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ESTIMATING THE DEPTH OF INVESTIGATION IN ELECTRICAL RESISTIVITY SURVEY: LABORATORY MEASUREMENTS

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ABSTRACT
The depth of investigation in geo-electrical resistivity surveys is an important parameter required to make a reasonable interpretation of the measured apparent resistivity. Even though it is generally accepted that the wider the electrode spread the deeper the investigation, no definite relationship has been developed between the depth of investigation and the current electrode spread (AB) for geological formations, especially in Ghana. The most commonly used depth factor for Schlumberger array (AB/2) for example, have been found not to be accurate from field observations. This study, thus, explores the depth of investigation for the Schlumberger and Wenner arrays through a laboratory investigation. A rectangular wooden box filled with compacted silty sand to different depths was placed directly on the natural ground, and the interface between the silty sand and natural ground was investigated through geo-electrical sounding. The vertical electrical sounding curves were inspected for points of conspicuous changes in apparent resistivity, which were attributed to the change from the silty sand to the natural ground interface. Then comparing the known depths of the interface to AB, it was established that, for both the Schlumberger and Wenner arrays, the depth of investigation is about 0.26 of AB (i.e., ~AB/4).

Keywords: Depth of investigation, Vertical electrical sounding, Schlumberger array, Wenner array, Apparent resistivity

INTRODUCTION

The electrical resistivity (ER) method has been used for investigations in several fields including hydrogeology, geotechnical engineering, environmental and archaeological studies. It has proven to be a very viable, quick and cost-effective method for obtaining subsurface information such as fracture and water bearing zones/table (Bernard and Valla, 1991; Helaly, 2017; Metwaly and AIfouzan, 2013;mohamaden et al, 2016) depth to bedrock (Cardarelli and De Donno, 2017; Coulouma et al, 2019; Coulouma et al, 2013; Yadav and Singh, 2007), detection of sinkholes (Metwaly, 2013; Samyn et al, 2014; Van School, 2002; Youssef, 2012) mapping of contaminant plumes (De Lima et al, 1995; Mao et al, 2015; Maurya et al, 2017) and delineation of fresh/salt water contact zones (Mao et al, 2015; Maurya et al, 2017; Youssef et al 2012). In many of the applications of the electrical resistivity method, the depth to targets of interest is very important, and an accurate estimation of the depth can be very critical in some of the investigations.

The depth of investigation (DoI) in the electrical resistivity method is related to the current electrode separation; the wider the current electrodes separation, the deeper the depth of investigation (Ray and Apparao, 1971). However, there appears to be no definite relationship between the DoI and the current electrodes separation, which is a universally acceptable in the geophysics community. Researchers and geophysicists therefore use any of the several existing relationships, AB/2 (Schlumberger and Schlumberger, 1932), 0.125AB (Roy and Apparao, 1971), 0.190AB (Edwards, 1977), 0.192AB (Barker, 1989), with no certainty of which is most suitable for their environment or application. For example, in Ghana, the most common relationship used is the AB/2. Estimation of the depth of investigation from this relationship (DoI = AB/2) has, however, been observed by some practicing geophysicist in Ghana and other tropics with similar formation to be inaccurate when compared with information obtained from drilling logs. Gomez-Trevino and Esparza (Gomez-Trevino and Esparza, 2014) queried the use of AB/2 or AB/3 (Fröhlich, 1967; Keller, 1966; Zhody, 1969) as the depth of investigation in their study of the use of electrical resistivity methods for deeper depth investigations.

The inability to accurately estimate the DoI within local geological formations may limit the usefulness of the electrical resistivity method since targets of interest in the subsurface may be missed. This study therefore seeks to determine the depth factor for the two most commonly used electrical resistivity arrays (i.e., Schlumberger and Wenner) in hydro-geophysical studies; specifically in estimating the overburden thickness of geological formations in Ghana. Being able to accurately estimate the overburden thickness in such studies will help in planning for a drilling project -e.g., deciding the total length of temporal casing needed for the completion of borehole drilling, the maximum depth to drill, and the overburden thickness as related to groundwater availability.

