Adamawa State University Journal of Scientific Research
ISSN: 2251-0702 (Paper)
Volume 5 Number 2, August, 2017
http//www.adsujsr.com

Geophysical investigation for Basement Rock Structures around a proposed Dam site

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Abstract

A combination of carefully selected geophysical surveys comprising very low frequency electromagnetic (VLF-EM) and electrical resistivity (VES) methods was employed to study the basement rock structures in a proposed dam site within University of Ilorin campus. Data acquired in the survey were processed to inverted subsurface geological model, 2D conductivity structures and geo-electric cross-sections for the area. The results were interpreted to delineate the subsurface rock and structure, the number of geo-electric layers, and to select a suitable area for the construction of dam extension. The four geo-electric layers delineated correspond to lateritic top-soil layer, weathered rock layer, fractured rock layer, and the fresh basement rock. The VLF-EM and resistivity cross-section revealed a series of competent and weak zones. The weak zones are characterized by weathered/fractured rocks, and they correspond to areas of low resistivity anomalies in VES survey and high conductivity anomalies in VLF-EM survey. Competent rock zone corresponds to area of high electrical resistivity anomalies and low conductivities in VLF-EM tomogram. Depth to fresh basement rock in the weak zone ranges from 7.8 – 14.8 m. The competent rock zones correspond to high resistivity anomalies in electrical resistivity cross-section and low conductivity anomalies in VLF-EM tomograms. Depth to fresh basement rock in the competent zone ranges from 3.3 – 6.8 m. the competent zone recommended for the construction of the dam extension.

Keyword: Vertical Electrical Sounding Method (VES), Very Low Frequency Electromagnetic Method (VLF-EM); Basement Rock; Concrete Dam; Water seepage.

Introduction

With many years of uninterrupted academic activities and the merging of the two campuses, water supply from the existing University of Ilorin (mini) Dam is inadequate due to the geometric growth in the students and staff population. To solve the problem of water shortage, the University Administration is proposing the construction of a concrete dam extension along Asa River within the University Campus. University of Ilorin falls within the basement complex rocks of Nigeria (Fig. 1a). The existing dam and the proposed dam extension are shown in blue rectangle and red rectangle respectively in figure 1b. The dam extension is to serve as additional water storage to complement the current storage capacity. A combination of Vertical Electrical Sounding (VES) and Very Low Frequency Electromagnetic (VLF-EM) methods of geophysics was deployed to the area to probe, image, and evaluate the basement rock around the proposed dam extension site. The purpose of this study is to determine the competence of the bedrock to host and support concrete foundation for the proposed dam extension. The aim of the study was to delineate an area that is suitable for the construction of dam extension. The objectives of the study were to delineate an area that is (i) free of brittle structures and weathered rocks within the proposed site, and (ii) to determine depth to fresh basement rocks.

Geophysical mapping of proposed dam site using electrical methods plays important role in the comprehensive assessment of bedrock for brittle structures (e.g. fractures and faults) and weak zones that may compromise the integrity of dam foundation through water seepage. When water seepage reaches a critical stage, it gives ways to weathering that could lead to subfussion and subsidence leading to the collapse of the dam (Panthulu *et al.,* 2001; Oglivy *et al.,* 2002). Geophysical study on proposed site for dam construction is becoming a popular practice due to advances in equipment and data processing. Two-dimensional image of the subsurface produced from processed resistivity data have been used to delineate structural and stratigraphic features that may affect the performance of dams (Dahlin, 1996; Panthulu *et al.,* 2001; Di and Wang, 2010). Application of geophysics to the study of buildings and other engineering construction is known as engineering geophysics. The method is cheaper and time inexpensive compared to the traditional method of drilling and rock sampling.

Geophysical study on bedrock competence for the purpose of dam construction is essentially the search for a zone that is free of weathered or fractured rocks –fresh basement rock. In engineering geophysics fresh basement rock is otherwise known as competent rock. Weathered and fresh basement rocks have contrasting resistivity or conductivity signatures. Resistivity signatures of rocks can be measured directly from electrical resistivity surveys, while conductivity structures of subsurface rocks can be evaluated by VLF-EM surveys. Availability of fresh basement rock at near-surface reduces the volume of excavations, thickness of a dam foundation, and the cost of dam construction. Determination of depth to the basement rock is required for the estimation of the materials required for dam foundation. Therefore, a combination of VLF-EM and VES methods has the capability to illuminate vertical and lateral subsurface geology of a proposed dam site, to delineate zones that are free of intense weathering, fractures, or faults that may compromise the integrity of the proposed dam. The direct relationship between electrical conductivity or resistivity and rock rippability at subsurface informed the choice of VLE-EM and VES methods for this study.

