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Estimating Depth of Investigation in Electrical Resistivity Survey from Laboratory Measurements

by

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MASTER OF SCIENCE

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DECLARATIONS

I declare that I have wholly undertaken the study reported herein under supervision, except for references made from some past students‟ works and other people that I have acknowledged; this thesis presented is a result of my own investigations.

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SUPERVISOR'S DECLARATION

I declare that I have supervised the student in undertaking the study reported herein and I confirm that the student has my permission to present it for assessment

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ABSTRACT

The depth of investigation in geo-electrical resistivity surveys is an important physical parameter required to make a reasonable interpretation of the measured apparent resistivity. Even though it is generally agreed that the wider the spread the deeper the investigation, no definite relationship has been established between the depth of investigation and the electrode spread (AB). Different depth factors have been proposed by researchers; the most commonly used is AB/2, proposed by the Schlumberger brothers. However, field observations do not support this. This work is a laboratory study of the depth of investigation in some commonly used electrode configurations in resistivity surveys (i.e. Schlumberger, Wenner and Dipole-Dipole). A rectangular wooden box filled with silty-sand was placed directly on the ground, and the interface between the sand and the natural ground was investigated. The three array types were each used to sound for the interface while varying the depth of sand above the ground. The 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 surface. 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). This seems to compare favourably with field data and some of the results obtained by earlier researchers. However, the results from the dipole-dipole test did not appear to show any clear and consistent anomaly for the interface; this could be the result of insufficient dipole separation.

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GLOSSARY

A	Cross sectional area
AB	Current electrode spread
Bgrd	Background data
G	Geometric factor
I	Current
K	Geometric coefficient
MN	Potential electrode spread
r	Radial distance of potential electrode from current source
R	Resistance
$\square_a$	Apparent resistivity
V	Potential difference
VES	Vertical electrical sounding
HEP	Horizontal electrical profiling

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Electrical resistivity surveys have been applied in hydrogeological, geotechnical and environmental studies over the past 60 years (Reynolds, 1998). In hydrogeological investigations for example, the electrical resistivity method has proven to be a viable and cost effective method of obtaining subsurface information about aquifer zones, water table and bedrock surfaces, and in the detection of freshwater-saltwater interfaces (Muchingami et al., 2012; Meena, 2011). However, the depth of investigation has always been in contention. It is generally accepted that, the depth of investigation increases as the current electrode spread (AB) increases, but the exact relationship between the electrode spread and depth of investigation is still under investigation. Different authors have given different relations or ratios between AB and the depth of investigation –e.g. Schlumberger and Schlumberger, 1932; Roy and Apparao, 1971; Edwards, 1977and Barker, 1989. These still do not correlate well with field observations, and this work seeks to continue the investigation to provide a good estimate of the depth of investigation.

1.2 PROBLEM STATEMENT

In many engineering and environmental applications, the depth to certain features can be very critical in the investigations. For example, in geotechnical engineering the depth to bedrock or competent formation, water table, fracture zone, etc., are all very important parameters for foundation design. In groundwater exploitation knowledge of the overburden thickness, the depth to water-bearing zones and fractures are essential, and are expected to be obtained from exploration results. Unfortunately, the correlation between resistivity and drilling logs still remains a big challenge. However, if the geoelectrical resistivity method would be useful in these practical areas, then the prediction of depth of investigation must be reasonably accurately.

The inability to accurately determine (the depth) where a geo-electric signal is coming from may limit the usefulness of resistivity data. In fact, the depth factor to use in the interpretation of resistivity data is being debated among many geophysical engineers. In Ghana, where AB/2 (Schlumberger & Schlumberger, 1932) is the most common depth factor used, personal conversation with Dr Bukari Ali (2015) reveals that, this ratio has not always been consistent with the drilling logs from boreholes.

The depth of investigation in electrical resistivity surveys is important in several fields including groundwater exploration and exploitation, where information about depth to bedrock may be needed to decide the total length of temporal casing for the completion of borehole drilling. Depths to fracture zones are also needed in deciding the maximum depth to which the well may be drilled and/or stopped if the borehole appears dry.

The electrical resistivity method is also finding increasing use in geotechnical site investigation where the depths and/or thicknesses of subsurface layers are of great interest (Sudha et al., 2009; Sudduth et al., 2005; Giao et al., 2003; Abu-Hassanein et al., 1996). In environmental geophysical investigations, for example in the mapping of the extent of contamination plume travel, knowledge about the depth of investigation is required to give a reasonably accurate prediction of the depth of penetration. Electrical methods together with other geophysical methods (e.g. magnetic and gravity) have also been utilized in environmental investigations such as in delineating the extent of contamination plumes (Greenhouse & Harris, 1983), location of sinkholes (Van Schoor, 2002) and detection of geothermal resources (Hersir & Flóvenz, 2013).

At any given time, electrical resistivity method investigates the resistivity at a given point (i.e. depth) below the ground-surface. The commonly assumed depth of investigation is half or one third of the current electrode spread -i.e. AB/2 or AB/3 (Zhody & Jackson, 1969; Fröhlich, 1967; Keller, 1966), which have recently come under critical scrutiny (Gómez-Treviño & Esparza, 2014). In this research, the concern is to determine the actual depth investigated and its relationship with the current electrode spread -i.e. AB

1.3 OBJECTIVE OF THE RESEARCH

The main objective of the research is to estimate the depth of investigation in electrical resistivity survey using laboratory experiments. The specific objectives are to determine: (a) the variations in resistivities with different AB separations for the same target, but at different depths, and for the three most common array types, (b) the transition zone (depth to target) from plotted VES graphs, and (c) the relationship between AB and the depth to the transition zone.

These calculated depth factors are compared with those from the earlier researchers (Barker, 1989 Edward, 1977; Roy & Apparao, 1971; Schlumberger & Schlumberger, 1932).

CHAPTER TWO

LITERATURE REVIEW

The electrical method is a technique of measuring the resistances of electrical fields of force and using the measured data in predicting subsurface deposits or structure. The method was developed in the early 1900s by the Schlumberger brothers (Schlumberger and Schlumberger, 1932), but its application was limited to only 1-D investigations until the advent of computers when data could be easily processed in 2-D and 3-D models (Reynolds, 1998). The electrical resistivity method is used in the study of horizontal and vertical discontinuities in electrical properties of the subsurface and in detecting three-dimensional bodies of anomalous electrical resistivity (Kearey et al., 2002).

2.1 RESISTIVITY METHOD

This is an active geophysical method, which involves the injection of electrical currents into the ground and the resulting potential difference across a pair of electrodes placed at the surface is measured. The unit electrical resistance of a material is the resistivity, which is the ease or difficulty with which electrical currents pass through a material (Kearey et al., 2002). The resistivity gives important information about the subsurface properties.

2.1.1 Resistivity of Geological Materials

The resistivity of geological materials (soils, rocks and minerals) have the highest range in terms of physical properties; it ranges from $1.6 \times 10^{-8}\Omega m$ for native silver to $10^{16}\Omega m$ for pure sulphur (Reynolds, 1998). Igneous rocks have the highest resistivities, with sedimentary rocks having the lowest, and metamorphic rocks showing intermediate and overlapping resistivities (Reynolds, 1998)

The resistivities of geological materials are also affected by the age of formation –e.g. volcanic rock of Quaternary age may have resistivity falling in the range 10 - 200 Ωm while the range of similar volcanic rock of Precambrian age may be of higher values in range. These higher resistivities may be associated with compaction, sedimentation and recrystallization of the mineral grains that end up closing most of the pores and decrease conductivity.

2.1.2 Current Flow in the Subsurface

In the electrical resistivity method, the current flow in the subsurface is mainly by electrolytic conduction through which, there is a slow movement of ions within an electrolyte (Reynolds, 1998). The flow depends on the type of ions, the ionic concentration and the mobility, as well as the porosity of the medium. In most rocks, pore fluid acts as the electrolyte that aids the conductivity whiles the actual mineral grains contribute little to the overall conductivity of the earth material. High porosity and groundwater content are associated with lower resistivity, and vice versa (Kearey et al., 2002 and Sharma, 2004).

A single current electrode produces current flowing radially away from the point source (Fig. 2.1) and this makes the current distribution a uniform one over a hemispherical shell centred on the source. The equipotential lines are perpendicular to the current flow lines.

2.1.3 Effect of Inhomogeneous Ground

In developing the theory behind the application of electrical resistivity method, homogeneous isotropic ground was assumed, but it is extremely rare to find homogeneous ground and therefore would be of no practical significance (Telford et al., 1990). The objective of electrical resistivity exploration is to detect the presence of anomalous conductivity/resistivity in different forms -lumped bodies, dikes, faults and vertical or horizontal contacts between beds. The resistivity method is most suitable for detecting horizontal beds and vertical contacts, but less useful on bodies of irregular shape (Telford et al., 1990). Due to the inhomogeneity of the earth‶s crust the measured resistivity is referred to as a*pparent resistivity* (ρ_a).

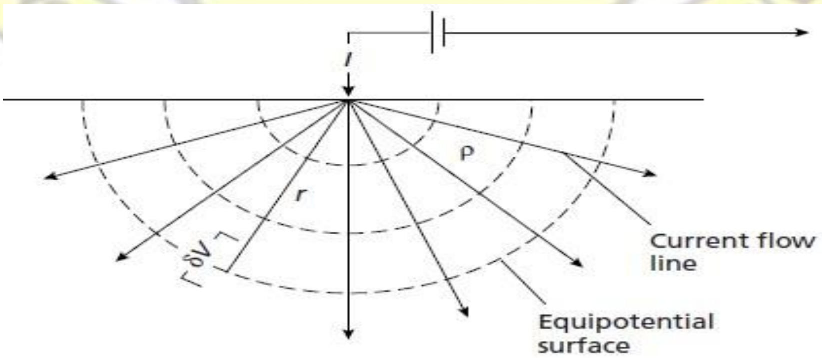

Figure 2.1: Current flow from a single surface electrode

2.1.4 Principles of Electrical Resistivity

Ohm‟s law relates the current, potential difference and the resistance such that $R = V/I$ (Fig. 2.2). This is written alternatively in terms of the electric field strength (E, volts/m) and the current density (J, amps/m^2) as $\rho = E/J$ (Ω-m) (Reynolds, 1998). The resistivity is related to the voltage, the current, the length and the cross-sectional area as $\rho = VA/IL$ (Ω-m) (Reynolds 1998).

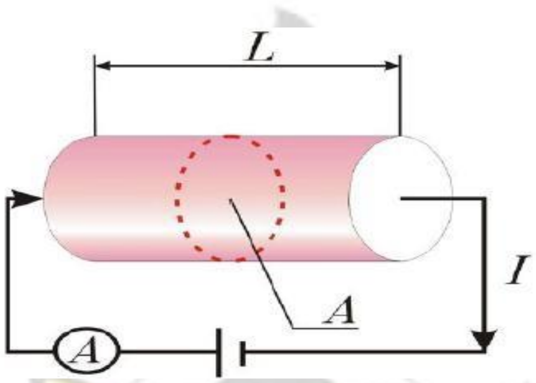

Figure 2.2: Electric circuit for illustrating Ohm's Law

Basic Theory

From Ohm‟s equation, the resistivity (ρ) is related to the current (I), the voltage (V), the surface area (A) and the length of the material (L) as

$$\rho = \frac{VA}{IL} \quad \text{……………………………………………………………………….. (2.1)}$$

The potential difference (δV) across a hemispherical shell of surface area $2\pi r^2$, r being the radial distance from the current source (I), and thickness (δr) may be obtained as:

$$\delta V = \frac{\rho I}{2\pi r^2}\delta r \quad \Rightarrow \quad \int \delta V = \frac{\rho I}{2\pi}\int \frac{\delta r}{r^2},$$

$$V = \frac{\rho I}{2\pi}\frac{1}{r} \quad \text{…………………..……………………………………… (2.2)}$$

Figure 2.3 is a schematic representation of current and potential distribution in a hemispherical earth as depicted in Equation 2.2.

