CHAPTER VI
GEOPHYSICAL INVESTIGATIONS
6.1.0 INTRODUCTION

The electrical resistivity method is highly useful to investigate the nature of subsurface formations by studying the variations in their electrical properties. This method assumed considerable importance in subsurface exploration because of very good resistivity contrasts among the lithological units, controlled depth of investigation, ease of field operations and low cost of instrumentation and operation.

Definition of Resistivity

Resistivity (denoted by $\rho$) is a physical property of a substance (like density). It is an inherent property of a substance and is independent of size and shape of the substance. The resistivity is defined as the resistance offered by a unit length of a substance of a unit area to the flow of electric current when the voltage is applied at the opposite faces. To understand the concept of resistivity let us consider a substance with a regular shape such as a cylinder (Fig. 6.1.1)

\[ R = \frac{\rho L}{A} \]  

Fig. 6.1.1

The resistance offered by this cylinder can be written as

\[ R = \rho \frac{L}{A} \]  

(1)

Where

- $R$ = resistance offered by the cylinder
- $L$ = length of the cylinder
- $A$ = area of cross section of the cylinder
- $\rho$ = resistivity of the substance

Arrows indicate the direction of the current. Rearranging the equation (1) we get:

\[ \rho = \frac{R A}{L} \]  

(2)

If $A$ and $L$ are unity, then
\[ \rho = R \]

Hence the resistivity of the substance is equal to the resistance offered by a substance of unit length and unit area of cross section. If ‘meter’ is taken as unit of length and ‘ohm’ is the unit for resistance, then units of \( \rho \) are

\[
\text{Ohm (R)} \times \text{meter}^2 (\text{L}^2) \times \frac{\text{meter (L)}}{\text{Ohm-m}} = \text{Ohm-m}
\]  

The inverse of resistivity is termed as conductivity (\( \sigma \)) and the inverse of resistance is called conductance.

**Electrical conduction through rocks**

Three types of electric conduction are possible in rock formations. They are Electronic, Ionic and Dielectric conductions.

**Electronic Conduction**

Electronic conduction is due to movement of electrons predominantly in metals. Certain minerals like pyrite, galena, graphite, magnetite etc. have high conductivities comparable to those of metals. The resistivities of these minerals are of the order of 0.01 ohm-m. However, rocks containing these minerals may show higher resistivities than this value because of imperfect contacts between the individual conductive crystals due to the host medium. The contribution of electronic conductivity in ordinary rock types is negligible except in metallic ores.

**Ionic Conduction**

The ionic conduction is due to the mobility of ions and electric current is carried through ionic charges. Most of the rocks conduct electricity because of the water/moisture present in its pores and fissures. A truly dry rock formation is highly resistant to pass electric current (excepting rocks with conductive minerals).

In general, all rocks and soils transmit current more are less readily due to the presence of the water in the pore spaces; no matter how minute is the moisture. In general...
the resistivity of a geological formation may be considered as a function of moisture content (porosity and water saturation) and salinity of the saturating water.

It can be expressed as:

$$\rho_t = \frac{\rho_w}{F_t \cdot F_s}$$  \hspace{1cm} (4)

Where $\rho_t$ = resistivity of the rock formation

$\rho_w$ = resistivity of the formation water

$F_t$ = factor depending on the texture (porosity)

$1/F_t$ is called formation factor

$F_s$ = factor depending on the degree of saturation.

When $F_t$ is considerably less than 1 (very low porosity) the resistivity value of the formation will be very high irrespective of the other two factors namely, the resistivity of water ($\rho_w$) and the saturation factor ($F_s$). But as the porosity of the formation increases, the factor $F_t$ becomes comparable to 1, its effect is felt on the factors $F_s$ and $\rho_w$. The resistivity of saturating water depends on its salt content. The effect of salinity on resistivity of water is shown in Fig. 6.1.2.

![Fig. 6.1.1. Resistivity of solutions of sodium chloride as a function of concentration and temperature]
It can also be seen from this figure that the relationship between resistivity and salinity is linear. The resistivity of naturally occurring water may vary from a fraction of an ohm-m to several tens or a few hundreds of ohm-m. The low end of the scale represented by seawater and salt-water found in brackish water wells, while the high end is represented by spring and river waters. If we consider 1200 ppm of dissolved salts as the limit of potability, it can be seen from the graph that the lower limit of resistivity for potable water is about 5 ohm-m (2000 μmhos/cm). Only in theoretical case of rock formation with 100% porosity (Ft =1) and 100% saturation (Fs =1), the observed formation resistivity would be that of formation water. The saturation factor Fs can reach unity but it is not possible to have 100% porosity. Hence the observed resistivity will always be more than the resistivity of the saturating water. Therefore the lower limit of the resistivity of a formation having potable water will be more than 5 ohm-m. This value depends on Ft (1/Ft called the formation factor). Since it is not possible to have 100% porosity for any formation it is generally observed that the formation resistivity is more than three times the resistivity of the saturating water and hence the lower limit of resistivity for a formation with potable water may be considered to be more than 15 ohm-m. Hence the measurement of resistivity of a formation gives an idea about the salinity of water it holds.