Very low frequency electromagnetic survey is a ground trotting geophysical method for mapping 2D/3D conductivity distribution in geological structures at subsurface. Primary electromagnetic field is usually provided by worldwide radio signal transmitters purposely built for electronic and submarine communication. The frequencies of the transmission station typically range from 15 kHz to 30kHz. To achieve deep penetration and reduce electromagnetic signal attenuation, low frequency range transmitters are preferred for VLF-EM survey. VLF- EM survey has many applications ranging from engineering and geotechnical studies (Dahlin 1996; Johnson 2003), to environmental studies, groundwater and mineral exploration (Philips and Richards, 1975; Benson *et al.,* 1997; Bernstone *et al.* 2000; Sundararajan et al., 2006; Abubakar *et al.,* 2014; Raji and Adeoye, 2017). Sundararajan *et al.,* 2011 used the in-phase component of VLF-EM to determine the spatial distribution of fractures in the basement rocks at Raigarh district, Chhattisgarh, India. The study showed strong correlation between high amplitude VLF signal and weathered/fractured zones in the basement rock. The low amplitude signals correspond to competent/ fresh bedrock.

Electrical resistivity methods have also been applied worldwide for dam pre-construction studies, dam performance evaluations, and dam failure investigations (Panthulu *et al.,* 2001; Sjodahl *et al.,* 2008; Sjödahl *et al.,* 2009; Di and Wang, 2010; Tabwassah and Obiefuna 2012). Tabwassah and Obiefuna (2012) used VES method to investigate Cham Dam in north-eastern Nigeria. In the study, areas of low resistivity values were found to correspond to weathered and fractured structures through which water seepage had occurred. Water seepages in the studied dam led to intensive weathering of the dam foundation, and subsequently to the dam failure. VES is particularly suited for probing shallow subsurface rock for resistivity distribution along depth axis. Resistivity measured by VES survey at regular intervals along straight lines can be used to invert 2D geological models to delineate weak zones and brittle structures in the subsurface. Fresh basement rocks are characterized by high resistivities (or low conductivities), due to the absence of fluids and dissolve ions in the rock. On the other hand, Fractured and other weak zones generally produce low-resistivity anomalies either by serving as active path for water seepage or because of the presence of clay or other weathering products.

The study area is part of the University of Ilorin Permanent campus along River Oyun and adjacent to an existing mini-dam – Unilorin Dam. The campus is bounded by longitude 4^{O} 39^{I} - 4^{O} 42^{I} E and Latitude 8^{O} 27^{I} – 8^{O} 29^{I} N. Oyun River formed the most prominent drainage system in the area. The river flows in approximately south – north direction; the south being topographically higher than the north. There are many streams adjoining River Oyun to form a trellis to sub-dendritic drainage system. The size of the drainage changes with season, reaching its maximum in the raining season and minimum in the dry season. The study area is part of the basement complex of Nigeria considered to be Precambrian to Lower Paleozoic in age (Oyawoye, 1964; Rahman, 1976). The basement rocks consist of migmatised to unmigmatise gneiss, schist; amphibolite, and quartzite intruded by 600 ± 50 Ma granitic to dioritic rocks (Oyawoye, 1964; Rahman, 1976; McMurry and Wright, 1977; Annor *et al.*, 1987).

Rocks identified in the study area are mainly metamorphic and igneous rocks, and are classified as:

i. The Gneiss Complex: Augen gneiss, banded gneiss, and granite gneiss.
ii. Granite Suite: Foliated granodiorite and foliated microgranite
iii. The veins: Pegmatites and Quartz veins
iv. Quartzite

These rocks out-crop in some places and are covered by the lateritic top-soil in other places. At shallow subsurface, the crystalline rocks have been fractured and disjointed by tectonic activities and weathering (Olasehinde and Raji, 2007). Rocks mapped around the proposed dam site include banded gneiss, microgranite, granodiorite, granite gneiss, augen-gneiss, and quartzite that have been reworked and intruded by pegmatites and quartz veins. Structural features include foliations, fractures, joints, and dip structures.

Materials and Methods

VLF-EM Data Acquisition and Processing

VLF data measurement commenced by selecting a 15.8KH transmission station that provided low frequency electromagnetic field approximately parallel to the general strike of the rocks in the study area. The primary electromagnetic field induces a secondary field in the rocks within the study area through the reception and transmission system of the VLF-EM equipment (Fischer *et al.,* 1983). The secondary field is shifted in phase to the primary field. Five (5) VLF profiles were established as shown in Figure 1c. The profiles are named EM1 to EM5. EM1 and EM2 are oriented in approximately Northwest-Southeast direction while EM3, 4, and 5 are oriented in Northeast-Southwest direction. Profile length ranges from 250 m to 320m depending on the width of the river course. Along each profile, the in-phase and quadrature components of the (vertical) secondary electromagnetic field were measured at every 5m using ABEM WADI VLF Equipment. The raw VLF data along profile 5 is shown in Figure 2.

