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Comparison of Six Classical Electrode Arrays of 1D Resistivity Survey for Subsurface Geo-electric Layer Delineation in the Basement Complex of Ilorin, Nigeria

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Abstract

Six classical Traditional Resistivity Survey methods comprising Schlumberger, Wenner, Dipole-dipole, Wenner-Schlumberger, Pole-dipole and Pole-pole arrays were tested for subsurface stratigraphic delineation in a series of field experiments conducted in the basement complex area of Ilorin, North central Nigeria. The aim of the study is to determine the suitability, strength, and weakness of the different array system for subsurface stratigraphic delineation. Interpretations and comparisons of results from the different arrays were based on the lithologic sections obtained from borehole drillers' logs in the study area. The results of the study showed that some arrays are more reliable for geo-electric layer delineation than others. Wenner-Schlumberger and Schlumberger arrays gave the overall best results in terms of estimating the vertical extent of layers and depth to hard rock (fresh basement rock). Wenner-Schlumberger array proved to be a reasonable alternative to Schlumberger array when strong vertical resolution is needed. Dipole-dipole, pole-dipole, and Wenner arrays consistently underestimate the number of horizontal layers in most of the study locations, thereby suggesting low sensitivity of the methods to vertical resistivity changes. In situations where the four electrodes cannot be situated within the vicinity of the target, results of the study showed also that pole-pole rather than pole-dipole is a better method of resistivity survey. Interestingly, none of the methods is one hundred percent accurate when compared to the borehole lithologic sections. The study recommends Schlumberger and Wenner-Schlumberger methods for high-resolution subsurface delineation in the study area. Descriptions of the field procedure and electrodes arrangement for the six classical arrays are detailed in this paper with the goal of providing guides to non-professional geophysicists like Agriculturists, Civil and Water engineers, and new-comers in the discipline of geosciences who sometimes engage traditional methods of resistivity survey for testing soil and concrete material and citing water-wells /boreholes.

Keywords: Electrical resistivity survey; geo-electric parameters; Wenner array and Schlumberger arrays; Wenner-Schlumberger array, dipole-dipole array, pole-pole array and pole-dipole array.

Introduction

One-dimensional (1D) electrical resistivity survey method is one of the oldest and most commonly used geophysical methods of exploration (Telford et al., 1990; Reynolds, 2011). The method had enjoyed great deal of patronage since early 1900's when Conrad Schlumberger developed Schlumberger array (Schlumberger, 1920) and Franklin Wenner developed the Wenner method to measure the electrical resistivity properties of rocks and soil in the subsurface for multipurpose applications (Kunetz 1966; Koefode 1979; Keary and Brooks; 1996). Later, other methods of 1D electrode arrays such as Dipole-dipole, Wenner-Schlumberger, Pole-dipole, Pole-pole, equatorial, square, bipole-bipole, gradient arrays were developed and used for similar applications. Due to simplicity, cost-effectiveness, and availability of the equipment, non-professional geoscientist like Agriculturists, Civil and Water engineers, and students of geoscience disciplines are on a daily basis applying different electrode arrays of 1D resistivity survey for testing soil and concrete materials, and citing locations for water-well/borehole construction. However, the workings and the preference of one method over the other for specific applications is not completely understood by many users. Therefore, it is important to describe the different methods of electrode arrays, test and compare their practical applications in a single publication with a view to improving users' understanding, especially among students of geoscience courses.

The resistivity of rocks and soil layers are related to various geological parameters such as the mineral, fluid content, porosity, grain size distribution, and degree of water saturation, and nature of the saturating fluid, among others (Jones, 1985; Raji, 2014). Therefore, different types of 1D electrical resistivity survey have been applied varieties of purposes including groundwater exploration, (Mazac et al., 1985; Ballukraya, 1996; Olasehinde, 1999; Olasehinde and Raji, 2007; Ayolabi et al., 2009; Abubakar et al., 2014; Thabit and Al-Hameedawi,2014), to study environmental pollution and groundwater contamination (Barker, 1990; Atekwanan et al., 2000; Ayolabi, 2005; Adepelumi et al., 2009; Akinrinmade et al., 2016) for engineering applications - to determine depth to foundation rocks and locate dams leakages (Ojo et al., 1990; Raji and Ibrahim, 2017), for archaeological mapping of buried ancient foundations and objects, mineral exploration and mining (Noel and Xu, 1991; Johnson, 2003; Ramazi et al., 2009; Ramazi and Mostafale, 2013) and other miscellaneous applications (Majumdar et al., 2000; Raju 1998; Pomposiello et al., 2012**)** in the different parts of the world. Different arrays have been applied in the literature cited above. But most of them did not give reasons for choosing the method they used over other existing methods.

