Panoramic azimuthal Schlumberger Vertical Electrical Sounding for fracture orientation and anisotropy quantification

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Abstract

Vertical electrical sounding (VES) data acquired with the Schlumberger configuration is popularly used to image the electrical resistivity variation with depth at a single azimuth. Apart from the random subjective choice of the single azimuthal direction by the field geophysicists, important hydrological information such as fracture orientation and anisotropic coefficients needed for understanding resultant groundwater flow direction are by design lost in the process. Panoramic (0°–360°) azimuthal VES data were acquired at two data points at the Federal University of Technology, Akure (FUTA) at angular step of 15°, making a total of 24 data sets per data point. Each azimuthal VES data was inverted using equal number of layers in order to confirm the presence of anisotropy, quantify the anisotropic coefficients and image the orientation of fracture at a particular depth. Little to large apparent resistivity data and model suggested the presence of anisotropy which otherwise would have been lost in a single azimuthal survey. Elliptical fit of each layer azimuthal inverted resistivity was used to quantify the fracture orientation and coefficient of anisotropy with depth. From
the results, it is established that anisotropy is present only at the near-surface: and the anisotropic coefficient increases from the surface to 7m. The result also showed the presence of an isotropic unit from 8m to the fresh basement. In agreement with existing published results on the geology of the area, the majority of the fractures trend North West and North East at stations 1 and 2 respectively. We hope that the methodology will foster detailed 3D panoramic imaging of the fracture network within and outside the study location, which will help in designing better groundwater management scheme and understanding resultant groundwater flow direction for contaminant and pollutant prevention and for flood control.

Keyword: Geophysics

1. Introduction

Few of the physical properties of a rock include electrical resistivity or conductivity, density, magnetic susceptibility, dielectric permittivity, acoustic impedance. The variance in the aforementioned properties of a geologic layer in space and direction would imply additional definition of inhomogeneity and anisotropy respectively. However, to simplify problem definitions, the limiting cases of homogeneity and isotropy for geophysical problems are usually presented in the literature. Thus the acquisition of the DC Schlumberger Vertical Electrical Sounding (VES) data over a 1D layered earth is based on the assumption of each layer being homogeneous and isotropic. The usual field procedure is to acquire the VES data at a single azimuth. 

Ekinci and Demirci (2008), Adelusi et al. (2013), Bayode (2013), Ojo et al. (2015), Ibironke et al. (2016), Taiwo et al. (2016), Adagunodo et al. (2018), Ogunbo (2018) presented examples of the cases where a single azimuthal VES data has been used for interpretation. An obvious troubling fact is that the choice of the single azimuth on the field is random, and perhaps subjective to the discretion of the acquisition team. In the presence of strong anisotropy, two independent acquisition teams may end up with different results for the same data point if their data are from different azimuths. The overhead cost of survey, both financially and logistically, may be responsible for deciding on using a single azimuth over that of panoramic or full azimuthal data acquisition; another constraint might be the presence of some geological field barriers or terrains on the field. Nevertheless, the importance of the full azimuthal Schlumberger VES data acquisition is rooted in the anisotropic benefits. Basically, anisotropy conceals a great deal of information about the geology in terms of slope of the bedrock surface, or dip of bedding or foliation, overburden thickness and similarly oriented, steeply dipping fractures (Lane et al., 1995). In other words, to confidently map the fracture orientations in the subsurface for groundwater flow directions the anisotropic resistivity image of the subsurface must be produced.
Literatures on the anisotropic evaluation of the subsurface geology are few. Carpenter (1990) jointly used azimuthal resistivity data (Wenner and Schlumberger configurations) and seismic refraction data for detecting cover fracturing favoring accumulation of leachate in Mallard North landfill in Chicago. By using the square-array DC resistivity method Lane et al. (1995) detected fractures in crystalline bedrock in New Hampshire. Tepper and Phelan (2001) located geologic structure at Fort Detrick, Maryland through the use of azimuthal square-array DC resistivity method. Following the approach of the foregoing references, we present the results of the panoramic azimuthal Schlumberger VES data acquired in the crystalline bedrock at the Federal University of Technology, Akure (FUTA), Ondo state, Nigeria. To the best of the authors’ knowledge the anisotropic investigation of the study area has not been done using the azimuthal DC resistivity method. For example Adelusi et al. (2013) integrated twelve single azimuth VES with 2D-Wenner and hydrochemistry to map groundwater contamination around Aule area of Akure. Eighteen single azimuth VES, in connection with Very Low Frequency EM and Horizontal profiling, were used by Bayode (2013) for the hydrogeophysical investigation for deep fracture columns at the Federal Housing Estate, Akure. Ojo et al. (2015) analyzed a huge number (513 to be precise) of single azimuth VES data to characterize subsoil competence of the Akure Metropolis. Ibironke et al. (2016) investigated the groundwater resources around FUTA staff quarters from the aquifer parameters. The geological component of the basement complex terrain that favors the prolific accumulation of groundwater is the weathered/fractured layer which is also known as the unconfined aquifer (Adelusi et al., 2013; Ojo et al., 2015; Adagunodo et al., 2018). Since the presence of fracture causes azimuthal resistivity (Lane et al., 1995), this research thus serves as a preliminary study that aims to investigate the presence and orientation of fractures in the bedrock and to quantify the coefficient of anisotropy in the region using full (panoramic) azimuthal VES data. The results from the experiment would therefore serve as a recommendation for designing a regional survey to map fracture network for groundwater flow pattern in FUTA community.