The in-phase component of VLF–EM data were processed to obtain information that can be used to interpret the subsurface geology. The VLF data were processed in two stages. First, the data is filtered to attenuate nose using frequency band-pass filter. The filtered data is transformed to a semi-qualitative contourable data. The filtering scheme transforms crossovers to peaks or trough, thereby placing VLF in-phase anomaly on the geological bodies causing the anomaly (Fraise, 1969; Ramesh Babu *et al.*, 2007; McNeill and Labson, 1991). Secondly, Karous–Hjelt (1983) inversion scheme was applied to the data to produce a 2D (conductivity-depth) image of the subsurface. Karous–Hjelt Scheme is based on the concept that conductivity response of rocks at the measurement station is induced by the interaction of the primary and secondary magnetic fields. The Karous-Hjelt (1977) operator transforms electromagnetic field strength to conductivity at the depth of the body causing the electromagnetic field (Sundararajan *et al.*, 2006). The optimized Karous-Hjelt scheme can be defined as:

$$\frac{\Delta Z}{2\pi I_a(0)} = 0.205H_{-3} - 0.323H_{-2} + 1.446H_{-1} - 1.446H_1 + 0.323H_2 - 0.205H_3,$$

where; $I_a(0) = 0.5\left[\left[I\frac{\Delta X}{2}\right] + \left[I\frac{-\Delta X}{2}\right]\right].$

I_a is the apparent current density, ΔX is the station interval along the profile, and H are measured data at six consecutive stations.