In the last twenty-five years or so, electrical resistivity methods have seen rapid developments in instrumentation, field survey, data modelling, and interpretations. Two-dimensional (2D) and three-dimensional (3D) resistivity survey methods have been developed and successfully applied to varieties of problem in different parts of the world (for examples, Loke and Barker, 1996; Mastrocicco et al., 2010; Chambers, et al., 2011; Santarato, et al., 2011; Aluko et al., 2017; Raji, et al., 2018; Raji and Adedoyin, 2020) The developments have led deciphering complex subsurface geological structures that are not possible with 1D survey methods, thereby making resistivity method compete with seismic refraction method for deciphering complex shallow geological structures (Raji and Adeoye, 2017). However, the cost of acquiring 2D resistivity survey equipment and the ambiguities in the interpretation of 2D/3D resistivity models still make 1D survey, despite its limitations, the choice of some geoscientists for non-complex subsurface investigation. The cost of acquiring or renting 2D/3D resistivity survey equipment and the interpretation software is not yet within the reach of many researchers in under-developed/developing countries where research grants are limited and monthly income is low. Quantitative interpretation of 2D/3D resistivity models is often characterized by some uncertainties as two (or more) different subsurface features can give rise to similar resistivity models. Improvised methods of combining 1D resistivity arrays to map 2D/3D features have been developed (e.g., Karous and Peru, 1985; Asfahani, 2018) to overcome some of the limitations of 1D survey methods.

Arising from the above 1D survey method will still be relevant for shallow subsurface investigation till the 2D/3D resistivity survey equipment are available and affordable worldwide. In practice, all the 1D electrical resistivity array require the use of four electrodes: two current electrodes through which electric current (I) is introduced to the ground, and two potential electrodes through which the potential difference is measured, a battery for supplying direct current to the ground and a resistivity meter to measure resistance. However, the arrangement and the spacing of the electrode differ from one array to another. Furthermore, some arrays are operationally simpler than the other, and some are more efficient and accurate than the other while some are impractical in some situations. For example, the use of Schlumberger array for vertical electrical sounding is becoming increasingly difficult in built-up area where long electrode spread is usually obstructed by facilities like tarred road, shelters, office buildings, among others. Therefore, it is important to describe the different methods of electrode arrays and applied them for data measurement with a view to compare their suitability and effectiveness.

In this study, six classical method of electrode arrays comprising Wenner, Schlumberger, Dipole-dipole, Schlumberger–Wenner, Pole-dipole, and Pole-pole arrays are applied for subsurface stratigraphic delineation. Data acquired were processed, inverted, and interpreted using the same method. The objective of the study is to compare and contrast the earth models inverted from the six different arrays. The aim of the study is to determine the suitability, strength, and weakness of the different array system for subsurface stratigraphic delineation. Borehole lithologic sections derived from borehole drillers' logs in the study areas are used as the benchmark standard for the interpretation of geo-electric parameters delineated by the different arrays.

Review of the Geology of the study area

The study area falls within longitude $4^{o} 39^{I}$ - $4^{o} 43^{I}$ and latitude $8^{o} 28^{I}$ - $8^{o} 31^{\mathbf{I}}$ (Figure 1) in Ilorin, Kwara State, Northcentral Nigeria. The area falls within the Savana region of Nigeria, has two main seasons: rain season and dry season. The mean annual rainfall and temperature ranges from 75 and 112 mm, and 27 and 35^{o}C respectively. Geologically, the study area falls within the Precambrian basement terrain of the northcentral Nigeria considered to be Precambrian to lower Paleozoic in age (Oyawoye 1964; Rahaman 1976; Annor et al. 1987). The rock comprised mostly of gneiss, granite, schist, and undifferentiated meta-sediment. In the study area, the rocks outcrop in some places and are covered by weathered rock and top-soil in many places. The rocks are well exposed along river channels. The top-soil comprised of laterites and sandy-clay.

The oldest rocks in the study area comprise the gneiss complex whose principal member is biotite-hornblende-gneiss with intercalated amphibolites (Annor et al. 1987). The younger suites are granites with medium to coarse-grained light coloured rocks with variation in biotite content. The feldspar mineral occurs as fine to medium grains. Other rock types include schist and quartzite. The quartzite is considered to be the metamorphic equivalence of major quartz that filled the pre-existing fractures in the area. Structural features mapped in the area include fault, fracture, pinch and swell structure, strikes and dips. The rocks are dipping to the west and east with angles ranging from 28^{o} to 45^{o}. Groundwater occurrence in the Precambrian basement terrain is hosted within zones of weathering and fracture which are often limited in size (Olasehinde and Raji, 2007). The main aquifer types in the study area are weathered rock aquifer, fractured rocks aquifer, and a combination of the two. A combination of the two The aquifers are overlain by different soil material of variable thickness.