Concept of depth factor in electrical resistivty survey

The depth factor in electrical resistivity survey can generally be considered as a factor which transforms a distance measured along the ground surface into a significant depth. Thus, the DoI in electrical resistivity survey may be given by the product of the depth factor and for instance, the current electrodes separation. Barker ,(1989) and Bernard, (2003) noticed that, apart from the current electrodes separation, the DoI also depends on the spacing between the receiving potential electrodes spread (MN)

According to Evjen (1938), the DoI may be considered to be the depth that exactly half of the total current injected penetrates to or below that depth. Evjen, (1938), again, indicated that the depth of penetration of the current depends on the distribution of the electrical properties of the ground with depth. For example, when a perfectly conducting layer is present in the ground, no current penetrates below this layer, and the depth of penetration does not exceed the depth to this conducting layer. Similarly, when there is variability in the resistivity of the ground, the depth of penetration of the current will depend on this variation. For alternating current, the depth of penetration also depends on the frequency of the exploring current. Edwards [9] also states that the depth of penetration of the current is directly proportional to the current electrode spacing.

Sharma (1986) however, indicated that the actual depth of penetration of the current depends on (a) the power of the current source, (b) sensitivity of the array type to near surface inhomogeneities, (c) the resistivity contrasts between the surface layer and substratum and (d) degree of electrical anisotropy of the layered media. It appears the depth factor has not been determined empirically by correlation with well logs. There are, however, shortcomings that may arise, as the resistivity may change somewhat along the surface of the ground, and such change, unless properly balanced out, often will give rise to bigger and more sharply defined fluctuations in the apparent resistivities than any change in the real resistivity with depth could possibly give.

Also, even if the depth factor has been properly determined by empirical or some other means at one location, there is no guarantee that the factor will be applicable in other locations (Evjen 1938); like different geological units. From earlier findings and as indicated by Evjen (1938) there may be no universal depth factor given as a fraction of the electrode spread. However, the depth factor method of analysis is simple to use and interpret, and therefore, very desirable from the practical point of view. It is therefore imperative to establish the appropriate depth factor that will be suitable for use especially in the geological formations found in Ghana.

MATERIALS AND METHODS

The study was aimed at determining the appropriate depth factor for electrical resistivity measurements, especially in hydrogeophysical studies, specifically for estimating the overburden thickness of geological formations in Ghana. A laboratory setup was designed to simulate an overburden of varying thicknesses overlying a bedrock. A wooden box, of dimensions 100 x 240 x 110 cm^3, was placed over a compacted natural ground as shown in Figure 1. The box was filled with homogeneous silty sand material to varying depths from 25 to 75 cm at an interval of 5 cm, which represented varying overburden thicknesses. For each depth of placement, vertical electrical soundings were conducted about the central point on the surface of the filled soil material using the ultra MiniRes resistivity equipment. Both the Schlumberger and Wenner arrays were utilized for the electrical resistivity measurements.

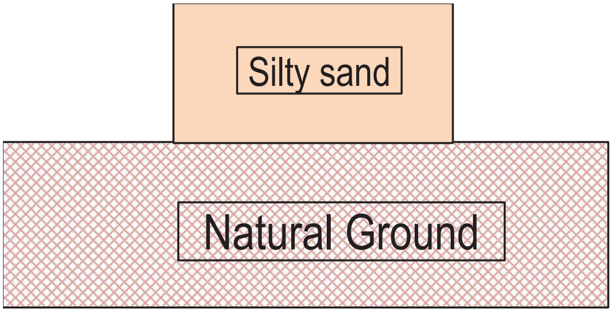

Figure 1: Schematic representation of the experimental set up at the laboratory

For the Schlumberger array measurements, a constant potential electrode separation (MN) of 20cm was used while the current electrode spacing (AB) was increased from 30cm to 230cm at 10cm intervals. The Wenner array measurements were started with electrode spacing *'a'* of 10cm (AB of 30cm) and successively increased by 10cm to a maximum of 70cm. It is expected that the transition or interface between the silty sand material and the natural ground will be clearly marked by the resistivity signatures; this information may then be used to estimate the depth of investigation. For each thickness of placed soil material (overburden) above the natural ground surface, the AB at which the distinct change in resistivity occurs is determined. This value is compared with the thickness of the placed material, which is referred to as the depth of investigation. This was done for all the thickness of the placed material and the results tabulated and plotted in MS Excel® as "Depth *versus AB*".

