2.1: INTRODUCTION:

Electrical prospecting is defined as prospecting of geologic structures by using electricity. All methods of geophysical exploration are based on some physical properties. Due to variations in lithology and chemical composition, different rock types have different physical properties. Physical properties, which are important and useful in geophysical exploration, are density, magnetic susceptibility, elasticity, radioactivity and resistivity (or electrical conductivity).

Most of the geophysical methods use only one field of force like gravity, magnetic or elastic. In electrical prospecting, there is greater variation in electrical fields and in methods of observation. Electrical methods depend upon the electrical conductivities (or resistivities) of different rocks and minerals. For example, minerals like Pyrite, Chalcopryrite, etc. are very good conductors of electricity. Other ore minerals have low conductivity, while majority of nonmetallic minerals are bad conductors (Gangadhara Rao, 1992). When current is passed into the ground, it gets distributed according to the conductivities of the rocks and minerals coming under its influence. Due to the above concept, concentration of current is appreciable where there are large masses of conductive bodies. As far as electrical prospecting of groundwater is concerned, a geological formation appreciably saturated with moisture, acts as conductive body and hence posse’s low resistivity. A geological formation which is dry or poorly saturated with moisture, acts like poor conductor of current and hence posse’s appreciably high resistivity relative to saturated geological formation (Gangadhara Rao 1992).
concept is the key factor, which facilitates resolutions, which are useful to locate aquifers in the subsurface. Due to the scientific factors stated above, among all geophysical methods, electrical methods are the best techniques and they are widely used for groundwater exploration.

2.2: DEFINITIONS:

2.2.1 Resistivity

Resistivity \( (\rho_a) \) is a physical property of a substance. It is defined as the resistance offered for the flow of current by a unit cube of substance when voltage is applied across its opposite faces. The unit of measurement of resistivity is ohmmeter or ohm-feet or ohm-centimeter. This parameter is an inherent property of the substance, dependent on the shape and size of the substance. Ohmmeter is recognized as the standard unit of measurement of resistivity.

2.2.2: Resistance

Resistance offered by a substance is the function of resistivity, shape and size of the substance. For substances with known shapes, such as cylinders, cubes etc, the resistance can be determined from the formula

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

Where, \( \rho \) is the resistivity of the substance in ohmeters, \( L \) is the length of the substance in meters and \( A \) is the area of cross section of the substance in meters square.

2.2.3: True and Apparent Resistivity

Geological formations possess a property called electrical resistivity. Resistivity determines the ease with which current flows through a geologic medium. For homogeneous formations, measured electrical resistivity is the true resistivity. Apparent resistivity of a geological formation is equal to the resistivity of
A fictitious homogeneous and isotropic medium, in which for a given electrode arrangement and current strength, the potential difference measured is equal to that for the given homogeneous medium. The apparent resistivity depends upon the geometry and the resistivity of the elements constituting the geologic medium. It does not represent the average resistivity. It can be lower than the lowest and higher than the highest resistivity within the subsurface to which it pertains.

2.3: MEASUREMENT OF RESISTIVITY:

A Pair of current electrodes and potential electrodes are essential for measuring the resistivities of the subsurface. The two current electrodes are termed as A and B and the potential electrodes are termed as M and N. While measuring the resistivity, the point of investigation is called as center C. All the four electrodes are kept in a straight line with respect to the center C. A current electrode and a potential electrode are kept away at some distance to the right of the center. Similarly the other two, current and the potential electrodes are kept to the left of the center. The distance between the center C and a current electrode is called the half current separation and is termed as AB/2. The distance between the center C and a potential electrode is termed as MN/2. The electrode arrangement for Schlumberger and Wenner arrays are shown in Figure (2.1) in chapter one. When current I is introduced into the subsurface through the two current electrodes, the potential difference produced due to the flow of current, is measured by the two potential electrodes. If the potential difference is ΔV, the apparent resistivity is measured the following equation.

Apparent Resistivity = ΔV/I × G  (Where G is the geometrical constant)

The formula to calculate the constant is given by the following equation

\[ G = \left[ (AB/2)^2 - (MN/2)^2 \right] / 2 \times (MN/2) \times \pi \]
For practical purposes, the value of $\pi$ is taken as 3.14. As mentioned earlier, the unit of measurement of apparent resistivity is ohmmeter.

Figure 2.1: Wenner and Schlumberger Arrays Electrode Arrangement

2.4: EQUIPMENT USED TO MEASURE RESISTIVITY:

The equipments used to measure resistivity are as follows.

- Power source.
- Resistivity meter to measure current (I) and potential (V).
- Two current electrodes (Iron crowbars one meter in length)
- Two potential electrodes (copper rods immersed in saturated copper Sulphate solution) and

  - Winches wound with cables to connect the terminals of the four electrodes to the resistivity meter.

