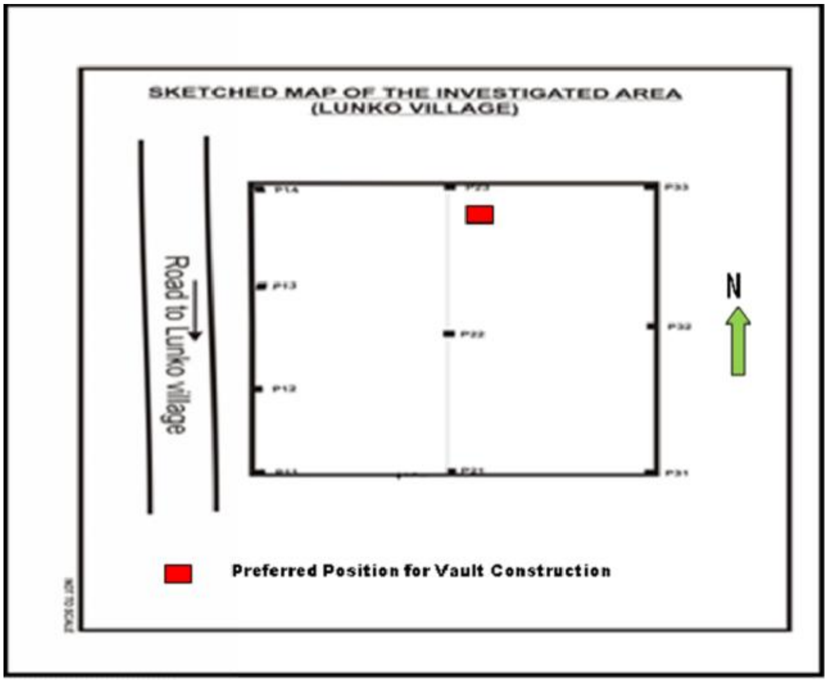


Fig. 9. The Sketch Diagram of the work plan carried out at Lunko village, FUT Minna. (Not to scale)

5.4 Data Processing and Interpretation

A computer program "IP12win" was used to processed the measured apparent resistivity field data and to compute the inverse model of resistivity variation with depth [25]. This program has provision of accomplishing three tasks: (i) smoothing of noisy field data, (ii) accurate computation of apparent resistivity models, and (iii) inversion of resistivity data. The output is the inverse resistivity model providing layer wise distribution of resistivity value (*n*) and thickness (h) of the corresponding layer.

Data smoothing for Schlumberger array includes single point correction and vertical curve branch shifting. The vertical curve branch shifting consists of a linear shift of one or more branches to correct misties between the branches. The correction of the misties is by the amount of the difference between two apparent resistivity observations with the same current electrode distance (AB), but with different potential electrode separation (MN). An equal correction (on the logarithmic scale) is applied to all points of a selected branch.

5.5 Geophysical Survey in Ebonyi State University, Abakaliki

Although the geology of Abakaliki is more complex than that of Minna, the same geophysical technique was adopted for both areas. The method utilized were selected based on applicability for detection of specific features of interest, the bedrock. The electrical resistivity was used to provide high-resolution two-dimensional (2-D) slices of subsurface features, including the ability to potentially identify fractures, faults, and voids. Vertical Electrical Soundings (VES) using Schlumberger array were carried out at Site Three in Abakaliki. A regular direction of N-S azimuth was maintained in the orientation of the profiles. Overburden in the basement area is not as thick as to warrant large current electrode spacing for deeper penetration, therefore the largest current electrode spacing AB used was 144 m, that is, 1/2AB=72 m.

5.6 The Work Plan Sketch for Abakaliki and analysis of the Geophysical Survey

In Abakaliki, the pre-selection exercises considered the two sites close to each other and therefore it was assumed that the local geology is similar. It was as a result of this that a triangulation mapping technique was employed (Fig. 9A). Therefore, the three stations P1, P2 and P3 which are about 35 m interval in a triangular shape were investigated as shown in the sketched diagram (Fig. 9A).

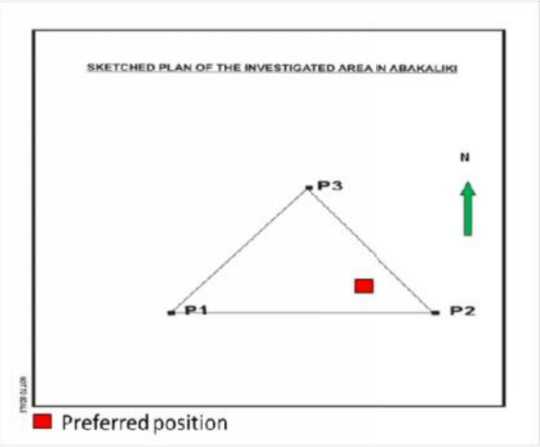


Fig. 9A. The sketched diagram of the geophysical work plan carried out at Abakaliki (Not to scale)

6. PRESENTATION OF OVERALL RESULTS

6.1 Results on Pre-seismic Station Site Selection Exercises

The pre-seismic station site selection activities served as necessary monitors for quality sites selection.