Effect of moisture and potential electrode spacing on measured apparent resistivity values

To ensure that results obtained from this study is applicable under different field conditions the effect of moisture and potential electrode spacing (MN) on the measured resistivity values were explored. Resistivity measurements were first measured with the setup prepared at an average moisture content of 10%. The soil was then left exposed to the atmosphere for about 24 hours reducing the moisture to about 6%, and the resistivity measurements repeated. It was observed from the results (Figure 2) that, though the apparent resistivity values changed for the different moistures, the trend in terms of the variation in resistivity with depth did not change for both conditions.

Similar results were obtained when different potential electrode separations (MN of 20 and 30 cm) were used. Again, the measured apparent resistivity values changed but the trend remained the same (Figure 3).

RESULTS AND DISCUSSION

For each depth of placement (i.e., overburden thickness), the variations of apparent resistivity with current electrode separation was investigated for both the Schlumberger and Wenner arrays. As shown in Figure 4, resistivity was found to decrease with depth till an AB value of 130 cm, after which the resistivity values began to increase. The noticeable change in the apparent resistivity from low to high values is attributed to the transition from the placed soil material into the natural ground. The AB value obtained at this transition point is compared to the thickness of the placed soil material. Similar AB values, representing change in apparent resistivity from low to high values, for each depth of soil placement is determined.

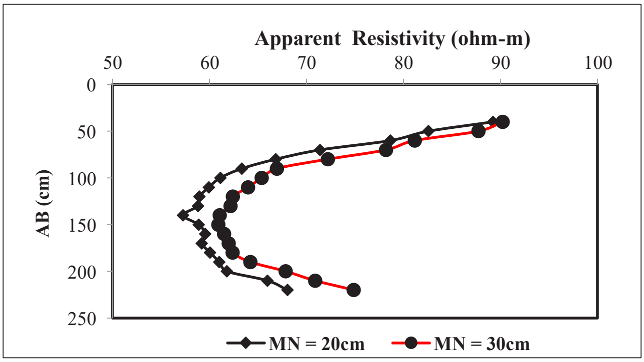

Figure 2: Effect of MN separation on apparent resistivity

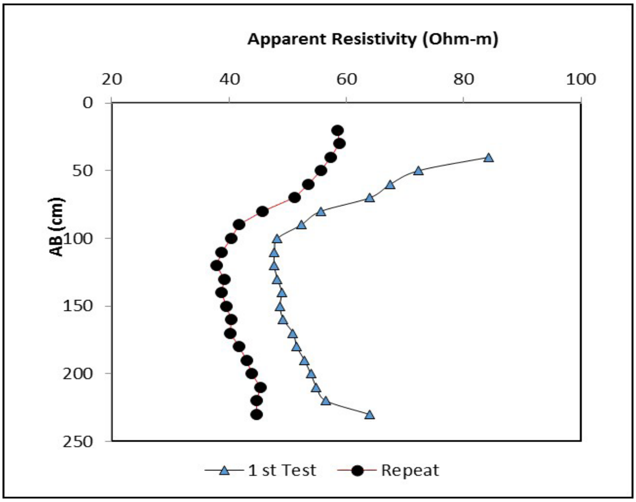

Figure 3: Apparent Resistivity curves (Schlumberger) for depth of 25 cm

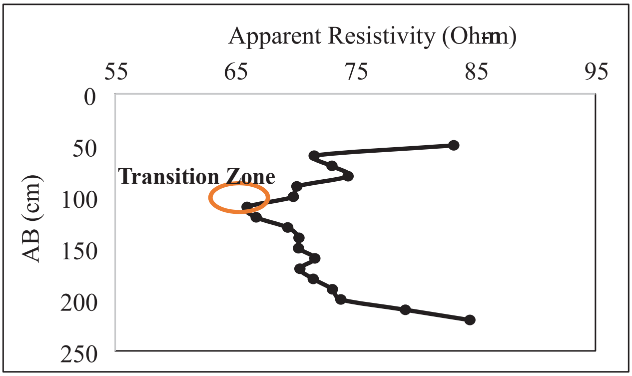

Figure 4: Typical anomaly showing the transition zone in a Schlumberger array

The determined transitional AB values were plotted against the depths of soil placement (Figure 5). In fitting an equation to the data in the plot two scenarios were explored –one in which the line is forced through the origin and the other in which the mathematical best fit is used. Both scenarios show a remarkable relationship between the depth to the interface and transitional AB.