Methodology

Field operations and data acquisition

Equipment used for field operation and data acquisition comprised SAS 3000 ABEM Resistivity Meter, metallic electrodes, reels of cables, measuring tapes, portable Geographic Positioning System (GPS), hammer, battery, measuring tapes and other accessories. The general description of electrical resistivity measurement on the field is that current is introduced into the ground through a pair of electrodes, known as current electrodes, separated by a distance AB. Another pair of electrodes, known as the potential electrode is introduced to the ground to measure the resulting potential. The resistivity meter (basically a current meter and voltmeter in one) measures the resistance of the earth material (soil/rock) posed to the free flow of electric current in the ground. In the conventional arrangement, the potential electrodes (MN) are usually placed in-between the current electrodes (AB). The potential electrodes are usually separated by a smaller distance compared to the current electrodes. Resistivity is obtained by multiplying the measured resistance by the geometric factor. The geometric factor is an expression of the electrodes arrangement and the spacing. The list of the geometric factor, k are given in Figure 1. Current electrodes AB are also known as the transmitter electrode, while the potential electrodes MN are also known as the receivers' electrodes. The description of the different electrode array are given below.

Schlumberger array: the four electrodes are arranged on a straight line such that the two potential electrodes, MN are placed in between the two current electrodes, AB as shown in Figure 1a(i**).** After the first measurement, AB is gradually expanded and measurements are taken until the observed voltage is too small to measure. Then, MN is expanded and AB is expanded incrementally for another series of measurement (Fig1a(ii)). Usually, the MN spacing is about one-third to one-fourth of AB spacing at the start. The longer the separation between electrodes AB, the deeper the depth of investigation, DOI. A plot of the apparent resistivity against half of the current electrode separation, AB/2, usually yields a curve that can be inverted for the subsurface geo-electric layers and their parameters.

Wenner Array: the arrangement is similar to the Schlumberger array, but the four electrodes are equally spaced (Fig. 1b(i)). The distance between the potential electrodes MN is the same as the distance between AM and NB. After a measurement, the electrode spacing AM, MN, NB are expanded by the same distance to probe greater depths (Fig. 1b(ii)), or the arrangement is moved laterally to probe horizontal layers. A plot of apparent resistivity against electrode separation (a) gives a curve that can be interpreted for the geo-electric layers, their thicknesses and resistivity. This array was invented by Franklin Wenner (1873 -1954)

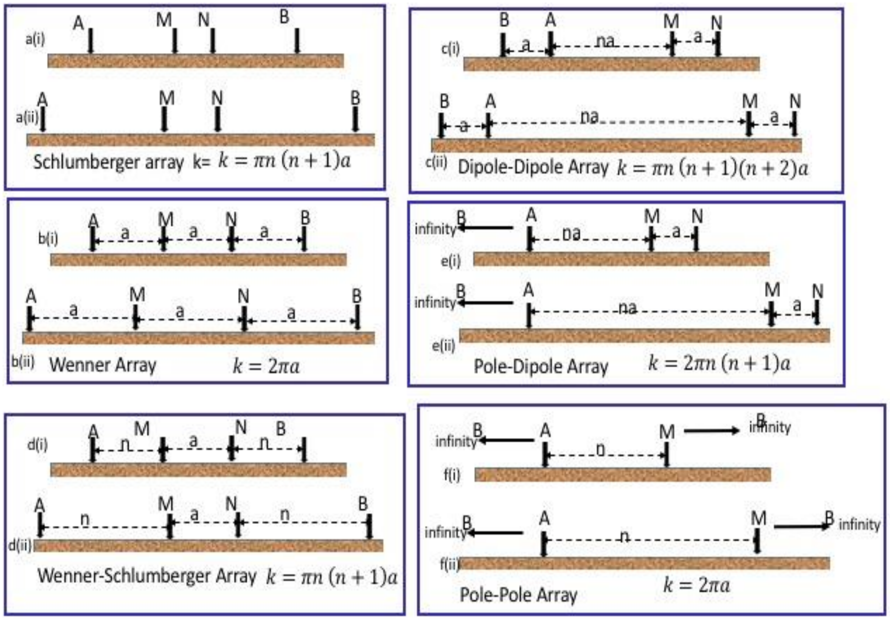


Figure 1: Schematic image of field layout for the different arrays.

Wenner-Schlumberger Array: This array combined the features of Wenner and Schlumberger arrays. At the start, the separation between the MN electrodes is the same as that of AM and MB, just like in Wenner array (Fig. 1c(i)). After the first measurement, the electrodes A and B are moved out incrementally, and measurement are taken at every increment as AB increases, the electrode array assumes the feature of Schlumberger array (Fig. 1c(ii)). MN may be increased when signal strength is almost diminished. The apparent resistivity is plotted with AB/2 to obtain a curve that can be interpreted for subsurface geo-electric parameters.

Dipole-Dipole Array: In dipole-dipole array, the potential electrodes MN and current electrodes AB are arranged on the two extreme ends of the survey line as shown in figure 1d(i) where the separation between NM and AB is the same – a. To probe deeper, the separation between the two dipole is increased by a dipole separation as shown in figure 1d(ii)). The distance between AM (na) is usually a multiple of a. Where n= 2, 3, 4, 5 ....10. Resistivity obtained by multiplying the measured resistance by the geometric factor k. Resistivity is plotted against the half the separation of the two dipole, na/2.

