DRAFT TANZANIA STANDARD

TBS/MMDC1 (5183) P3 Geological Exploration by Geophysical Method (Electrical Resistivity) — Code of Practice

TANZANIA BUREAU OF STANDARD

1st edition

Geological Exploration by Geophysical Method (Electrical Resistivity) — Code of Practice

0. Foreword

This draft Tanzania Standard is being prepared by the Exploration Technical Committee (MMDC 1), under the supervision of the Mining and Minerals Standards Divisional Committee (MMDC).

In preparation of this draft Tanzania standard main assistance was drawn from IS 15736:2007 Geological Exploration by Geophysical Method (Electrical Resistivity) — Code of Practice

1. Scope

This draft Tanzania Standard lays down a summary of the best practice for geological exploration by electrical resistivity method including equipment, field procedures, and interpretation of data for measurement of the electrical properties of subsurface materials. Resistivity measurements as described in this Code are applicable in geological, geotechnical, environmental and hydrological investigations.

2. Terms and definition

For the purposes of this standard, the following terms and definitions shall apply:

2.1 Array

The arrangement of electrodes in resistivity prospecting, also called configuration.

2.2 Anomaly

A deviation from uniformity in physical properties

2.3 Anisotropy

Variation of a physical property depending on the direction in which it is measured. The resistivity anisotropy coefficient is the square root of the ratio of the resistivity measured perpendicular to the bedding to that measured parallel to the bedding.

2.4 Apparent resistivity

The ground resistivity calculated from measured resistance and a geometric factor derived for the condition where the ground is homogeneous and isotropic.

2.5 Apparent resistivity curve

A graph of apparent resistivity plotted against electrode separation. In case of soundings, apparent resistivity curves are plotted on double logarithmic paper for comparison with normalized theoretical curves, for the purpose of interpreting the resistivity, thickness and depth of surface layers. In case of profiling, the apparent resistivity curve is plotted on semi log paper.

2.6 Electrode

A piece of metallic material that is used as an electrical contact with a non-metal. May also refer to a grounding contact used for field surveying, to the metallic minerals in a rock.

2.7 Homogeneous

Uniformity of a physical property throughout a material.

2.8 Inversion

The technique for deriving a subsurface geological model from observed field data that is, solving for a spatial distribution of parameters in terms of thicknesses and true resistivities which could have produced on observed set of measurements.

2.9 Profiling

A resistivity method whereby an array with a fixed electrode spacing is moved progressively along a traverse to create a horizontal profile of the apparent resistivity.

2.10 Resistivity

The property of a material which resists the flow of electric current.

2.11 Resistivity method

Observation of electric fields caused by current introduced into the ground as a means for studying earth resistivity in geophysical exploration.

2.12 Resistivity imaging

It is an advanced technique for gathering continuous subsurface resistivity distribution in two and three dimensions through an automatic electrode switching mechanism. In this technique, large amount of data is collected, and therefore, it offers more reliable results than the conventional resistivity sounding/profiling. It requires special equipment and software package.

2.13 Sounding

A depth probe or expander. A series of electrical resistivity readings, with successively greater electrode spacing, made while maintaining one point in the array fixed, thus giving resistivity versus depth information.

2.14 True resistivity

In the idealized condition of a perfectly uniform conducting half space (homogeneous, isotropic semi-infinite), the current flow lines resemble a dipole pattern and the resistivity determined with a four-electrode configuration is the true resistivity of the half space.

However, in real situations the resistivity is determined for different lithology and geological structures (inhomogeneous and anisotropic medium).

3. Parameters measured and representative values

3.1 The generally accepted unit of resistivity is ohm-meter. In most rock materials, the porosity and the chemical content of the water filling the pore spaces is more important in governing resistivity. The salinity of the water in the pores is probably the most critical factor determining the resistivity. When pores, particularly those with large concentrations of magnetite or graphite, lie above the water table at shallow depths, or when they occur at such great depths that all pore spaces are closed by ambient pressure, the conduction through them takes place within the mineral grains themselves. Under these conditions, the resistivity of the rock will depend on the resistivity of the grains. When the pores are saturated with fluids, the resistivity will be governed by the fluid resistivity as well.

3.2 The range of resistivities among rocks and rock materials is enormous, extending from 10^{-5} to 10^{15} ohm-m. Rocks and minerals with resistivities from 10^{-5} to 10^{-1} ohm-m are considered good conductors; those from 1 to 10^{7} ohm-m, intermediate conductors, and those from 10^{8} to 10^{15} ohm-m poor conductors.

Igneous rocks have the highest resistivity, sedimentary the lowest, with metamorphic rocks intermediate. However, there is considerable overlapping, as in other physical properties. In addition, the resistivities of particular rock types vary directly with age and lithology, since porosity of the rock and salinity of the contained water are affected by both. The resistivities of some common rocks, soils, waters and minerals are as shown in Table 1.