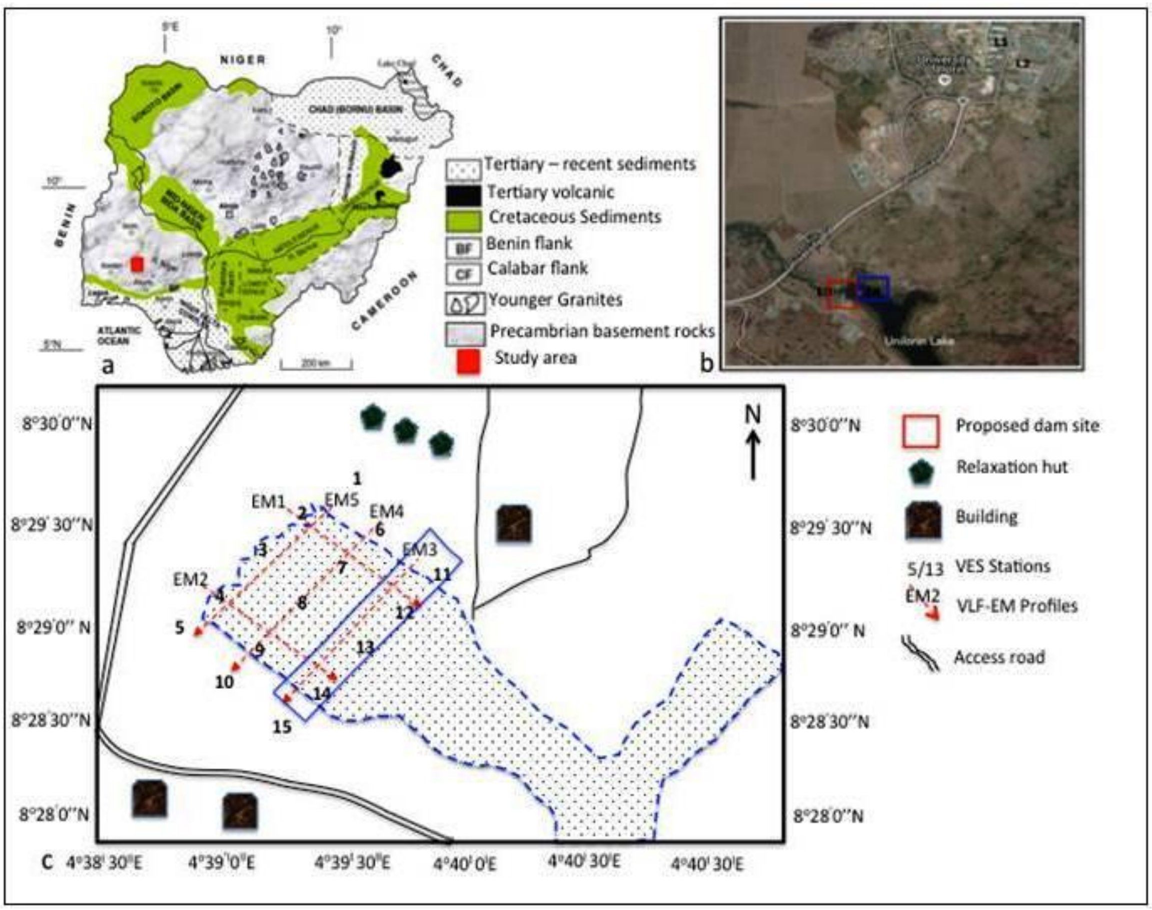

Figure 1: Maps: (a) Geological map of Nigeria, showing the location of the study area (Obaje, 2009); (b) Aerial photo showing the proposed site for the dam; and (c) site map showing the geophysical surveys lines.

Electrical Resistivity Data Acquisition and Processing

Electrical resistivity data were acquired using vertical electrical sounding (VES) method with Schlumberger electrode array. The acquisition system comprised ABEM S540 OMG Terrameter, metallic electrodes, reels of cables, and other accessories. Low frequency current was injected to the ground through the two extreme electrodes. Current flow induced a potential difference across the two potential electrodes. The apparent resistivity of the rock at a depth is measured as:

$$\rho_a = KV/I;$$

where K is the geometric factor which depends on the arrangement and spacing of the four electrodes, V is the potential difference, I is the injected current and ρ_a is the apparent resistivity. Apparent resistivity ρ_a is measured at fifteen (15) VES stations as shown in Figure 1c. Half current electrodes separation, AB/2 was varied from 1m to 30 m. Previous studies in the area (Olasehinde and Raji, 2007; Raji 2014) have shown that fresh basement rock in the area lie within a depth range of 0 -18 m. Hence there was no need for AB/2 greater than 30 m. Plots of resistivity against AB/2 for the VES stations are shown in Figure 3a & 3b.

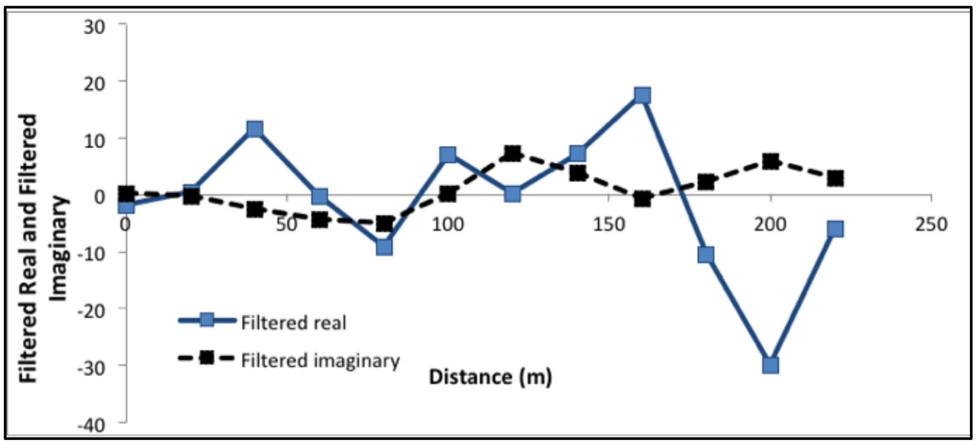

Figure 2: VLF field data along profile EM5.