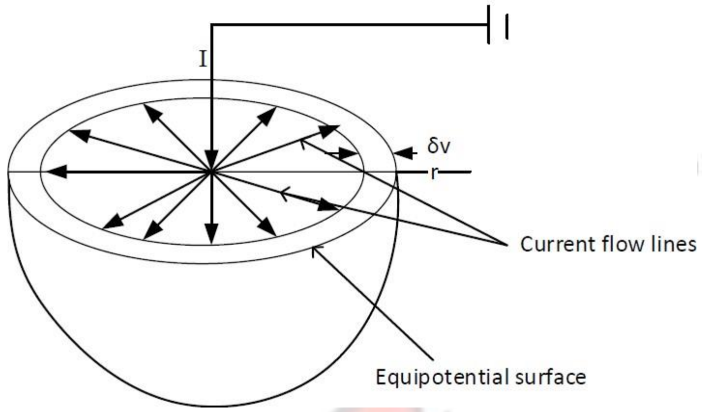

Figure 2.3: Current flow and equipotential surfaces from a single electrode

The potentials at P_1 due to current sources C_1 and C_2 (Fig 2.4) are respectively given as:

$$V_{P_1C_1} = \frac{\rho I}{2\pi}\frac{1}{r_1} \quad \text{(2.3)}$$

$$V_{P_1C_2} = \frac{\rho I}{2\pi}\frac{1}{r_2} \quad \text{(2.4)}$$

Therefore, the total potential at P_1 resulting C_1 and C_2 is given by:

$$V_{P_1} = V_{P_1C_1} + V_{P_1C_2} = \frac{\rho I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad \text{(2.5)}$$

Similarly, the total potential at P_2 resulting from currents at C_1 and C_2 is given as:

$$V_{P_2} = \frac{\rho I}{2\pi}\left(\frac{1}{r_3} - \frac{1}{r_4}\right) \quad \text{(2.6)}$$

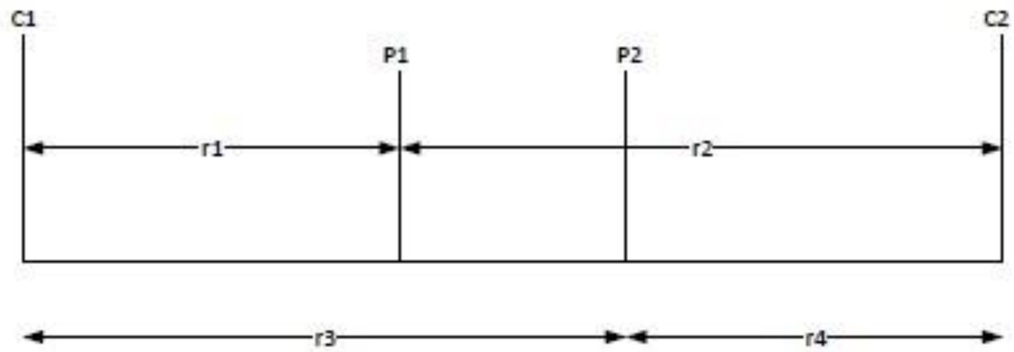

Figure 2.4: Electrode geometry in resistivity survey

Therefore the potential difference (ΔV) between P1 and P2 is given as:

$$\Delta V = \frac{\rho I}{2\pi}\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

From Equation (2.7), the resistivity ρ is given as:

$$\rho = \frac{2\pi \Delta V}{I}\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right]^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

2.2 TYPES OF GEOELECTRICAL RESISTIVITY SURVEY

There are two general procedures that are employed in geo-electrical resistivity surveys namely, vertical electrical sounding (VES) and horizontal electrical profiling (HEP). The main objective of electrical resistivity survey is the delineation of both the horizontal and vertical resistivity layers in the heterogeneous anisotropic subsurface.

In the HEP, the main focus is the study of the lateral variations in the subsurface resistivities resulting from lithological changes and near surface discontinuities like faults (Kearey et al,. 2002). The electrode spacing remains unchanged in this method, and all four electrodes are moved along the line of investigation. In the Wenner array, all the four electrodes, with constant spacing of *'a'*, are moved in a successive steps.

HEP in the Schlumberger array has two different procedures, viz.

(a) the current electrodes AB are kept at a relatively large distance with the potential electrodes (MN) of a small constant spacing being moved in between AB, and

(b) all the four electrodes are moved in successive resistivity measurements, which is the most common procedure.

The VES measures the resistivity at points downward from the earth"s surface, and it is used to study the vertical variations in resistivity with depth leading to the delineation of geoelectrical horizons within the subsurface -e.g. the depth to bedrock and groundwater surface zones. VES is used mainly in studying the changes in the horizontal or nearhorizontal layers occurring in a medium. The basic principle of the VES is based on the principle that the wider the electrode spread, the deeper the investigating depth, thus giving electrical properties of deeper subsurface layers (Sharma, 2004).

In the symmetric Schlumberger array, the potential electrodes spacing is maintained at a fixed position, with the investigation point being at the centre of the two potential electrodes. In the normal Wenner array the electrode spacing *'a'* is increased at a regular interval with the centre of the array kept fixed (Sharma, 2004). The electrode dipoles are expanded about a fixed point in the application of the Dipole-Dipole method in VES survey.

2.3 THE DIFFERENT TYPES OF ELECTRODE ARRAYS

Currently there are several combinations of electrode arrangement that are used in electrical resistivity survey but the three most widely used electrode configurations are the Wenner, Schlumberger and dipole-dipole. An electrode array for resistivity surveys generally consists of four earthed contacts, two for current passage and two for voltage measurements. Apart from these three listed, other electrode arrangements exist including pole-pole, gradient array, Lee Partition.

The subsurface is not an ideal homogeneous and/or isotropic material, and thus the resistivity measured is not the true resistivity but the *apparent resistivity* (Kearey et al., 2002; Reynolds, 1998;.and Telford et al., 1990). The measured resistivity will vary on altering the arrangement of the electrodes or on moving them on the ground without altering their geometry (Parasnis, 1962). That is, the ratio of the voltage to current will not be directly proportional to the geometry (*G*) as on a homogeneous earth. The value of ρ, obtained on multiplying the measured *V/I* and the corresponding geometric coefficient „*K'* is called the *apparent resistivity* (ρ_a). Factors affecting the choice of array type include the amount of space available to layout an array and the labourintensity of each method.

2.3.1 Schlumberger Array

Conrad Schlumberger was the first to explore the earth using electrical method (Telford et al., 1990). In the Schlumberger array, four collinear electrodes are employed (i.e. two outer current electrodes and two inner potential electrodes) as shown in Figure 2.5.

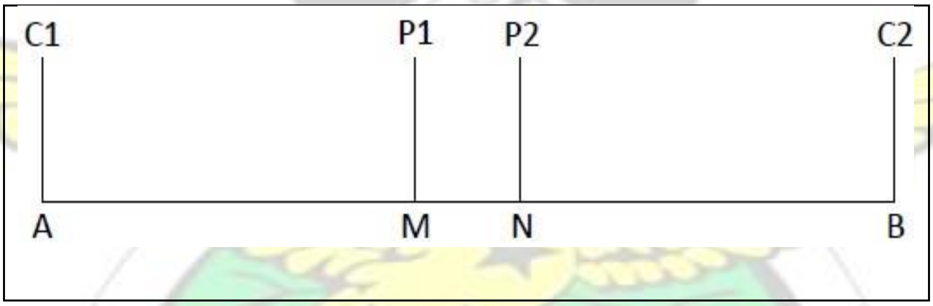

Figure 2.5: Schlumberger array geometry

The potential electrodes are located about the centre of the array, which is the centre of investigation; their separation is small compared to the total array length, usually less than one fifth of the total electrode aperture (Keller, 1966). When making a depth sounding (VES) with the symmetric Schlumberger array, the current electrode separation is gradually increased at regular intervals. The measuring potential electrodes separation is increased only when the observed voltage becomes too small to measure. Moreover, VES employing asymmetric Schlumberger array may be done by maintaining any of the current electrodes at a fixed position whiles moving the other current electrode to a position that will give the current separation required.

The effect of near surface inhomogeneities remains constant in the VES with Schlumberger electrode configuration since the measuring potential electrodes remain fixed about the centre (Sharma, 2004). The measured apparent resistivity is calculated from the relationship:

$$\rho_a = \frac{\pi V}{I}\left(\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN}\right), \quad \ldots\ldots (2.9)$$

and it is valid for only collinear symmetrical arrays.

2.3.2 Wenner Array

The Wenner array is similar to, if not a modification of, the Schlumberger array; the main difference is that the four electrode are place at equal intervals apart (Fig 2.6).

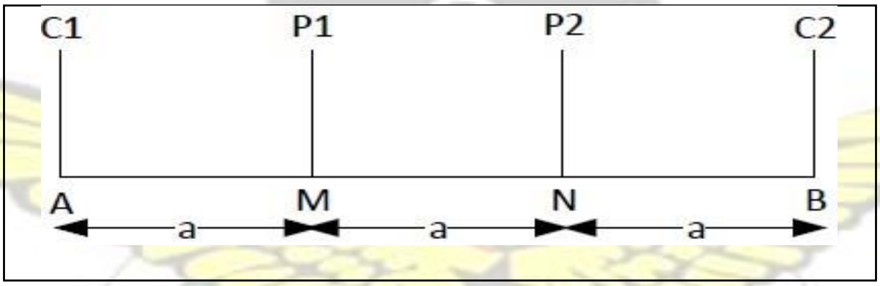

Figure 2.6: Normal Wenner electrode array

The array spacing is expanded about the array midpoint in making an electrical sounding, but all four electrodes are separated by equal distances at all times (Keller, 1966). Variant Wenner arrays may take three different forms, the alpha (α) Wenner (normal)-CPPC-arrangement, beta (β)-CCPP-array, and gamma (γ)-CPCP-array.

The advantages of the Wenner array are that the apparent resistivity is easily calculated in the field and the instrument sensitivity is not as crucial as with the other array geometries. Relatively small current magnitudes are needed to produce measurable potential differences (Keller, 1966). As far as field operations for profiling are concerned, the

Wenner arrangement seems more advantageous due to the equal spacing between consecutive electrodes (Roy & Apparao, 1971).

The estimated depth of investigation proposed by Fröhlich (1967), as AB/3 is still under scrutiny. Despite the simple geometry of this array, the arrangement is quite inconvenient for field work and, theoretically, it has some disadvantages as well (Telford et al., 1990). Some of the disadvantages include the moving of all four electrodes for VES, thereby requiring more time and resources in the field. The Wenner array is relatively more sensitive to vertical variations but less sensitive to horizontal variations in the subsurface resistivity. The apparent resistivity (ρ_a) in Wenner array is given as:

$$\rho_a = 2a\pi\frac{V}{I} \qquad \text{(2.10)}$$

2.3.3 Dipole-Dipole Array

Dipole-dipole arrays use four electrodes which are placed in pairs – current dipole and the potential dipole- as shown in Figure 2.7, and it has been used extensively by Russian geophysicists since 1950 (Reynolds, 1998). The main advantage of the method is the relatively small amount of cable that has to be laid out in comparison to the requirement of other electrode arrangements (Keller, 1966). In the dipole-dipole array, the current dipole is short, compared to the total spread of the array; this minimises the length of the current cables and hence the attendant hazards and operational inconvenience.

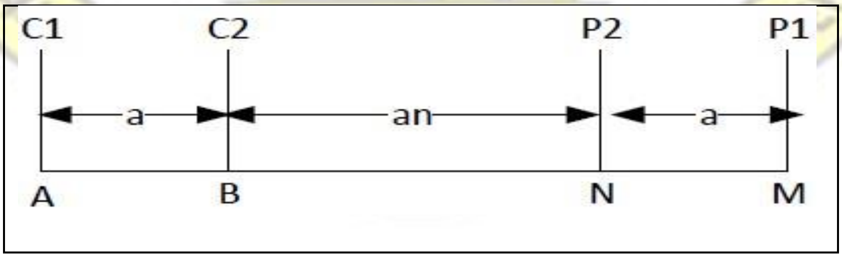

Figure 2.7: Dipole-dipole array geometry

Resistivity measurements in the dipole-dipole (VES) usually involve the use of a fixed dipole length „*a*‟, with the dipoles being separated by a distance of „*an';* the larger the *n*-

value, the deeper the depth of investigation (Edwards, 1977). This array type is the most sensitive to resistivity variations below the electrodes in each dipole pair and very sensitive to horizontal variations in the subsurface resistivity. Thus it is the most preferred array for mapping vertical structures like dikes and cavities (Keller, 1966).