**Dielectric Conduction**

Dielectric conduction takes place in poor conductors is due to the displacement of atomic electrons under the influence of an external varying electric field and is affective only at very high radio frequencies. In resistivity measurements, the dielectric conduction is of secondary importance in earth materials since electrical prospecting methods employ DC current or very low frequency alternating currents (a few Hz) for the measurements.

**6.1.2 Range of Resistivity for Rocks and Minerals**

In water bearing rocks there is also an indirect relationship between resistivity and lithology or geologic age, since these two factors tend to control the porosity and water storage capacity of rocks. The dependence of resistivity on age and lithology is indicated in general way by Keller and Frischknecht (1966) and presented in Table-6.1.1 The magnitude of rock resistivities has a wide range from a fraction of ohm-m to several thousands of ohm-m. The
rocks containing high concentration of metallic minerals and saline water may show resistivities less than 1 ohm-m to a few ohm-m.

Table - 6.1.1. Dependence of resistivity on lithology

<table>
<thead>
<tr>
<th>Age</th>
<th>Marine Sedimentary</th>
<th>Terrestrial Sedimentary</th>
<th>Extrusive rocks (basalt, rhyolite)</th>
<th>Intrusive rocks (granite, gabbro)</th>
<th>Chemical precipitate (limestones, salt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary and tertiary age</td>
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<td>1-10</td>
<td>10-200</td>
<td>500-2000</td>
<td>50-5000</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>5-20</td>
<td>25-100</td>
<td>20-500</td>
<td>500-2000</td>
<td>100-10,000</td>
</tr>
<tr>
<td>Carboniferous Paleozoic</td>
<td>10-40</td>
<td>50-300</td>
<td>50-1000</td>
<td>1000-5000</td>
<td>200-100,000</td>
</tr>
<tr>
<td>Early Precambrian</td>
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<td>100-500</td>
<td>100-2000</td>
<td>1000-5000</td>
<td>10,000-100,000</td>
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<tr>
<td>Precambrian</td>
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<td>300-5000</td>
<td>200-5000</td>
<td>5000-20,000</td>
<td>10,000-100,000</td>
</tr>
</tbody>
</table>

The clays and marls show one to a few tens of ohm-m. Sands and sandstones show from ten to a few hundreds of ohm-m. Table-6.1.2 gives the general range of resistivities for different rock types. The resistivity of a given formation also changes depending on the degree of weathering and number of fractures.
### Table 6.1.2. Approximate ranges for the resistivity of rocks and soils

<table>
<thead>
<tr>
<th>Formation</th>
<th>Resistivity in ohm-m</th>
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<tr>
<td></td>
<td>$10^1$</td>
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<td>Quartzite</td>
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<tr>
<td>Basalt</td>
<td></td>
</tr>
<tr>
<td>Jointed/fractured basalt</td>
<td></td>
</tr>
<tr>
<td>Fresh granite</td>
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<tr>
<td>Weathered granite</td>
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<td>Limestone</td>
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<td>Sandstone</td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td></td>
</tr>
<tr>
<td>Alluvium</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
</tr>
</tbody>
</table>

#### 6.2.0 MEASUREMENT OF EARTH RESISTIVITY

From the foregoing section it is possible to understand that the resistivity of a formation can be used to know the nature of the formation and distinguish the saline and fresh water zones. Hence for using the earth resistivity as a prospecting tool we have to consider the following aspects:

i) The procedure to measure resistance values at the ground surface

ii) The equipment needed for these measurements

Methods to estimate the resistivities and thicknesses of the subsurface formations, from the resistance measurements taken on the surface

iii) Interpretation of these parameters to infer about the nature of the subsurface formations and their thicknesses.
Measurement of Earth Resistance

\[ I = \frac{V}{R} \]  \hspace{1cm} (5)

Where \( V \) = Voltage applied
\( R \) = the resistance being measured

From the above equation for a given ‘V’, the current \( I \) is inversely proportional to the resistance \( R \). Therefore the meter gives deflection proportional to the current, which can be calibrated in terms of resistance.