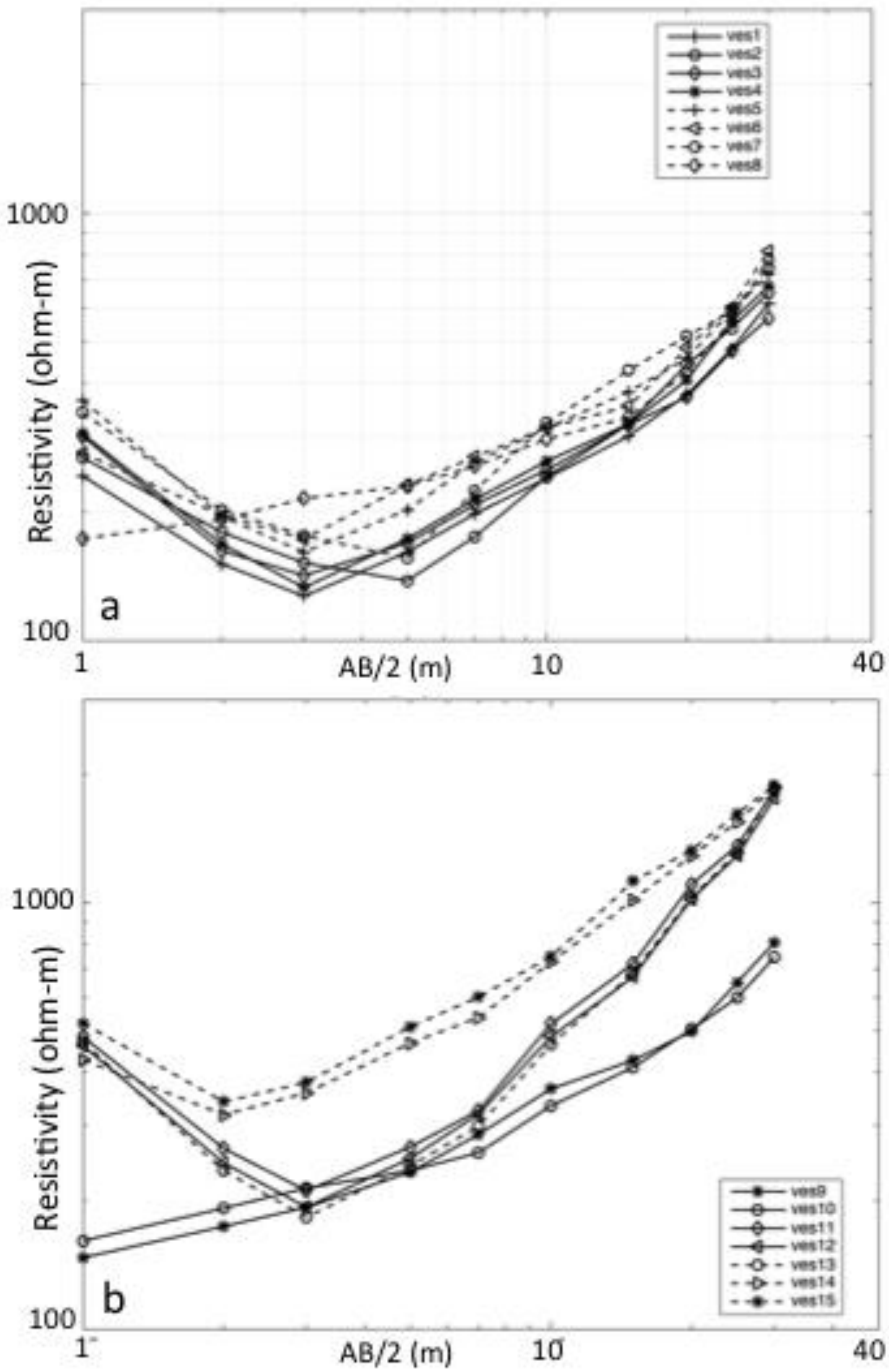

Figure 3: Apparent resistivity versus AB/2 plotted on bi-logarithm chart. (a) Data from VES stations 1-8; (b) data from VES stations 9-15.

VES data were pre-processed to eliminate spurious resistivity values. Outrageous resistivity values were corrected using an in-house least-square code that uses four neigbouring data points (Raji and Adeoye, 2017). The preprocessed resistivity data were interpreted using auxiliary curves (Koefoed, 1979). The curve matching process was used to produce some preliminary results, such as the number of geo-electric layers, resistivity, and thickness of each geo-electric layer. Subsequently, the pre-processed data was input to a semi-automatic inversion scheme –IPI2Win (Alex *et al.*, 2002) for final interpretation. The geo-electric parameters obtained from the curve matching process were used as reference model (a priory information) for the semi-automated inversion to guide the final interpretation. Some of the results of VES data interpretation using IPI2Win are shown in figure 4.

Results and Discussion

Interpretation of VES curves (Figure 4) indicated the presence of Three to four geo-electric layers. These geo-electric layers correspond to: top soil layer; weathered rock layer; the fractured rock layer; and the fresh basement rock layer. Top soil layer is absent in the VES stations interpreted with three Geo-electric layers. The top soil layer comprised dry unconsolidated silt, sand, and clay particle sizes. The layer has resistivities that range from 315 to 695 Ωm and thickness in the range of 0.36 m to 0.86m. Weathered rock layer is 1.55 to 7.63 m thick and has resistivity that ranged from 73 to 192 Ωm. Weathered rock layer is formed by in-situ chemical decomposition of rock minerals due to the presence of water. The fractured rock layer is 5.4 to 11.7 m thick and has resistivities that range from 277 to 809 Ωm. Although 1D resitivity data is not good enough for fracture interpretation, deviation from 1D structure indicated by the presence of kinks and spike in the curve segment corresponding to the layer below the weathered rocks suggests the presence of faults (Fig. 4).