Table 1. Resistivity values of some common materials

Igneous and Metamorphic Rocks	
Material	**Resistivity (Ωm)**
Granite	$5\times10^{3}-10^{6}$
Basalt	$10^{3}-10^{6}$
Slate	$6\times10^{2}-4\times10^{7}$
Marble	$10^{2}-2.5\times10^{8}$
Quartzite	$10^{2}-2\times10^{8}$
Sedimentary Rocks	
Material	**Resistivity (Ωm)**
Sandstone	$8-4\times10^{3}$
Shale	$20-2\times10^{3}$
Limestone	$50-4\times10^{2}$
Soil and water	
Material	**Resistivity (Ωm)**
Clay	**1 – 100**
Alluvium	**10 - 800**
Groundwater (fresh)	**10 - 100**
Sea Water	**0.2**
Minerals	
Material	**Resistivity (Ωm)**
Galena	$3\times10^{-5}-3\times10^{2}$
Bauxite	$2\times10^{2}-6\times10^{2}$
Cuprite	$10^{-3}-300$
Hematite	$3.5\times10^{-3}-10^{7}$
Magnetite	$5\times10^{-5}-5.7\times10^{3}$
Quartz	$4\times10^{10}-2\times10^{14}$
Uraninite	$1-200$
Calcite	2×10^{12}
Rock Salt	$30-10^{3}$
Diamond	$10-10^{14}$
Mica	$9\times10^{12}-10^{14}$

4. Purpose of electrical resistivity survey

The purpose of electrical resistivity survey is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters, such as, the mineral and fluid content, porosity and degree of water saturation in rock. Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations. More recently, it has been used for environmental surveys. It has the following other purposes:

a) To rapidly explore the subsurface conditions in order to locate ground water, thickness of overburden, depth to different rock types and stratigraphic features.

b) To delineate weak formations, faults and dykes, if any, and to identify location of steeply dipping contacts between different rock types and earth material.

c) To delineate zones of seepage and identify its source around various structures of river valley projects.

d) Assessment of groundwater potential, quality and determination of aquifer characteristics.

e) To correlate data from resistivity survey with those obtained from borehole and trial pit logs.

f) For earthing of electrical conductors

5. Methodology

The measurement of electrical resistivity requires that four electrodes be placed in contact with the surface material as shown in Fig. 1. The geometry, separation of the electrode array and spacing are selected on the basis of the application and required depth of investigation. A direct current, or a very low frequency alternating current, is passed into the ground through a pair of current electrodes, and the resulting potential drop is measured across a pair of potential electrodes as shown in Fig.1. The resistance is then derived as the ratio of the voltage measured across the potential electrodes and the current electrodes. The apparent resistivity of subsurface materials is the resistance multiplied by a geometric factor determined by the geometry and spacing of the electrode array.

$$\rho = -K\frac{\Delta V}{I} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

where,

$\rho =$ apparent resistivity

$K =$ geometric factor

$\Delta V =$ potential drop

$I =$ applied current

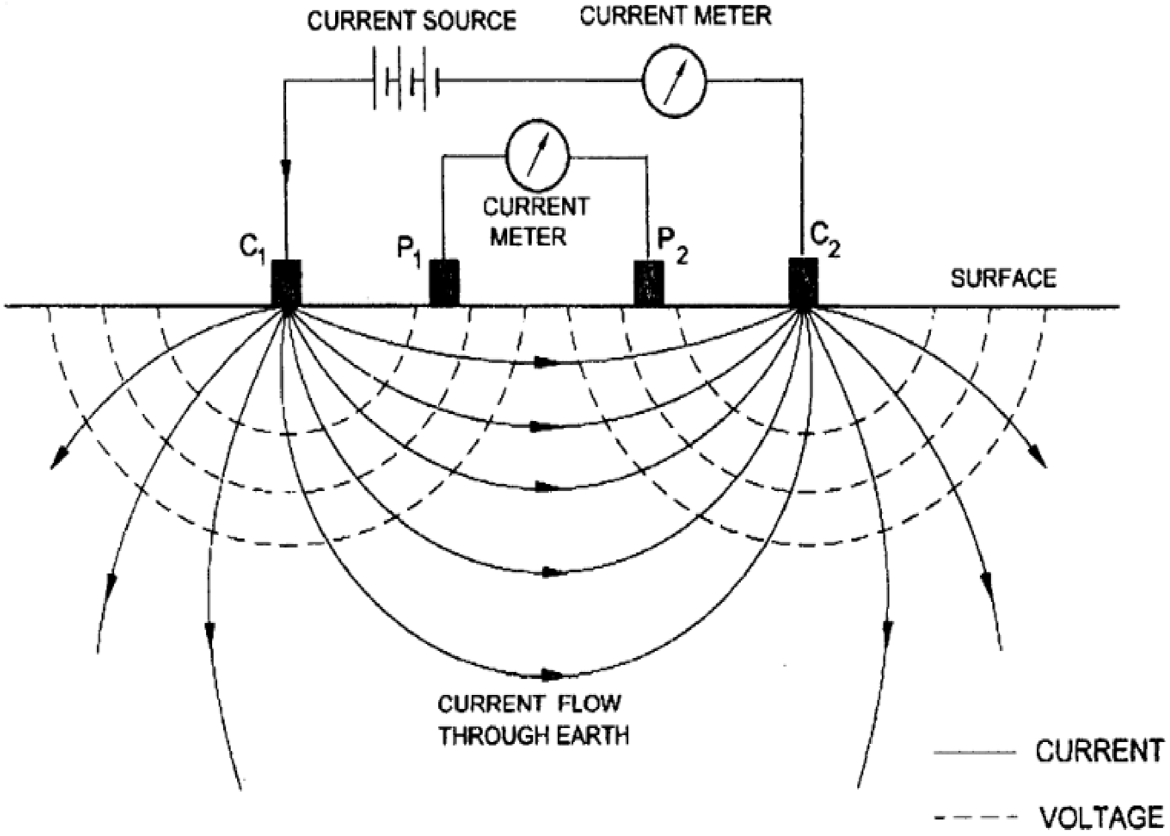


Figure. 1 Equipotential and current flow lines for four electrode array

The apparent resistivity depends on resistivity contrast between adjacent layers. The apparent resistivity depends not only on the nature of geoelectric section but also on geometric configuration of the electrode used for the measurements. This apparent resistivity is different from the true resistivity unless the subsurface materials are homogenous. Two main procedures are employed in resistivity survey.