Pole – dipole Array: In this array, only three electrodes are grounded at the vicinity of the measurement point. The potential electrodes, NM are placed at one end of the line with a separation (a) as shown in figure 1e(i), while one current electrode A is placed on the other end of the survey, the second current electrode, B is placed at infinity. Mathematically, a distance that is about 10 times larger than MN is considered to be at infinity for this electrode array. After the first measurement, electrodes MN is moved away from A by a dipole distance (i.e., a) for the second measurement. Then the process continues by increasing AM separation as 3a, 4a, 5a, 6a, until one begins to loose signal between the current and potential electrodes (Fig. 1e(ii)). In this array, electrodes A and the electrode at infinity (B) are fixed. Only electrodes MN are moved. The longer the AM, the deeper the depth probe by the survey. The apparent resistivity is plotted against the separations between AM to obtain the resistivity curve.

Pole-pole Array: In this type of electrode array, only two electrodes are grounded at the vicinity of the measurement point. As shown in figure 1f, current electrode A is fixed at a point separated by distance n from potential electrode M while the second current electrode, B and the second potential electrode, N are placed at infinity (∞), where $\infty > 15n$. After the first measurement, electrode M is moved out in order to increase the distance between A and M in order to take the second measurement. For the subsequent measurements, distance AM is continually increased while the electrodes at infinity – B and N and the electrode A are fixed (Fig. 1e(ii)). The longer the distance AM, the deeper the penetration. The apparent resistivity obtained is plotted against n to obtain a curve that will be interpreted for geo-electric parameters.

Data processing

Each of the six electrode arrays described above were used to acquire data in eight study locations. Borehole are present at five of the eight locations (Fig.2). Apparent resistivity data were computed by multiplying the measured resistance values by the respective geometric factor, k. Then the apparent resistivities were plotted against AB/2, a, AB/2, na/2, na, and n for Schlumberger, Wenner, Wenner-Schlumberger, dipole-dipole, pole-dipole, and pole-pole arrays respectively. The curves plotted for the different locations were qualitatively inspected. In cases where spikes and spurious data values are noticed from the curves, data filtering was performed using an in-house MATLAB-based programme (Raji and Adeoye, 2017). The programme uses four neighbouring data point to attenuate spurious data.

Then, the data were processed and modelled using 1D Resistivity packages (Koefoed, 1979; Alex and Vladimir, 2002; Van Nostrand and cook, 1966; Loke, 2002; Geotomo - AGI USA). Some of the output of the modelling and interpretations of results are shown in Figure 3. Parameters such as the geo-electric layers, thickness and resistivities of the layers, and depth to fresh basement rock were estimated using an automated curve matching method. Some of the curves matching templates for the field data are shown in Figure 3. Geo-electric parameters estimated from each array in a particular location were compared using borehole lithologic section drawn from borehole drillers' logs. Comments on the interpreted parameters are given in the next section