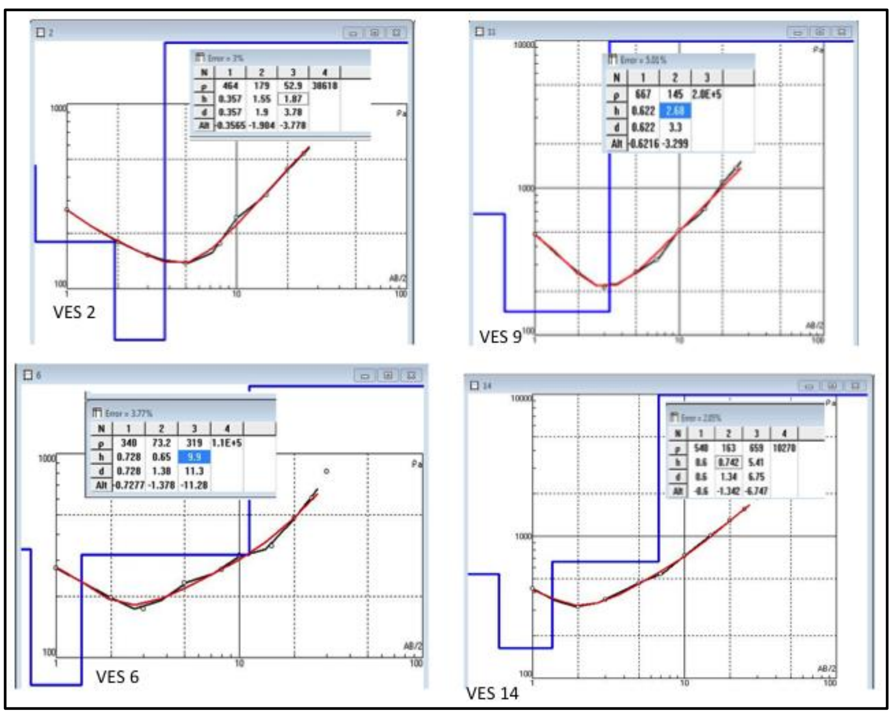

Figure 4: VES data interpretation showing the Thickness and resistivity of the Geo-electric layers**.**

The presence of fracture in the layer is also inferred from it resistivity values which is higher than that of the weathered rock layer and lower than that of the fresh basement rock). The fresh basement rock has resistivities ranging from 6269 to 20,000 Ωm. Generally, depth to fresh basement rock ranges from 3.3 to 14.8 m in the study area.

2D resistivity cross-sections were built across some VES locations. For the purpose of comparison, VES stations 1, 2, 3, 4, 5, 11, 12, 13, 14, &15 were concatenated to build the geo-electric cross-section shown in Figure 5a. Similarly, VES stations 6, 7, 8, 9, 10, 11, 12, 13, 14, &15; and VES stations 2, 3, 4, 12,13,14,15, 7, 8, 9 were concatenated to build Geo-electric cross-section shown in Figure 5b and 5c respectively. The 2D resistivity cross-sections show that the basement rock corresponds to the highest resistivity values and that the unconsolidated rock layers correspond to the lowest resistivity values. The resistivity cross-section also shows the vertical and lateral extents of the different geo-electric layers. The three-to-four resistivity layer sequence seen in the VES resistivity data is corroborated by the 2D resistivity cross-sections. In the 2D resistivity cross-section, the lateritic top-soil layers are represented by blue-black colours. The weathered rock is represented by the green-yellow colour, while the purple-red colours represent the fresh basement rock. The area around VES stations 11-15 has the thinnest unconsolidated layers (i.e., thinnest weak zone). The area also has the shallowest depth to the fresh basement rock. The fresh basement rock is here referred to as the competent rock. Fresh basement rock has the highest resistivity (see Figures 4 & 5). Interpretation of the cross-section also shows that depth to competent rock beneath VES 11-15 ranges from 3.3 – 6.8 m, whereas, depth to basement rock along VES 1-5, and VES 6-10 ranges from 7.8 -13.9 m and 9.3 – 14.8 m respectively. This result is consistent with previous studies in the area (Olasehinde and Raji, 2008; Raji, 2014).

The 2D conductivity tomograms computed from the VLF data are shown in Figure 6. The tomogram showed a variety of amplitudes that range from -10 to 10. The blue colour represents highest conductivity (or lowest resistivity), green represents moderate conductivity while red represents the lowest conductivity (or highest resistivity). Interpretation of EM1 and EM2 tomogram shows that the western (or arrow) edge of the two VLF profiles is underlain by low conductivity (or high resistivity) rocks, while the southern edge are underlain by high conductivity (low resistivity) rock. Among the horizontal profiles- EM3, EM4, and EM5, the rocks underlying EM3 has the least conductivity. The eastern edge of EM1 and EM2, and line represented by EM3 correspond to the area of lowest conductivity structures. This area coincides with the location of VES stations 11-15 that showed the highest resistivity in the VES survey.