a) Electrical profiling

It is used to determine lateral variation of resistivity. The current and potential electrode are maintained at a fixed separation and progressively moved along a profile. This method is employed in mineral prospecting to locate faults or shear zones and to detect localized bodies of anomalous conductivity. It is used in geotechnical survey to determine variations in bedrock depth, the presence of steep discontinuities and to evaluate the resistivity of layers for earthing of electrical conductors.

b) Vertical Electrical Sounding (VES)

Also, known as electrical drilling or expanding probe. It is employed to investigate changes in resistivity of the earth’s layer in vertical direction. The current and potential electrodes are maintained at the same relative spacing and the whole spread is progressively expanded about a fixed central point. Consequently, readings are taken as the current reaches progressively greater depths. The technique is extensively used in geotechnical surveys to determine overburden thickness and also in hydrogeology to define horizontal zones of porous strata.

5.1 Electrode array geometry

Resistivity measurements can be made with any combination of current and potential electrodes desired. Several standard electrode geometries have been developed for various applications. For geological survey, Wenner, Schlumberger and dipole-dipole array are used as shown in Fig. 2.

5.1.1 Wenner array

This arrangement uses four electrodes equally spaced along a straight line. It is the simplest and the most symmetrical arrangement. It is designed to measure the potential difference (ΔV) between M and N as shown in Fig.2. The formula for calculating apparent resistivity from a Wenner measurement is:

$$\rho = 2\pi a\left(\frac{\Delta V}{I}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where **'a'** is the spacing between adjacent electrodes.

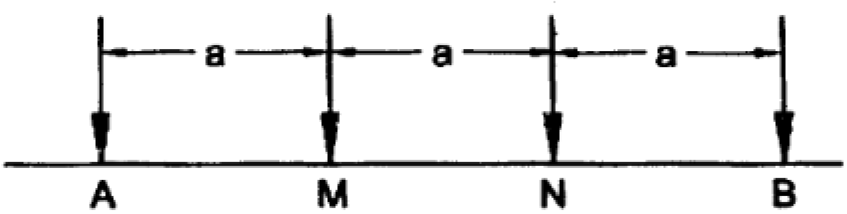


Figure 2a. Wenner spread

5.1.2 Schlumberger array

This arrangement is symmetric, collinear and uses four electrodes. In this arrangement, the current electrodes are denoted by A and B while the potential electrodes are denoted by M and N. The interval between M and N is denoted by 2l, while the interval between A and B denoted by 2L as shown in Fig. 2. For this array the current electrodes are placed much farther apart than the potential electrodes (AB > 5 MN). The formula for calculating apparent resistivity is:

$$\rho = \frac{\pi L^2}{2I} \times \frac{\Delta V}{I} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots . (3)$$

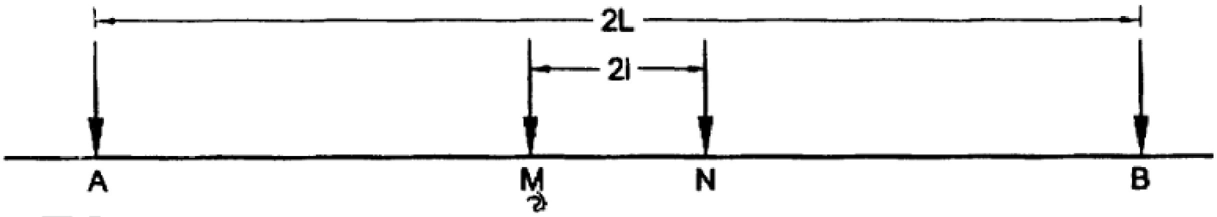


Figure. 2b Schlumberger spread

In depth probing the potential electrodes remain fixed while the current electrode spacing is expanded symmetrically about the centre of the spread. For larger values of **L**, it may be necessary to increase **I** also, in order to maintain a measurable potential as shown in Fig. 2b.

5.1.3 Dipole-dipole array

In this array the current electrodes are planted on one side of the array and the potential electrodes on the other side. There is always the same distance between the two current electrodes in the current dipole and the potential electrodes in the potential dipole as shown in the Fig. 2c. The formula for calculating apparent resistivity is:

$$\rho = \pi n(n + l)(n + 2)a\frac{\Delta V}{I} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