6.2 Minna Sites

The pre-seismic site selection exercises allowed a comparison of the sites based on signal-to-noise ratio, which was used as the main guiding parameter for the quality of a site during this study. It was against this background that four sites were provided by Federal University of Technology, Minna, to select the suitable one that can offer good data. The sites were carefully examined considering different guiding parameters discussed in this study. The sites investigated within FUT Minna are as follows:

6.2.1 Site one (Existing station)

This is the existing site earlier selected in 1998 by NASENI, where some investigations had been carried out and the vault and an office accommodation were built to certain requirement. However, the station was vandalized, as shown in Plate 3.

In this study, detailed investigations were carried out at this site and the following observations noted:

(a) The site is situated close to a stream and Earth dam of less than 300 m and 500 m respectively.
(b) There is a man-made forest of about 550 m away from this site.
(c) This existing station is sited few meters away from the Minna – Bida road earmarked for dualization in the nearest future.

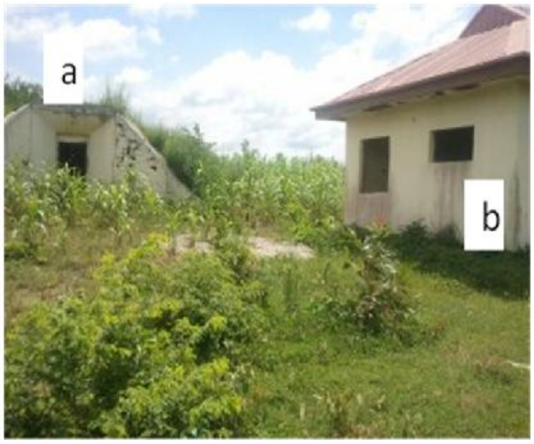


Plate 3. The existing structure at the Site earlier selected for the seismic station (a) Proposed Vault and (b) Proposed office accommodation at FUT Minna (Gidan Kwano Campus)

Based on the afore-mentioned conditions, this site was not suitable for a good seismic station and therefore not considered.

6.2.2 Site two (Lunko Village)

This site is close to Lunko village within FUT Minna permanent site (Gidan Kwano). It has an average altitude of 295 m above sea level. This site met almost all the basic seismic site selection requirements, and it was pre - selected and detailed field investigations were carried to confirm its suitability.

6.2.3 Site three (FUT Minna)

This site is not far from the existing site discussed above, that means by implication all factors that might likely affect site one could as well affect the site two. It is closer to the Minna – Bida road and also to the Earth dam. Therefore, based on these factors stated above, it was knocked down but was visited again after detailed field studies.

6.2.4 Site four (Gaso Village) FUT Minna

This site is located within few meters to Gaso village. It was resolved that human activities may likely impair the desired data quality, hence this site was also not considered.

6.3 Abakaliki Sites

Four potential sites were provided by the Ebonyi State University, to carefully select the best for the establishment of the seismic station. All the sites were subjected to pre-selection exercises. The criteria considered at Minna sites were also carefully studied in Abakaliki. These include; accessibility to the station, good seismo-geological conditions, power source, favourable climatic conditions, tolerable noise interference etc. Based on those points, three sites were knocked down and one was selected for a detailed field investigations. The results of the further sites' investigations are presented below.

7. DISCUSSION

Using Fig. 8, for Schlumberger array, we can define some constants $b = \frac{P_1P_2}{2}$ and $L = \frac{C_1C_2}{2}$; where P_1P_2 and C_1C_2 are respectively potential and current electrodes spacing. The letter 'b' is the cross-sectional area through which current flows and 'L' is the length on the material. As the value of apparent resistivity depends on the geometry of the electrode array used (K factor), the geometric factor, K, was then first calculated for all the electrode spacing, where: K= π (L2/2b – b/2), for Schlumberger array with $P_1P_2 = 2b$ and $1/2(C_1C_2) = L$. The values obtained, were then multiplied with the resistance values to obtain the apparent resistivity, ρ_a, values. Then the apparent resistivity, ρ_a, values were plotted against the electrode spacing ($\frac{1}{2}C1C2$) on a log-log scale to obtain the VES sounding curves using an appropriate computer software *IPI2win* in this study.