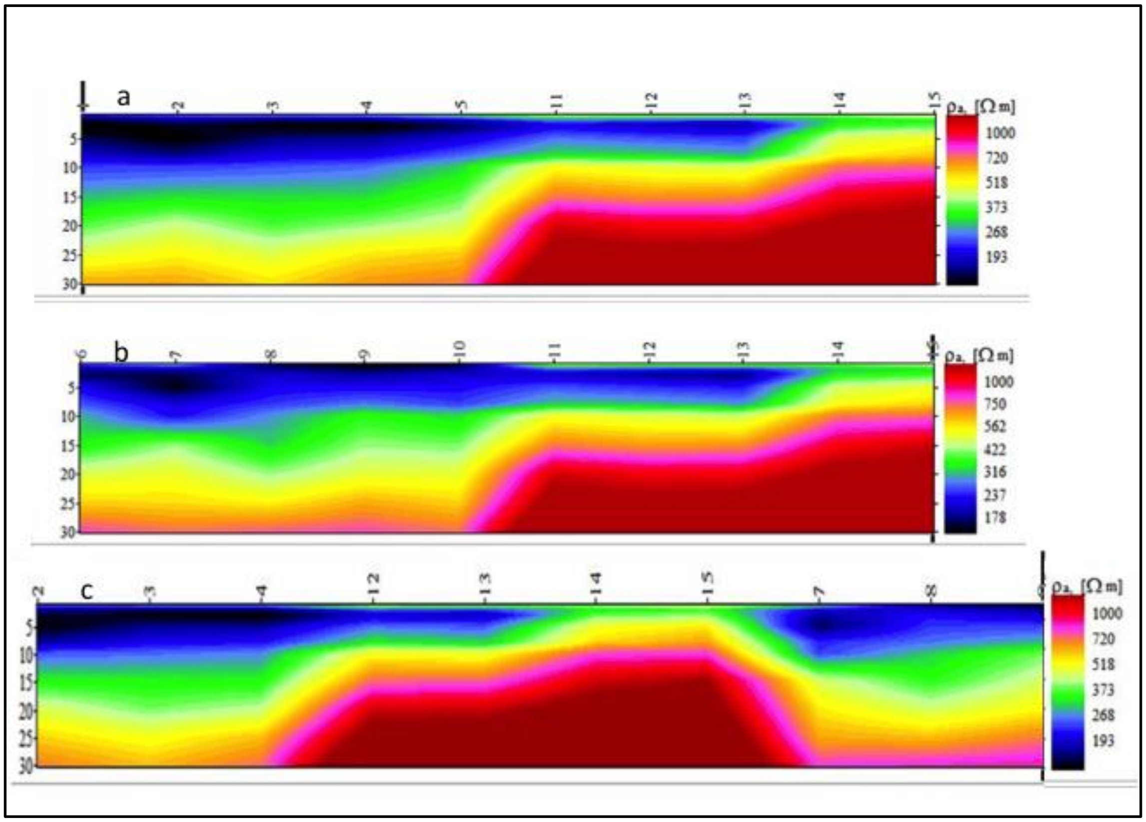

Figure 5: 2D Resistivity cross-section across some VES stations. The VES station numbers are indicated on the cross-sections.

Overall, there are strong agreements in the results of electromagnetic and electrical resistivity surveys. The north-western axis and the central part of EM1 and EM2 are underlain by high conductivity rocks. These high conductivity rocks are interpreted as weak zones, or less competent rocks. Rocks in this area will compromise dam integrity through water seepage, unless a deep excavation is done to remove the weathered rock before dam construction. The eastern axis of EM1 and EM2 and the line represented by EM3 showed low conductivity from depth of about 5 downward. This low conductivity rocks are interpreted as competent rock. The area showing low conductivity in the VLF-EM survey corresponds to VES station 11-15 that showed highest resistivities and least weathering in electrical resistivity survey. This area, marked by blue rectangular box in Figure 1c, is recommended for citing the dam extension.