In the case of earth resistance measurements the current through the circuit is affected by four resistances; viz., the ground resistance \( R_G \), the contact resistance between the current electrodes A and the ground \( R_A \), the contact resistance between the current electrode B and the ground \( R_B \), and the resistance due to cables and real contacts etc. \( R_C \). Hence the total resistance \( R \) will be: \( R = R_A + R_B + R_C + R_G \) (Fig. 6.2.1).

It is found that the values of \( R_A \) and \( R_B \) are always very high compared to the earth resistance \( R_G \). Hence the current I through the circuit is controlled more by \( (R_A + R_B + R_C) \) than \( R_G \). The effect of \( R_A \), \( R_B \) and \( R_C \) cannot be eliminated in the two-electrode system, since the current is affected by the total resistance ‘R’. (In the case of laboratory measurements the contacts are metal to metal and hence the contact resistances are negligible compared to the resistance being measured). Even in the laboratory, when very low values of resistance measurements are involved the multi-meter is not dependable.
To eliminate the effects of $R_A$, $R_B$ and $R_C$ in earth resistance measurements, a modification is made in which four electrodes (probes) are used instead of two. In this four-electrode system two electrodes are used to send current into the ground. The total resistance $R$ as discussed earlier controls the value of current.

\[
V = \frac{I}{R_G + R_A + R_B + R_C}
\]  \hspace{1cm} (7)

The passage of this current through the earth produces potentials across the surface depending on the section of the subsurface formations through which the current flows. If the potential gradient or the potential difference is measured with two other electrodes, it will be proportional to the current flowing through the formations and the effective resistance of the formation section ($R_G$)

\[
\Delta V = R_G \times I
\]

and

\[
R_G = \frac{\Delta V}{I}
\]  \hspace{1cm} (8)

where $\Delta V$ = the potential difference measured

*Fig. 6.2.1 four electrode arrangement*
Potential Distribution

It is seen from the foregoing paragraphs that through the measurement of potential difference over the ground, the ground resistance can be measured. The potential at any point M due to current (I) is proportional to the resistivity of the formation and inversely proportional to the distance between the point and the source. For a semi-infinite half space the constant of proportionality is $1/2\pi$. Therefore:

$$V_M = \frac{\rho \cdot I}{2 \pi a} \quad (9)$$

Where:

- $V_M$ = Potential at the point M
- $\rho$ = resistivity of the medium
- $a$ = the distance between the source and the point M.

Actually the current entering the medium through one electrode must return through a second electrode to have the continuity. The principle of super-position states that the potential at any point will be equal to the sum of two potentials one calculated as though a current $+I$ is passing through first electrode (source) and the other calculated as though a current $-I$ is passing through the second electrode (sink). Therefore the potential at a point M due to a pair of electrodes can be expressed as:

$$V_M = \frac{\rho I}{2\pi a_1} - \frac{\rho I}{2\pi a_2} \quad (10)$$

Where:

- $a_1$ is the distance between point M and the source ($+I$)
- $a_2$ is the distance between point M and the sink ($-I$)
A vertical cross section showing the flow of current through the medium and the equipotential lines (the lines along which the potentials are equal) are shown in Fig. 2-3.

![Fig. 6.2.3 Current line and equi-potential surfaces](image)

The lateral variation of potential between a pair of electrodes is shown in Fig. 6.2.4.

![Fig. 6.2.4 Potential distribution between current electrodes](image)

These two figures show the concept of potential distribution in homogeneous semi-infinite medium. From Fig. 6.2.4, it can be seen that the potential variation in the central one-third part of the curve is nearly linear.
From this section we learn that the potential at a point on the surface of the earth is dependent on the resistivity of the formation. If the formation is homogeneous the potential is a function of resistivity of the formation \( \rho \) and if it is inhomogeneous, the potential is dependent on a fictitious resistivity value \( \rho_a \) known as 'apparent resistivity'. This apparent resistivity depends on the position of electrodes (electrode configuration) and on the subsurface resistivity distribution. Hence in the case of inhomogeneous medium the term \( \rho \) is replaced by \( \rho_a \). Thus

\[
V_M = \frac{\rho_a}{2\pi a_1} - \frac{\rho_a}{2\pi a_2}
\]

**Electrode Configurations**

The electrode arrangements used in resistivity investigations are called configurations or arrays. The disposition of electrodes in Wenner, Lee portioning, Schlumberger and dipole (equatorial and polar) configurations are shown in fig. 6.2.5

The effect of electrode arrangements on the measurements of potentials which are, in turn used in the calculation of apparent resistivities. The different types of configurations commonly used in resistivity investigations.