As expected, the results of the Wenner array did not show any significant difference from the Schlumberger array; however, the DoI to AB ratio changes with depth in the Schlumberger is similar to that of Wenner. Again, in the fitting an equation to the data for the Wenner array (Figure 6) the two scenarios were considered and both show a remarkable relationship between the depth to the interface and AB similar to the Schlumberger.

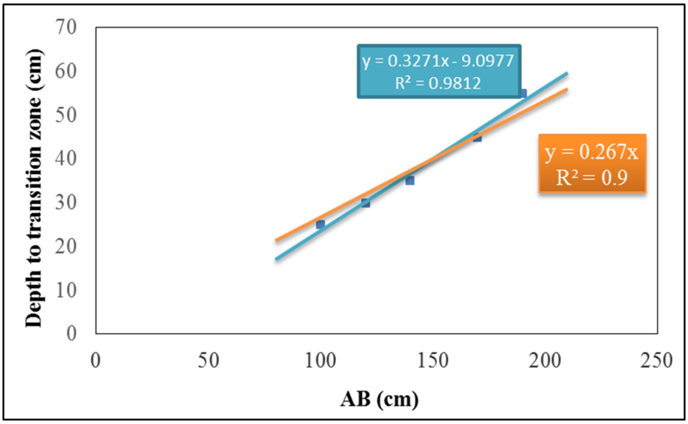

Figure 5: Depth of investigation versus current electrode spacing (AB) using the Schlumberger array

Choosing the second scenario, the relation for the Wenner may be expressed as DoI = *0.258AB*. The depth of investigation to current electrode separation ratios for both the Wenner (0.258) and Schlumberger (0.267) arrays may be conveniently taken as 0.26 for ease of calculation.

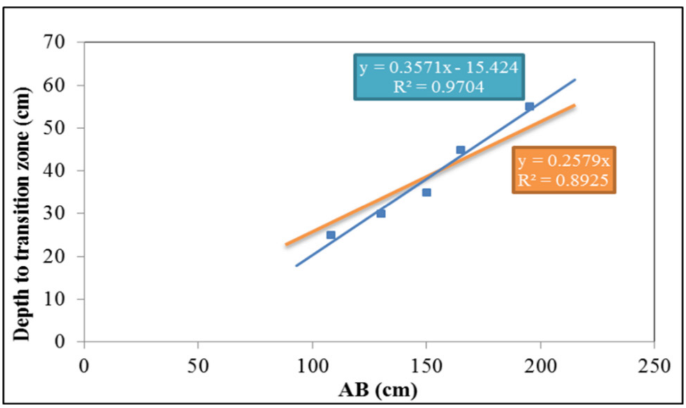

Figure 6: Depth of investigation versus current electrode spacing (AB) using the Wenner array

Assessment of Estimated Depths factors

The Schlumberger array has been used by the authors in geo-electric resistivity siting for point source groundwater supply systems in Ghana, particularly in the Ashanti Region (Jonas et al, 2016; Manu et al, 2019). In assessing the accuracy of the estimated DoI from the laboratory measurements, field data of twenty-seven (27) drilled borehole geological logs were used. The depths to bedrock at these locations were also estimated from resistivity profiles using the various depth factors suggested by earlier researchers and one from this study (Barker, 1989; Schlumberger and Schlumberger, 1932; Roy and Apparao, 1971). Figure 7 shows a typical example of the actual bedrock depth and the estimates of bedrock depth using the various depth. In this particular example, the transition zone (depth to bedrock) was considered to be where the apparent resistivity suddenly changed from an average of 392 Ωm to 674 Ωm.