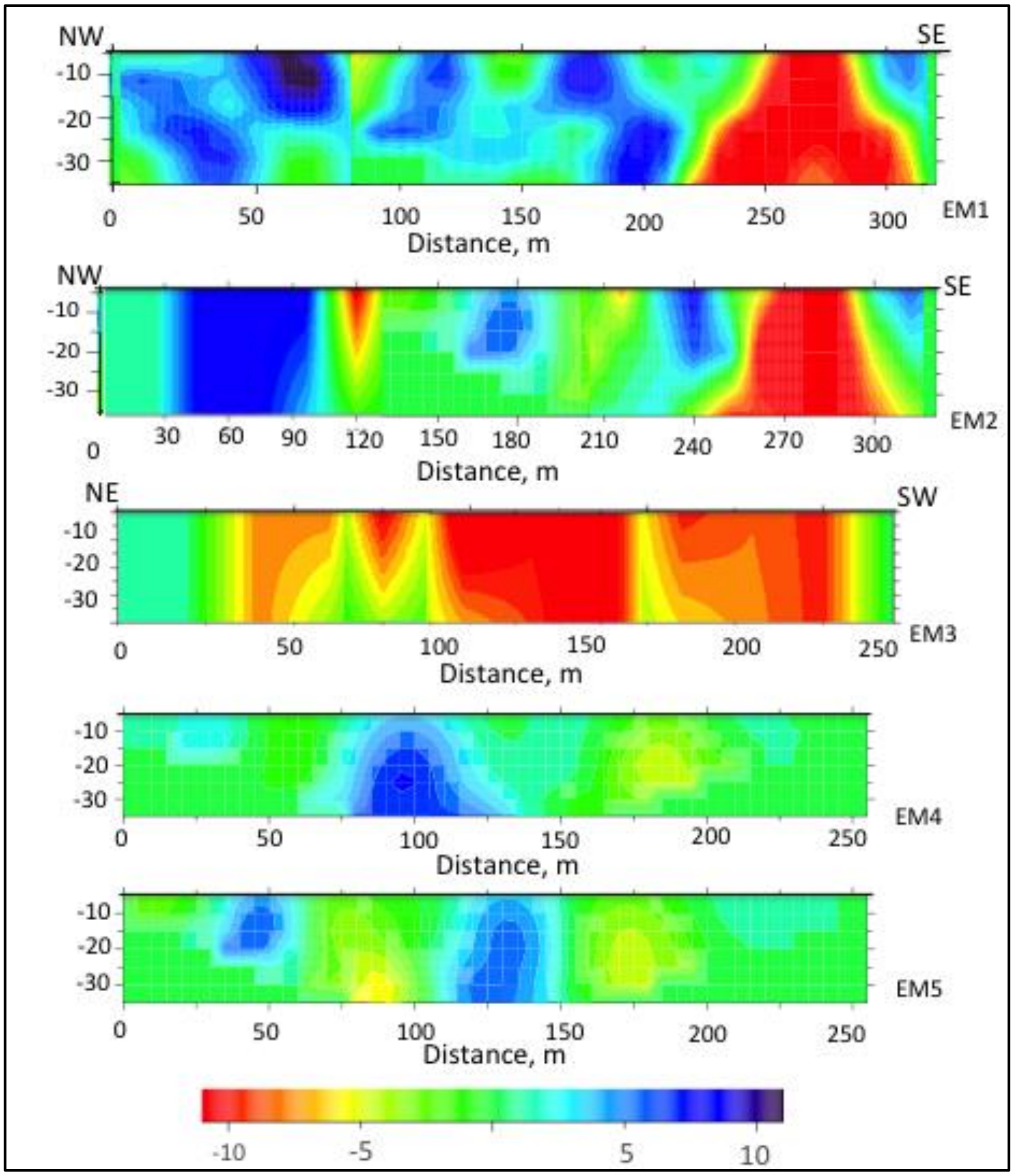

Figure 6: 2D conductivity structures computed from VLF data along EM1, EM2, EM3, EM4, and EM5, respectively.

Conclusion

VES and VLF-EM surveys have been successful applied to study the basement rock structures along Asa River within University of Ilorin Campus for the purpose of constructing a dam extension. The study area was delineated into weak zones and competent rock zone using the conductivity structures from VLF-EM and the resistivity signatures from electrical resistivity survey. The weak zones correspond to low resistivity values in the electrical resistivity cross-sections and high conductivity structures in the VLF-EM tomograms. The weak zones are characterized by thick layers of weathered and fracture rocks that cannot support the life span of the proposed dam extension. Building a concrete dam wall in the weak zone will require deep excavation and high cost of construction. The competent rock zone is characterized by high resistivity values in the 2D-resistivity cross-section and low conductivity anomalies in the VLF-EM tomograms. The competent rock zone corresponds to the area around VES 11-15. This area is characterized by thin layers of weathered and fractured rocks, and has a depth of 3.3 – 6.8 m to the fresh basement rock. This area can support dam foundation without compromising the dam integrity. The area is recommend for the construction of the dam extension. The 3.3- 6.8 m depth of weathered and fractured rock should be excavated before casting dam foundation in the area.

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