*Various electrode arrays*

\[
\text{Fig 6.2.5 Wenner electrode array - } \rho_a = 2\pi a R
\]
Configuration Factor

The earth resistance measurements are made by using four electrodes, two for sending current and the other two for measuring the potential difference. Now let us suppose that we are sending a current $+I$ into the earth through electrode A and a current $-I$ (return current) through electrode B and measuring the potential difference across MN as shown earlier.
Then

Potential at the point \( M \) due to \( A = \frac{\rho_s \cdot 1}{2 \pi AM} \)

Potential at the point \( M \) due to \( B = \frac{\rho_s \cdot 1}{2 \pi BM} \)

Potential at the point \( N \) due to \( A = \frac{\rho_s \cdot 1}{2 \pi AN} \)

Potential at the point \( N \) due to \( B = \frac{\rho_s \cdot 1}{2 \pi BN} \)

\[
\Delta V = \frac{\rho_s \cdot I}{2 \pi} \left[ \frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \right]
\]

\[
\rho_s = \frac{2 \pi \cdot \Delta V}{\left[ \frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \right]} (12)
\]

\[
\rho_s = K \cdot R \quad (13)
\]
The value of $K$ depends on the geometric disposition of the electrodes and is called "Geometric Factor" or "Configuration Factor". During the field investigations, the potential difference ($\Delta V$) and the current ($I$) are measured either separately or the ratio $\Delta V/I$ (resistance) directly. The resistance values are then multiplied by the configuration factor to get the apparent resistivity values. If the measurements are made over a semi-infinite homogeneous and isotropic medium, the resistivity calculated with the above formula will be the true (absolute) resistivity of the medium. However if the medium is inhomogeneous, the resistivity calculated will be the apparent resistivity. This apparent resistivity is a function of several variables, namely the electrode disposition, the true resistivities of the subsurface formations (medium) and their thicknesses. By studying the variation of apparent resistivity for different electrode spacings, and by making simplified assumptions for the subsurface resistivity distribution, it is possible to find the thickness and resistivities of the subsurface formations. For carrying out such investigations several electrode arrangements (configurations or arrays) have been suggested and the most commonly used arrays are discussed here.

**Wenner array**

This is one of the most commonly used arrays proposed by Wenner (1916). The four electrodes ($C_1$, $P_1$, $P_2$, $C_2$) are placed on the surface of the ground along a straight line symmetrically about a point ‘O’ so that $C_1P_1 = P_1P_2 = P_2C_2 = a$ where ‘a’ is called electrode

$$K = \frac{2 \pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} - \frac{1}{BN}}$$ (14)

$$R = \frac{\Delta V}{I}$$ (Apparent resistance) (15)
separation. Current (I) is sent into the ground through C₁ and C₂ and potential (ΔV) is measured through P₁ and P₂. The configuration factor for this array is 2π a (By substituting AM = a, AN = 2a, BM = 2a and BN = a in equations (14). Therefore the apparent resistivity (ρₜₜ) for Wenner configuration is

\[
ρ_{aw} = 2 \pi a \frac{Δv}{I} \quad \text{or} \quad ρ_{aw} = 2 \pi a \frac{R}{I} \quad (16)
\]

**Lee Partitioning Method**

This array is same as the Wenner except at an additional potential electrode is placed at the center of array 'O' between the potential electrodes P₁ and P₂ and potential measurements are made between P₁-O; O-P₂. The configuration factor for this array is (4πa) and the apparent resistivity is calculated with the formula:

\[
ρ_{al} = 4πa \frac{Δv}{I} \quad \text{or} \quad ρ_{al} = 4 π a \frac{R}{I} \quad (17)
\]

**Schlumberger Array**

This array is most widely used in electrical prospecting. The four electrodes (A,M,N,B) are placed along a straight-line symmetrically over centre point 'O'. The separation between potential electrodes (MN) is kept small when compared to the current electrode separation AB. Current is sent through the outer electrodes AB and potential across MN (the inner electrodes) is measured in a similar way as in Wenner array.

Using \( L = \frac{AB}{2} \) and \( l = \frac{MN}{2} \) the configuration factor for Schlumberger array is

\[
κ = \frac{π}{2l} \left( \frac{L^2 - l^2}{L^2} \right)
\]

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and the apparent resistivity is calculated with the formula:

\[ \rho_{\text{as}} = \frac{\pi (L^2 - l^2) \Delta V}{2l} \quad \text{or} \quad \frac{\pi (L^2 - l^2) R}{2l} \]  

(18)

or

\[ \rho_{\text{as}} = \frac{\pi l^2 R}{2l} \]

when ‘2l’ is very small compared to ‘L’,

6.3.0 INSTRUMENTATION, CONCEPTS AND METHODOLOGY

Instruments used

The geoelectrical survey has been carried out using DDR3 of IGIS make.