It is acknowledged that dipole-dipole data have the greatest near-surface resolving power but it is also used to investigate the shallowest (Oldenburg & Li, 1999). However, the dipole-dipole array is so sensitive to lateral inhomogeneities that relatively small lateral changes may lead to serious errors (Keller, 1975). From Figure
2.7, the apparent resistivity is determined by the relationship:

$$\rho_a = \pi a n\ (n+1)\ (n+2)\frac{V}{I} \quad \text{…………………………………………… (2.11)}$$

The Schlumberger is more convenient than the Wenner simply because whiles all four electrodes are moved at each measuring depth in Wenner, here only two electrodes (current) are moved and also the effect of shallow resistivity variations is constant with fixed potential electrodes (Telford et al., 1990).

2.4 FACTORS AFFECTING DEPTH OF INVESTIGATION (DOI)

It is generally acknowledged that the wider the electrode spacing, the deeper the investigation in the resistivity survey. Apart from the current electrode separation, the depth of investigation also depends on the spacing between the receiving potential electrodes MN (Bernard, 2003). Bernard (2003) however, explained further that, the farther the receiving electrodes (MN) are from the current electrodes (AB) in a Schlumberger array, the more representative the measured resistivity on the ground surface are to the subsurface conditions.

Edwards (1977) states that the depth of penetration of the current is directly proportional to the total electrode spacing. On the other hand, Barker (1989) held that in whatever way the depth of investigation is defined, that depth must necessarily depend on the relative positions of both the current and potential electrodes. Sharma (2004) however, states that the actual depth of penetration of the current also depends on (a) the power of the current source, (b) sensitivity of the array type to near surface inhomogeneities, (c) the resistivity contrast between the surface layer and substratum and (d) degree of electrical anisotropy of the layer media.

2.5 ESTIMATES OF Depth Of investigation BY OTHER AUTHORS

The estimation of the depth of investigation in electrical resistivity surveys dates as far back as 1938, where Evjen (1938) first investigated what he termed as the depth factors in electrical measurements. He defined the depth of investigation as the depth at which a thin layer makes a maximum contribution to the measured signal. He went further to state that, due to the different parameters that may be controlling the depth of penetration of currents in electrical resistivity surveys, there exists no universal depth factor relationship to the electrode spread. He proposed that, the depth factor can properly be estimated empirically when well logs are correlated with resistivity measurements. Other researchers (Barker, 1989; Roy, 1972; Roy and Apparao, 1971) focused on computing a curve that shows that portion of the final measured signal from a thin layer of soil material at depth having the maximum contribution towards the measured signal in homogeneous half-space model. Edwards (1977) also used the same definition by Evjen (1938) and Roy & Apparao (1971); however, in his analysis, the maximum signal is assumed to be at a point within the subsurface where half of the measured signal is coming from geological layers above and the other half from below.

On the other hand, Fröhlich (1967) explains that the depth of current penetration is about 1/4 to 1/3 the distance between the current electrodes AB. The suggested depths by the earliest researchers provided helpful guidelines by which electrical resistivity survey is planned. The depth of investigation in the Schlumberger array is assumed to be half of the current electrode spread (i.e. AB/2), one-third of the spread (AB/3) in Wenner and half of the distance between the dipoles in the dipole-dipole method (Zhody and Jackson, 1969; Fröhlich, 1967; Keller, 1966).

However, the estimated depths by Roy & Apparao (1971), Roy (1972), Edwards (1977) and Barker (1989) show that, the depths of investigation determined are far less than the generally considered depth factor by Schlumberger & Schlumberger (1932). Roy and Apparao (1971) also states that:

(i) The depth of investigation in the electrical resistivity survey is smaller than what is generally acknowledged in any of the electrode arrangements.

(ii) The depth in any electrode system is determined by both the current and the potential electrodes and not by the current penetration alone.

(iii) The pole-pole array system has the largest depth of investigation.

These depth estimates by the earlier researchers are far less than the assumed (AB/2 or AB/3) and therefore the use of such depth factors may not be helpful for deeper resistivity surveys in areas with limited space for the survey.

Oldenburg and Li (1999) also studied the depth of investigation in the DC electrical resistivity and IP surveys. In their research they defined the term "depth of investigation" as the depth below which surface data are insensitive to the value of the physical property of the earth. Oldenburg and Li (1999) solved an inverse problem in estimating the depth of burial of a perceived conductive material. In their method, an objective function for solving a forward model is used, and the misfit existing between the predicted model and the actual model is determined. The pole-dipole array was used in their study, but this array has less application in geophysical electrical resistivity exploration in this part of the world, and therefore limits its application. Meanwhile, the final solution may not be the ultimate (true) solution due to the non-uniqueness that exists in solving inverse problems; different combinations of different model parameters may give the same solution to the inverse problem, and therefore in applying this method, appropriate boundary conditions must be obtained.

The dipole-dipole has the greatest near surface resolving power but sees the shallowest, while the pole-pole has the poorest resolution power but sees deepest (Oldenburg & Li, 1999). They contended that there exists no clear cut definition for the depth of investigation with respect to the electrode spacing. Barker (1989) focussed on the depth of investigation in the various Wenner arrays, viz. α- □- and λ-Wenner. According to Barker (1989), depth of investigation has a variety of physical definitions, but they all come from a need to relate apparent resistivity measurements made at the ground surface to a certain depth within the subsurface, so that the survey parameters may be optimized for effective identification.

CHAPTER THREE

METHODOLOGY

The main assignment in the study was to try to identify resistivity signatures from a limited target at a known depth. A conducting material was buried under a heap of sand, and vertical electrical sounding (VES) was conducted across the target for different thicknesses of the sand. However, when it was difficult to pick the target signature from the initial tests it was decided to use the natural ground, which provided a laterally extensive target –i.e. the interface between the natural ground and the heap of sand over the ground. The tests simply involved vertical geo-electrical resistivity sounding conducted at about the same point on the surface and gradually increasing the depth of the interface with the aim of finding conspicuous signatures that may be associated with the transition zone.

3.1 MATERIALS AND EQUIPMENT USED IN THE STUDY

The main material used was a heap of silty-sand placed directly over the natural ground surface. In order to contain the sand, a wooden box with an open bottom was constructed and filled with the sand. The dimensions of the box were 120 x 240 cm^2 and variable thickness with a maximum of 110cm (Fig. 3.1a); the thickness was varied to increase the depth of the target below the surface of the sand.

Figure 3.1a: Wooden box with the sand

Figure 3.1b: Resistivity meter and accessories

The soil used in the investigation was classified by the routine geotechnical soil particle size analysis. The other main equipment used was the UltraMiniRes IP & Earth Resistivity meter with its accessories –i.e. the electrodes and cables (Fig. 3.1b).

3.1.1 Setting the Target Depth

The box was placed on the ground and filled with sand initially to a height of 25cm above the ground surface (Fig 3.2); this means the target was at a depth of 25cm below the surface where the tests were conducted. Vertical electrical depth sounding (VES) was conducted about the central point at the surface of the sand at regular intervals. This was done for all three array types –i.e. Schlumberger, Wenner and Dipole-Dipole. When the sounding was completed for the three arrays, the depth of the target was increased by topping up the sand to the required thickness, and the depth soundings repeated. In all, seven target depths -25, 30, 35, 45, 55, 65 and 75 cm- were investigated; the sand-ground interface was considered as the target depth.

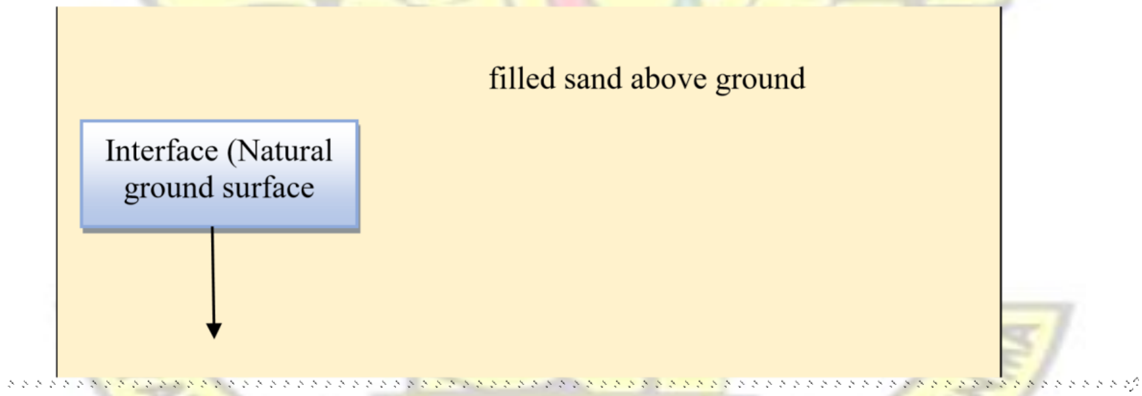

Figure 3.2: Schematic representation of the experimental set up at the Laboratory

3.2 RESISTIVITY MEASUREMENTS

The resistivity measurements were done along a traverse line passing through the central portion of the sand box parallel to the longer side. The resistivity measurements were conducted with the target at different depths, buried between 25 and 75 cm below the sand surface, and using the three common array types -Schlumberger, Wenner and Dipole-

Dipole. In the array types, collinear and symmetrical electrodes arrangement was used, to ensure uniformity and remove any ambiguities.

3.2.1 The Schlumberger Array

In the Schlumberger array (Plate 3.1) the potential electrode separation (MN) relative to the total spread is very important in the test. To check the effect of the MN spacing on the measured apparent resistivities for the scale of the investigation, two MN spacings of 20 and 30 cm were first tested. The difference between the two was not significant, and for reasons of convenience and to get more data points MN spacing of 20cm was used for the main tests. The current electrode spacing (AB) was started from 30cm and increased by 10cm to a maximum of 230cm; this gave 20 data points for each thickness of sand over the interface. This was repeated for all seven (7) thickness of sand (20, 25, 30, 45, 55, 65 and 75 cm) over the interface.

Since these tests were performed over several weeks with varying atmospheric moisture conditions, for each thickness the test was repeated after 24 hours to check consistency and/or precision of the measurements. This was to ensure that the moisture condition would not have any significant effect on the apparent resistivity measurements.

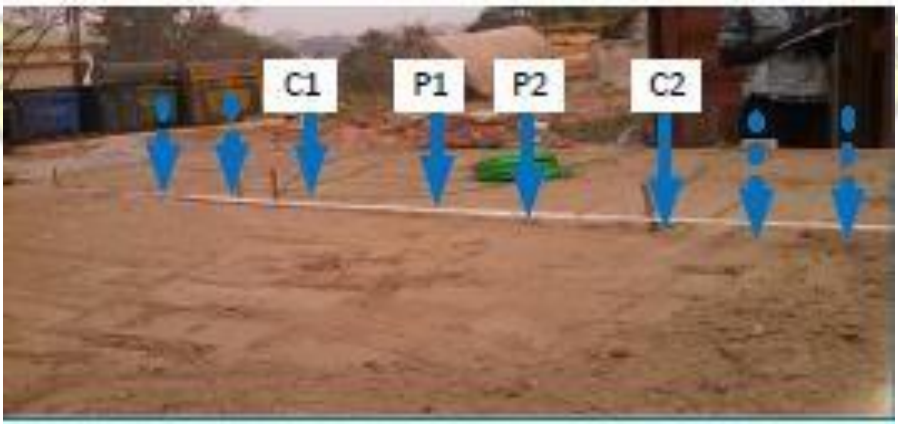

Plate 3.1: Data collection using Schlumberger array

3.2.2 The Wenner Array

The normal Wenner array is, in fact, a modification of the Schlumberger array; the main difference is that in the Wenner the four electrodes are at equal distances apart–i.e. adjacent electrodes are the same separation (*a*) from each other as shown in Plate 3.2. The electrode spacing *'a'* was started from 10cm, and successively increased by 10cm to a maximum of 70cm i.e. AB spacing reaching 210cm. The same depths of investigation were studied as in the Schlumberger array.