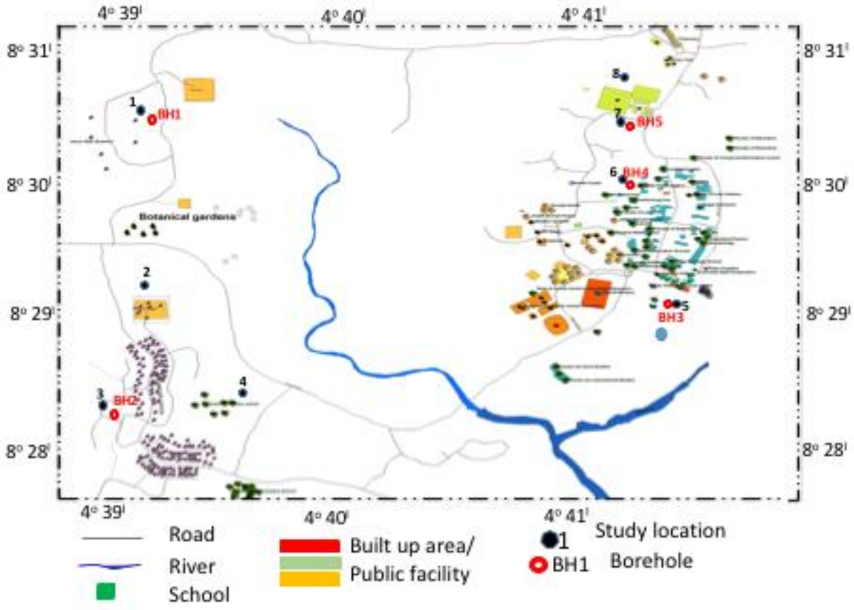


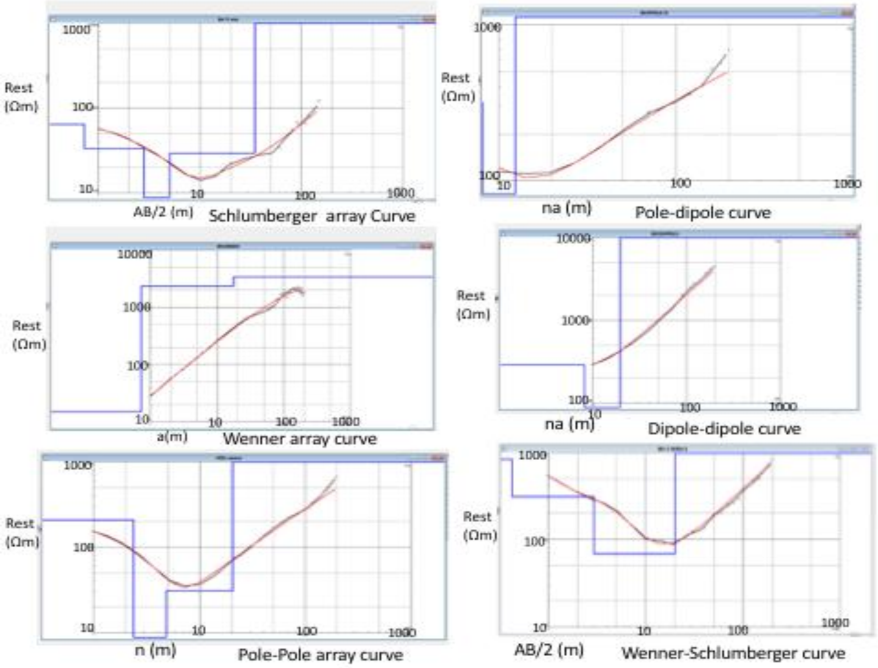
Figure 2: Geographic Map of the study area showing study locations and boreholes

Results and Discussion

The ithologic sections derived from borehole drillers' logs are available in five of the eight study locations and unavailable in the three other locations. The borehole drillers' log is used as the standard benchmark for determining the accuracy of the geo-electric parameters estimated from the resistivity curves generated for different electrode arrays. In the interpretations and comparisons, emphases were placed on layers' thickness and depth to the basement rock. The number of geo-electric layers delineated were compared with caution considering the fact that a geological layer is not realistically the same as a geo-electric layer (Olayinka, 1996; Olorunfemi and Opadokun, 1987; Olasehinde and Raji, 2007). A geological unit/layer is discriminated from another in terms of grain size, colour, and composition, depositional environment and agent, among others. One geological unit may give rise to 2 (or more) geo-electric layers if the top is dry and the bottoms is wet, or if the top and bottom sections are saturated with different fluids (Olayinka and Barker, 1990). On the other hand, two or more geological layer may correspond to a single geo-electric layer if the difference between the geological layers did not translate in different electrical resistivity properties.

Arising from the above, cautions were taken while comparing geo-electric layers from the different electrode arrays with lithologic layers derived from the borehole driller's logs. Comparisons were based on the generalized stratigraphy of basement complex rock with regards to the thickness of the overburden material, thickness of the aquifer, and depth to the basement rock (Jones and Hockey, 1964; Jones., 1985; Olorunfemi and Opadokun, 1986). The overburden material, in this case, comprised the rock and soil materials between the earth's surface and the aquifer.

Location 1: borehole (BH1) driller's log from location 1 indicated the presence of five lithological units as shown in Figure 3. The aquifer corresponds to the 4th layer – which is the weathered/fractured layer and has a thickness of about 32 m. Overburden thickness is 4.2 m and depth to the fresh basement rock is 36.2 m. Schlumberger, Wenner, Pole-pole, Pole-dipole, Dipole-dipole and Wenner-Schlumberger indicated the presence of 5, 3, 4, 3, 3, and 6 layers respectively. Schlumberger and Wenner-Schlumberger arrays gave the best estimate among the six arrays when compared with the Borehole driller's log. Wenner-Schlumberger array estimated aquifer thickness, overburden thickness, and depth to the basement rock as 30.9, 8.4, and 39.3 m respectively, while Schlumberger array estimated the respective parameters as 34.9 m. 5.5 m, and 40.4 m. Pole-pole array gave the third best results, while pole-dipole gave the least accurate results in this case.



Schlumberger array Curve

Pole-dipole curve

Wenner array curve

Dipole-dipole curve

Pole-Pole array curve

Wenner-Schlumberger curve

Figure 3: Resistivity curves plotted for the data acquired by the different arrays at location 3.

At location 3**,** a borehole (BH2) is present. The borehole driller's log indicated the presence of 5 geological units with the aquifer layer being the 4th layer. The aquifer corresponds to the weathered/fractured rock unit. According to the BH2 driller's log, the aquifer thickness, thickness of the overburden material, and depth to the basement rock are 23.6, 4.8, and 28.4 m respectively. Of the six electrode arrays, Schlumberger, Wenner-Schlumberger, and pole-pole arrays gave the best three results in the respective order. As shown in table 1 location 3, Schlumberger estimated aquifer thickness, overburden thickness and depth to basement rock to be 29.4, 5.1, and 34.5 m respectively. Estimates from Wenner-Schlumberger and pole – pole arrays were 17.2, 2.9, 20.1; and 15.8, 4.8, 20.6 m, respectively. Pole-dipole array gave the least accurate results in this case.