2. Theory

2.1. 1D DC Schlumberger configuration

A single azimuthal Schlumberger configuration is shown in Fig. 1a. The pair of potential electrodes (P1 and P2) are located in between the pair of current electrodes (C1 and C2). Current is injected through current electrodes and the potential difference is measured by the pair of potential electrodes. Using Ohms law, the rock resistance can be computed from the ratio of the potential difference to the magnitude of the electric current. By multiplying the resistance with a geometric factor the apparent resistivity data is eventually known. The apparent resistivity data can be
plotted against half current electrode spacing (AB/2) for the data display. Apparently, to probe deeper, the distance between C1 and C2 has to be increased in Fig. 1a. The panoramic azimuthal Schlumberger configuration is illustrated in Fig. 1b where azimuthal data is acquired at different azimuths.

The forward (apparent resistivity) response for an isotropic and homogeneous 1D-layered earth is computed using (Ghosh, 1971):

$$\rho_a = s^2 \int_0^\infty T(\lambda)J_1(\lambda s)\lambda d\lambda, \quad (1)$$

where $s$ is the Schlumberger electrode configuration half current spacing, $J_1$ is the first-order Bessel function of the first kind and $\lambda$ is integration variable. $T(\lambda)$ is the resistivity transform given by the recurrence relationship:

$$T_i(\lambda) = \frac{T_{i+1}(\lambda) + \rho_i \tanh(\lambda h_i)}{1 + T_{i+1}(\lambda)\tanh(\lambda h_i)/\rho_i} \quad i = n, \ldots, 1 \quad (2)$$
where \( n \) is the number of layers, \( \rho_i \) and \( h_i \) are resistivity and thickness of the \( i \)th layer, respectively. Ekinci and Demirci (2008) provides the computer code for calculating the above equations.

### 2.2. Ellipse and circle fit

Whereas a circular geometry can be traced out for an isotropic medium, the trend for an anisotropic medium is elliptical (Hart and Rudman, 1997). Hart and Rudman (1997) provided an open source code (FITELLIPSE written in Maple programming language) that fit both a circular and an elliptical models on the anisotropic data distribution by least-squares method. In the rectangular coordinates, the equation for such an ellipse, centered at the origin in rectangular coordinates, is given as

\[
a x^2 + b x y + c y^2 = \bar{p}^2,
\]

where \( a, b, \) and \( c \) are the unknown coefficients, \( x \) and \( y \) are the rectangular coordinates and \( \bar{p} \) is the mean value of the data. For a uniformly distributed random noise in the data with variance of \( \sigma^2 \), the reduction in variance, \( R^2 \) is defined as the percentage of the variance from the circular model which has been removed by the elliptical model. Mathematically, \( R^2 \) is

\[
R^2 = \frac{(\sigma^2(\text{circle}) - \sigma^2(\text{ellipse}))}{\sigma^2(\text{circle})}.
\]

From Eq. (4) \( R^2 \) approaches 1 when there is little or no variance in the ellipse; which implies that the elliptical model fits the data distribution very well indicating the presence of anisotropy. On the other hand, large variance in elliptical model would suggest that the circular model fits the data better; and that invariably indicates an isotropic medium. Another output from the FITELLIPSE code is the angle of declination of the major semiaxis from the North axis that identifies the direction of maximum predicted value in the elliptical model. The degree of anisotropy is quantified by the coefficient of anisotropy \( \lambda \) which is simply the ratio of the lengths of major and minor axes of the fitted ellipse.