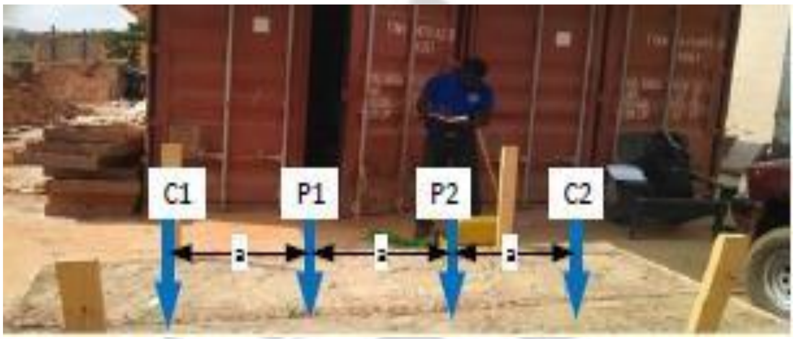

Plate 3.2: Data collection using normal Wenner array

3.2.3 The Dipole-Dipole Array

In the Dipole-Dipole (sometimes referred to as the Double Dipole) array (Plate 3.3) a constant dipole spacing of 20cm was maintained throughout the resistivity measurements for the seven (7) different sand thicknesses studied. The separation factor, *n*, started from 1, and increased systematically by 1 to a maximum of 9; thus the maximum spread distance was 220 cm.

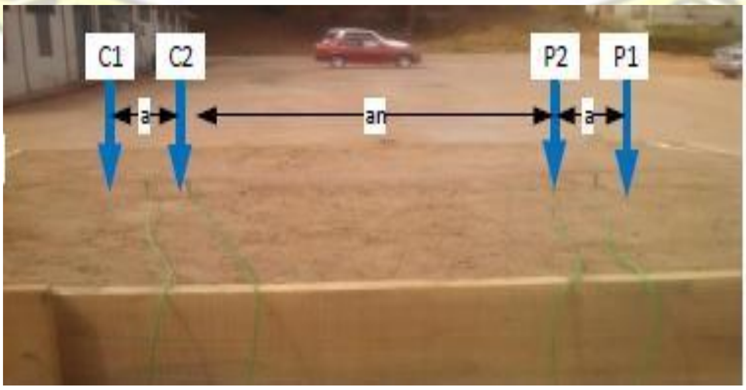

Plate 3.3: Dipole-Dipole electrode arrangement data collection

CHAPTER FOUR

RESULTS AND DISCUSSION

In this chapter, the results obtained from the resistivity measurements using the Schlumberger, Wenner and Dipole-Dipole arrays are presented and discussed. The Ultra miniRes IP & Earth Resistivity meter was used; this instrument displays the resistances directly, and the apparent resistivities were calculated by multiplying the resistances with the corresponding geometric factors.

4.1 PRELIMINARY TESTS RESULTS

To understand the test conditions and their likely effect on the results some preliminary tests were performed including soil classification for the sand, effect of potential electrode separation (MN) and moisture conditions of the sand.

4.1.1 Soil Classification

The soil used in the investigation was classified by routine geotechnical particle size analysis. It was found to be a silty-sand with 40% fines –i.e. passing BS Sieve No. 200 (0.075mm); the fines ranged in size from 0.075 to 1.0 mm (Fig. 4.1).

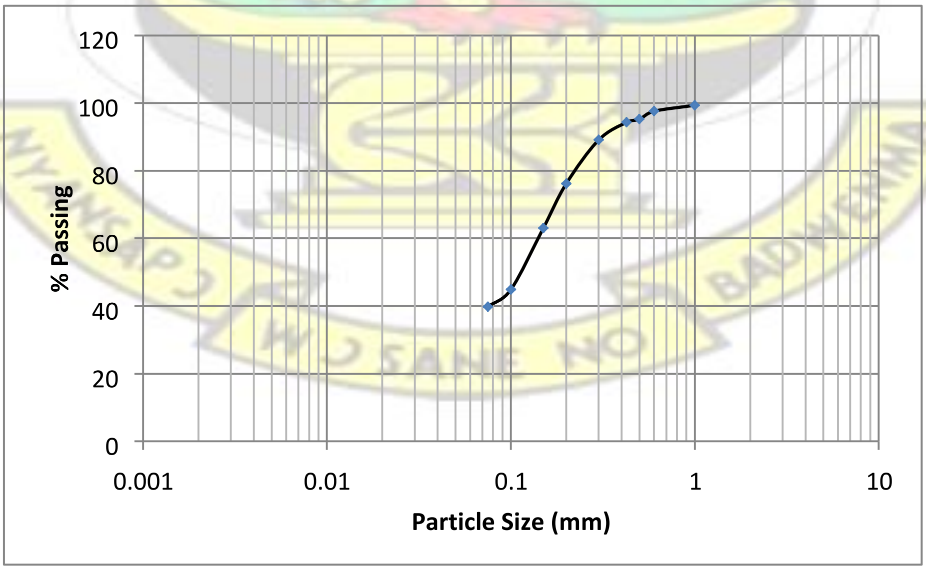

Figure 4.1: Particle size distribution curve of soil used in tests

The average field moisture content was about 10%. Under the weather conditions during the period of testing, and the fact that the soil was left exposed, variations in moisture content were expected between tests.

4.1.2 Potential Electrode Separation (MN) on Apparent Resistivity (ρ_a)

When the depth of investigation increases the potential electrode separation (MN) may have to be increased to be able to obtain readable potential differences across the electrodes. However, this may also have implications on the interpretation; reasons for changes in apparent resistivity values may be difficult to assign since there –i.e. whether it is attributable to a different (resistivity) material at greater depth or simply because the volume has changed. Two MN spacing of 20 and 30 cm were tested, which showed there were consistent increases in ρ_a, but not the pattern which was used to determine the transition zone for all depths of investigation (Figs. 4.2 a – d).

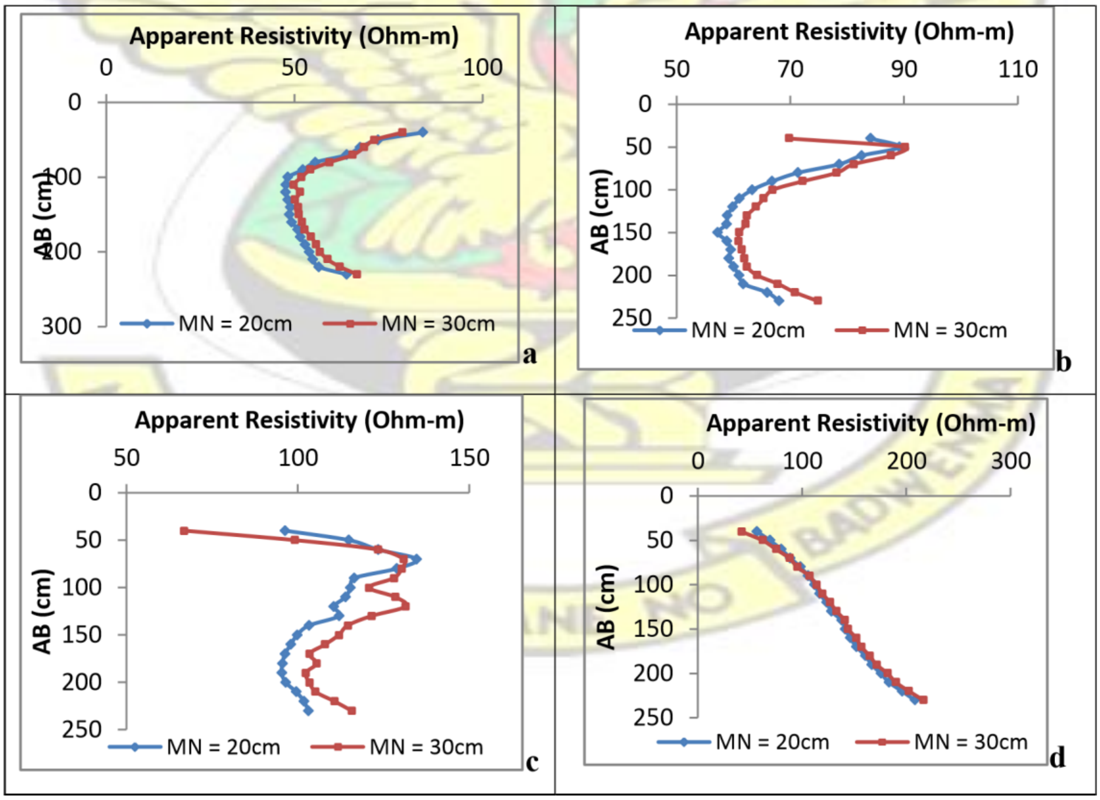

Figure 4.2: Effect of MN separation on apparent resistivity for a) 25, b) 35, c) 55 and d) 65 cm depths of investigation.

4.1.3 Moisture Effect on Test Results

Sometimes a particular test could not be completed in the same day that it was started and suspecting moisture changes when left overnight initial tests were performed to verify the effect of these minor changes in moisture content of the test soil. This was investigated by repeating the tests after 24 hours; no set of tests went beyond 24 hours. The repetition showed that in most of the tests the apparent resistivity values changed but the pattern did not change; Figures 4.3 – 4.5 are typical examples of the repeated tests for the three arrays.

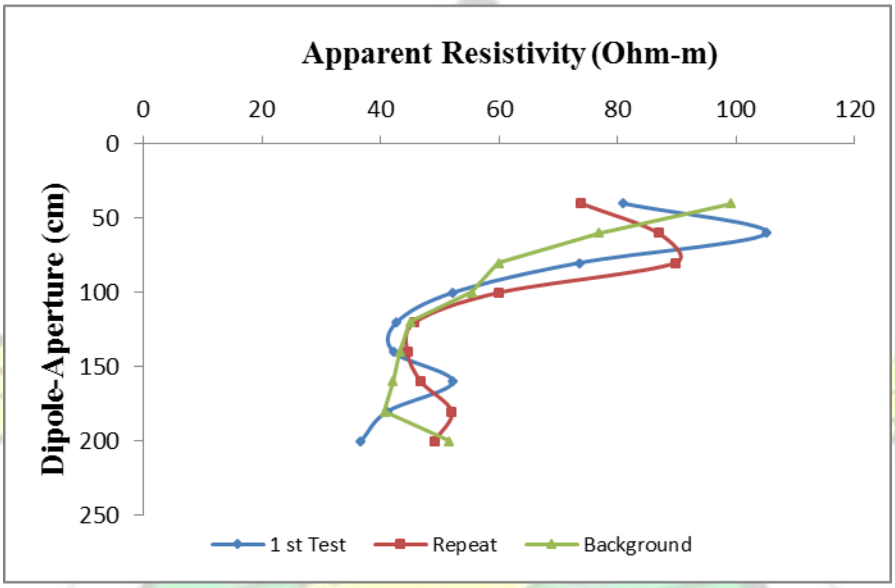

Figure 4.3: Apparent resistivity curves (Dipole-Dipole) for depth 25cm

These tests were initially performed using a conducting material buried under a heap of sand of different thicknesses. However, when the tests were also performed without the conducting material there was no difference in the patterns as shown Figures 4.3 – 4.5. In those figures "Background" represents the test without the conducting material; it was found that the apparent change in the resistivity patterns was due to the transition from the sand to the natural ground on which the sand was placed. It was therefore decided to use the natural ground as the target; this provided a laterally extensive target –i.e. the interface between the heap of sand and the natural ground.