The sounding curves and their models as well as the geo-electric sections are shown in Figs. 10 to 13.1. For profile 1, Two resistivity sounding curve types were obtained from the studied area and these are the H ($\rho1>\rho2< \rho3$) and KH ($\rho1>\rho2>\rho3<\rho4$) type curves. profile 2, Two resistivity sounding curve types were obtained from the studied area and these are the H ($\rho1>\rho2<\rho3$) and HK ($\rho1>\rho2>\rho3<\rho4$) type curves and also in profile 3, Two resistivity sounding curve types were obtained from the studied area and these are the H ($\rho1>\rho2< \rho3$) and HK ($\rho1>\rho2> \rho3<\rho4$) type curves. However, there are few points which show two geologic layer cases. The results of the interpreted VES curves are shown in Table 1. The modelling of the VES measurements carried out at the three profiles been used to derive the geoelectric .The three VES points appeared not to have cut through similar lithologies. While P1 cut shales although, P2 and P3 respectively cut the same lithologies of which limestone is inclusive (Tables 1, 2 and 3). However, in the three survey points, layers three of each model appear stronger and more stable than other layers, which suggest they are good for foundation purposes. While layer 3 in VES 1 is shale, in VES 2 and 3. These have revealed that there are mostly four and three geologic layers beneath each VES station. The geologic sequence beneath the study area is composed of top soil, weathered basement, partly weathered/fractured basement, and fresh basement.

7.1 Profile 1

The topsoil is at P1 composed of clayey and sandy-lateritic hard pan with resistivity values ranging from 355 Ωm to 2186 Ωm and thickness varying from 1.5 to 2.4m, thinnest at P11 and thickest at P14. The second layer is the weathered basement with resistivity and thickness values varying between 16 Ωm and 355 Ωm and 3.5 to 11.8 m respectively. Thinnest layers are P11 and 8. The third layer is partly weathered and fractured basement with resistivity and thickness values varying between 305 Ωm to 1009 Ωm and 5.9 to 13 m respectively. The layer is extensive and thickest at P13. The fourth layer is presumably fresh basement whose resistivity values vary from 1215 Ωm to 2150 Ωm with an infinite depth. However, the depth from the earth's surface to the bedrock surface varies between 5.9 to 13 m, deepest at P11 and shallowest at P14 (Fig. 10).

7.2 Profile 2

The topsoil at P2 composed of clayey and sandy-lateritic hard pan with resistivity values ranging from 849 Ωm to 1106 Ωm and thickness varying from 1.0 to 1.6 m, thinnest at P11 and thickest at P14. The second layer is the weathered basement with resistivity and thickness values varying between 117 Ωm and 162 Ωm and 1.8 to 5.5m respectively. The thinnest is at P21. The third layer at P21, P22 and the second layer of P23 are of the same material. The forth layer at P21, P22 and third at P23 are same and partly weathered and fractured basement but grade into fresh basement with resistivity and thickness values varying between 474 Ωm to 8292 Ωm and 9.8 – 15 m to infinity respectively. The layer is extensive and thickest at P23 (Fig. 11.3).

7.3 Profile 3

The topsoil at P2 is composed of clayey and sandy-lateritic hard pan with resistivity values ranging from 330 Ωm to 2019 Ωm and thickness varying from 2.0 to 0.7 m, thinnest at P33 and thickest at P31. The second layer is the weathered basement with resistivity and thickness values varying between 16Ωm and 307 Ωm and 2.2 to 6 m respectively. The thinnest is at P33. The second layer at P31, P32 and the third layer of P33 are of the same material (Fig. 12). The forth layer only appears at P33 is partly weathered and fractured basement but grade into fresh basement with resistivity and thickness values varying between 407 Ωm to 8292 Ωm and 17 to infinity respectively. It can be observed that the layer 3 of VES 1(shale) has greater thickness (28.5 m) than that of VES 2 and 3 (10.16 m and 2.93 m thick) respectively.

It can be observed from Abakaliki site that the layer 3 of VES 1(shale) has greater thickness (28.5 m) than that of VES 2 and 3 (10.16 m and 2.93 m thick) respectively.

The VES interpretation results in form of subsurface layer, resistivity and depth to resistivity interfaces are given in the Table 1.

Table 1. Layer model (P1) in Minna

Profile	Station	Layer	Resistivity (Ωm)	Depth (m)	Thickness (m)	Curve type	Remark
P1	P11	1	1115	1.5	1.5	AH	Lateric clay
		2	111	4.6	6.1		Weathered gneiss
		3	41	7.2	13		Fractured
		4	305	Ω			Fairly weathered basement
	P12	1	2186	1.7	1.7	H	Hard pan lateric
		2	54	9.9	11.6		Weathered gneiss
		3	874				Fresh basement (Migmitite gneiss)
	P13	1	823	1.7	1.7	H	Hard pan lateric
		2	357	11.8	13		Weathered gneiss
		3	1009				Fresh basement
	P14	1	355	2.4	2.4	H	Hard pan lateric
		2	16	3.5	5.9		Weathered gneiss
		3	607				Fresh basement
P2	P21	1	849	1	1	AH	Lateric clay
		2	162	1.8	2.8		Weathered gneiss
		3	43	7.4	9.8		Fractured
		4	474				Fairly fractured basement
	P22	1	1106	1.3	1.3	AH	Lateric clay
		2	117	5.5	6.8		Weathered gneiss
		3	30	5.8	12.6		Fractured
		4	1665				Fairly fractured basement
	P23	1	1076	1.6	1.6	H	Hard pan lateric
		2	44	14	15.6		Weathered gneiss
		3	8292				Fresh basement
P3	P31	1	330	2	2		Hard pan lateric
		2	16	4	6	H	Weathered gneiss
		3	370				Fresh basement
	P32	1	630	1.6	1.6		Hard pan lateric
		2	17	2.8	4.8	H	Weathered gneiss
		3	307				Fresh basement
	P33	1	2019	0.7	0.7		Lateric clay
		2	343	1.5	2.2	AH	Weathered gneiss
		3	42	15	17		Fractured
		4	407				Fairly fractured basement