The power source used is A.C. or D.C. Current. However, with some precautions, the use of D.C. is preferred. When the electrodes come in contact with the ground, they produce potential, because the moisture present in the ground, acts as an electrolyte. This potential has to be eliminated. For this purpose, a pair of nonpolarising electrodes, which are basically metal rods immersed in its own, saturated solution are used. Copper rods immersed in saturated solution of copper sulphate solution are the most commonly used nonpolarising electrodes. Self-potential is the other factor that affects the D.C. resistivity measurements. Self potential may exist between two points on the
ground by virtue of mineralisation potentials, potentials due to fluid streaming, varying electrolytic concentrations in groundwater, geochemical actions and telluric fields (Gangadhara Rao 1992). A device provided in the resistivity meter cancels this unidirectional self-potential and the readings are observed and averaged during positive and negative cycles. The current (I) is measured in milliamperes by an ammeter. The potential (V) is measured by a high impedance a voltmeter. Figure (2.2) shows the diagrams of the nonpolarising electrode and a simple resistivity meter.

![Diagram of a nonpolarising electrode and a simple resistivity meter.](image)

**Figure 2.2: Non-polarising Electrode and Circuit of Resistivity Meter.**

### 2.5: ELECTRODE CONFIGURATIONS:

In general, the electrode arrangements may be classified broadly into two categories, based on the system of positioning the four electrodes. (i) those in which all the four electrodes are placed along a straight line, for example, Wenner and Schlumberger configurations and (ii) those in which the pairs of current and potential electrodes are separated and four electrodes are not necessarily along a straight line, for examples some Dipole systems. As the investigations concerned
with the thesis are carried out in a system where all the electrodes are kept in a straight line, only the Schlumberger and Wenner arrays are discussed. The configurations (Schlumberger and Wenner arrays), which are system of placing the four electrodes during investigations, which are commonly in use, are as follows.

2.5.1: WENNER ARRAY:

This array is laid by using four point electrodes, which are collinear and equi-spaced. The four electrodes A, M, N & B are placed on the surface of the ground along a straight line symmetrically about the point ‘O’, so that the distances AM=MN=NB=a, where ‘a’ is called the inter-electrode separation. Current (I) is sent into the ground through current electrode A and B and the potential (ΔV) is measured through M and N. The configuration factor for this array is 2πa. Apparent resistivity (pa) for this array becomes pa = 2πa (ΔV/I). Figure (2.1) represents the Wenner array electrode arrangement. In the figure, A and B are the current electrodes for introducing the current and M, N are the potential electrodes to measure the potential difference.

2.5.2: SCHLUMBERGER ARRAY:

This array also uses four collinear point electrodes, but measures the potential gradient at the mid-point by keeping the measuring electrodes close to each other. Four electrodes are placed along a straight line symmetrically over center point ‘O’. Current (I) is sent through the outer current electrodes A, B and the potential is measured across inner potential electrodes M & N. The separation between the potential electrodes is kept small compared to the current electrode separation, such that always t (MN/2 < or = to 1/5 AB/2). Electrode arrangement in the Schlumberger array is shown in Figure (2.1).
The configuration or geometric factor (which is constant $K$ for any set of electrode separation) for the Schlumberger array is given by

$$K = \frac{(AB/2)^2 - (MN/2)^2 \pi}{(MN/2)^2} \frac{\pi}{2}$$

and the apparent resistivity is obtained by the formula

$$\rho_a = K (\Delta V/I)$$

2.5.3: TWO ELECTRODE ARRAY:

In this array, one current electrode (A) and one potential electrodes (M) are in active operation, whereas the other current electrode (B) and potential electrode (N) are kept at a very large distance (infinity). These may also be called infinity electrodes. Keeping the passive electrodes at infinity means keeping these at a distance ten times the electrodes spacing, more or less along the perpendicular bisector of the profile. This array is shown in Figure (2.3).

In this, configuration factor is $2\pi a$, and apparent resistivity is

$$\rho_a = 2\pi a (\Delta V/I)$$

![Figure 2.3: Two Electrode Array](image)

2.5.4: DIPOLE-DIPOLE ARRAY:

In this array, the potential electrodes are outside the current electrodes, each pair having a constant mutual separation ($a$). If the distance between the two pairs i.e., current electrode pair and potential electrode pair, is relatively large, the current source may be treated as an electric dipole, which consists of a positive and negative electric pole, having a separation that is small compared to
the distance from the observation point. The configuration factor is $\pi n a (n+1) (n+2)$ and the apparent resistivity can be obtained with formula. This array is shown in Figure (2.4).

$$\rho a = n (n+1) (n+2) a (\Delta v / l)$$

In Figure 2.4, 'na' is the distance between the two innermost electrodes, B and N. The Dipole-Dipole systems are of different kinds, the most important of which are Radial Azimuthal, Parallel and Perpendicular arrangements.