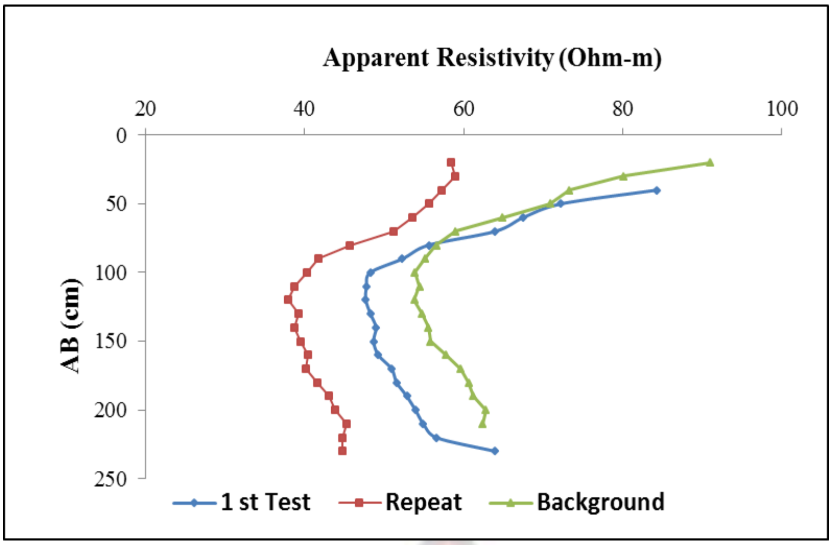

Figure 4.4: Apparent Resistivity curves (Schlumberger) for depth of 25 cm

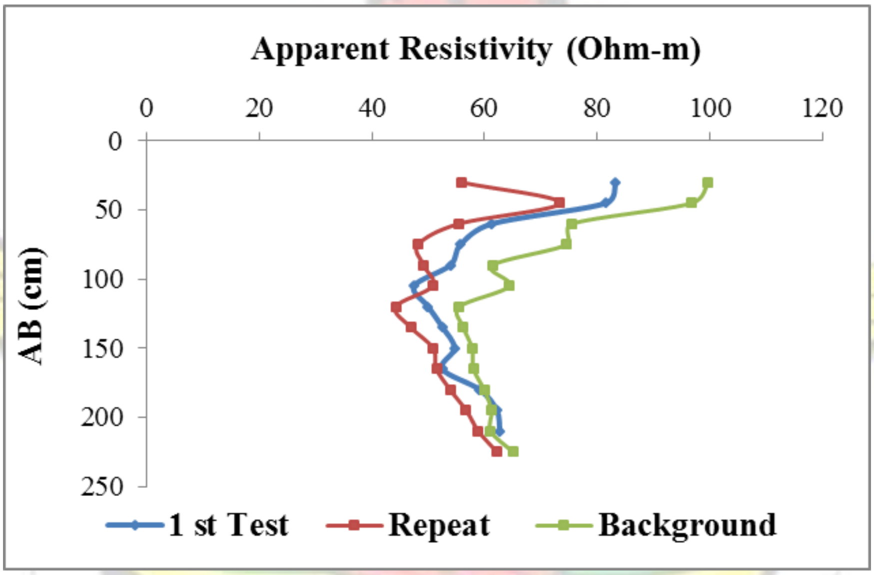

Figure 4.5: Apparent resistivity curves (Wenner) for depth of 25 cm

4.2 DIPOLE-DIPOLE TEST

The tests results from the Dipole-Dipole array as plotted for all the depths did not appear to show any discernable change for either the conducting material, as explained earlier, or for the interface between the sand and the natural ground (Fig. 4.6). Typical discernable change, which may be described as an anomalous zone, in both the

Schlumberger and Wenner arrays are shown in Figures 4.7 & 4.8, and these were consistent with the depth of investigation. In view of this the study subsequently excluded the Dipole-Dipole array, and no further discussion would be made on it.

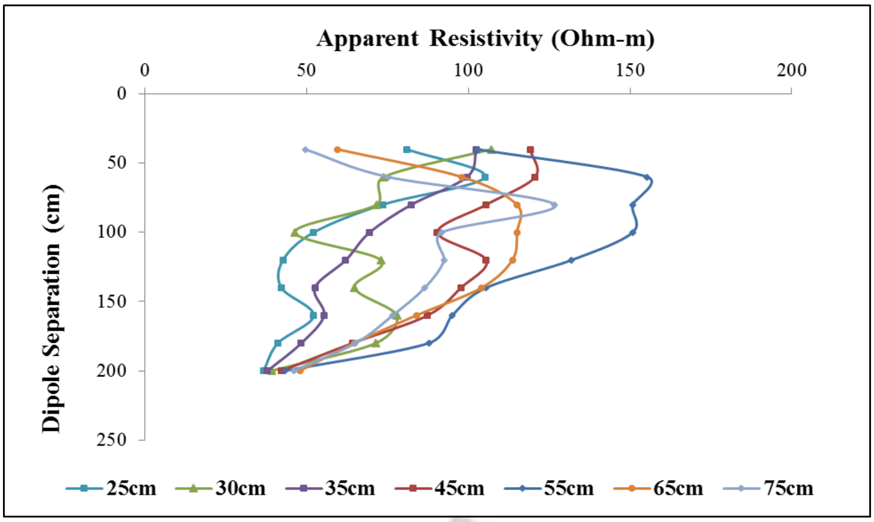

Figure 4.6: Apparent resistivity curves for different depths of investigation using the Dipole-Dipole array.

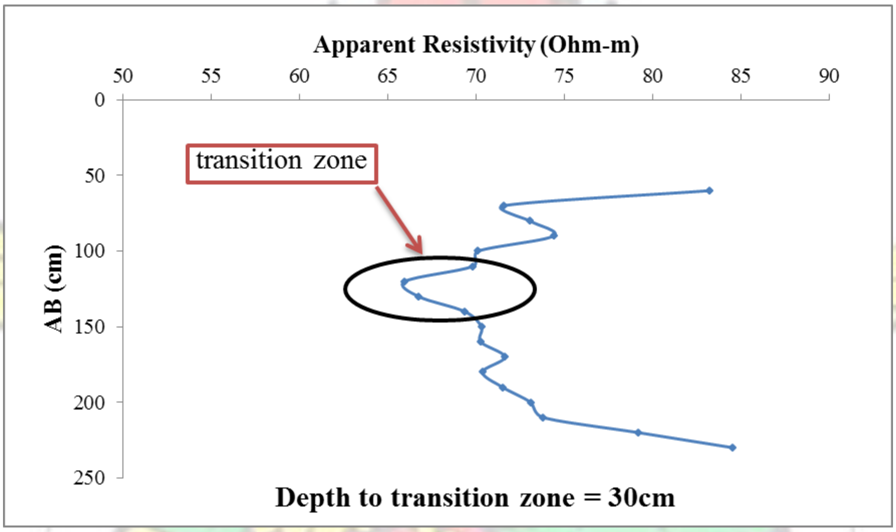

Figure 4.7: Typical anomaly showing the transition zone in a Schlumberger array.

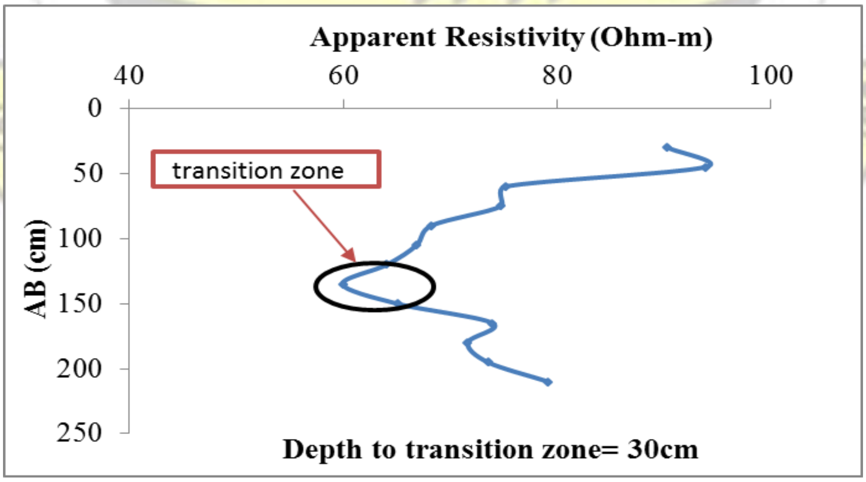

Figure 4.8: Typical anomalies showing the transition zone in a Wenner array

4.3 THE SCHLUMBERGER AND WENNER ARRAYS

In the Figures 4.7 and 4.8, of apparent resistivity versus current electrode separation (AB) as plotted for the Schlumberger and Wenner arrays, there was a very conspicuous discernible change in the apparent resistivity, which could be related to the transition from the silty-sand to the natural ground that lay below. For each thickness of sand above the natural ground surface, which is referred to as the depth of investigation, the AB at which the change was noticed was matched with the particular depth. This was done for all the depths of investigation and the results tabulated and plotted in MS Excel® as "Depth versus AB".

4.3.1 Schlumberger Array

Table 4.1 shows all data points in the investigation using the Schlumberger array and the ratios between the current electrode aperture (AB) and the depth to the interface; the average ratio is 0.261. This result is closest to Barker"s (1989) among the several others who have also investigated the phenomena.

Table 4.1: Depth to AB aperture ratios using the Schlumberger array

Depth (cm)	25	30	35	45	55	***Average***
AB (cm)	100	120	140	170	190	-
Ratio	0.25	0.25	0.25	0.265	0.289	**0.261**

In the plot of AB versus depth to the interface as shown in Figure 4.9, there are two scenarios –one in which the plot is forced through the origin and the other in which the mathematical best fit is used. Both show a remarkable relationship between the depth to the interface and AB; even though the latter has a better coefficient of determination, it may be easier to work with the former –i.e. $y = 0.267x$, where y is the depth of investigation and x is the current electrode separation, AB. In any case, it does not make theoretical sense if AB is zero; thus, one constraint would be that AB > 0.

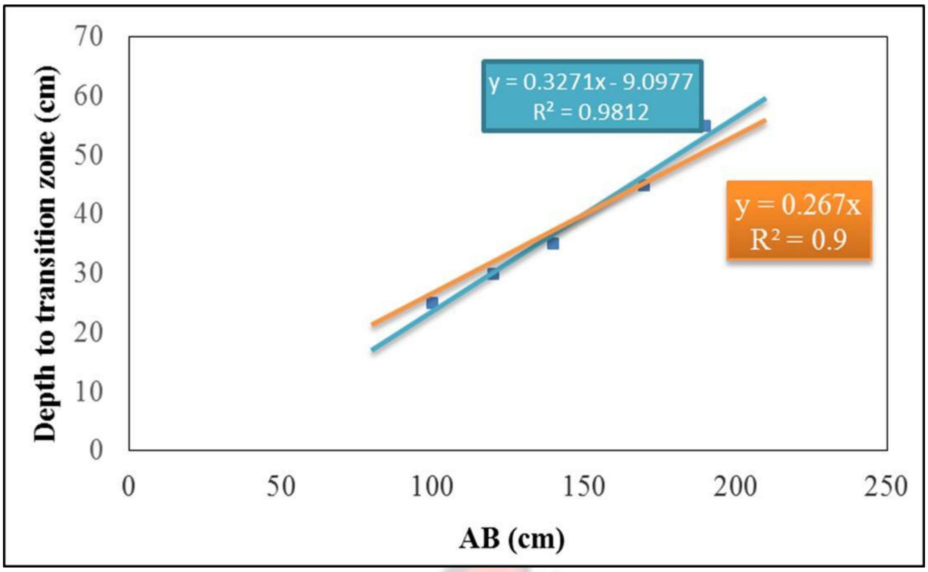

Figure 4.9: Depth of investigation versus AB (Schlumberger array).

4.3.2 Wenner Array

As expected, the results of the Wenner array did not show any significant difference from the Schlumberger array. Table 4.2 shows an average ratio of 0.25 as compared to the 0.267 obtained in the Schlumberger array.

Table 4.2: Depth to AB aperture ratios using the Wenner array

Depth (cm)	25	30	35	45	55	***Average***
AB (cm)	108	130	150	165	195	-
Ratio	0.231	0.231	0.233	0.273	0.282	**0.250**

Again, in the plot of AB versus depth from the Wenner array (Fig. 4.10), the two scenarios were considered. Both show a remarkable relationship between the depth to the interface and AB similar to the Schlumberger; in the Wenner it may be easier to work with the relation $y = 0.258x$. Again, the constraint would be that AB > 0.

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 (or approximately 0.25 for ease of fieldwork).

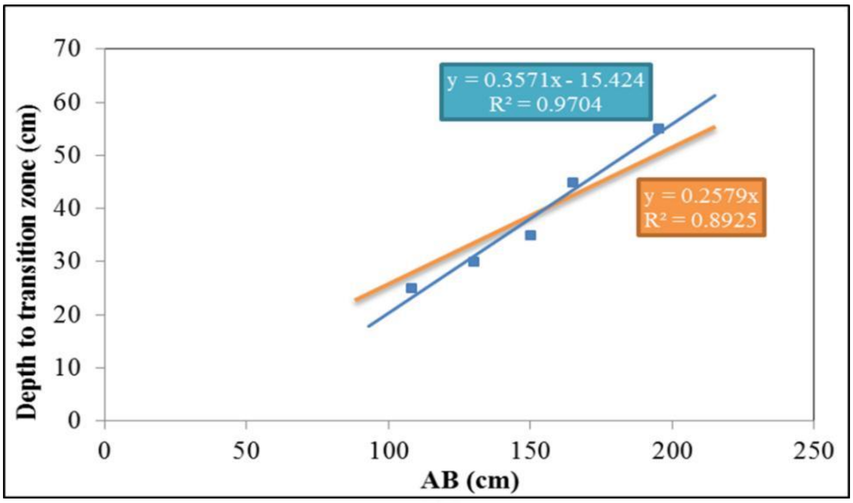

Figure 4.10: Depth of investigation versus AB (Wenner array).