Table 2. Layered model (P1)

Layers	Resistivity	Thickness (m)	Depth to top of the layer (m)	Inferred lithology
1	1311.1	1.30	0	Laterite overburden
2	21.35	1.58	1.30	soft shale
3	35.45	28.5	2.88	Hard shale
4	12.42	Nil	Nil	Soft shale

Table 3. Layered model (P2)

Layers	Resistivity	Thickness (m)	Depth to top of the Layer (m)	Inferred Lithology
1	964.9	1.19	0	Laterite overburden
2	20.47	7.62	1.19	soft shale
3	410.3	10.16	8.81	Limestone
4	0.94	Nil	Nil	Clay

Table 4. The layered model (P3)

Layers	Resistivity	Thickness (m)	Depth to top of the layer (m)	Inferred lithology
1	1443.7	1.19	0	Laterite overburden
2	14.70	6.82	1.19	soft shale
3	410.3	10.16	8.81	Limestone
4	0.51	Nil	Nil	Clay

(i) Geo-electric Section and Resistivity cross Section from Minna Sites

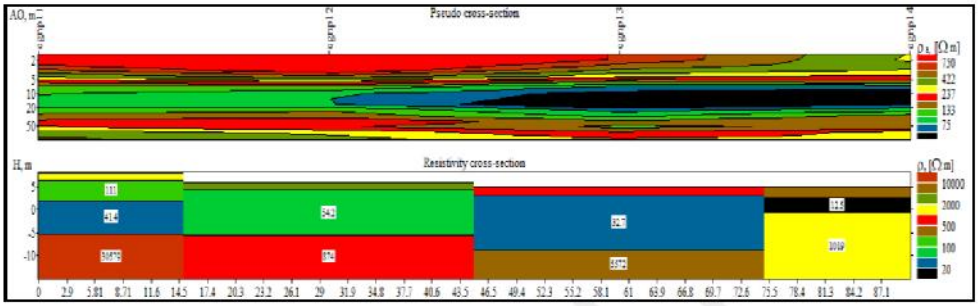
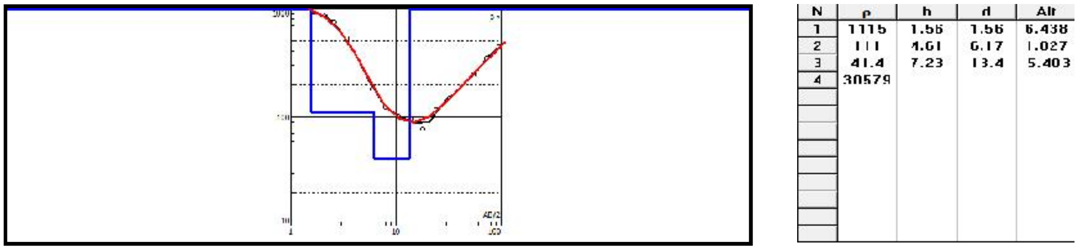
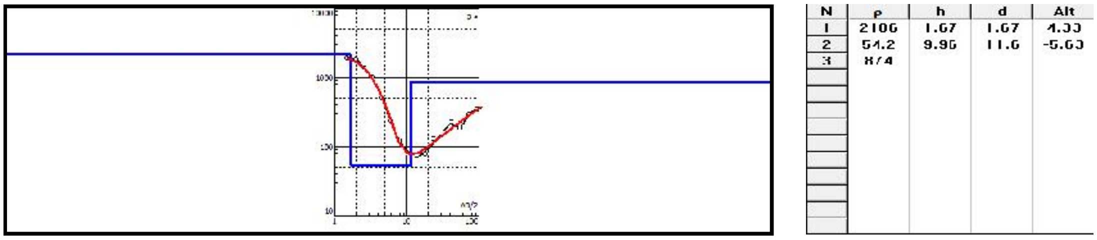


Fig. 10. Pseudo cross section and Resistivity cross of the investigated area for profile P1 (P11, 12, 13 and 14)