2.6: RESISTIVITY PROFILING:

Profiling is a technique used to study the lateral (horizontal) variations in resistivity in the subsurface, to delineate the various important geologic and hydrogeologic features, like disposition and extent of an aquifer or an ore body. Structural features like buried Dykes, sheared zones, Faults and other linear structures can be satisfactorily demarcated. In the field, traverses, perpendicular to the suspected target are laid. Measurements are made at various station intervals. The distance between two consecutive stations is chosen according to the expected width of the target. For example, to locate linear structures having appreciable width, the station interval may vary from about 5 to 15 meters. For
structures, which are not very wide, generally the station interval may vary from about 2 to 5 meters. However, the station interval can be decided depending upon the conditions in the field. Profiling is carried out by keeping the distance same, between any two consecutive electrodes this is called the interelectrode spacing and is termed as (a). Two current and two potential electrodes are used for profiling. The interelectrode separation (a) is chosen depending upon the expected depth of the target. For shallow targets, (a) can vary from about 2 to 10 meters and can vary from about 5 to 25 meters for deeper targets. The observation stations are located on the surface, appreciably well before the suspected structural or geologically anomalous feature and continue to be located through out the suspected width of the anomalous feature and well beyond. The stations are serially numbered from one end of the traverse to the last station on the other end. Measurements of current (I) and potential (V) are made at all the stations. The resistivity Da is calculated by using the formula V / I * (K). K is the geometric constant estimated by the formula 2πa. Where (a) is the interelectrode spacing. The geometric constant remains the same for all stations, as the interelectrode spacing “a” is same for all observations throughout the profile. The resistivities observed at all the stations are plotted serially on a simple centimeter graph sheet. Resistive features like dykes show a striking anomaly of high resistivity when the stations of the profile pass over and cross the resistive geologic feature. A conductive ore body shows a remarkably low resistivity anomaly when the stations of the profile pass over or cross the conductive geologic feature. A resistive feature for example a dyke shows a remarkably high resistivity anomaly when the stations of the profile pass over or cross the geologic feature. A high resistivity profile observed across a dyke is shown in Figure 2.5.
Once the targets presence is confirmed by profiling, resistivity values observed for a desired interelectrode spacing (a), over a few profiles carried out on different selected traverses laid parallel to each other on the geologic structure, are contoured. An equi-resistivity map is prepared, which gives an insight about the epicentral location and the lateral extent of the (resistive /conductive) feature. In profiling, to understand the lateral inhomogeneities, different resistivity methods 1) potential methods, 2) potential difference methods and 3) gradient methods are used. Potential difference methods give sharper anomalies than absolute potential methods. However, the gradient methods register the sharpest anomalies.

**2.7: VERTICAL ELECTRICAL SOUNDING (RESISTIVITY SOUNDING):**

By carrying out Vertical electrical sounding we can measure the change in resistivity with depth, at the point of measurement on the surface. Resistivity sounding method is useful to investigate vertical disposition of the subsurface geological layers. With context to groundwater studies, resistivity sounding is useful to infer the depths and thicknesses of various subsurface layers and their
relative water yielding capabilities. To carry out or conduct resistivity sounding, a D.C. or low frequency A.C. current is passed into the ground through the two current electrodes A and B. The current (I) passing into the ground is measured in milliamperes (ma). The potential difference (ΔV) developed between the two points on the ground surface along the line through the current electrodes, is measured in millivolts (mv), through the two-nonpolarising potential electrodes M and N. As explained earlier, naturally developing potentials (self potential, SP) are eliminated and nullified, each time when the electrode spacing changes or even when the readings are repeated at any electrode spacing, during the course of sounding. Hence the potential developed only due to the externally impressed current should be taken into consideration. The equipments required to carryout resistivity sounding are stated in 2.4. Depending upon the distance between various electrodes, the apparent resistivity of the ground for that particular electrode arrangement can be calculated by using the

\[ \rho_a = K \left( \frac{\Delta V}{I} \right) \]

There are various types of resistivity meters. Some measure the potential (ΔV) and the current (I) separately. Few others measure the ratio (ΔV/I) directly. Some meters are null type while few others show digital display of potential (ΔV) and current (I). Similarly there are different types of current sources also. An ideal and simple source can be a neatly packed dry battery cells of 1.5 volts capacity arranged in series. Batteries containing 90 volts source, having tapings for various voltages are available in the market. The commonly provided voltage slots in the battery boxes are 9, 18, 36, 54, 72 and 90 volts. The batteries are called as power packs. During the course of investigations, if more power is required to measure appreciable voltage, two or more battery boxes can be connected in series by
using patch cords. Patch cords are small pieces of wires with clips used to connect two batteries. Generally in sedimentary, volcanic and alluvial terrains, to acquire reliable geophysical data (particularly appreciable potential), three to four power packs are essential. When injection of high current is warranted, a low frequency a.c. generator of high capacity is used as the source of power.