4.3.3 Investigation of Deeper Transition Zones

In the study, when the depth of the heap of sand -i.e. the depth of investigation- was increased to 65 and 75 cm, the interface could not be identified in the plot for both the Schlumberger and Wenner arrays (Figs. 4.11 and 4.12). This appears to support the contention that the commonly used ratio of 0.5 (Schlumberger and Schlumberger, 1932) is over stated. In this study the maximum AB that could be obtained from the size of the box was 230 cm; thus, with a ratio of 0.5, the AB required to investigate a depth of 65 or 75 metres would be 130 and 150 cm respectively, which were within the dimensions of the box; however, the interface could not be found. On the other hand, a ratio of 0.26 (or even 0.28) would require an AB of 250 (or 232) and 288.5 (or 268) cm, which were beyond the dimensions of the box; that is probably why the interface could not be detected.

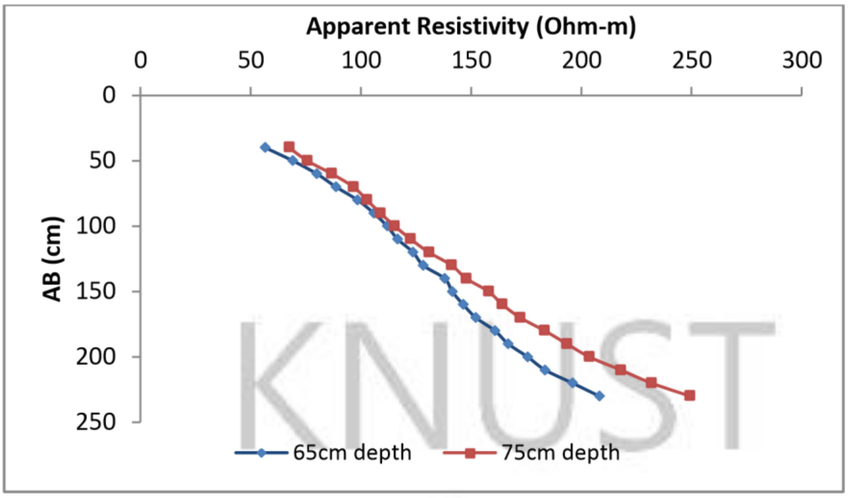

Figure 4.11: Schlumberger apparent resistivity profile with sand 65 and 75 cm thick**.**

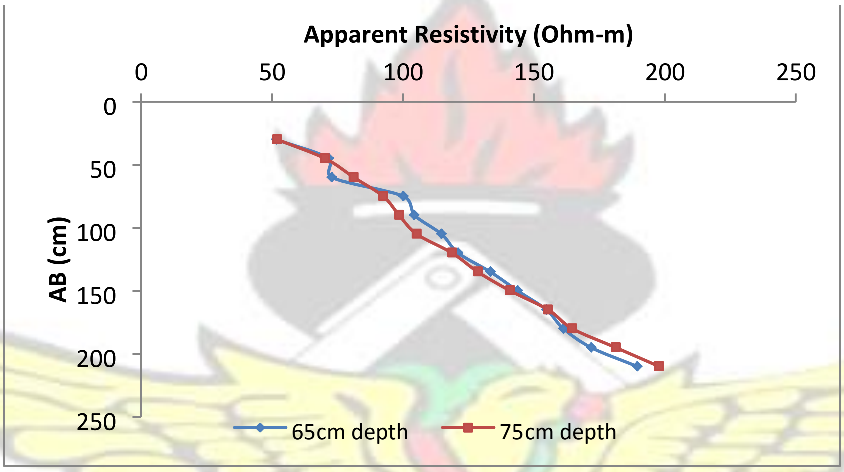

Figure 4.12: Wenner apparent resistivity profile with sand 65 and 75 cm thick.

4.4 FIELD OBSERVATIONS

The Schlumberger array has been used by this author in geoelectric resistivity exploration for point source water supply boreholes in the Ashanti Region. Seventeen (17) drilled borehole logs for which the depths to bedrock could also readily be picked from the resistivity profiles were compared using the depth factors found by some researchers. Figure 4.13 is a typical example of the estimates from the depth factors and the actual bedrock depth; in this example, the transition zone was considered to be where the apparent resistivity suddenly changed from an average of 392 to 674 Ω-m.

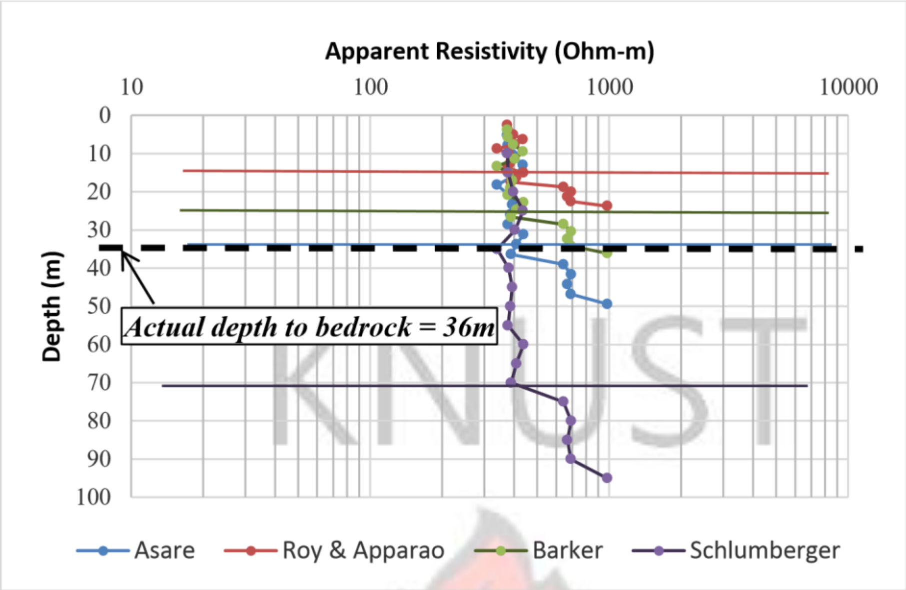

Figure 4.13: A comparison of various estimated depths to actual depth to bedrock.

Table 4.3 shows a comparison of results obtained from the 17 borehole logs with the depth factors; it also shows the deviations of all the estimated depths from the actual one using the *sum of squared errors of predictions* (SSE).

Table 4.3: Comparison of field data with estimates from some authors

		Act.	***Schlumberger***		***Roy & App***		***Barker***		***Asare***	
Site	***Geology***	***Log, m***	***Est.***	***SSE***	***Est.***	***SSE***	***Est.***	***SSE***	***Est.***	***SSE***
1	Granitoids	30	50	400	12	324	19	121	32	4
2	Granitoids	7	20	169	4	9	8	1	10	9
3	Granitoids	36	50	196	17	361	27	81	36	0
4	Granitoids	18	25	49	7	121	10	64	15	9
5	Granitoids	12	25	169	6	36	10	4	12	0
6	Granitoids	30	40	100	10	400	15	225	20	100
7	Granitoids	11	35	576	8	9	13	4	17	36
8	Granitoids	26	35	81	10	256	14	144	20	36
9	Granitoids	15	35	400	7	64	13	4	17	4
10	Granitoids	25	50	625	13	144	20	25	25	0
11	Granitoids	30	45	225	11	361	15	225	25	25
12	Granitoids	32	50	324	13	361	21	121	32	28
13	Granitoids	25	50	625	13	144	20	25	25	26
14	Metasediments	18	25	49	6	144	10	64	16	4
15	Metasediments	32	50	324	13	361	20	144	26	36
SSE				**4.38**		**3.71**		**2.36**		**1.08**
16	Voltaian	6	20	196	5	1	8	4	12	36
17	Voltaian	10	35	625	8	4	15	25	22	144
SSE				**4.57**		**3.28**		**2.11**		**1.20**

1. *Pakoso*; 2. *Boankra*; 3. *Appiadu*; 4; *Fumesua* (1); 5. Fumesua (2); 6. *Kotei*; 7. *Nsennie*; 8. *Emena*; 9. *Deduako*; 10. *Aprabo;* 11. *Apemso*; 12. *Okyerekrom*; 13. *Pruso* 14. *Trede* 15. *Donaso*; 16. *Anyinasu*; 17. *Konongo*.

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 a deviation of 1.20 (SSE). 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 = 1.08).

It is also important to note that the apparent resistivity values are picked at AB intervals of 10m. Using the depth factor of 0.26AB means the sampling interval is 2.6m (about 3m) whereas the actual depth to bedrock can be known to within 1m accuracy from the borehole logs. Thus, the SSE of 1.08 using the depth factor obtained from this study is actually less than the half the resistivity sampling interval (1.3m), which make the prediction very good; in fact, the prediction efficiency is about 80% (Fig. 4.14).

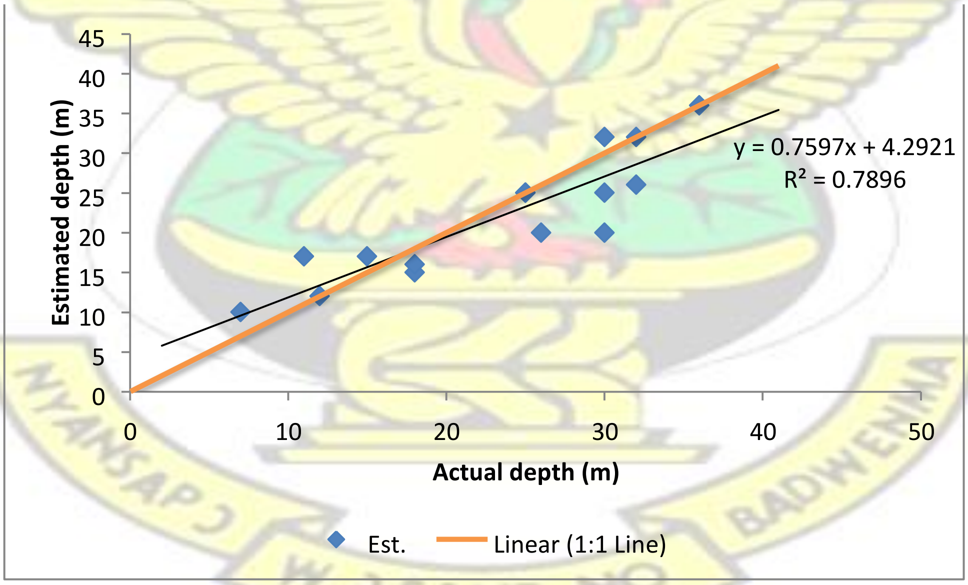

Figure 4.14: Comparison of actual and estimated depths to bedrock using depth factor 0.26.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The main aim of this research was to estimate the depth of investigation in electrical resistivity measurements from laboratory experiments, and then validate the results with actual VES data. The literature does not appear to show that there is a theoretical relationship between AB and the depth of investigation; however, several empirical relationships exist.

Resistivity measurements were done using the three most common arrays viz. Schlumberger, Wenner and Dipole-Dipole. The resulting VES curves were analysed by picking the anomalous zones and the corresponding electrode separation (AB) at which they occur. The AB was then plotted against the actual overburden thicknesses –i.e. depth to the transition zone.

This study has shown that there is an empirical relationship for the Schlumberger and Wenner arrays given as $y = \mathbf{0.26}x$, where y is the depth of investigation and x is the current electrode separation. This depth factor (**0.26**AB) compares favourably with field data obtained from logs of water supply boreholes that were sited using geoelectric resistivity (Schlumberger array) method.