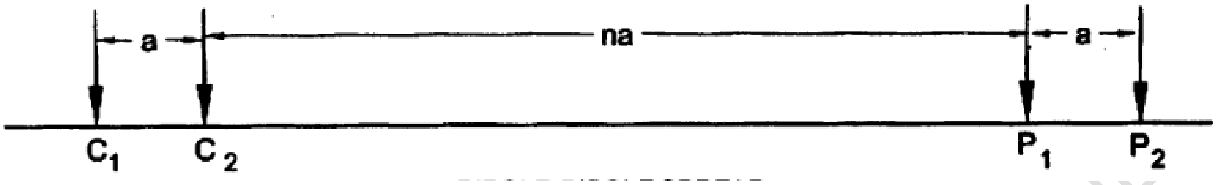


Figure. 2c Dipole-dipole spread

5.1.4 Pole-dipole array

The pole-dipole array is an asymmetrical array and has three collinear electrodes: one current electrode on one end and two potential electrodes on other. The potential electrodes are separated by a distance **'a'** and the second current electrode is placed at infinity. The distance between the current and the near potential electrode is **'na'**, where **'n'** doesn't have to be an integer (though it commonly is). The total length of the array is **(n+I) a** excluding the current electrode at infinity. The formula for calculating apparent resistivity is:

$$\rho = 2\pi a(n + I)n\frac{\Delta V}{I} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

The geometry of this array is as shown in Fig. 2d. Pole-dipole sounding data is plotted as apparent resistivity versus spacing **'n'**

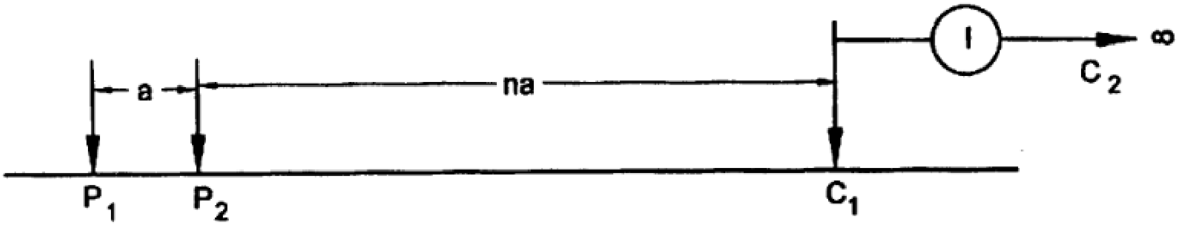
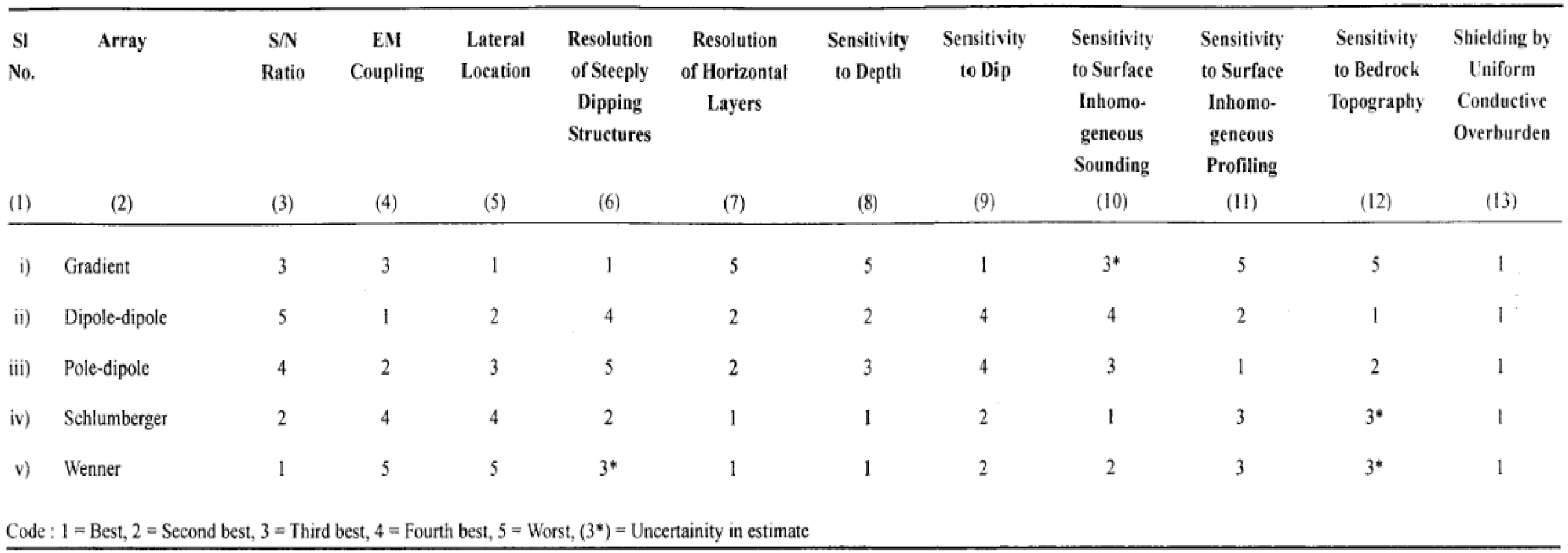


Figure. 2d Pole-dipole spread.

