RESEARCH ARTICLE OPEN ACCESS

DETERMINATION OF HYDROGEOLOGICAL PARAMETERS FROM VERTICAL ELECTRICAL SOUNDING

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Abstract:

Vertical electrical sounding (VES), a fast, efficient and cost-effective surface geophysical investigation tool has been successfully applied to probe and characterize the subsurface at a study location within the permanent site of the University of Port Harcourt, Nigeria. The aquifer was clearly delineated at the two sounding points where the soundings were executed. The Dar-Zarrouk parameters were computed from the measured resistivity values, from which critical hydrogeologic parameters were estimated using established empirical and mathematical relations. The study clearly corroborates earlier reports on the reliability of the VES for hydrogeological investigation and subsurface characterization.

Keywords: vertical electrical sounding, Dar-Zarouk parameters, subsurface characterization, transverse resistance.

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I. INTRODUCTION

Surface geoelectrical measurements were carried out at a location within the Permanent site of the University of Port Harcourt to characterize the area and determine some fundamental geoelectrical and hydrogeological parameters. Vertical electrical sounding (VES) technique was adopted. The VES survey program was part of the preliminary site investigation activities performed to acquire baseline hydrogeologic information of the area in an ongoing study whose primary aim is to non-invasively investigate pollutant transport characteristics of the study area.

VES is a one-dimensional (1-D) surface resistivity technique used typically to delineate vertical discontinuities in the electrical properties of the subsurface. Like other surface electrical resistivity surveying techniques, its operation is based on the principle that the distribution of electrical potential in the ground around a current-carrying electrode depends on the electrical resistivity distributions of the surrounding soils and rocks.

The conventional field practice in VES involves applying direct current (dc) or low frequency alternating current (ac) between two metal stakes (known as electrodes), implanted in the ground and then measuring the resulting difference in potential between two other electrodes that do not carry current, known as the potential electrodes. Usually, the potential electrodes are in line between the current electrodes, but in principle, they can be located anywhere (Figure 1). The current used is either direct current, commutated direct current (i.e., a square-wave alternating current), or AC of low frequency, typically about 20 Hz.

The distribution of potential can be related theoretically to ground resistivities and their distribution for some simple cases, notably, the case of a horizontally stratified ground and the case of homogeneous masses separated by vertical planes. For other kinds of resistivity distributions, interpretation is commonly done by qualitative comparison of observed response with that of idealized hypothetical models or on the basis of empirical methods.

The VES technique can be applied independently or in conjunction with other geophysical and non-geophysical methods to delineate subtle subsurface features. A number of researchers have indeed predicted some aquifer hydraulic properties from these surface electrical measurements (Kelly, 1977; Niwas and Singhal, 1981; Onuoha and Mbazi, 1988; Mbonu, *et al.,* 1991; Ehirim and Nwankwo, 2010; Majumdar and Das, 2011). The methods have also been applied in structural and hydrological investigations (Stewart, *et al*., 1983; Yadaf and Abolfazli, 1998) as well as in ascertaining the vertical distribution of water bearing zones contributing to aquifer bodies (Majumdar and Das, 2011).

Typically, interpreted results of VES furnish information on resistivities and thicknesses of different layers at the

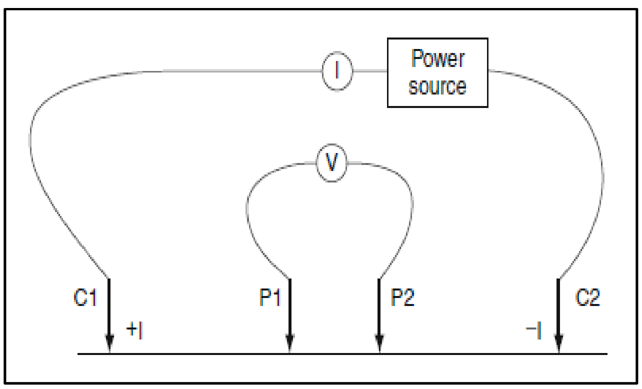

Figure 1: Schematic diagram for the basic setup for an electrical resistivity survey. The current is injected into the ground through the C1 and C2 electrodes, and the resulting voltage difference is measured by the P1 and P2 electrodes.