The commonly used **0.5**AB (Schlumberger and Schlumberger, 1932) appears to overestimate the depth of investigation by about two-fold. Three other depth factors which were studied -**0.125**AB (Roy and Apparao, 1971), **0.192**AB (Edwards, 1977) and **0.19**AB (Barker 1989) - also found to underestimate the depth, albeit not as much as the common AB/2 by the Schlumberger brothers.

During the study a limited investigation of the effect MN -the potential electrode separation- was done for two apertures of 20 and 30 cm, and which showed that the wider aperture always gave higher apparent resistivity values. However, the signatures were similar, showing that the depth of investigation was not significantly affected by the MN separation (from this study).

5.2 RECOMMENDATIONS

- In spite of the apparent success of this project, it is recommended that the work be repeated using a larger and thicker conductor as target layer.
- In the meantime we should revise the use of AB/2 as the depth of investigation since this appears to grossly overestimate depth and it is not comparable with the other investigators.
- The effect of MN separation on the apparent resistivity values and their patterns may be studied further by investigating more MN apertures.
- The Dipole-Dipole array may be studied further to estimate the depth of investigation.

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APPENDICES

Appendix A1: Schlumberger measurements for different depths

Depth = 25 cm			MN/2	0.15	*MN/2*	0.1	*0.05*	*MN_20*			
				MN = 20cm		*MN = 30cm Repeat (24hrs)*					*Bgrd*
AB(cm)	*AB/2(m)*	*K20*	*K30*	*R25*	□25	*R25*	□25	□25	□25	*R*	□25
40	0.20	0.47	0.18	178.7	84	430.0	79	122	57	193	91
50	0.25	0.82	0.42	87.6	72	170.2	71	68	56	97	80
60	0.30	1.26	0.71	53.7	67	97.0	69	43	54	58	73
70	0.35	1.77	1.05	36.2	64	62.6	66	29	51	40	71
80	0.40	2.36	1.44	23.6	56	41.2	59	19	46	28	65
90	0.45	3.02	1.88	17.3	52	28.8	54	14	42	20	59
100	0.50	3.77	2.38	12.8	48	21.8	52	11	40	15	57
110	0.55	4.59	2.93	10.4	48	17.0	50	8	39	12	55
120	0.60	5.50	3.53	8.7	48	14.6	52	7	38	10	54
130	0.65	6.48	4.19	7.5	48	12.0	50	6	39	8	54
140	0.70	7.54	4.90	6.5	49	10.4	51	5	39	7	54
150	0.75	8.68	5.65	5.6	49	9.1	51	5	40	6	55
160	0.80	9.90	6.47	5.0	49	8.0	52	4	40	6	56
170	0.85	11.19	7.33	4.6	51	7.2	53	4	40	5	56
180	0.90	12.57	8.25	4.1	52	6.6	54	3	42	5	58
190	0.95	14.02	9.22	3.8	53	6.1	56	3	43	4	60
200	1.00	15.55	10.24	3.5	54	5.6	57	3	44	4	61
210	1.05	17.16	11.31	3.2	55	5.2	59	3	45	4	61
220	1.10	18.85	12.44	3.0	57	5.0	62	2	45	3	63
230	1.15	20.62	13.61	3.1	64	4.9	67	2	45	3	62
Depth = 30 cm											
				MN = 20cm		*MN = 30cm*					
AB(m)	*AB/2(cm)*	*K20*	*K30*	*R30*	□30	*R30*	□30				
40	0.20	0.47	0.18	145.2	68	445.8	82				
50	0.25	0.82	0.42	93.2	77	210.9	88				
60	0.30	1.26	0.71	66.2	83	119.5	84				
70	0.35	1.77	1.05	40.5	72	72.5	76				

80	0.40	2.36	1.44	31.0	73	51.2	74				
90	0.45	3.02	1.88	24.6	74	32.6	61				
100	0.50	3.77	2.38	18.6	70	25.6	61				
110	0.55	4.59	2.93	15.2	70	21.8	64				
120	0.60	5.50	3.53	12.0	66	18.3	65				
130	0.65	6.48	4.19	10.3	67	15.6	65				
140	0.70	7.54	4.90	9.2	69	13.4	66				
150	0.75	8.68	5.65	8.1	70	12.6	71				
160	0.80	9.90	6.47	7.1	70	11.8	76				
170	0.85	11.19	7.33	6.4	72	10.8	79				
180	0.90	12.57	8.25	5.6	70	9.4	78				
190	0.95	14.02	9.22	5.1	71	8.7	80				
200	1.00	15.55	10.24	4.7	73	8.1	83				
210	1.05	17.16	11.31	4.3	74	7.6	86				
220	1.10	18.85	12.44	4.2	79	7.4	92				
230	1.15	20.62	13.61	4.1	85	7.2	98				
Depth = 45 cm								***MN_20***			
				MN = 20cm		***MN = 30cm***		***Repeat (24hrs)***			***Bgrd***
AB(cm)	***AB/2(m)***	***K20***	***K30***	***R45***	***□45***	***R45***	***□45***	***R20***	***□45***	***R***	***□45***
40	0.20	0.47	0.18	232.9	110	459.6	84	215	101	213	100
50	0.25	0.82	0.42	158.9	131	255.1	107	140	115	121	100
60	0.30	1.26	0.71	100.7	127	168.6	119	96	120	82	103
70	0.35	1.77	1.05	72.0	127	111.4	117	67	119	58	102
80	0.40	2.36	1.44	52.8	124	78.3	113	48	112	43	100
90	0.45	3.02	1.88	37.6	114	57.6	109	37	110	32	97
100	0.50	3.77	2.38	30.6	115	43.6	104	27	100	25	95
110	0.55	4.59	2.93	23.7	109	34.2	100	21	97	20	93
120	0.60	5.50	3.53	20.9	115	28.7	101	17	93	16	90
130	0.65	6.48	4.19	17.2	111	24.7	103	13	87	13	86
140	0.70	7.54	4.90	14.2	107	21.4	105	11	83	11	82
150	0.75	8.68	5.65	12.1	105	17.3	98	9	81	10	82
160	0.80	9.90	6.47	10.8	107	14.5	94	8	78	8	82

170	0.85	11.19	7.33	8.6	96	13.4	98	7	76	8	84
180	0.90	12.57	8.25	8.2	103	11.2	92	6	77	7	82
190	0.95	14.02	9.22	7.3	102	10.5	97	6	80	6	81
200	1.00	15.55	10.24	6.5	101	9.6	98	5	81	6	86
210	1.05	17.16	11.31	6.2	106	8.5	96	5	86	5	86
220	1.10	18.85	12.44	5.8	109	8.2	102	5	87	5	90
230	1.15	20.62	13.61	5.5	113	8.0	109	4	89	5	97

Depth = 35 cm								*MN_20*			
				MN = 20cm		*MN = 30cm*		*Repeat (24hrs)*			*Bgrd*
AB(cm)	***AB/2(m)***	***K20***	***K30***	***R35***	□35	***R***	□35	***R***	□35	***R***	□35
40	0.20	0.47	0.18	178.6	84	381.2	70	193	91	233	110
50	0.25	0.82	0.42	108.2	89	215.4	90	117	96	139	114
60	0.30	1.26	0.71	65.7	83	124.1	88	70	88	88	111
70	0.35	1.77	1.05	44.5	79	77.5	81	47	83	60	106
80	0.40	2.36	1.44	30.3	71	54.3	78	32	75	43	101
90	0.45	3.02	1.88	22.1	67	38.3	72	22	65	32	97
100	0.50	3.77	2.38	16.8	63	28.1	67	16	61	23	88
110	0.55	4.59	2.93	13.3	61	22.3	65	12	56	18	82
120	0.60	5.50	3.53	10.9	60	18.1	64	10	54	14	76
130	0.65	6.48	4.19	9.1	59	14.9	62	8	51	11	73
140	0.70	7.54	4.90	7.8	59	12.7	62	6	48	10	72
150	0.75	8.68	5.65	6.6	57	10.8	61	6	53	8	72
160	0.80	9.90	6.47	6.0	59	9.4	61	6	55	7	70
170	0.85	11.19	7.33	5.3	60	8.4	61	5	56	6	71
180	0.90	12.57	8.25	4.7	59	7.5	62	5	59	6	72
190	0.95	14.02	9.22	4.3	60	6.8	62	4	60	5	74
200	1.00	15.55	10.24	3.9	61	6.3	64	4	61	5	76
210	1.05	17.16	11.31	3.6	62	6.0	68	4	62	4	77
220	1.10	18.85	12.44	3.5	66	5.7	71	3	65	4	80
230	1.15	20.62	13.61	3.3	68	5.5	75	3	58	4	83

Depth = 55 cm											
				MN = 20cm		*MN = 30cm*		*Repeat (24hrs)*			*Bgrd*
AB(m)	***AB/2(m)***	***K20***	***K30***	***R55***	□55	***R55***	□55	***R20***	□55	***R55***	□55
40	0.20	0.47	0.18	204.30	96	364.7	67	184	87	193	91.1
50	0.25	0.82	0.42	139.30	115	236.7	99	125	103	138	113.6
60	0.30	1.26	0.71	98.20	123	174.5	123	89	111	101	126.3
70	0.35	1.77	1.05	76.20	135	125.0	131	66	116	73	129.0
80	0.40	2.36	1.44	54.70	129	90.5	130	48	114	61	142.8
90	0.45	3.02	1.88	38.50	116	67.9	128	38	114	45	136.7

100	0.50	3.77	2.38	30.60	115	50.7	121	30	113	37	138.0
110	0.55	4.59	2.93	24.80	114	43.8	128	24	111	30	136.5
120	0.60	5.50	3.53	20.10	111	37.2	131	20	109	25	135.8
130	0.65	6.48	4.19	17.30	112	29.0	121	17	109	20	130.2
140	0.70	7.54	4.90	13.70	103	23.4	115	14	103	18	131.9
150	0.75	8.68	5.65	11.50	100	19.8	112	12	100	15	126.7
160	0.80	9.90	6.47	9.90	98	16.7	108	10	99	13	123.7
170	0.85	11.19	7.33	8.60	96	14.1	103	9	97	11	123.1
180	0.90	12.57	8.25	7.60	96	12.8	106	8	97	10	123.2
190	0.95	14.02	9.22	6.80	95	11.1	102	7	95	9	123.4
200	1.00	15.55	10.24	6.20	96	10.1	103	6	96	8	124.4
210	1.05	17.16	11.31	5.80	100	9.3	105	6	100	8	128.7
220	1.10	18.85	12.44	5.40	102	8.9	111	5	102	7	131.9
230	1.15	20.62	13.61	5.00	103	8.5	116	5	107	7	136.1
Depth = 65 cm								***MN_20***			
				MN = 20cm		***MN = 30cm***		***Repeat (24hrs)***			
AB(cm)	***AB/2(m)***	***K20***	***K30***	***R65***	□65	***R65***	□65	***R20***	□65		
40	0.20	0.47	0.18	120.2	57	227.9	42	128	60		
50	0.25	0.82	0.42	83.8	69	148.5	62	86	71		
60	0.30	1.26	0.71	63.7	80	106.2	75	64	80		
70	0.35	1.77	1.05	50.2	89	83.9	88	50	88		
80	0.40	2.36	1.44	41.8	98	66.3	95	41	96		
90	0.45	3.02	1.88	35	106	56.8	107	34	102		
100	0.50	3.77	2.38	29.7	112	47.7	114	29	109		
110	0.55	4.59	2.93	25.4	117	40.8	120	25	115		
120	0.60	5.50	3.53	22.5	124	35.9	127	22	119		
130	0.65	6.48	4.19	19.8	128	31.8	133	19	124		
140	0.70	7.54	4.90	18.3	138	28.8	141	17	130		
150	0.75	8.68	5.65	16.3	141	25.5	144	16	135		
160	0.80	9.90	6.47	14.8	146	23.5	152	14	142		
170	0.85	11.19	7.33	13.6	152	21.4	157	13	145		
180	0.90	12.57	8.25	12.8	161	20.0	165	12	153		
190	0.95	14.02	9.22	11.9	167	18.6	171	11	160		

200	1.00	15.55	10.24	11.3	176	17.8	182	11	168		
210	1.05	17.16	11.31	10.7	184	16.8	190	10	178		
220	1.10	18.85	12.44	10.4	196	16.3	203	10	188		
230	1.15	20.62	13.61	10.1	208	15.9	216	10	202		