Table 2. Resistivity array evaluation



Sl No. (1)	Array (2)	S/N Ratio (3)	EM Coupling (4)	Lateral Location (5)	Resolution of Steeply Dipping Structures (6)	Resolution of Horizontal Layers (7)	Sensitivity to Depth (8)	Sensitivity to Dip (9)	Sensitivity to Surface Inhomo-geneous Sounding (10)	Sensitivity to Surface Inhomo-geneous Profiling (11)	Sensitivity to Bedrock Topography (12)	Shielding by Uniform Conductive Overburden (13)
i)	Gradient	3	3	1	1	5	5	1	3*	5	5	1
ii)	Dipole-dipole	5	1	2	4	2	2	4	4	2	1	1
iii)	Pole-dipole	4	2	3	5	2	3	4	3	1	2	1
iv)	Schlumberger	2	4	4	2	1	1	2	1	3	3*	1
v)	Wenner	1	5	5	3*	1	1	2	2	3	3*	1

Code : 1 = Best, 2 = Second best, 3 = Third best, 4 = Fourth best, 5 = Worst, (3*) = Uncertainity in estimate

5.2 2-D Resistivity imaging surveys

The most severe limitation of resistivity sounding method is that horizontal (or lateral) changes in the subsurface resistivity are commonly found. Lateral changes in the subsurface resistivity will cause changes in the apparent resistivity values that might be misinterpreted as changes with depth in the subsurface resistivity. In many engineering and environmental studies, the subsurface geology is very complex where the resistivity can change rapidly over short distances.

The resistivity sounding method might not be sufficiently accurate for such situations,a more accurate model of the subsurface is a two-dimensional (2-D) model, where the resistivity changes in the vertical direction as well as in the horizontal direction along the survey line. In many geological situations, 2-D electrical imaging surveys can give useful results that are complementary to the information obtained by other geophysical method. 2-D imaging surveys involve about 100 to 1000 measurements. 2-D electrical imaging surveys are usually carried out using a large number of electrodes, 25 or more, connected to a multi-core cable. A laptop microcomputer together with an electronic switching unit is used to automatically select the relevant four electrode array for each measurement. At present, field techniques and equipment to carry out 2-D resistivity surveys are fairly well developed. The electrode layout of 2-D imaging survey is as shown in Fig. 3a.

To plot the data from a 2-D imaging survey, the pseudosection contouring method is normally used. In this case, the horizontal location of the point is placed at the mid-point of the set of electrodes used to make measurement. The vertical location of the plotting point is placed at a distance which is proportional to the separation between electrodes. The pseudosection gives a very approximate picture of the true subsurface resistivity distribution. Further this pseudosection is inverted using available standard computer programs of resistivity imaging. After inversion, a 2-D image of subsurface true resistivity is obtained and can be interpreted in terms of subsurface geology.

5.3 3−D Resistivity imaging surveys

Since all geological structures are three dimensional in nature, a 3-D resistivity survey using 3-D interpretation model gives the most accurate result. With the development of multichannel resistivity meters which enables the recording of more than one measurement at a time and the availability of sophisticated fast computers, the inversion of very large data sets comprising more than 8000 data points and survey grid of greater than 30 m x 30 m is enabled.

The pole-pole, pole-dipole and dipole-dipole arrays are frequently used for 3-D surveys because other arrays have poor data coverage near the edge of the survey grid. The electrode layout of 3-D resistivity imaging is as shown in Fig. 3b.

6. Equipment

The necessary components for making resistivity measurements include a power source, meters for measuring current and voltage, electrodes, cable and reels. The power may be either direct current or low frequency alternating current. If direct current is used, a set of batteries may be connected in series to give an output of several hundred volts. However, due to the limited current capacity and short life, battery sources have little advantages except portability. For large-scale work, it is preferable to use a motor-generator having a capacity of several hundred watts.

7. Planning the survey

Planning and design of a resistivity survey should be done with due consideration to the objectives of the survey and the characteristics of the site. These factors determine the survey design, the equipment used, the level of effort, the interpretation method selected, and the budget necessary to achieve the desired results. Important considerations include site geology, depth of investigation, and the topography. The presence of noise-generating activities and operational constraints should also be considered. It is good practice to obtain as much relevant information as possible about the site prior to designing a survey and mobilizing to the field. Before conducting electrical sounding in an area, it is useful to study the local geology, well sections, depth to water table, quality of water, yield of water, etc. The place for conducting a sounding should be carefully selected keeping in view the requirement of plain topography for maximum current electrode separation. The field survey should guard against proximity to houses, rivers, ponds, disturbing metallic features like power lines, buried pipes and other objects. In areas of complex geology, where formations dip, electrode separation should always be parallel to strike of formation. In hard rock regions, electrode separation should be parallel to strike direction of joints and fractures. This minimize errors caused by random separation. The current electrode separation is chosen in a manner that when plotted on a log-log graph, the distance between neighboring points are approximately equal. This is achieved by increasing the current electrode separation by a factor of 2 or 1.5.