sounding point. For this reason, the method is most useful for investigation on horizontal or nearly horizontal stratified earth. This, though, is considered a limitation of the vertical electrical sounding method, as some parts of the earth from which information may be sought through VES are not laid out in horizontal layers. In the VES method, the spacing of the current electrode is gradually increased symmetrically, keeping the centre of the electrode system fixed. As a result, the current is made to penetrate deeper and deeper layers and the apparent resistivity is measured for each current electrode separation to find the variation of apparent resistivity as the current electrode spacing increases (Bhattacharya and Patra, 1968; Koefoed, 1979).

2. GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

The University of Port Harcourt, within which the study area lies, is located within the Niger Delta region of Southern Nigeria (Figure 2). The area is underlain by the Tertiary Niger Delta Benin Formation. The Benin Formation consists of massive, unconsolidated, permeable and highly porous fresh water bearing sandstones with minor intercalations of clay (Reyment, 1965). Being water-bearing, it serves as the main source of potable water for both domestic and industrial use within the Niger Delta region (Ehirim *et al*., 2015).
Structurally, the sediments in the area are deposited in the NW-SE trend and groundwater flow occurs inline with this trend. However, local variations occur in places due to the anisotropic character of the sediments. Rainfall is significant most months of the year, particularly between the months of March and November. Dry season lasts for a few months between late November and early March, the effect of which is relatively minimal in comparison with the predominantly wet season. Accordingly, the climate of the region is considered to be *Am* according to the Köppen-Geiger climate classification scheme (Essien and Ehirim, 2019).

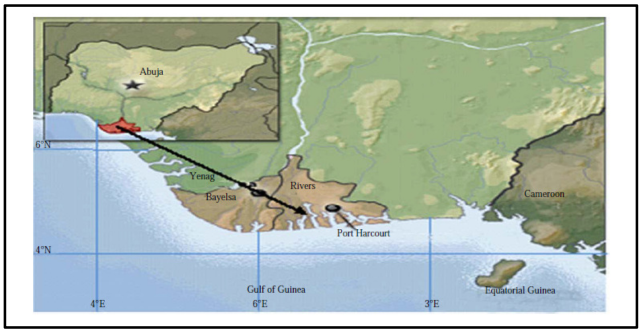

Figure 2: Location map of study area

3. THEORETICAL BASIS

The theoretical basis for the use of geoelectrical methods for hydrogeological investigations is dependent on the existing analogy between fluid flow and electric current flow. Fluid flow follows from Darcy's Law which gives the relationship between the quantity of water discharged per unit time as a function of hydraulic conductivity, cross-sectional area and hydraulic head as:

$$Q = KAI \quad (1)$$

where K is the hydraulic conductivity, A the total cross-sectional area through which the water percolates and I is the hydraulic gradient.

On the other hand, the differential form of Ohm's law for current flow is given as:

$$J = \delta E \quad (2)$$

where J is the current density, δ the conductivity (inverse of resistivity) and E the electric field intensity.

On the basis of the foregoing, a number of researchers realized that aquifer parameters obtained from existing borehole locations could be integrated with subsurface resistivity parameters extracted from resistivity measurements to derive correlations which would be effective in obtaining hydrogeologic parameters in similar geologic environments where borehole information do not exist (Niwas and Singhal, 1981; Ekwe, *et al*., 2006; Zohdy, 1976).

In this study, surface geoelectrical measurements (vertical electrical sounding) were conducted at two sounding points within a marked-out area to determine some fundamental geoelectrical properties and to furnish information on the suitability of the area for the ongoing study on pollutant transport monitoring.