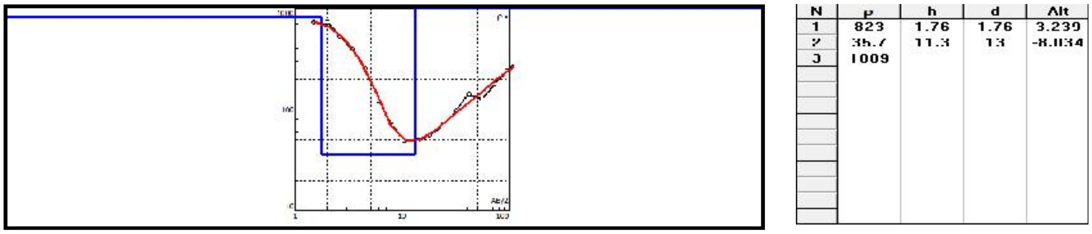
N	ρ	h	d	Alt
1	1115	1.56	1.56	6.438
2	111	4.61	6.17	1.027
3	41.4	7.23	13.4	5.403
4	30579			

Fig. 10.1. P11 (A) the plot of the field data and the inversion curve. (B) The sub-surface



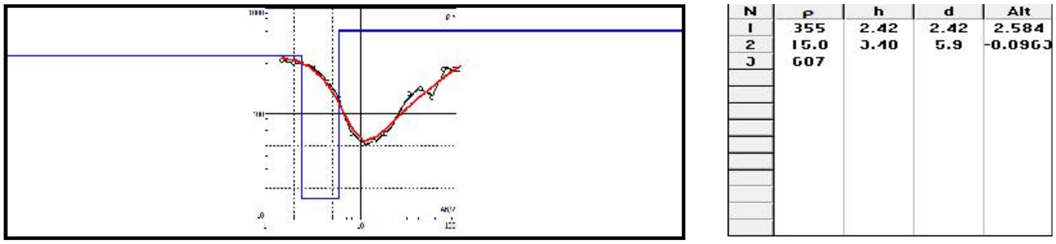
N	ρ	h	d	Alt
1	2106	1.67	1.67	4.33
2	54.2	9.96	11.6	-5.63
3	874			

Fig. 10.2. P12 (A) the plot of the field data and the inversion curve. (B) The sub-surface model



N	ρ	h	d	Alt
1	823	1.76	1.76	3.239
2	35.7	11.3	13	-8.034
3	1009			

Fig. 10.3. P13 (A) the plot of the field data and the inversion curve. (B) The sub-surface model



N	ρ	h	d	Alt
1	355	2.42	2.42	2.584
2	15.0	3.40	5.9	-0.0963
3	607			

Fig. 10.4. P14 (A) the plot of the field data and the inversion curve. (B) The sub-surface model

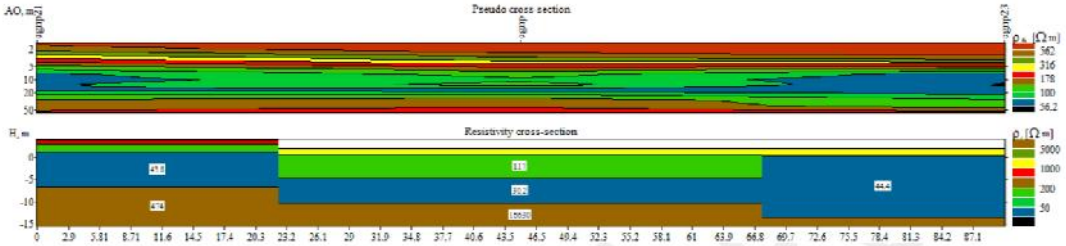
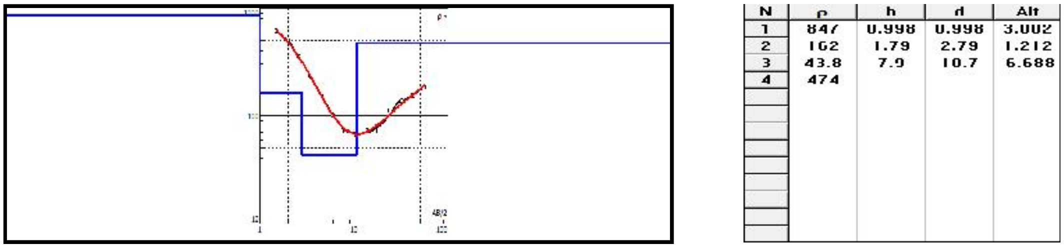
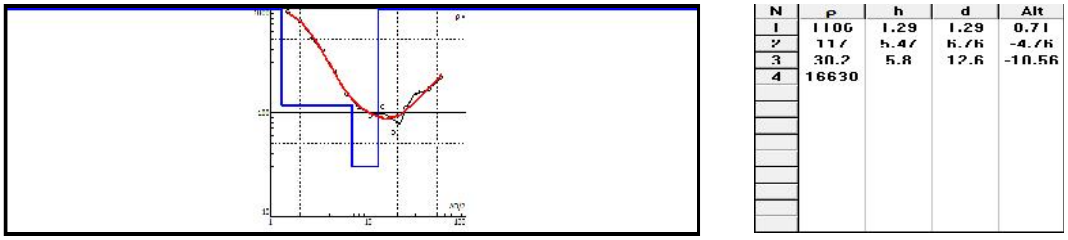