### 3. Materials and methods

#### 3.1. Field procedure and inversion result

Two data points were used in this project. The first data point is located at longitude of 5° 7’ 59” E, and latitude 7° 18’ 13”N while the second data point is located at longitude of 5° 7’ 56”E, and latitude 7° 18’ 17”N. The geology of the area consists of hard basement rock types. Fractured rock units in the basement rock are usually the targets of the groundwater storage in this geological setting. Hence, the quantification of anisotropic coefficients and orientations of these fractures are important...
for accurate understanding of the groundwater flow directions and storage. Therefore, there is a need to acquire resistivity data from all the azimuths in order to measure these fracture parameters. The azimuthal resistivity data were acquired at the two sounding points at 20m station separation using the Ohmega resistivity equipment. The minimum and maximum AB/2 for the experiment are 1 and 65m respectively. For consistent referencing, the zero azimuth is set at the geographical north direction.

The initial setup of the single azimuthal configuration in Fig. 1a is simply rotated at a constant (constancy is not a requirement for successful implementation) azimuthal offset, say 15° (as used in this experiment) to produce Fig. 1b. At each azimuth (say θ degree), the current electrode positions are interchanged to measure the data of the complementary azimuth (in this case θ + 180 degree). This approach provides an efficient design for quickly acquiring the data.

The data type at the two data points is what is typically known as the “HA” type curve, which is a four-layer geoelectrical model, whose second layer resistivity is the least among others (see Fig. 2). We observe that the apparent resistivity data is reciprocal at the complementary angles when the current electrode positions are interchanged. This information eliminates the possibility of attributing changes in azimuthal data to instrument accuracy and field noise. Hence, the magnitude of the differences in the apparent resistivity data in Fig. 2 immediately suggests that the subsurface is indeed anisotropic. The nonlinear least squares inversion of the data is performed using the singular value decomposition (SVD) approach presented in Ekinci and Demirci (2008). Maximum iteration number is set to 50. A total overburden thickness of 15 m is used and divided into 60 thicknesses (each layer thickness is thus 0.25 m) in order to vary only the layer resistivity values.

The constant thickness layer inversion also enables the tracking of the trend of anisotropic changes per layer at certain fixed depth. Inverted results are shown in Fig. 3. Fig. 3a and b are inverted resistivity models for stations 1 and 2 respectively. The range of layer resistivity values in each layer (difference between the largest and smallest) is also indicative of the presence of anisotropy. At the shallow depth, around 1 m, the range is the smallest while at about 8 m depth there exists the biggest difference between the highest and smallest resistivity values, although station 1 shows a smaller range than station 2 at this depth.

To demonstrate the quantification of the fracture orientation and anisotropic coefficients using the software FITELLIPS (Hart and Rudman, 1997), both circle and ellipse are fitted to inverted resistivity values at depth 0.25m for station 1 in Fig. 4. From Eq. (4) $R^2$ calculated for resistivity distribution in Fig. 4 is 1 which is indicative of strong anisotropic presence. Qualitatively, Fig. 4 also shows that the elliptical fit is better than the circular fit over the azimuthal apparent resistivity which also supports the strong anisotropic assertion of the value of $R^2$. Recalling that the ratio of the major and minor axes of this ellipse is the anisotropic coefficient; the
anisotropic coefficient of Fig. 4 is estimated to be 1.8298 corroborating the value of $R^2$. Using the paradox of anisotropy (Carpenter, 1990), fracture direction is the direction of the maximum resistivity for collinear configuration like the Schlumberger array configuration. However, the direction of the fracture is perpendicular to the maximum resistivity value using the square-array configuration. And finally the declination of the major axis from the north is estimated as 12° East of North, which is the orientation of fracture.

Similarly, the anisotropic coefficient variations with depth (or layer) for both stations are plotted in Fig. 5. Station 2 anisotropic coefficients values are generally higher

Fig. 2. Azimuthal field apparent resistivity data acquired at (a) stations 1 and (b) 2. The curve type is the “HA” type.
The anisotropy seems to increase linearly with depth from 1 to 4 m for both stations 1 and 2; and it continues to 7 m for the 1st station. Setting the minimum anisotropic coefficient to unity, isotropy exists for depth value deeper than 5 m at station 2 indicating the fresh basement rock.