2.8: PRELIMINARY STUDY OF THE TERRAIN:

Before starting detailed geophysical investigations, a fair insight of the area to be investigated has to be accomplished. The geology, hydrogeology and the terrain conditions like accessibility to the desired sites have to be assessed. The nature of groundwater occurrence for example information about the nature of lithological, geomorphological and structural controls on the occurrence and movement of groundwater should be collected. The groundwater condition namely the depth to the shallow and deeper aquifers, their thicknesses and sustainability should be ascertained. These preliminary but essential tasks can be accomplished by carrying detailed dug well and borehole inventory at selected representative sites. In any study area, at a couple of successful and failed wells, vertical electrical soundings must be carried out. These are called as the parametric soundings. The data should be interpreted to know the resistivities of the weathered zone, aquifers, aquicludes and aquitards and depth to the basement. Other terrain specific hydrogeological situations prevailing in the area should be investigated. The above-mentioned tasks can be performed by carrying out a short reconnaissance survey in the area to be investigated. The data collected should be analysed. The understanding of the qualitative geological and hydrogeological conditions of the study area facilitates the proper planning of the geophysical investigations, the amount of work to be carried out, the equipment to
be carried to the field area, time and the financial budget required to complete the task. Reconnaissance survey should be taken seriously as it is the key factor which facilitates in reliable analyses of the virgin geophysical data collected and interpreted. Other important field procedures are site selection, line surveying, setting up of the equipment and measurement.

2.9: SITE SELECTION AND LINE SURVEY:

The site to be investigated should be so selected that the entire spread of the sounding should be on a more or less a flat topography, without any lateral inhomogeneity like dykes, veins, big nalas and rivers. Thick cultivation of crops also creates a problem in laying out the traverse in the field. Hence it is convenient to carry out the geophysical investigations, particularly vertical electrical soundings after the harvesting of the crops carried out. Sufficient soil cover on the surface along the sounding line favours good galvanic contact between the ground and the electrodes. Absence of constructed structures, overhead power cables and underground water pipes along the sounding line can generate a smooth and reliable data, representing the true subsurface condition existing at the site of investigation. Last but not the least, the site should be a natural surface and not made up, by filling.

Depths, thicknesses, resistivities and the nature of various subsurface layers (which correspond to different geological and hydrogeological units) at the site of investigation can be inferred by carrying out a sounding. In this method, the site of investigation or the sounding point, which is the mid point (center) of the electrode system, is fixed. This point can is called as center (C). Passing through this point, a straight-line traverse is fixed with the help of surveying instruments like a compass or a theodolite. This line should be parallel to the strike direction of the
geological formation, exposed at the site of investigation. In alluvial and hard rock terrains that do not exhibit strike or dip, the sounding traverse can be oriented as per the convenience in the field and laid with the help of measuring tapes and wooden pegs. Positions of the current and potential electrodes, where potential (V) and current (I) are to be measured, are marked all along the traverse, on either of the sounding point (C). These locations are marked by driving the wooden pegs a few inches onto the subsurface, with the help of small hammers. The positions of the electrodes vary depending upon the configuration chosen to carry out the sounding. For soundings applying the Wenner configuration, current electrodes are to be placed at a distance of 1.5, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, 40, 50, 60, 80, 100, 150, 200, 250, 300, 400, 500 meters and so on, on either side of the center (C), along the traverse. Consequently, on either side of the center (C), corresponding to the current electrode positions, potential electrodes are placed at a distance of (half of the current electrode distance) 0.5, 1, 1.5, 2.5, 3, 4, 5, 6, 7.5, 10, 12.5, 15, 20, 25, 30, 40, 50, 60, 75, 90, 120, 150, 200 and 250 meters respectively. Such an arrangement of electrode spacing will keep the current electrode distance 3 times the distance of the potential electrode, namely 1.5, 3, 4.5, 6, 7.5, 9, 12, 15, 18, 22.5, 30, 37.5, 45, 60, 75, 90, 120, 150, 180, 225, 300, 375, 450, 600 and 750 meters. For example, if the potential electrode is kept at a distance of 0.5 meters from the center C, then the current electrode will be kept at distance of 1.5 meters from the center C, as mentioned above.

When a sounding is carried out in Schlumberger configuration, the distance's (half current electrode separation AB/2=L) at which the current electrodes (A and B) are to be placed on either side of the center (C) along the traverse are 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, 40, 50, 60, 80, 100,
120, 150, 200, 250, 300, 400, 500 meters and so on. Throughout the sounding, the potential electrodes should be kept on either side of and close to the center (C) and at a distance not more than one-fifth the distance of (half current electrode separation AB/2). For example, if the half current electrode distance AB/2 is 5 meters, then the potential electrode distance on either side of the center (C) which is called as the distance MN/2, should be well below 1 meter. However, the maximum MN/2 for AB/2 of 5 meters can be 1 meter. These criteria of placing the AB/2 and MN/2 electrodes should be adhered seriously for any reading taken in Schlumberger configuration.

While carrying out the sounding in any configuration, (Wenner or Schlumberger), the four electrodes move away from the center (C) as the survey progresses, according to the distance's mentioned above. For a sounding carried out in Wenner configuration, the current and potential electrodes are shifted to new locations for each reading of (potential V) and (current I). While in the case of a Schlumberger sounding, the potential electrode is shifted to a new location only when the measured potential drops below a certain measurable value, within the required accuracy.