At location 5, Wenner-Schlumberger array gave the best results. The method delineated 5 geo-electric layers and a depth to the basement rock of 36.1 m. Aquifer thickness and the overburden thickness were estimated to be 24.8 and 11.3 m respectively. Borehole driller's log for the location (BH3) revealed the presence of 5 lithologic layers and showed that the actual thickness of the aquifer, overburden material, and depth to the basement rock are 23.5 m, 13.4 and 36.9 m respectively.

The second-best estimates of subsurface layer thickness and depth were derived from Schlumberger array with values of 27.4, 4.3, 31.7m as the thickness of the aquifer, overburden material and depth to basement rock respectively (table 1 location 5). But Schlumberger array delineated six geo-electric layers. Pole-dipole array gave the least accurate results in this case.

Borehole driller's log for location six (6) revealed the presence of five lithological layers. The logs showed that the aquifer corresponds to the 4th layer and has a thickness of 17.2 m, the overburden thickness is 10.8 m and depth to fresh basement rock is 28 m. As shown in table 1 under location 6, all the arrays, except pole-pole, gave a fairly good result, especially with regards to the estimates of depth to the fresh basement rocks and aquifer thickness. Wenner-Schlumberger, Schlumberger, and dipole-dipole arrays gave the best results in the respective order. Wenner-Schlumberger array estimated 15.6, 11.6, and 27.2 m; Schlumberger array estimated 18.1, 8.8, 26.4 m, while dipole-dipole array estimated 15.7, 8.6, and 24.3 m as the thickness of the aquifer, overburden materials, and depth to the fresh basement rock respectively. The least accurate estimates were from pole-dipole array. The number of layer delineated by Schlumberger, Wenner, pole-pole, pole-dipole, dipole-dipole, and Wenner-Schlumberger arrays were 5, 4, 4, 4, 4, 4 respectively.

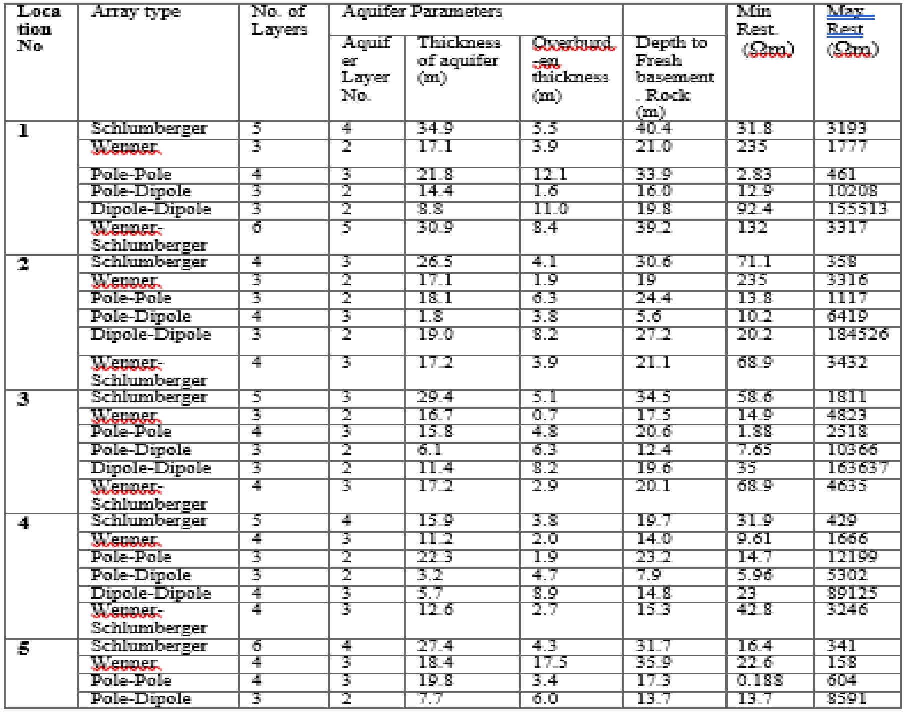
At location seven (7), borehole driller's log revealed 6 geological layer with the aquifer being the 5th layer and having a thickness of 24 m. The log also showed that the overburden thickness and depth to fresh basement rock are 4.3m and 28.3 m respectively. From table 1 location 7. Schlumberger Array gave the best results followed by Wenner-Schlumberger array and then Wenner array. Results from the three arrays showed that estimates for aquifer thickness, overburden thickness, and depth to fresh basement rock are 26.0, 2.9 and 29.5 m for Schlumberger array; 22.4; 4.0, and 26.4 m in Wenner-Schlumberger; and 19.8, 4.6, and 24.4 m in Wenner array. In this case, dipole-dipole method presented the least accurate results. The number of geo-electric layers delineated by the six arrays are shown in the table I location 7.