To show the lateral and vertical orientations of the fracture anisotropic polar plots for four depth slices at 0.25, 4.25, 8.25 and 12.25 m depths are shown in Fig. 6. Except at depth 4.25m, the fracture declinations at depths 0.25, 8.25 and 12.25m is NE-SW at both stations. However at depth 4.25m the fracture trends NW-SE and NE-SW at
stations 1 and 2 respectively. It should be noted that elliptical symmetry is lost at the depth interpreted as fresh basement rock (from 8m downwards). Fig. 7 displays the fracture-strike directions with depth for both stations. The anisotropic trends at the near-surface (0–6m) are highly variable for both stations. From 0 to 2m depth, station 1 fracture trend is SE but it is NE at station 2. Fracture orientation majorly declines along NW at station 1 but it is SE trending at station 2. However, the fracture
strike is similar at both stations from 6 to 15m. The fracture orientations for 6—7m, 7—9m and 10—15m are SE, NW and SE respectively at both stations. The rose diagrams in Fig. 8 display the statistics of distribution of the fracture orientations. At station 1, the majority of the orientation is NNW while it is NNE at station 2 which agree with the reports from Ojo et al. (2015).

4. Discussion

Groundwater flow direction is essential to understanding its storage and could help in its optimal management. In the basement terrain, like at the Federal University of Technology, Akure (FUTA), fractures usually play important roles as conduits for the flow of the groundwater especially when the fracture network is dense. Thus it is necessary to image the density of the fracture network, quantify their anisotropic coefficients and their orientations. At a single data point, it is difficult to estimate the anisotropic orientation of the fractures using a single azimuthal collinear
Schlumberger data set. We acquired two panoramic (full-azimuths) Schlumberger data sets from which we were able to quantify both the anisotropic coefficients and orientations with depth. Results revealed that anisotropy indeed exists in the subsurface and the fracture-strike orientations mostly vary at the near-surface (0–7m) at the two data points but are the same in the fresh basement. In comparison with a published article (Ojo et al., 2015), the frequency of the fracture orientations are mostly along NNW and NNE for stations 1 and 2 respectively. However, expanding the survey to include more data points will give more accurate results than simply generalizing them to NNW and NNE. The study serves as a preliminary research for embarking on a larger scale regional groundwater flow investigation that will allow for 3D anisotropic resistivity mapping of the region for groundwater management and flood control.

5. Conclusions

We have presented a methodology for interpreting panoramic azimuthal vertical electrical sounding (VES) data by the Schlumberger configuration for detecting fractures, their orientation and the coefficient of anisotropy. Following similar field procedure for acquiring VES Schlumberger data at a single azimuth, the set-up is simply rotated about the sounding point in step of 15° from 0° through 360°. Two data points were used for the experiment. Nonlinear least-square inversion by the singular value decomposition (SVD) method was performed on each of the azimuthal VES data of constant layer thickness of 0.25m and total overburden thickness of 15m. Qualitative confirmation of the presence of anisotropy is established from differences between field data; and the deviation of the inverted layer resistivity values. Fracture orientations and the coefficient of anisotropy were quantitatively measured from the elliptical fit on the inverted layer resistivity values and the ratio between the major and minor axes of the ellipse respectively. Results showed that fracture orientations and the coefficient of anisotropy vary vertically with depth and laterally especially at the near surface (0–7m). The fresh basement encountered, from depth of 8m and deeper, is isotropic with anisotropic coefficient of 1. The majority of the fractures are oriented along North West and North East at stations 1 and 2 respectively. Although the panoramic azimuthal field procedure appears to be more laborious than the single azimuthal VES experiment, without the full azimuthal data acquisition the fracture orientations, coefficient of anisotropy estimations would be completely unavailable from the random choice of a single azimuthal direction. It is thus recommended to carry out extensive and detailed investigation of using more data points to have a holistic anisotropic view of the subsurface for the development and protection of the groundwater resources in and outside of the survey location.
Declaration

Author contribution statement

Jide Nosakare Ogunbo: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Emmanuel Abiodun Mamukuyomi: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Wahab Stephens Adepoju, Harrison Adebowale, Olamide Akinro, Chukwuebuka Richard Ukaegbu: Performed the experiments.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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