2.10: EQUIPMENT SET UP (IN THE FIELD):

All current electrode positions are marked by fixing wooden pegs as per the configuration. Potential electrodes (Porous pots) are kept in small pits of about 2 TO 3 inches diameter with the help of driving rods. After keeping the Potential electrodes in the pits, the pit is filled with soil excavated while making the pit to fix the porous pot and little water is poured on the sides of the electrode to facilitate good contact with the ground. The current electrodes are driven into the ground with the help of hammers and little water is poured if the surface is very hard and
compact, to get proper contact with the ground. Small crowbars are used as current electrodes and cylindrical pots, with copper rods immersed in saturated copper sulphate solution are used as potential electrodes. With the help of good quality cables, terminals of the two current electrodes are connected to the two plugs provided in the resistivity meter. Similarly the terminals of the two potential electrodes are connected to the two plugs provided in the instrument. The positive and negative terminals of the power sources are connected to the positive and negative plugs of the instrument. Now the setup is ready for taking the readings, which is nothing, but a record of field geophysical data. The area around the sounding point should not be disturbed by human activities. It should be treated as a holy place.

2.11: MEASUREMENTS:

The procedure of measurements depends upon the type of instruments used. The sounding begins with the smallest separation of the current and the potential electrodes and sequentially progresses to the next consecutive separation, till the data for the last separation is recorded. The last separation will be the farthest distance (the longest half current electrode separation AB/2) from the center C, which is the point of investigation. The half current electrode separation at any point of investigation depends upon the depth at which the aquifers are encountered in different geological formations. In granitic terrains the half current electrode separations about 200 to 250 meters. Basaltic terrains are underlain by different layers like massive and vesicular basalts, red bole beds etc. Hence aquifers occur at deeper levels also. Hence in such terrains, the half current electrode separation various from a minimum of about 200 meters to 800 meters. In sedimentary and alluvial terrains also the evolutionary history of the formations is not simple and continuous. This depends upon the sequence of the
geological events which are the cause of the sedimentary rocks. Hence the aquifers occur fat shallow to deeper depths. Hence the half electrode separation varies from about 200 to 1000 meters.

The following operations carry out the sounding.

- All the necessary connections, of electrodes, porous pots and the battery to the proper plugs provided in the instruments, are made.
- Before passing the current into the subsurface, self-potential developed should be cancelled. This can be done by using the coarse and fine knobs provided for canceling the self-potential in the instrument itself.
- Current is pressed into the ground. (Keeping the instrument in the direct mode by operating the switch provided)
- Depending upon the type of the instrument, the potential difference (ΔV) and the ratio (ΔV/I) is measured. (This is the direct reading)
- Keeping the instrument in the reverse mode, again the measurement of (ΔV) and (ΔV/I) is made. (This is the reverse reading)
- Record the data on a data sheet systematically..
- Using the proper formula according to the array (Wenner or Schlumberger), the apparent resistivity is calculated. The average of the apparent resistivity obtained for the direct reading and for the reverse reading is the apparent resistivity for any reading.
- Plot the apparent resistivity value against the electrode separation on a double logarithm graph sheet, matching with the modulus of the master curves to be used for data interpretation. There are two types of double logarithm graph sheets. One with a modulus of 62.4 mm and the other with a modulus of 82.3 mm. Modulus means the length of each cycle of
on the graph sheet. A graph sheet with 62.4 mm modulus will have three cycles each on X and Y axis. The length of each cycle is 62.4 mm. A graph sheet with 82.3 modulus will have three cycles each on X and two cycles on Y-axis. The length of each length is 82.4 mm.

- Continue the sounding till the data is recorded for the last half electrode separation planned or till a desired geophysical data is acquired.

- The plotted points on the double logarithmic sheet should give smooth curve. If the date is scattered and the curve is not smooth, either the readings measured are not correct or the site selected is anomalous compared to the ideal geological conditions observed in the terrain. If necessary the data of deviating points should be recorded again and the curve be plotted. If the scattering still persists and the curve is not smooth, then the site has to be shifted to a better location.

- The electrode separation is plotted on the abscissa and the corresponding apparent resistivity is plotted on the ordinate on the graph sheet.

- By joining the plotted points, a smooth curve is drawn. This is called as the sounding curve. Depending upon the subsurface geological and hydrogeological situations, various types of sounding curves are obtained for specific subsurface conditions. They are discussed bellow. Figure (2.6) shows ideal curve types.

- On the reverse of the data, important geological and hydrogeological information should be recorded.
2.12: TYPES OF SOUNDING CURVES:

Simple sounding curves are ascending or descending type. If the apparent resistivity values show an increasing trend in the graph, it is an ascending type of curve. On the other hand if the values of apparent resistivity go on reducing in the graph, then the sounding curve is an descending type. Ascending types are typical cases of a two-layer structure that is a thin soil layer, followed by weathered zone, which is underlain by a highly resistive basement. Descending type are ideal cases of a top layer overlying a thick clay layer or a saline water aquifer.