Concepts and methodology

Numbers of electrical configurations are in vague such as linear, symmetrical, asymmetrical etc., of these configurations, symmetrical collinear set up of Schlumberger and Wenner are frequently used for groundwater prospecting. In the present investigations Schlumberger configuration was used.

Site selection

To select the locations for conducting the VES, the geological, geomorphological, structural elements and the results of the hydrogeochemical survey of the area were considered. The VES locations have been spread out both in the granitic gneiss and schist.
The other conditions considered for site selection were the area all along the wire spread was flat and without any inhomogenities. The sounding site was selected away from any conductive features like overhead power cables, transformers etc.,

**Vertical Electrical Soundings (VES)**

Vertical electrical soundings, also called as ‘depth probes’ were conducted at 20 locations. These have been used by following Schlumberger electrode configuration. The depth probing was done about a fixed point by increasing the horizontal spacing between electrodes by small increments in successive steps. By successively increasing the electrode separation about a central point, the resistivity of deeper layers (upto 100 mtrs depth) of the earth’s crust were measured.

The apparent resistivity values were plotted against the electrode spacing AB/2 and the curves were interpreted by using the RESIST87 software.

**Interpretation of VES data**

The data obtained through VES can be interpreted either qualitatively (empirical method) or quantitatively.

**Qualitative methods**

There are number of qualitative interpretation methods proposed by many workers. A few of these empirical methods have been applied successfully in many parts of the world (Gish and Rooney, 1925; Swartz, 1934; Moore, 1945; Sarma, 1960 and Shankaranarayan & Ramanujachary, 1967). Most widely used methods are the Cumulative techniques of Gish and Rooney (op. cit) and inverse slope method of Shankaranarayan and Ramanujachary (op. cit).

**Inverse slope method**

The inverse slope method of interpretation is a direct method of determining the thickness and absolute resistivities of different subsurface layers. It involves plotting the values of 1/2πR against electrode separation on a linear graph, where ‘R’ is the apparent resistivity measured in the field. The inverse slope of the line segments obtained by joining
the plotted points gives the true resistivity values, the intersection of the line segments extended to the X-axis give the depth and the distance between the two such intercepts gives the thickness of that layer.

Quantitative methods

Quantitative interpretation techniques enable to quantify the parameters of different subsurface layers. In these methods, first the field curves are plotted using the apparent resistivity against electrode spacing on a double log graph paper. Then these curves are matched with standard curves developed by different pioneers. Among these, the master curves of Mooney and Witzel (1956), Orellana and Mooney (1966) are most commonly used.

6.4.0 RESULTS OF GEOELECTRICAL STUDIES

The VEs data were interpreted using the above discussed interpretation techniques. Table 6.4.1 gives the subsurface layer parameters viz., the number of layers, their resistivities and thickness. The field curves are of 4 layers, A, AH, and HA type (Fig ). The results indicated that in general the subsurface up to the depth of investigation is made up of a layered structure.

The resistivity of the first layer in most cases a soil layer or soil with highly weathered layer varies from less than 1 ohm meter to as high around 50 ohm meter. A lot of heterogeneity in the soil characters is clearly noticed. The thickness of the first subsurface layer varies from 1 meter to around 4 meter. The second subsurface layer is weathered, jointed and fractured layer. The resistivities vary from 50 ohm meter to 150 ohm meter with the thickness varying from 5m to 15 m. The third subsurface layer is fractured and in few cases massive. The resistivity varies from 150 ohm meter to 300 ohm meter. The fourth subsurface layer is massive with minor fractures. The reactivity varies from 300 ohm meter to 600 ohm meter and above this, massive layer.

In some cases, after the third layer, a low resistivity layer is encountered indicating fractured or sheared zone at that depth. This indicates presence of deeper aquifers.
<table>
<thead>
<tr>
<th>SI No</th>
<th>VES No</th>
<th>Location</th>
<th>Curve type</th>
<th>$p_1$</th>
<th>$h_1$</th>
<th>$p_2$</th>
<th>$h_2$</th>
<th>$p_3$</th>
<th>$h_3$</th>
<th>$p_4$</th>
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<th>$h_6$</th>
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<td>VES 1</td>
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<td>3.3</td>
<td>2.5</td>
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<td>7.3</td>
<td>203.5</td>
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<td>H Malai</td>
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Fig: 6.4.1 FIELD CURVES

VES 13

VES 14

VES 15

VES 16

VES 17

VES 18