At locations 2, 4, and 8, borehole lithologic logs were unavailable. The number and thickness of the layers and depth to the basement rock estimated by the different arrays are presented in table 1 at the appropriate locations. The performances of the arrays were judged based on the borehole driller's log close to the location (figure 3). For example, the accuracy of the estimates at location 2 was based on the driller's logs at BH1 and BH3. So aquifer and overburden thickness and depth to basement rock would have values that may varies between values at BH1 and BH3 locations. Similar expression was applied to interpret data at locations 4 and 8.

At location 2, it is surmised based on the foregoing that Schlumberger, dipole-dipole, and pole-pole arrays gave the best three estimates in the respective order. Pole-dipole array gave the least accurate results in this case. At location 4, judging by BH3 and BH5, pole-pole array gave the best results. It estimated aquifer thickness, overburden thickness, and depth to basement rock to be 22.3, 1.9, and 23.2 m respectively. Pole-dipole array gave the least accurate results.

Judging estimates at location 8 by BH7, Wenner-Schlumberger, Schlumberger, and pole-dipole array gave the best three results in the respective order. Estimates by the different array are shown in table 1 location 8. The least accurate results at location 8 is given by dipole-dipole array. The estimated thickness of the aquifer using the six arrays are compared with result of the borehole lithologic section in figure 4.

Table 1: Estimated geo-electric parameters from the different across eight locations



Location No	Array type	No. of Layers	Aquifer Parameters				Min Rest. (Ωm)	Max. Rest (Ωm)
			Aquifer Layer No.	Thickness of aquifer (m)	Overburd-en thickness (m)	Depth to Fresh basement . Rock (m)		
1	Schlumberger	5	4	34.9	5.5	40.4	31.8	3193
	Wenner	3	2	17.1	3.9	21.0	235	1777
	Pole-Pole	4	3	21.8	12.1	33.9	2.83	461
	Pole-Dipole	3	2	14.4	1.6	16.0	12.9	10208
	Dipole-Dipole	3	2	8.8	11.0	19.8	92.4	155513
	Wenner-Schlumberger	6	5	30.9	8.4	39.2	132	3317
2	Schlumberger	4	3	26.5	4.1	30.6	71.1	358
	Wenner	3	2	17.1	1.9	19	235	3316
	Pole-Pole	3	2	18.1	6.3	24.4	13.8	1117
	Pole-Dipole	4	3	1.8	3.8	5.6	10.2	6419
	Dipole-Dipole	3	2	19.0	8.2	27.2	20.2	184526
	Wenner-Schlumberger	4	3	17.2	3.9	21.1	68.9	3432
3	Schlumberger	5	3	29.4	5.1	34.5	58.6	1811
	Wenner	3	2	16.7	0.7	17.5	14.9	4823
	Pole-Pole	4	3	15.8	4.8	20.6	1.88	2518
	Pole-Dipole	3	2	6.1	6.3	12.4	7.65	10366
	Dipole-Dipole	3	2	11.4	8.2	19.6	35	163637
	Wenner-Schlumberger	4	3	17.2	2.9	20.1	68.9	4635
4	Schlumberger	5	4	15.9	3.8	19.7	31.9	429
	Wenner	4	3	11.2	2.0	14.0	9.61	1666
	Pole-Pole	3	2	22.3	1.9	23.2	14.7	12199
	Pole-Dipole	3	2	3.2	4.7	7.9	5.96	5302
	Dipole-Dipole	4	3	5.7	8.9	14.8	23	89125
	Wenner-Schlumberger	4	3	12.6	2.7	15.3	42.8	3246
5	Schlumberger	6	4	27.4	4.3	31.7	16.4	341
	Wenner	4	3	18.4	17.5	35.9	22.6	158
	Pole-Pole	4	3	19.8	3.4	17.3	0.188	604
	Pole-Dipole	3	2	7.7	6.0	13.7	13.7	8591

	Dipole-Dipole	5	3	9.7	10.2	19.9	18.5	47872
	Wenner-Schlumberger	5	4	24.8	11.3	36.1	39.7	3615
6	Schlumberger	5	3	18.1	8.8	26.4	52.7	3292
	Wenner	4	3	13.0	7.4	20.4	16.7	1482
	Pole-Pole	4	3	12.6	5.6	18.2	0.168	617
	Pole-Dipole	4	3	10.5	3.8	14.3	0.293	9811
	Dipole-Dipole	4	3	15.7	8.6	24.3	7.82	31357
	Wenner-Schlumberger	4	3	15.6	11.6	27.2	10.1	4124
7	Schlumberger	5	3	26.0	2.9	29.5	80.4	1103
	Wenner	3	2	19.8	4.6	24.4	6.89	1966
	Pole-Pole	4	2	16.0	2.3	18.3	0.847	337
	Pole-Dipole	3	2	8.8	5.7	14.5	6.05	6372
	Dipole-Dipole	3	2	9.3	5.9	15.2	9.02	46132
	Wenner-Schlumberger	4	3	22.4	4.0	26.4	6.87	4589
8	Schlumberger	4	3	24.3	2.9	27.3	12.7	957
	Wenner	3	2	35.6	0.7	36.3	1.46	305
	Pole-Pole	3	2	21.5	2.8	24.3	0.311	4303
	Pole-Dipole	3	2	26.4	4.2	30.6	9.39	4748
	Dipole-Dipole	4	2	18.5	3.3	21.0	0.277	147122
	Wenner-Schlumberger	4	3	23.6	4.3	27.9	78.2	1701