In case of three layered structures, there are four fundamental types of sounding curves. They are A, H, K and Q types. The sounding curves can be classified into four types, based on the trends of resistivity of the interpreted subsurface layers. If $\rho_1$, $\rho_2$ & $\rho_3$ are the resistivities of the three successive subsurface layers, a sounding curve with a central low (i.e. a case where $\rho_1 > \rho_2 < \rho_3$) is said to be a H-type curve. This sounding represents an ideal hard rock terrain commonly associated with a Granitic country. The first high resistivity layer corresponds to dry topsoil. The second low resistivity layer corresponds to saturated weathered layer. The third layer possessing a very high resistivity corresponds to a very hard and compact rock generally the basement.

A-type ascending curves are characteristic features in ideal Hard rock terrains. In such cases the three layered structure is a situation where $\rho_1 < \rho_2 < \rho_3$. It is a situation where the subsurface layers progressively become harder and harder. Hence the prospects of finding groundwater are not very bright. However, in favorable geomorphological locations like peniplanes, pediplains and low lying areas, H-type curves can be expected and if so they are
sites of better groundwater potential when the thickness of weathered zone is appreciable.

Sounding curves, which show a hump, flanked by low resistivity layer, are called as K type curves. The three layered structure for this class is of the type $\rho_1 < \rho_2 > \rho_3$. These are typical curves of basaltic terrains, showing hard and compact massive basalt progressively hardening with depth in the first two resistive layers, followed by less resistive vesicular basalt. In coastal terrains such curves reflect a fresh water aquifer underlain by clay, overlying a saline water aquifer.

Sounding curves showing a subsurface structure of decreasing resistivities for successive subsurface layers $\rho_1 > \rho_2 > \rho_3$ are called as Q type curves and are typical terrains, reflecting a condition where the ground is progressively becoming saline with depth. These are characteristic features in delta regions adjacent to the coast, where the saline water intrusion is remarkably high.

Complicated sounding curves containing four-layered structure are combinations of more than one of the above mentioned four fundamental types of curves. Some common combination curves obtained in the field are HK, HA, KH, KQ, AA, AK, QQ, and QH. There could be more varieties of curves representing multiplayer situations like HKHK, KHKH, HAA and so on. Generally, such curves are indications of specific subsurface geologic and hydrogeologic situations localized within a large area, exposed by particularly well-identified and demarcated geological formations. Prominent sounding curves are shown in Figure (2.6).
2.13: INTERPRETATION OF SOUNDING CURVES:

The interpretation of resistivity data is basically interpretation of sounding curves, to infer the various subsurface geoelectric layers, their resistivities and thicknesses. The interpreted results are correlated with the available hydrogeological knowledge to arrive at the realistic picture of the sub-surface layers, namely their water bearing characteristics. There are many ways to interpret the resistivity data into physical parameters starting from empirical methods to sophisticated techniques using fast computers. The most commonly and widely used method among the interpretation techniques is the curve matching (Orellana and Mooney, 1966). This is an indirect interpretation. In this technique the field curve is matched against the standard curves prepared from the Stafenesco's expression (1930) for the potential due to point source of current on stratified earth. An album of theoretical curves for different combinations of resistivities and depths are prepared by various researches, for two, three and four layered earth models, for matching with the field curves (Mooney and Wetzel, 1956; Orellana and Mooney, 1966; Rijkswaterstat, 1969). The number of
theoretical curves increases with the number of layers and it becomes difficult to carry out interpretation, if the numbers of layers are more than four.

Flathe (1955a); Baranov and Tessencourt (1959); Deppermann (1961); Baranov (1962); Van Dam and Kamp (1965) suggested alternate methods for calculation of exact theoretical curves for given parameters to match with the field curves. Kalenov (1957); Ono (1959); Zhody (1965) and Orellana and Mooney (1966) suggested auxiliary point methods with two and three layer theoretical curves for interpreting multilayer cases. However, the curve matching procedure requires a great deal of practice and costs time and at times can become a very difficult task even to the experienced interpreter.

Methods for directly interpreting the field data were also attempted by many researchers. The idea of obtaining the layer parameters directly from the field measurements was suggested by Slichter (1933). He showed that the layer parameters could be obtained directly from the field measurements in two steps. The first step was determination of Kemal function in the Stafenesco's integral from the field measurements and the second step was deduction of layer parameters from Kemal function. Pekeris (1940) gave an extremely useful method of carrying out Slichter's second step. These suggestions were of little use because of the difficulty in carrying the first step namely deriving the Kemal function from the field data. Koefoed (1968) suggested a method to obtain Kemal function from the field data. Koefoed (1969) also suggested a modified method to carry out the second step by introducing a new function called Resistivity Transform. Koefoed's methods were complete to get the layer parameters from the field curve. Using the knowledge of sampling and filter theory in the field of communication theory, Ghosh, 1971 suggested a speedy method of obtaining the
Kemal function from the field data. Das and Verma, 1977 have written a monograph RESIST describing the theory of linear filtering and its application to the interpretation of resistivity sounding measurements with appendices containing computer programmes for getting theoretical sounding curves for any configuration.