Fig. 11. Pseudo cross section and Resistivity cross of the investigated area for profile P2 (P21, 22 and 23)



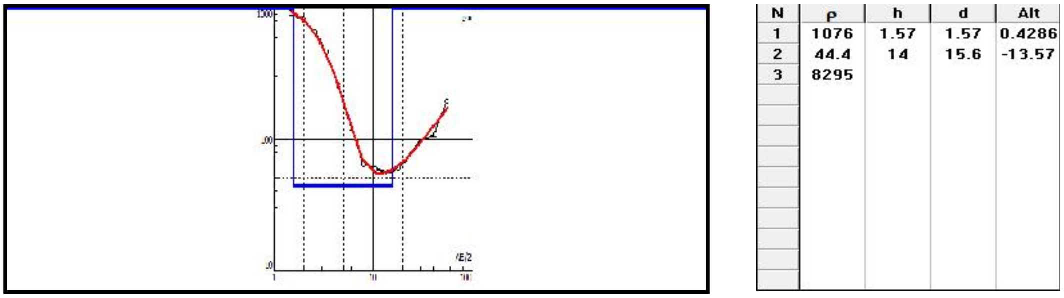
N	ρ	h	d	Alt
1	847	0.998	0.998	3.002
2	162	1.79	2.79	1.212
3	43.8	7.9	10.7	6.688
4	474			

Fig. 11.1. P21 (A) the plot of the field data and the inversion curve. (B) The sub-surface model



N	ρ	h	d	Alt
1	1106	1.29	1.29	0.71
2	117	5.47	6.76	-4.76
3	30.2	5.8	12.6	-10.56
4	16630			

Fig. 11.2. P22 (A) the plot of the field data and the inversion curve. (B) The sub-surface model



N	ρ	h	d	Alt
1	1076	1.57	1.57	0.4286
2	44.4	14	15.6	-13.57
3	8295			

Fig. 11.3. P23 (A) the plot of the field data and the inversion curve. (B) The sub-surface model

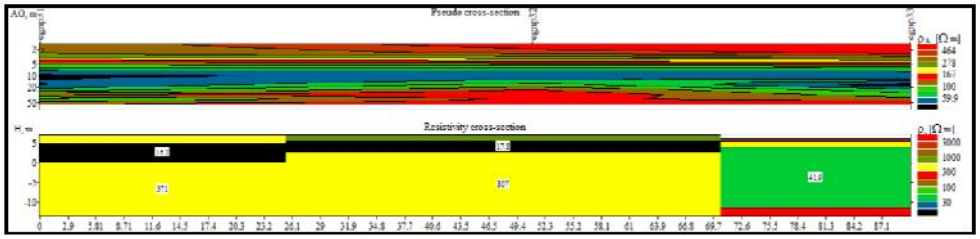
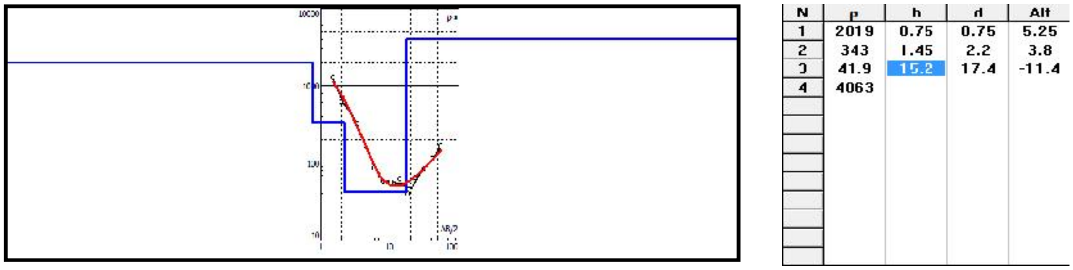
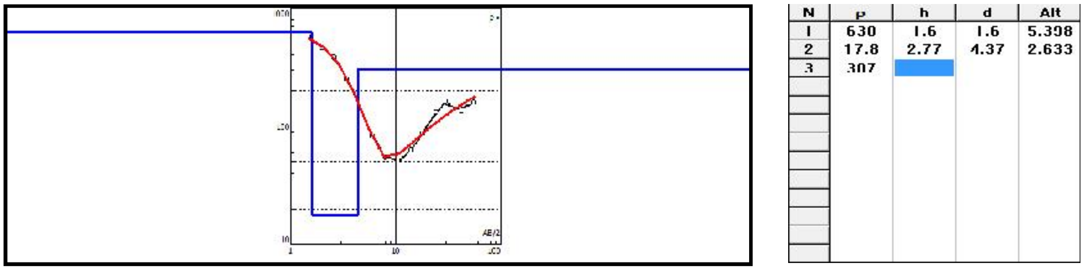