Schlumberger array, being the most commonly employed array configuration type in vertical electrical sounding surveys was adopted. The Schlumberger array consists of four electrodes placed in line around a common midpoint (Figure 3). The outer two electrodes (A and B) are current (source) electrodes, while the inner two electrodes (M and N) are the potential (receiver) electrodes. The potential electrodes are installed at the centre of the electrode array with a small separation, typically less than one fifth of the spacing between the current electrodes.

The apparent resistivity, ρ_a, for the Schlumberger array is expressed in terms of the inter-electrode spacings (Figure 3) as:

$$\rho_a = \frac{\pi\left(\frac{S^2-a^2}{4}\right)}{a}\frac{\Delta V}{I} \quad (3)$$

where ΔV is the potential difference and I is the current.

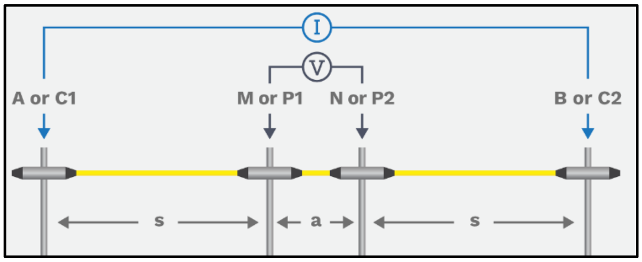

Figure 3: Schlumberger array configuration (modified after Morrison and Gasperikova, 2012)

4. DETERMINATION OF HYDRAULIC PARAMETERS FROM GEOELECTRIC MEASUREMENTS

The thickness and resistivity of geoelectric layers can be combined into single variables of transverse resistance (R) and longitudinal conductance (S) known collectively as the Dar-Zarouk parameters. The Dar-Zarouk parameters can be used as a basis for the evaluation of aquifer properties such as transmissivity and protective capacity of the overburden rock materials (Ehirim and Nwankwo, 2010; Ekwe et al., 2006; Mbonu, et al., 1991; Kelly, 1977).

If we consider a homogenous, isotropic and horizontally-layered geologic unit (Figure 4), the Dar-Zarouk parameters are computed as:

$$R = \sum_{i=1}^{n} h_i \rho_i \qquad (4)$$

and

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \sum_{i=1}^{n} h_i \sigma_i \qquad (5)$$

where h_i, $\rho_i$and $\sigma_i$are the thickness, resistivity and conductivity of the *i*th layer respectively. Aquifer transmissivity (T), a crucial hydraulic property, which measures the ability of the aquifer to transmit groundwater throughout its entire saturated thickness, is expressed as:

$$T = Kh \qquad (6)$$

where K is the hydraulic conductivity and K is the entire aquifer thickness.

Kelly (1977), Mbonu*et al*. (1991), Hubbard and Robbin (2005) and Ehirim and Nwankwo (2010) reported that for clean saturated aquifers whose natural fluid characteristics are fairly constant, the hydraulic conductivity is proportional to the resistivity of the aquifer. Thus, in the absence of a pumping test data, the aquifer hydraulic conductivity can be approximated to the true resistivity of the aquifer derived from geoelectric investigation. This can be numerically expressed as

$$T = Kh = \rho h \qquad (7)$$

Equation (7) shows that the product of hydraulic conductivity and aquifer thickness, known as hydraulic transmissivity, T, is equivalent to the product of resistivity and aquifer thickness, referred to as transverse resistance, R:

$$T = R \qquad (8)$$

Ehirim and Nwankwo (2006) further reported that the protective capacity, Pc, of the overburden layer of an aquifer is proportional to its longitudinal conductance. The longitudinal conductance gives a measure of the impermeability of a confining clay/shale layer. Such layers have low hydraulic conductivity and low resistivity.