Zhody, 1975 suggested another procedure for calculating the layer parameters directly from the field curve by use of Dar Zarrouk curve. In his method, the layer parameters, the thicknesses and resistivities are obtained to the first approximation by digitizing the field curve and considering them to be the point on a modified Dar Zarrouk curve. The vertical sounding curve is calculated theoretically for this layering and then compared with the field curve. A second approximation to the modified Dar Zarrouk curve is obtained utilizing the difference between calculated and field curves. The iteration is continued until the best match is obtained between calculated and field curves.

Besides these sophisticated methods a few empirical methods also were tried and claimed to have met with success (Moore, 1945; Barnes, 1952). A Semi-empirical method was suggested by (Sankamarayana and Ramanujachary, 1967) which can give approximate values of absolute values of resistivities and thicknesses of the sub-surface layers.

Curve matching is the most widely used technique for interpreting sounding curves. The master curves are theoretically generated. Hence their can be infinite number of master curves. Figures (2.7 and 2.8) show, samples of two, three and four layer master curves. When investigations are carried out in a given study area, in ideal conditions, simple two or three layered sounding curves are obtained. However this is not always possible. Depending upon the changing
hydrogeological and geological conditions, generally soundings containing multiple layers are obtained. Two or three layered cases can be interpreted by directly matching the field curve with a master curve and the subsurface layer parameters can be estimated. Sounding curves containing multiple layers do not match completely with a single master curve. Hence the whole curve is interpreted by carrying out part-by-part matching. Using auxiliary charts does this. Steps for interpreting the sounding curves are explained below.

2.14: INTERPRETATION OF TWO LAYERED CURVE:

- Plot the sounding curve on a transparent double log-tracing sheet. The modulus of the plot and the master curve to be used for matching should be the same.

- Select the sheet containing ascending or descending type of two-layer master curve. Shown in Figure (2.7).

- Superpose the field curve over the master curve sheets.

- Move the field curve, keeping both the x and Y-axis of the field curve parallel to the corresponding axis of the master curves, until the plotted field curve fits or matches with one of the master curves.

- Trace the origin of the master curve and the corresponding resistivity ratio, of the master curve, which matches with the field curve. This is shown on the right side, at the end of the master curve. It is the ratio of the value of \( \frac{\rho_2}{\rho_1} \).
On the transparent double log sheet on which the field curve is plotted, the values of X and Y coordinates of the origin give the resistivity ($\rho_1$) and the thickness ($h_1$) of the first layer.

- The resistivity of the second layer is determined by using the $\rho_2 / \rho_1$ ratio and substituting the estimated resistivity ($\rho_1$) value in the equation ($\rho_2 / \rho_1 =$ ratio value).

- As the sounding curve shows only two layers, the thickness of the first layer can be determined. For the second layer only the resistively $\rho_2$ can be estimated and not the thickness.

2.15: INTERPRETATION OF A THREE LAYERED CURVE:

- Figure (2.8) shows the interpretation of three and four layered curve.

- Identify whether the field curve is A, H, K or Q type.
• Superimpose the transparent field curve on the corresponding three layer master curve.

• Move the field curve, keeping both the (X and Y) axis parallel to the corresponding axis of the master curves, until the plotted field curve fits with one of the master curves.

• Trace the master curves origin on the transparent sheet and note down the \( p_2 / p_1 \) and \( p_3 / d_2 \) and \( h_2 / h_1 \) ratios given on the master curve.

• Values of Coordinates (X and Y) of the origin traced on the field curve are the thickness \( h_1 \) and resistivity \( p_1 \) of the first layer respectively.

• By substituting the value of \( p_1 \) in \( p_2 / p_1 \) and \( h_1 \) in \( h_2 / h_1 \), the resistivity \( p_2 \) and the thickness \( h_2 \) of the second layer can be calculated.

• For the third and the last layer, only the resistivity \( p_3 \) can be calculated, by substituting the calculated value of \( p_2 \) in \( p_3 / p_2 \) ratio.

• For example the curve to be interpreted is an A type curve and matches with the master curve whose resistivity ratios are 1-1.5 -2.5, it means that if the resistivity of the first layer is one ohmmeter, the second layers resistivity is 1.5 times the resistivity of the first layer and the resistivity of the third layer is 2.5 times of the resistivity of the first layer. Hence the resistively of the second layer \( p_2 \) can be calculated by substituting \( p_1 \) in \( p_2 / p_1 \) ratio and the resistivity \( p_3 \) of the third layer can be estimated by substituting the value of \( p_2 \) in the equation \( p_3 / p_2 = \text{ratio value} \). In the same way the thicknesses \( h_1 \) and \( h_2 \) can be estimated.