Fig. 12. Pseudo cross section and Resistivity cross of the investigated area for profile P3 (P31, 32 and 33)



N	ρ	h	d	Alt
1	2019	0.75	0.75	5.25
2	343	1.45	2.2	3.8
3	41.9	15.2	17.4	-11.4
4	4063			

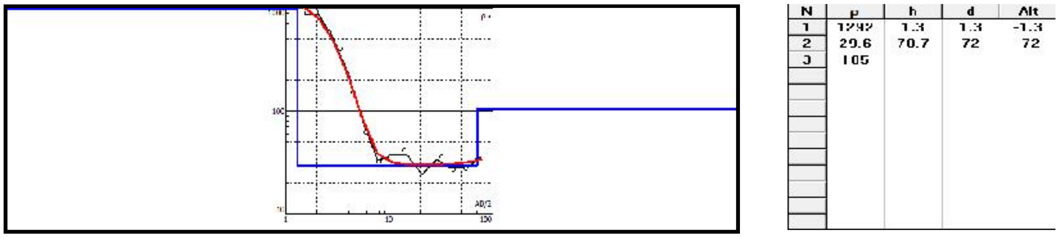
Fig. 12.1. P31 (A) the plot of the field data and the inversion curve. (B) The sub-surface model



N	ρ	h	d	Alt
1	630	1.6	1.6	5.398
2	17.8	2.77	4.37	2.633
3	307			

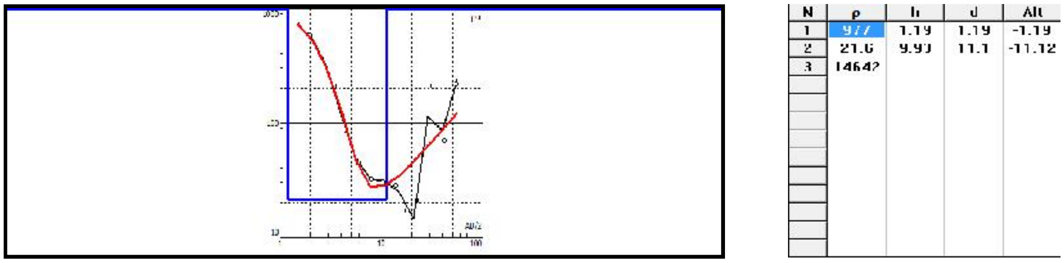
Fig. 12.2. P32 (A) the plot of the field data and the inversion curve. (B) The sub-surface model

(ii) Geo-electric Section of Profiles from Abakaliki Selected Site



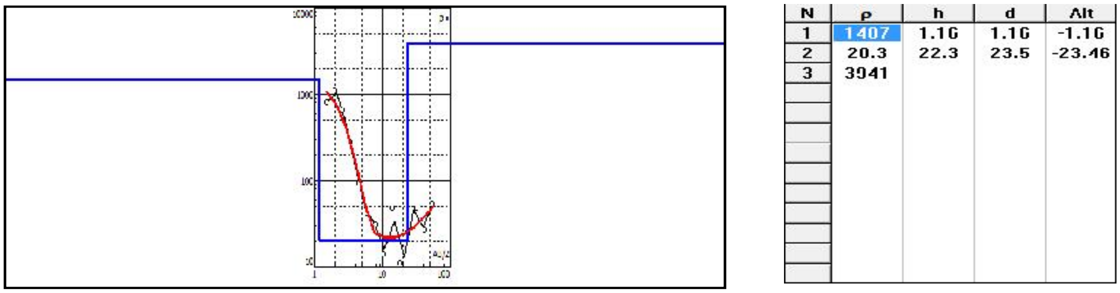
N	ρ	h	d	Alt
1	1292	1.3	1.3	-1.3
2	29.6	70.7	72	72
3	105			

Fig. 13. Pseudo cross section and Resistivity cross of the investigated area for station P1



N	ρ	h	d	Alt
1	977	1.19	1.19	-1.19
2	21.6	9.93	11.1	-11.12
3	14642			

Fig. 13.1. Pseudo cross section and Resistivity cross of the investigated area for station P2



N	ρ	h	d	Alt
1	1407	1.16	1.16	-1.16
2	20.3	22.3	23.5	-23.46
3	3941			

Fig. 13.2. Pseudo cross section and Resistivity cross of the investigated area for station P3

8. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

Detailed geological, geophysical and seismological investigations have been carried out to select most suitable sites to host sensitive seismic equipment in Minna in the North-Central (Precambrian basement complex) and Abakaliki in the South-East (Cretaceous Sedimentary Basin) in Nigeria, respectively. The quest to improve seismic data quality and better network detectability to record local events in Nigeria, formed the nucleus for this study.