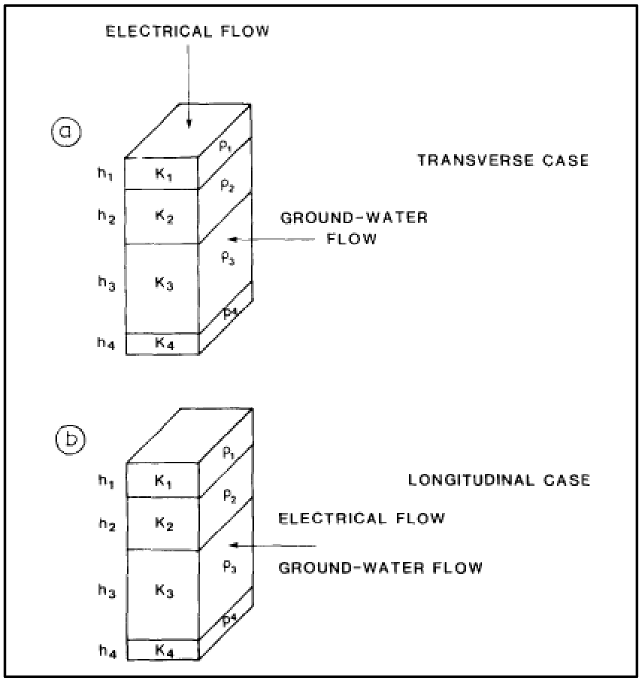

Figure 4: (a) Layered model transverse case (b) Layered model longitudinal case (Modified from Kelly and Reiter, 1984)

5. MATERIALS AND METHOD

Schlumberger vertical electrical sounding was carried out at two points within the marked-out location in the study area with a maximum current electrode spacing of 200 metres (AB/2 = 100m). ABEM terrameter SAS 300B was used in the data acquisition. For each measurement, the current electrodes (A and B) were moved outward to a greater separation throughout the survey, while the potential electrodes (M and N) stayed in the same position until the observed voltage became too small to measure (Keller, 1966; Sherma, 1997),at which point the potential electrodes were moved outward to a new spacing. As a rule of thumb, the reasonable distance between M and N was kept equal or less than one-fifth of the distance between A and B at the beginning.

The measured resistance values R (Ω) at each sounding point were converted to apparent resistivity values ρ_a(Ωm) using the appropriate geometric factor as expressed in equation (3). The resistivity Sounding curves were then generated and interpreted by 1D inversion technique using IPWIN proprietary software.

6. RESULTS AND DISCUSSION

The results of the VES surveys show that five interpretable geoelectric sections were delineated at each of the two locations (VES1 and 2) as shown in Table 1 and in Figures 5a and 5b. The observed trend in

TABLE I
LAYER PARAMETERS OF THE VERTICAL ELECTRICAL SOUNDING SECTIONS (VES 1 AND 2)

VES Location	No. of layers	Layer no.	Apparent resistivity (m)	Depth (m)	Layer thickness (m)
1	5	1a	313.00	1.96	1.96
		1b	606.20	5.88	3.92
		1c	1197.00	20.40	14.52
		1d	343.60	52.7	32.30
		1e	193.60	-	-
2	5	2a	197.50	1.97	1.97
		2b	496.20	5.73	3.76
		2c	980.20	21.40	15.67
		2d	246.20	53.76	32.36
		2e	152.30	-	-

apparent resistivity values at VES Location1 was an initial increase in apparent resistivity with depth to a maximum value in the third layer (1197 Ωm), before a decrease in value with depth set in and continued till the last delineated layer. A similar trend was observed at the second location (VES 2) but with slightly lower values for each corresponding layer. Based on the observed results and apriori information of the local geology of the area, a geolectric section was constructed as shown in figure 6. The two locations showed similar lithology. The third layer at each of the two locations is interpreted to be the aquifer with average thickness of 20.4 and 21.4 metres respectively. The apparent resistivity values at the zones stand at 1197 and 987.2 Ωm respectively. The transverse resistance (from which the transmissivity of the aquifer can be approximated from the relations in Equations 4, 7 and 8) at VES 1 location is 17380 Ωm^2. At VES 2 Location, the transverse resistance value stands at about 15360 Ωm^2. Hydraulic conductivity can be similarly derived and approximated from the true resistivity value as expressed in Equation 7 (Ehirim and Nwankwo, 2010). The resistivity values are 1197 Ωm and 980 Ωm respectively at the VES 1 and VES 2 sounding points.