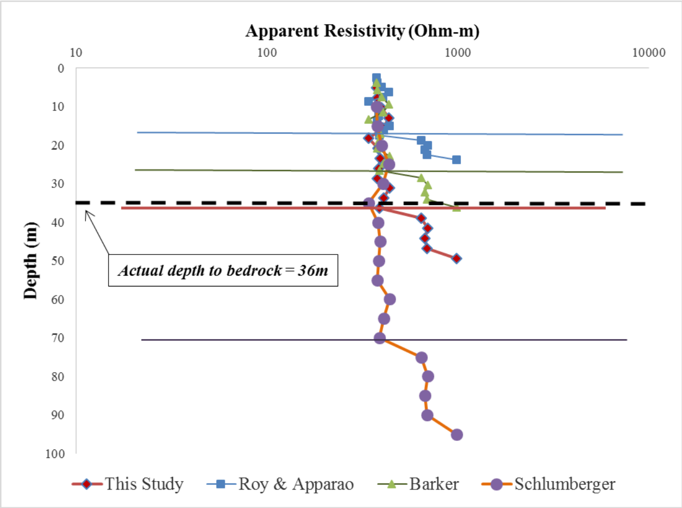

Figure 7: A comparison of estimated depth to bedrock (VES curves) using different depth factors and actual depth to the bedrock from the borehole logs

Table 1 shows a comparison of estimated overburden thickness for some 27 borehole logs and the actual overburden thickness from the various depth. Their deviations of the estimated depths from the actual were quantified, using the sum of squared errors (SSE). The SSEs show distinctively that the use of AB/2 (Schlumberger and Schlumberger, 1932) over estimates the depth of investigation; the closest of the four depth factors to the actual is 0.26 found in this study, with SSE of 0.69.

In fact, when the Voltaian is excluded –i.e. considering only the crystalline basement rocks (granitoids and metasediments of the Birimian), there is a significant reduction in the error of prediction (SSE = 0.54). It is also important to note that the apparent resistivity values were picked at AB intervals of 10m and therefore using the depth factor of 0.26AB, means the sampling interval is 2.6m (about 3m). In comparison with drilling geological logs, the actual depth to bedrock can be known to within 1m accuracy. Thus, the SSE of 0.69 using the depth factor obtained from this study is actually less than half the resistivity sampling interval (1.3m), which makes the prediction very good.

Table 1: Comparison of overburden thicknesses (drill log data) with estimated overburden from the different depth factors

Community	Geology	Act.	Schlumberger		Roy & App		Barker		This Study	
		Log, m	Est.	SSE	Est.	SSE	Est.	SSE	Est.	SSE
Pakoso	Granitoids	30	50	400	12	324	19	121	29	1
Boankra	Granitoids	7	20	169	4	9	8	1	10	9
Appiadu	Granitoids	36	50	196	17	361	27	81	36	0
Fumasua	Granitoids	18	25	49	7	121	10	64	20	4
Fumasua 2	Granitoids	12	25	169	6	36	10	4	10	4
Kotei	Granitoids	30	40	100	10	400	15	225	29	1
Nsenia	Granitoids	21	35	196	8	169	13	64	20	1
Emena	Granitoids	26	35	81	10	256	14	144	20	36
Deduako	Granitoids	15	35	400	7	64	13	4	17	4
Aprabo	Granitoids	25	50	625	13	144	20	25	25	0
Apemso	Granitoids	30	45	225	11	361	15	225	25	25
Okyerekrom	Granitoids	32	50	324	13	361	21	121	32	0
Pruso	Granitoids	25	50	625	13	144	20	25	25	0
Trede	Metasedi-ments	18	25	49	6	144	10	64	18	0
Donaso	Metasedi-ments	32	50	324	13	361	20	144	26	36
Kokoben	Granitoids	23	50	729	13	100	19	16	18	25
Anwomaso	Granitoids	27	45	324	11	256	17	100	26	1
Krapa2	Granitoids	24	45	441	11	169	17	49	26	4
Abofo	Granitoids	25	30	25	8	289	11	196	26	1
Kotoku	Granitoids	11	25	196	6	25	10	1	10	1
Aboaso	Granitoids	30	35	25	9	441	13	289	29	1
Pakoso(2)	Granitoids	25	50	625	13	144	19	36	26	1
IDL	Granitoids	22	55	1089	10	144	15	49	21	1
Boubang	Granitoids	18	45	729	11	49	17	1	23	25
Rubi	Granitoids	6	15	81	4	4	6	0	8	4
SSE				**3.62**		**2.79**		**1.81**		**0.54**
	Voltaian	6	20	196	5	1	8	4	12	36
	Voltaian	10	35	625	8	4	15	25	22	144
				3.35		**2.36**		**1.58**		**0.69**