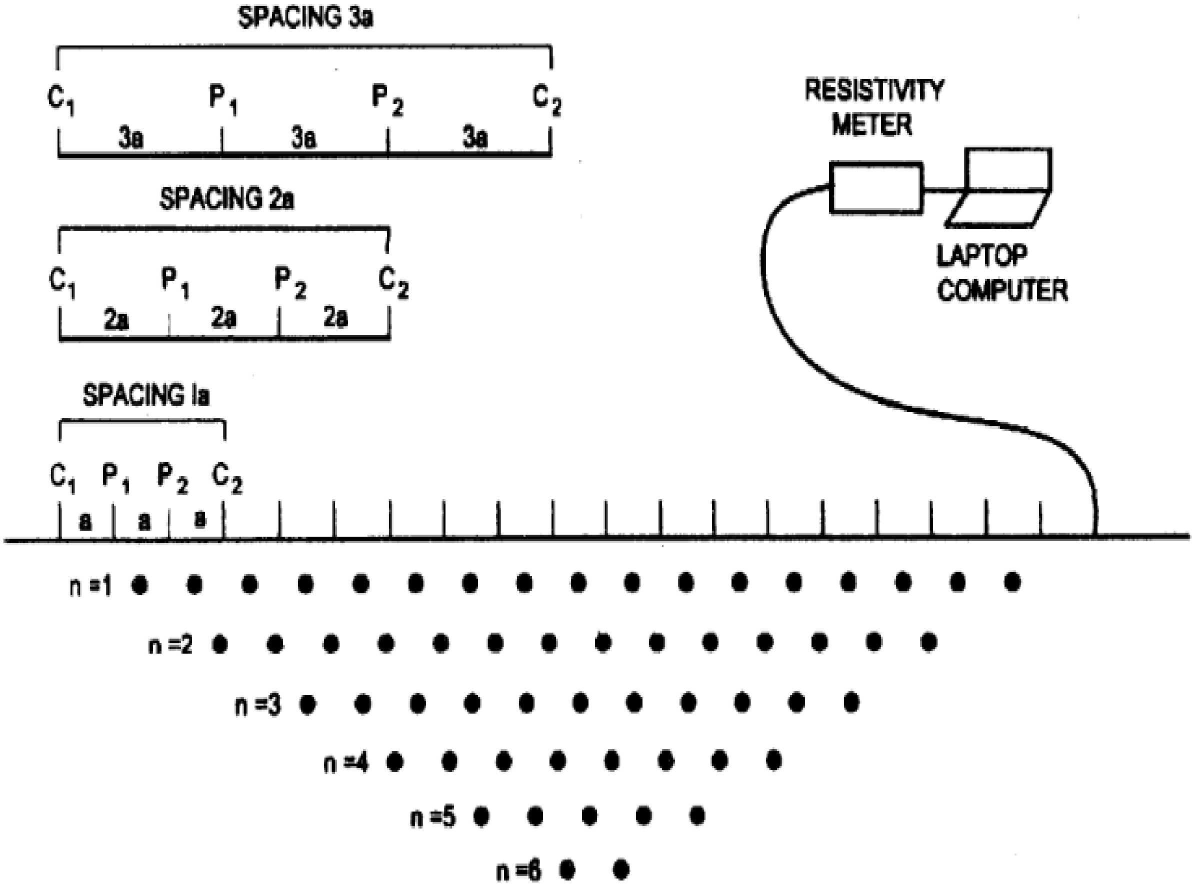


Figure. 3a Electrode layout for 2-D imaging survey

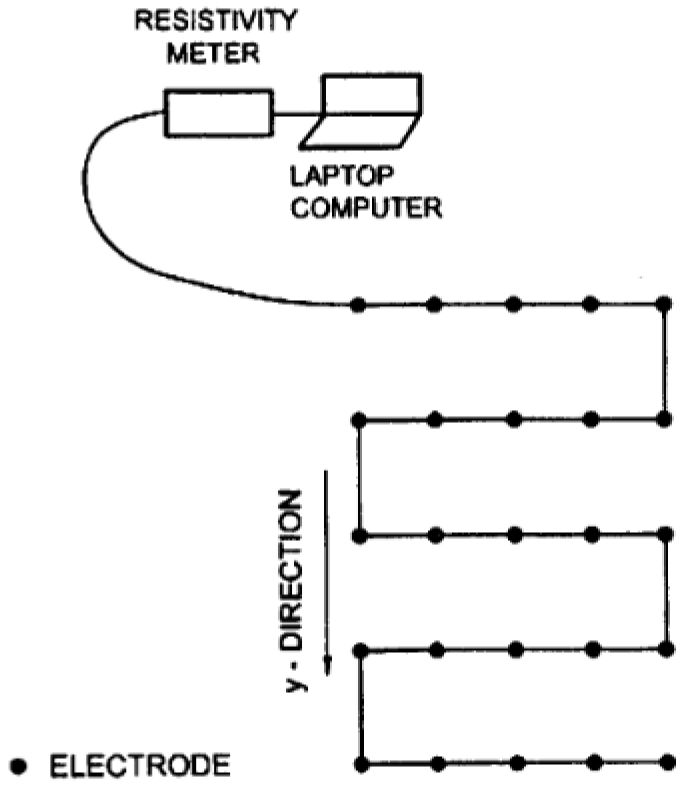


Figure. 3b Electrode Layout for 3-D imaging survey

8. Interpretation

8.1 The interpretation of electrical profiling data is mainly qualitative in nature and is useful only for deciphering areas of different resistivities. The anomalies obtained in the profiling data are interpreted in terms of possible geological structures corresponding to the set of geological conditions.

8.2 Generally, the profiling data for constant electrode separation may be presented as graphs showing resistivity variation along a traverse as shown in Fig. 4 or as a map showing isoresistivity contours. Such a map is an expression of the lateral resistivity variation of the ground for the arbitrary depth range corresponding to the chosen current electrode separation. The value of apparent resistivity, for a given lithology, will depend on the location and the local geologic setting. The isoresistivity contour maps are interpreted to locate the zones of low and high resistivity as related to local geological structures. In a number of cases, the interpretation is confined to locating two dimensional structures such as dykes, faults and contact zones, provided the spread is run across the strike of the formations with suitable station interval.