The Centre for Geodesy and Geodynamics has been operating a network of seismic stations in Nigeria since 2008 and proactive measures have been adopted to improve the quality of data from the new stations to be added to the network, in order to improve data quality. Hence, the various stages adopted towards achieving this lofty goal were done in collaboration with the Nigeria's disaster management agency, NEMA, and the Federal Ministry of Science and Technology. This joint study had assisted in the selection of most suitable sites in Minna and Abakaliki, even though, 100% of the desired results may not have been achieved.

For instance, from the three VES survey points carried out in Minna, layer 3 at each point is good to serve as foundation for the seismic station. Depths to the top of the 3rd layers are about 3.0 m, 9.0 m and 8.0 m respectively. Depending on the interest, the second layers which are soft shales can serve as foundation. If depth and cost are less considered and our priority is the stability of the surface therefore layer 3 is suitable for the foundation purposes. The geophysical survey delineates four subsurface layers and these include the Topsoil, the coarse-sandy, the weathered layer and the bedrock. The weathered and/ or fractured layer constitutes the main area for engineering purpose. Establishing sensor's platform is feasible at P11, P21, P22, P31 and P32. For groundwater purposes, P14, P23 and P33 locations are feasible i.e. (VES 2 and 3) but P14 is more preferred.

If the noise level at Minna (site 2) is considerably maintained at low decibel as it is observed and measured during the investigation, it is an indication that the Signal-to-Noise ratio would be impressive and good for seismic station and for telemetry purposes. Therefore, a well designed and constructed vault can help in keeping at bay potential human and environmental noise at this site in future.

For Abakaliki site, it would also be observed that depth to the top of the 3rd layer for P1 is shorter (3.0 m) when compared to others (9.0 m and 8.0 m respectively) which makes it cheaper to site the station at P1. Also, the thickness of layer 3 in VES 1 is higher (28.5 m) than that of P2 and P3 (10.16 and 2.93 respectively), which suggests the layer 3 of P1 to be more stable than others. Consequently, It is strongly recommended that P1 for the sitting of the seismic station. The noise measurements at Abakaliki were carried out in details, although there arose some issues resolving the noise at lower frequency bands by the instrument, the microseismic peak at 0.7Hz was distinct. It showed the departure of low frequency noise from that of high frequency one. If this is not observable, the data is as good as meaningless. A vault is dearly needed at this site and to a desired depth as suggested from the geophysical investigation, to correct most of these anomalies that will likely make nonsense of the recordings and performance of the instrument.

It is expected therefore, the two additional stations will not only boost the network of seismic stations in Nigeria operated by CGG, and enhancing local events recording capability; the stations is also seen as a booster towards actualization of NEMA's mandates in disaster management towards prediction of natural hazards like earthquakes. As this is the first time these kinds of investigations were holistically undertaken to select sites for seismic equipment in Nigeria, it is anticipated this study would set standard practices for future site selection to host sensitive equipment in Nigeria and in the sub-region.

8.2 Recommendations

After careful investigations of all the sites in Minna and Abakaliki, the following are deduced:

- Site Two (near Lunko village, Minna) was selected for the establishment of the seismic station based on pre-selection exercises and detailed field studies, therefore, the excavation to the hard bedrock (compact migmatite gneiss rocks) should be up to 6 m depth at VES P12. Concrete platform reinforcement is advisable during vault construction. While at Ebonyi State University, the average depth to the compacted shale is about 10 m, same reinforcement is also required to avoid water logging.
- Site Three in ESU is suitable based on the noise level and topographic nature of the area, therefore recommended for the establishment of the seismic station. All parameters considered will avoid horizontal tilt and water logging and this is also in agreement with the geophysical, geological preference.
- Based on the noise measurement level and analysis, Site two (near Lunko village) in FUT Minna is within the tolerable standard limit for a good seismic station. This result also is in agreement with the geophysical survey and geologic mapping carried out. Basement rock (Migmatite Gneiss) was delineated at shallow depth.
- Modern methods of data communication is desirable to make it easy to link the newly established stations to the national network, to exchange waveform data in real time and to perform joint data analysis at local data centre (CGG, Toro). Therefore, this interconnectivity is very important.
- Accessibility to both sites is good enough and should devoid from further development to avoid heavy traffic.
- Human activities such as farming, grazing, quarrying and general mining activities, buildings etc near the stations should be avoided.
- Power and security should be provided to the stations by the host universities to avoid vandalization of facilities. Therefore, both stations should be fenced and secured by security personnel.
- The data acquisition, processing, interpretation and sharing within stakeholders should be considered and be well articulated for the benefit of the end users.
- The sustainability is paramount and duty to all stakeholders in this national project in monitoring Earthquake and related activities in Nigeria, therefore, responsibilities assigned to each party should be taken seriously.
- The structures to house the equipments should be constructed as soon as possible and CGG Toro be involved during vault construction stage for technical design input and advice.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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