Depth = 75 cm									
				MN = 20cm		***MN = 30cm***		***Repeat (24hrs)***	
AB(cm)	***AB/2(m)***	***K20***	***K30***	***R75***	□75	***R75***	□75	***R20***	□75
40	0.20	0.47	0.18	143.2	67	241.8	44	131	62
50	0.25	0.82	0.42	91.8	76	153.8	64	85	70
60	0.30	1.26	0.71	69.1	87	108.3	77	63	79
70	0.35	1.77	1.05	54.7	97	82.5	86	50	88
80	0.40	2.36	1.44	43.6	103	67.6	97	41	97
90	0.45	3.02	1.88	36.0	109	54.3	102	34	101
100	0.50	3.77	2.38	30.6	115	45.7	109	29	109
110	0.55	4.59	2.93	26.7	123	39.9	117	25	117
120	0.60	5.50	3.53	23.8	131	35.9	127	22	123
130	0.65	6.48	4.19	21.8	141	32.3	135	20	130
140	0.70	7.54	4.90	19.6	148	29.1	142	18	137
150	0.75	8.68	5.65	18.2	158	26.9	152	17	146
160	0.80	9.90	6.47	16.6	164	24.8	160	16	154
170	0.85	11.19	7.33	15.4	172	23	169	15	163
180	0.90	12.57	8.25	14.6	183	21.8	180	14	171
190	0.95	14.02	9.22	13.8	193	20.5	189	13	181
200	1.00	15.55	10.24	13.1	204	19.5	200	12	193
210	1.05	17.16	11.31	12.7	218	18.8	213	12	204
220	1.10	18.85	12.44	12.3	232	18.8	234	12	219
230	1.15	20.62	13.61	12.1	249	18	245	11	233

Appendix A2: Wenner measurements for different depths

Depth = 25cm									
			1st Test		***Repeat (24hrs)***		***Bgrd***		
AB(cm)	***a***	***K***	***R***	□	***R***	□	***R***	□	
30	0.10	0.63	132.6	83	89	56	159	100	

45	0.15	0.94	86.6	82	78	73	103	97	
60	0.20	1.26	48.8	61	44	55	60	76	
75	0.25	1.57	35.5	56	31	48	48	75	
90	0.30	1.88	28.6	54	26	49	33	61	
105	0.35	2.20	21.6	48	23	51	29	64	
120	0.40	2.51	19.9	50	18	44	22	56	
135	0.45	2.83	18.6	53	17	47	20	56	
150	0.50	3.14	17.4	55	16	51	18	58	
165	0.55	3.46	15.2	53	15	51	17	58	
180	0.60	3.77	15.7	59	14	54	16	60	
195	0.65	4.08	15.2	62	14	57	15	61	
210	0.70	4.40	14.3	63	13	59	14	61	
225	0.75	4.71			13	62	14	65	

			Depth = 30cm			***Depth = 75cm***			
			1st Test			***1st Test***		***Repeat (24hrs)***	
AB(cm)	***a***	***K***	***R***	□		***R***	□	***R***	□
30	0.10	0.63	144	90		82.9	52	87	55
45	0.15	0.94	100	94		74.6	70	69	65
60	0.20	1.26	60	75		64.7	81	61	77
75	0.25	1.57	48	75		58.9	93	56	88
90	0.30	1.88	36	68		52.3	99	49	93
105	0.35	2.20	30	67		47.9	105	48	105
120	0.40	2.51	26	64		47.3	119	45	112
135	0.45	2.83	21	60		45.5	129	45	126
150	0.50	3.14	21	65		44.9	141	44	137

165	0.55	3.46	21	74		45.0	156	44	153
180	0.60	3.77	19	72		43.7	165	42	158
195	0.65	4.08	18	74		44.4	181	44	178
210	0.70	4.40	18	79		45.0	198	44	194
225	0.75	4.71						46	216

Depth = 35cm								
			1st Test		***Repeat (24hrs)***		***Bgrd***	
AB(cm)	***a***	***K***	***R***		***R***		***R***	
30	0.10	0.63	147.3	93	149	94	173	108
45	0.15	0.94	97.2	92	106	100	139	131
60	0.20	1.26	69.6	87	76	95	83	104
75	0.25	1.57	55.7	87	57	89	60	95
90	0.30	1.88	38.7	73	38	72	47	88
105	0.35	2.20	32.5	71	31	67	38	82
120	0.40	2.51	24.9	63	26	65	29	73
135	0.45	2.83	21.9	62	21	60	24	67
150	0.50	3.14	19.8	62	18	58	21	67
165	0.55	3.46	17.6	61	18	62	19	65
180	0.60	3.77	17.1	64	16	61	17	64
195	0.65	4.08	16.0	65	16	65	16	67
210	0.70	4.40	15.7	69	15	67	15	68
225	0.75	4.71			16	74	15	72

Depth = 45cm								
			1st Test		***Repeat (24hrs)***		***Bgrd***	
AB(cm)	***a***	***K***	***R***		***R***		***R***	

30	0.10	0.63	140.2	88	158	99	153	96
45	0.15	0.94	107.1	101	118	111	121	114
60	0.20	1.26	85.6	108	90	113	81	102
75	0.25	1.57	69.5	109	73	115	67	105
90	0.30	1.88	59.1	111	59	112	53	100
105	0.35	2.20	50.4	111	49	108	46	100
120	0.40	2.51	39.1	98	39	98	36	90
135	0.45	2.83	35.5	100	33	92	30	84
150	0.50	3.14	31.3	98	25	79	28	88
165	0.55	3.46	25.5	88	22	76	25	87
180	0.60	3.77	24.8	93	21	79	23	86
195	0.65	4.08	23.2	95	21	85	21	85
210	0.70	4.40	21.8	96	20	86	20	88
225	0.75	4.71			19	91	20	95

Depth = 55cm								
			1st Test		***Repeat (24hrs)***		***Bgrd***	
AB(cm)	***a***	***K***	***R***	□	***R***	□	***R***	□
30	0.10	0.63	123.7	78	148	93	126	79
45	0.15	0.94	119.3	112	118	111	115	108
60	0.20	1.26	95.1	120	89	112	94	119
75	0.25	1.57	76.5	120	73	115	83	131
90	0.30	1.88	66.5	125	65	123	68	128
105	0.35	2.20	55.1	121	63	139	59	129
120	0.40	2.51	46.5	117	48	121	52	131
135	0.45	2.83	39.2	111	41	116	41	117
150	0.50	3.14	34.2	107	37	115	38	119

165	0.55	3.46	31.1	107	34	118	35	119
180	0.60	3.77	28.1	106	33	123	32	120
195	0.65	4.08	25.6	105	29	120	30	123
210	0.70	4.40	24.8	109	29	128	28	121
225	0.75	4.71			29	137	28	133

Depth = 65cm						
			1st Test		***Repeat (24hrs)***	
AB(cm)	***a***	***K***	***R60***	□60	***R60***	□60
30	0.10	0.63	82.3	52	96	60
45	0.15	0.94	76.1	72	72	68
60	0.20	1.26	58.0	73	62	77
75	0.25	1.57	63.8	100	56	87
90	0.30	1.88	55.4	104	53	99
105	0.35	2.20	52.2	115	49	108
120	0.40	2.51	48.2	121	45	112
135	0.45	2.83	47.2	133	42	118
150	0.50	3.14	45.8	144	41	129
165	0.55	3.46	44.8	155	40	139
180	0.60	3.77	42.8	161	40	149
195	0.65	4.08	42.1	172	39	158
210	0.70	4.40	43.1	190	40	174
225	0.75	4.71			41	194

Appendix A3: Dipole-Dipole measurements for different depths

Depth = 25cm										
a	**0.2**			***1st Test***		***Repeat (24hrs)***		***Bgrd***		
n	***an***	***DS***	***K***	***R***	□	***R***	□	***R***	□	

1	0.20	40	4	21.50	81	19.60	74	26.30	99
2	0.40	60	15	6.97	105	5.77	87	5.10	77
3	0.60	80	38	1.95	74	2.38	90	1.59	60
4	0.80	100	75	0.69	52	0.80	60	0.74	55
5	1.00	120	132	0.32	43	0.35	46	0.34	45
6	1.20	140	211	0.20	42	0.21	45	0.21	43
7	1.40	160	317	0.17	52	0.15	47	0.13	42
8	1.60	180	452	0.09	41	0.12	52	0.09	41
9	1.80	200	622	0.06	37	0.08	49	0.08	52

				Depth = 30cm			***Depth = 75cm***			
a	**0.2**						***1st Test***		***Repeat (24hrs)***	
n	***an***	***DS***	***K***	***R***	□		***R***	□	***R***	□
1	0.20	40	4	28.40	107		13.14	50	19.00	72
2	0.40	60	15	4.90	74		4.99	75	4.22	64
3	0.60	80	38	1.90	72		3.36	127	2.40	90
4	0.80	100	75	0.62	46		1.22	92	1.13	85
5	1.00	120	132	0.55	73		0.70	92	0.66	88
6	1.20	140	211	0.31	65		0.41	87	0.42	89
7	1.40	160	317	0.25	78		0.24	77	0.22	71
8	1.60	180	452	0.16	71		0.14	65	0.16	71
9	1.80	200	622	0.06	39		0.07	46	0.08	50

Depth = 35cm									

a	0.2			1st Test		Repeat (24hrs)		Bgrd	
n	***an***	***DS***	***K***	***R***	□	***R***	□	***R***	□
1	0.20	40	4	27.20	103	30.60	115	25.80	97
2	0.40	60	15	6.61	100	7.30	110	6.91	104
3	0.60	80	38	2.19	82	2.55	96	2.07	78
4	0.80	100	75	0.92	70	0.95	71	0.98	74
5	1.00	120	132	0.47	62	0.48	64	0.42	55
6	1.20	140	211	0.25	53	0.24	50	0.25	54
7	1.40	160	317	0.18	55	0.13	42	0.17	53
8	1.60	180	452	0.11	48	0.08	35	0.08	37
9	1.80	200	622	0.06	38	0.06	35	0.06	38

Depth = 45cm									
a	**0.2**			***1st Test***		***Repeat (24hrs)***		***Bgrd***	
n	***an***	***DS***	***K***	***R***	□	***R***	□	***R***	□
1	0.20	40	4	31.60	119	28.80	109	32.30	122
2	0.40	60	15	8.00	121	9.58	144	8.60	130
3	0.60	80	38	2.80	106	3.01	113	2.60	98
4	0.80	100	75	1.20	90	1.18	89	1.18	89
5	1.00	120	132	0.80	106	0.62	82	0.62	82
6	1.20	140	211	0.46	98	0.38	79	0.32	68
7	1.40	160	317	0.28	87	0.17	54	0.18	57
8	1.60	180	452	0.14	64	0.09	40	0.10	47
9	1.80	200	622	0.07	42	0.05	32	0.06	36

Depth = 55cm									
a	**0.2**			***1st Test***		***Repeat (24hrs)***		***Bgrd***	

n	an	DS	K	R	□	R	□	R	□
1	0.20	40	4	27.30	103	33.30	126	26.90	101
2	0.40	60	15	10.30	155	9.55	144	8.80	133
3	0.60	80	38	4.00	151	3.40	128	3.80	143
4	0.80	100	75	2.00	151	1.68	126	1.90	143
5	1.00	120	132	1.00	132	0.86	113	1.01	134
6	1.20	140	211	0.50	106	0.50	105	0.60	127
7	1.40	160	317	0.30	95	0.26	83	0.28	90
8	1.60	180	452	0.19	88	0.16	71	0.11	51
9	1.80	200	622	0.07	43	0.07	46	0.06	37

Depth = 65cm							
a	**0.2**			***1st Test***		***Repeat (24hrs)***	
n	***an***	***DS***	***K***	***R***	□	***R***	□
1	0.20	40	4	15.80	60	16.60	63
2	0.40	60	15	6.50	98	5.22	79
3	0.60	80	38	3.05	115	2.37	89
4	0.80	100	75	1.53	115	1.37	103
5	1.00	120	132	0.86	114	0.86	113
6	1.20	140	211	0.49	104	0.52	110
7	1.40	160	317	0.27	84	0.26	83
8	1.60	180	452	0.14	65	0.16	70
9	1.80	200	622	0.08	48	0.08	51