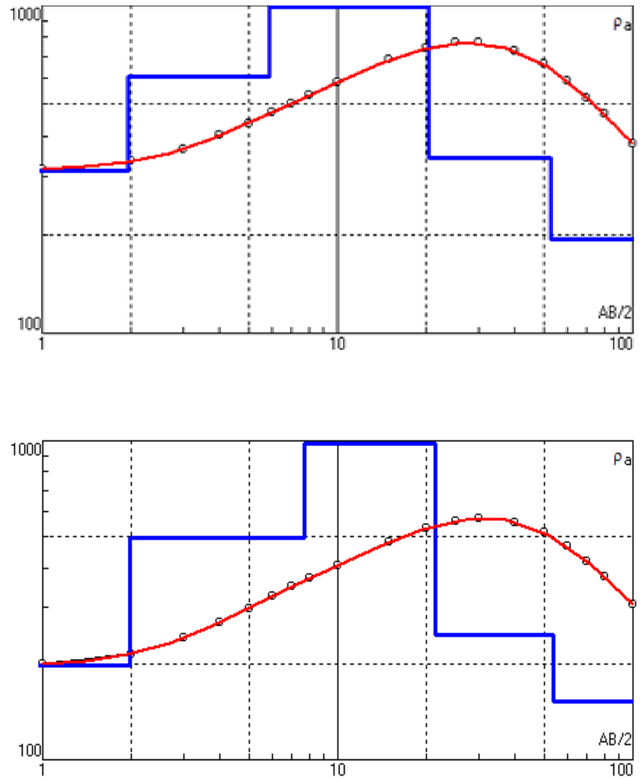

Fig. 5: Type curves for VES 1 and 2

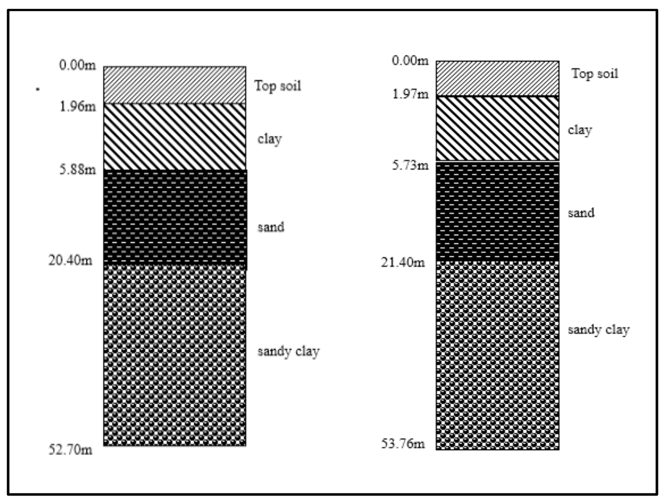

Figure 6: Interpreted geoelectric sections for VES 1 and 2

7. CONCLUSION

Vertical electrical sounding (VES) was successfully used to characterize the subsurface and determine some hydrogeologic properties at the study location. Results of the sounding revealed several subsurface layers and provided data for estimating some essential aquifer properties, which otherwise could only have been determined from pumping data, which is a rather expensive technique for hydrogeological investigations. The study lends credence to the reliability of surface geoelectric measurement as a fast, reliable and cost-effective tool for subsurface investigation and characterization.

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