The non-linear correlation coefficient was also used to assess the prediction efficiency of the various depth factors, compared with the measured depth, using the relationship:

$$E = 1 - \frac{\sum(m_i - c_i)^2}{\sum(m_i - \bar{m})^2}$$

Where, E is the prediction efficiency, m_i the actual borehole log depth, c_i the estimated depth and m the average of actual depths. Table 2 shows the data and the results of the efficiency test. It can be observed that, whilst the suggested factor of 0.26 AB compares favourably (about 81%) with the actual borehole records, all the other three ratios do not predict depths that correlate well with the actual determined overburden thicknesses; the Schlumberger factor being the least efficient.

Table 2: Comparison of prediction efficiency for the different depth factors assessed with the non-linear least-squares regression coefficient.

		This Study		**Schlumberger**		**Roy & App**		**Barker**	
m	$(m - \bar{m})^2$	*c*	$(m - c)^2$	*c*	$(m - c)^2$	*C*	$(m - c)^2$	*c*	$(m - c)^2$
30	70.1	29	1	50	400	12	324	19	121
7	214.0	10	9	20	169	4	9	8	1
36	206.5	36	0	50	196	17	361	27	81
18	13.2	20	4	25	49	7	121	10	64
12	92.7	10	4	25	169	6	36	10	4
30	70.1	29	1	40	100	10	400	15	225
21	0.4	20	1	35	196	8	169	13	64
26	19.1	20	36	35	81	10	256	14	144
15	44.0	17	4	35	400	7	64	13	4
25	11.4	25	0	50	625	13	144	20	25
30	70.1	25	25	45	225	11	361	15	225
32	107.5	32	0	50	324	13	361	21	121
25	11.4	25	0	50	625	13	144	20	25
18	13.2	18	0	25	49	6	144	10	64
32	107.5	26	36	50	324	13	361	20	144
23	1.9	18	25	50	729	13	100	19	16
27	28.8	26	1	45	324	11	256	17	100
24	5.6	26	4	45	441	11	169	17	49
25	11.4	26	1	30	25	8	289	11	196
11	113.0	10	1	25	196	6	25	10	1

30	70.1	29	1	35	25	9	441	13	289
25	11.4	26	1	50	625	13	144	19	36
22	0.1	21	1	55	1089	10	144	15	49
18	13.2	23	25	45	729	11	49	17	1
6	244.3	8	4	15	81	4	4	6	0
6	244.3	12	36	20	196	5	1	8	4
10	135.2	22	144	35	625	8	4	15	25
21.6	**1930.3**	∑	**365**	∑	**9017**	∑	**4881**	∑	**2078**
	Efficiency	***0.81***		***-3.67***		***-1.53***		***-0.08***	

CONCLUSION

This study shows that with the Schlumberger and Wenner arrays, there may be a relationship –albeit empirical- between the depth of investigation (*DoI*) and current electrode spacing (AB), the depth is approximately twenty-five (25) percent of AB.

This depth factor **(0.26)** used in estimating the overburden thickness from geo-electric resistivity (Schlumberger array) surveys compares favourably with field data obtained from the water supply borehole logs that were subsequently drilled. The commonly used **0.5**AB appears to overestimate the depth of investigation. Three other depth factors which were studied -0.125AB 0.192AB and 0.19AB were also found to underestimate the depth, albeit not as much as the common AB/2.

During the study, a limited investigation of the effect of MN -the potential electrode separation- was done for two apertures of 20 and 30 cm. The results show that, the wider aperture gave higher apparent resistivity values; however, the signatures were similar, suggesting that the estimation of the depth of investigation may not be significantly affected by the potential separation.

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FINANCIAL INTEREST

The authors have no relevant financial interests to disclose.

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