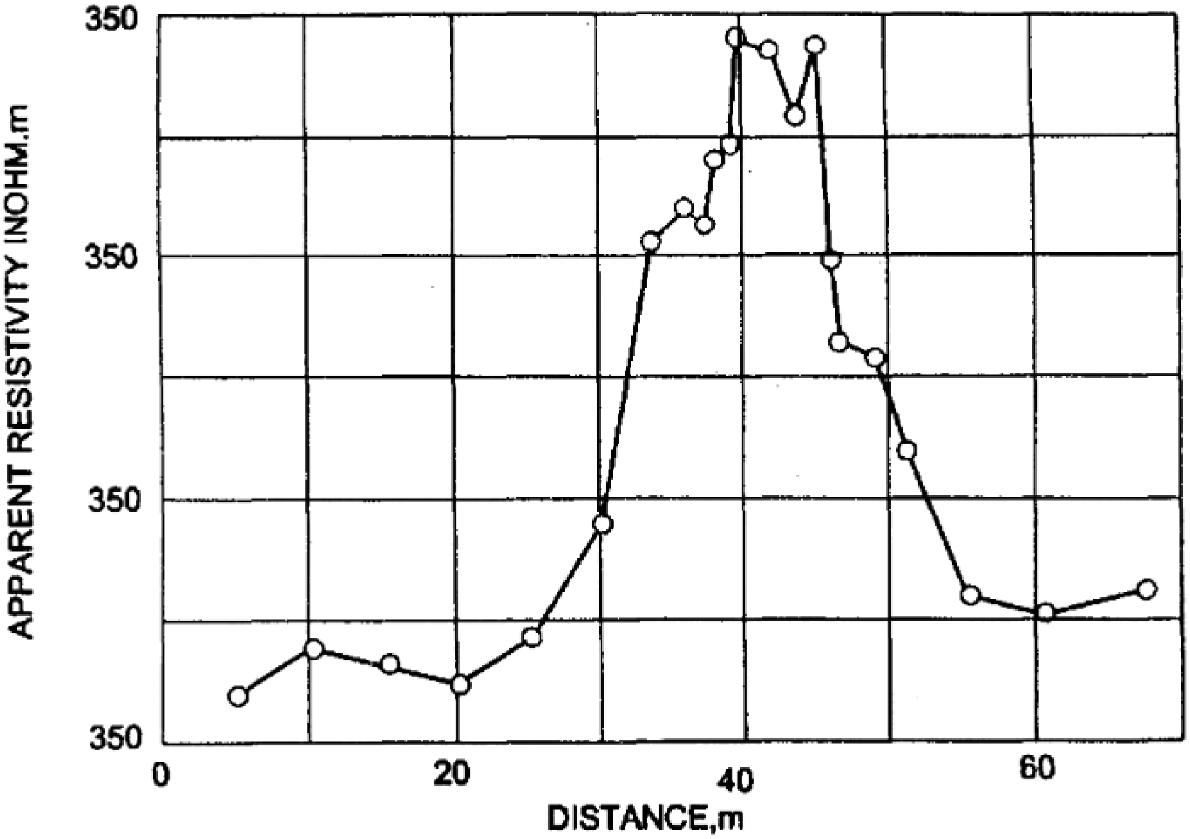


Figure. 4 Resistivity profile across resistive.

9. Presentation of data

The results of a series of profile measurements are presented as a profile or contour map as shown in Fig. 4. Sounding data are often presented as single geoelectric section as shown in Fig. 5. An interpreted geoelectric section showing layer thickness, depths and resistivity is constructed. Geoelectric cross sections can be helpful in determining the depth and lateral extent of layers.