2.16: INTERPRETATION OF A FOUR (MULTILAYERED) LAYERED CURVE:

These are multilayered curves, and are combinations of more than one type of standard curve types (A, K, H AND Q). They can be interpreted by using
more than one three layered master curves. They can also be interpreted by using the two layer master curves and the auxiliary charts. However, Due to the increase in the number of layers, inaccuracies will creep in. A more reliable interpretation is achieved by using 3 layer master curves and the auxiliary charts.

- For instance, take a four-layer field curve and identify its type HK, KH or any other type.
- Match the first part of the field curve by appropriate three-layer master curve (H type master curve in case of HK field curve or K type master in case of KH field curve) and trace the origin of the match point. This is called as the FIRST CROSS. $\rho_1$, $\rho_2$ and $h_1$, and $h_2$ can be calculated, with the help of the first cross.
- Take the auxiliary chart corresponding to the first part of the curve (H type auxiliary chart incase of HK type sounding curve and K type auxiliary chart incase of KH type sounding curve.) and place the first cross on the origin of all curves in case of auxiliary chart of H type curve, on the auxiliary chart. In case of auxiliary chart of K type curve, place the first cross on the master curve drawn for the ratio of $\rho_2/\rho_1$ on the auxiliary chart. Now keeping the X AND Y AXIS of the master curve and the field curve parallel to each other, trace the point of confluence of $\rho_2/\rho_1$ and in $h_2/h_1$ ratios shown in the auxiliary chart. This becomes the SECOND CROSS.
- Place the second cross on the origin of an appropriate 3-layer master curve, (K type for HK type of sounding curve or H type in case of KH type of sounding curve.) and match the remaining part of the plotted field curve. Note dawn the resistivity and thickness ratios of the master with
which it matches. This gives the \( \rho_3/\rho_2 \) and \( h_3/h_2 \) ratios. By using these ratios, \( \rho_3 \) and \( h_3 \) are calculated, by substituting \( \rho_2 \) and \( h_2 \) in the resistivity and the thickness ratios respectively. \( \rho_4 \) is the product of resistivity value (which is the value of \( Y \) coordinate) of the second cross and the resistivity ratio value given for the fourth layer in the master curve, which matches with the second cross. Figure (2.8) show the interpretation of three and four layer field curves.

![Figure 2.8: Interpretation of four layer sounding curves](image)

2.17: COMPUTOR INVERSION OF SOUNDING:

Inversion is a direct operation on the field data to evolve a model that will yield the observed response (namely the surface apparent resistivity values observed at various electrode separations in the field, at the point of vertical electrical sounding). After interpretation by curve matching technique, a subsurface-layered geophysical model is obtained. For example a three-layered case will be consisting of \( \rho_1, \rho_2 \) and \( \rho_3 \) which are the resistivities of the three layers and \( h_1, \) and \( h_2, \) are the thicknesses of the first and second layer respectively. Thickness of the last layer cannot be determined. This model can be
improved for accuracy by using many available software packages. The commonly used software packages are RESIST and GENEROUS. The software’s carry out the inversion of the interpreted subsurface model. Inversion is a process, which generates the field data (apparent resistivity data observed for the various electrode separations, while carrying out the sounding) for any given subsurface geophysical model, obtained by curve matching. Inversion uses the model values $p_1$, $p_2$ and $p_3$ and $h_1$, and $h_2$ for generating the field data. Model is the solution and facilitates resolution of the subsurface layer parameters. Inversion creates the field data and plots a curve responsible for the model. This is called as the computed curve. If this computed curve matches well with the plotted field curve, obtained while carrying out the sounding, the interpretation is reliable. The check is accomplished by superimposing the curve generated by the inverted subsurface model, on the plotted field curve, plotted on a double log graph sheet. Both the curves should match. The above tasks can be accomplished in the system. When experienced interpreters carry out the task, good matches are possible. However in the case of complicated multilayered sounding curves, the matches will not be perfect. The soft ware package has the facility to carry out iterations. To achieve a perfect match between the field curve and the computed curve, the software iterates the initial interpreted model parameters, till the inversion generates data which matches with the observe field data. When this is accomplished, the computed curve and the plotted field curve match perfectly with each other. The final model obtained after number of iterations is then to be accepted as the final interpretation.
2.18: STRATEGIES OF GROUNDWATER EXPLORATION:

As mentioned earlier, seriously carried out preliminary investigations during recognizance survey should be analyzed. Hydrogeological cross sections should be prepared. A groundwater potential map, showing qualitatively, the spatial variation of groundwater potential is prepared. Detailed terrain representative geophysical investigations (resistivity surveys) should be carried out. Iso-resistivity maps for different electrode separations, (keeping in view the depths, thickness of the aquifers observed in the dug-wells and boreholes and spatial variations of these parameters, in the study area) should be prepared. More soundings should be carried out in low resistivity regions. Finally using the resistivities of various subsurface layers at the parametric soundings sites and integrating the same with the hydrogeological data, the geophysical resolutions, namely the resistivities of the aquifers, their thicknesses at various representative locations of the virgin soundings should be finalized. This can be accomplished by making a geophysical fence diagram of the study area, showing the disposition of the water bearing zones and its characteristic resistivities in the region.