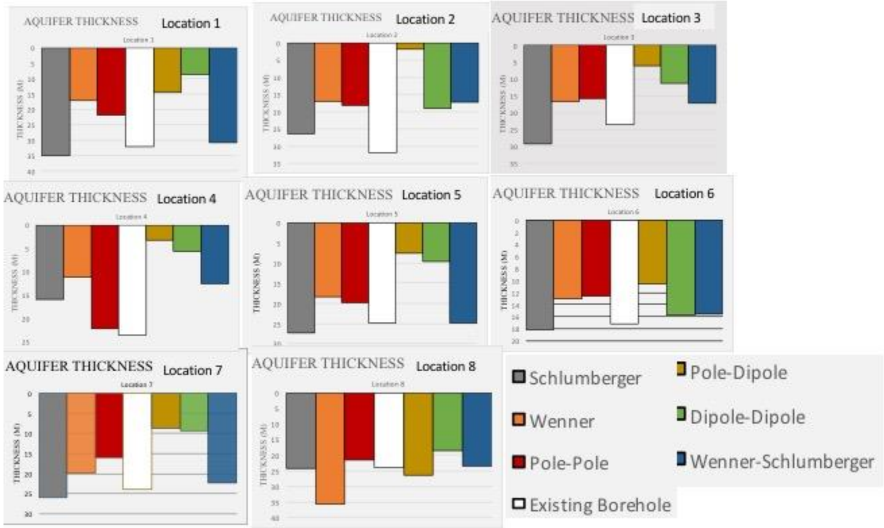


Figure 4: Graphical comparison of the thickness of aquifer layer estimated using the six methods of array and borehole lithologic section.

Comments and Conclusions

Generally, the six classical arrays of traditional four-electrode resistivity survey method are reliable for delineating subsurface geological units. However, some arrays are more accurate than others in terms of the number of geo-electric units, depth to the basement rock and thickness of the aquifer and overburden material delineated when compared to borehole lithologic section. Arising from this study, the results obtained, and observations from the comparison of the different arrays at the eight study locations, comments and conclusions are as follow:

- According to the study, Schlumberger and Wenner-Schlumberger are the best electrode arrays for 1D resistivity survey. The method gave the best estimates of aquifer thickness, overburden thickness, and depth to the basement rock, when compared to borehole lithologic sections.

- Wenner-Schlumberger array is a reasonable alternative to Schlumberger array when good vertical resolution is needed. Wenner-Schlumberger array, according to the study, has the highest penetrating power, it's more sensitive to the horizontal lithological boundary than Schlumberger and other arrays, and it gave reasonable depth of investigation, DOI.

- Comparison among the resistivity method having electrode(s) placed at infinity– the pole -dipole and pole-pole– showed that geo-electric parameters estimated by pole-pole are more accurate than those estimated by pole-dipole. This finding implies that in cases where physical object and engineering construction, constitute an obstruction to the placement of the four electrodes in the vicinity of the target, pole-pole, rather than pole-dipole should be given preference.

- Dipole-dipole, pole-dipole, and Wenner arrays consistently underestimate the number of horizontal layers in most of the study locations. This could be due to poor sensitivity of the methods to vertical variations in resistivity. Therefore, Schlumberger, Wenner-Schlumberger and pole-pole arrays should be given preference when the purpose of investigation is to delineate horizontal stratigraphic layers.

- Comparison of minimum and maximum resistivities among the six arrays across eight locations showed that dipole-dipole array consistently recorded the highest resistivity in all locations while pole-pole and pole-dipole consistently recorded the least resistivity in all locations. Although this is not unconnected with the weight of their geometric factor, it also suggests that pole-pole and pole-dipole array are more reliable for locating targets having subtle resistivity contrast with host-rock.

- An important lesson learnt from the experiment is that none of the survey methods is not 100% accurate when compared with borehole lithologic logs. They either reasonably underestimate or overestimate the dimension of the target layer. Therefore, RMS error in the estimation of ge-electric parameters should be considered in the interpretation. For example, a layer estimated to be 10 m thick with 10% rms error should be interpreted as a having thickness of 9 – 11m (i.e. 10±1m).

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