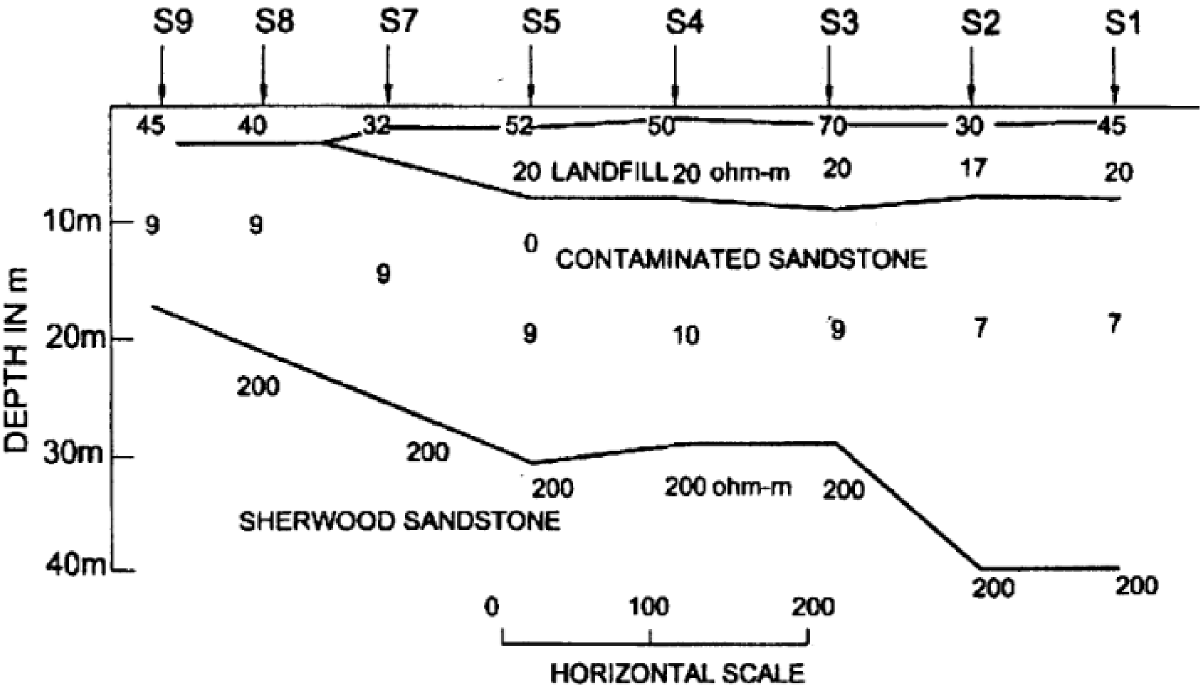


Figure 5. Geoelectrical section.

Dipole-dipole data are generally presented as resistivity pseudosections although they can also be presented as individual profile. The data can be interpreted in a qualitative fashion when only the presence or absence of an anomaly in a general area is required. In order to fully utilize the combination of vertical and horizontal information available with dipole-dipole data, two-dimensional modeling is required. The pseudosection for halfspace is as shown in Fig. 6. This model generates a simple apparent resistivity pattern.

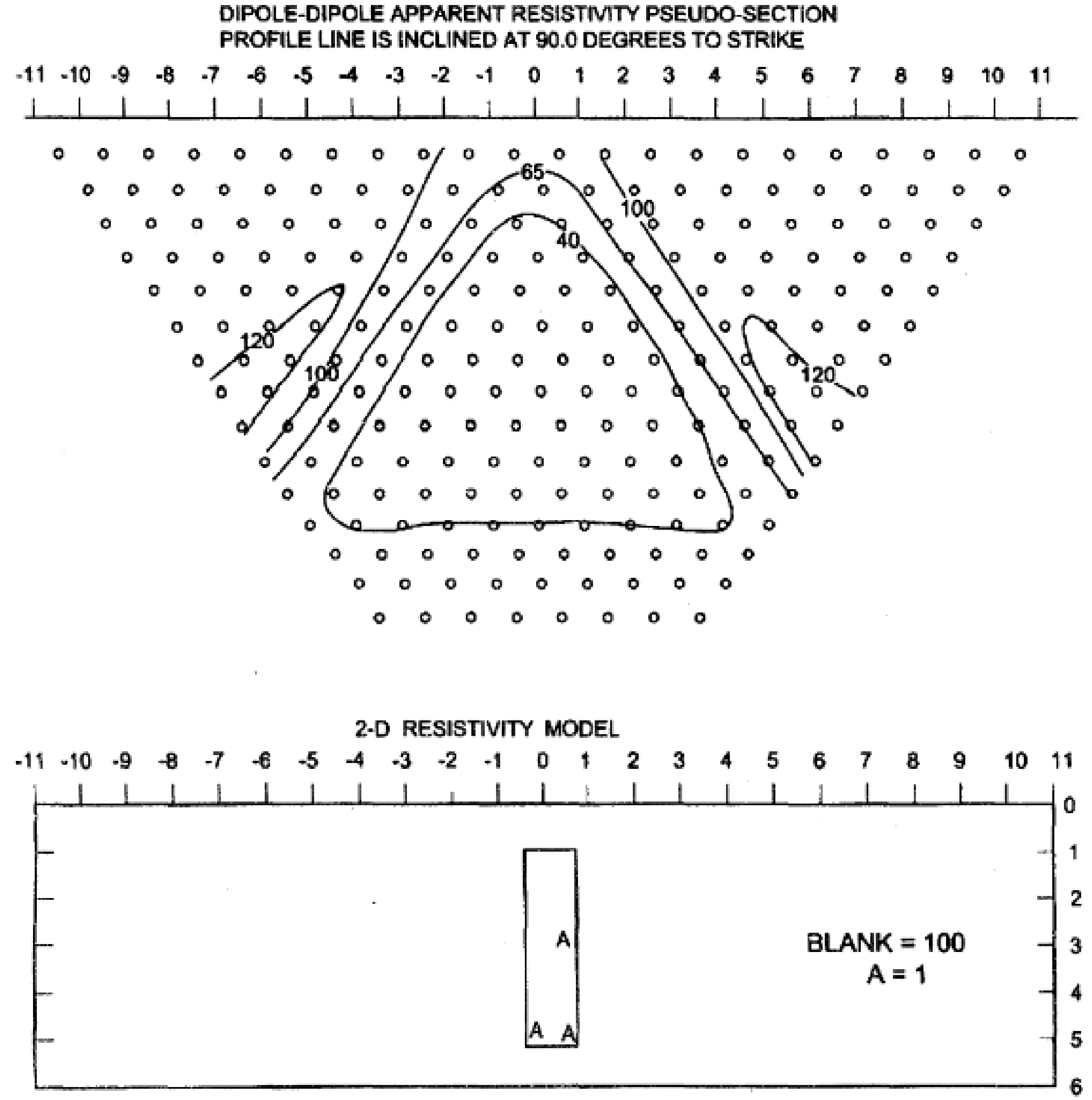


Figure. 6 Pseudo for a conductive rectangular body buried in a more resistive halfspace