4

Methods of Rock Exploration

(Geophysical Prospecting)

4·1. Introduction

Careful design of an engineering structure is not completed unless full information about environments of the strata, on which the structure is going to stand is available. Intelligent design for safe and economical construction requires thorough knowledge of subsurface conditions. Many useful engineering details are obtained from geological maps. Geological maps give information about the rock units directly underlying the project area. The characteristics of rocks are of prime importance in the selection of water retaining structures and dams. Conditions beneath the surface can often be correctly predicted by the three dimensional information given on geological maps. On geological maps rocks are identified by name and geological age. A formation is an individual bed or several beds of rock that extend over a large area, and that can be clearly differentiated from overlying or underlying beds because of a distinct difference in lithology, structure or age. Geological maps often carry one or more geological sections which describe the disposition of the various strata in depth along an arbitrary line usually marked on the map. These sections are somewhat hypothetical and is to be used with caution. They give a general strata condition and an exhaustive information can not be obtained with the study of geological map of an area. That is why for any important engineering project such as dams, multistoreyed buildings, or a massive structure, it is necessary to know the strata conditions in detail below the construction site. Some times minor modifications may serve the purpose and some times the site may be shifted if the strata condition is not favourable. Therefore after completion of the Civil Engineering Survey—that is survey of the surface ground—it is necessary to do survey of the substrata which may be said to the geological and rock mechanics survey. It is said that strong rocks such as granite are suitable for almost all engineering purposes, but it is not always true. Much depends on details of jointing, weathering, permeability, ground water conditions etc.

4·2. Object of Rock Exploration

While conducting geological or substrata survey following item of information are required to be described and measured.

(*i*) Homogeneous zones and their extent.
(*ii*) Rock type and their engineering properties.
(*iii*) Geological separations and their geomechanical significance.
(*iv*) Width of separations with details of fillings.
(*v*) Joint surfaces.
(*vi*) Determination of the degree of jointing, spacing of joints and their two and three dimensional extent.
(*vii*) Water conditions in respect to both rock material and joint and fault material.

Information of homogeneous zones and their extent gives us an idea of suitability of the strata as a supporting member of the foundation if the structure is to be built on or above the strata and some times they give an idea of materials available for a particular construction work if the structure is to be built with the material available along the strata. For example—extent of material available for a masonary dam.

Information about the Rock Type and their engineering properties helps the designer in selecting the type of foundations and limit of their dimensions. And details of joints, faults etc. caution the designer in selecting the dimensions of the foundations and to see if some treatment of sub-strata is required or not. Some times treatment of fractured sub-strata becomes absolutely necessary for successful life of the project.

If we summarise the objective of subsurface exploration then it can be said that the objective of sub surface exploration are to obtain quantitative data on the kinds, properties, amounts, distributions and structure of the material under and adjacent to a proposed structure.

4·3. Methods of Rock Exploration

Two groups of methods are available to obtain these data.

(*i*) By direct penetration of the materials.
(*ii*) By making certain physical measurements from the surface without direct penetration and then to interpret those data for ascertaining the above required information.

Before starting any engineering geological survey it is beneficial to study the available literature and official records on the geology and hydrogeology of the area. This helps to establish the extent of geological and hydrogeological exploration to be done on the construction site and correctly outlining a definite programme of the required survey work by determining the required number of exploration bore holes. The number of such bore holes and their depth depends upon the complicated nature (complexity) of the geological structures and suspectibility of the strata to settlement.

4.4. Rock Exploration by Direct Penetration of the Material

Instead of some indirect methods for ascertaining any property of a material it is always better to have some direct method. Direct penetration into the rock mass helps in direct observation of its structure with which its property can be inferred to a great reliability. Therefore, boring is the best method for rock or sub-surface exploration.

Borings are of two types

1. Core borings.
2. Large diameter calyx holes.

4.4.1. Core Borings

The primary purpose of core boring is to obtain samples of the materials penetrated and to get inference about the lower strata by direct observation and preliminary testing of the core samples. Core boring can be done in almost every type of rock and the samples are machined cylinders of the materials penetrated. Core holes are mostly vertical but in some exceptional cases inclined borings are also done.

The equipment commonly used are known as drilling rings and are run by variable speed machines. Drilling fluid is used inside the hole to progress further deep. Sometimes compressed air drilling is also done for greater depths. The bit makes an annular opening in the rock and as drilling continues the core barrel slides down over the central core of rock material. When the core barrel is raised a catcher holds the core in place and the core is raised with the core barrel.

Cutting tools commonly used are diamond bits and steel alloy toothed cutters.

Diamond bits cut even the hardest rocks but tend to clog in softer materials. Steel-alloy tooched bits are generally better adopted to shales and soft rocks and operates satisfactorily in dense and unweathered basalt. The diameters of cores with diamond or steel alloy bit range from 22 mm to 100 mm. Length of the core cut depends on core barrel.

4.4.2. Core Recovery

The success of core-drilling is measured by the percentage of core-recovered. Sometimes a good operator abtains between 90 to 100 percent recovery if the rock penetrated is sound. Bad rock conditions cause blocking of the core in the barrel and consequent grinding of the core. If the core recovery is not good it should be checked at the time of drilling how losses are occuring. From behaviour of the drill rig and character of the returning drilling fluid and cuttings, fracture systems in the rock mass very poor recovery is obtained. To get a correct picture of fracture etc. inside the rock mass sufficient number of borings are done and on the basis of core recovery from different bore holes inference is made.

4·4·3. Rock Quality Designation (R.Q.D.)

We have seen in the above para that good core recovery represents good quality of rock whereas poor core recovery represents poor rock strata. That weakness might be due to poor strength of the rock or due to presence of joints, fissures, faults etc. inside the rock mass. Of course this can be ascertained by observation of the fresh core being recovered.

Now-a-days designers, consulting engineers and geologists in several countries use the "R.Q.D." as yardstick for evaluating the quality of rock at site R.Q.D. stands for Rock Quality Designation.

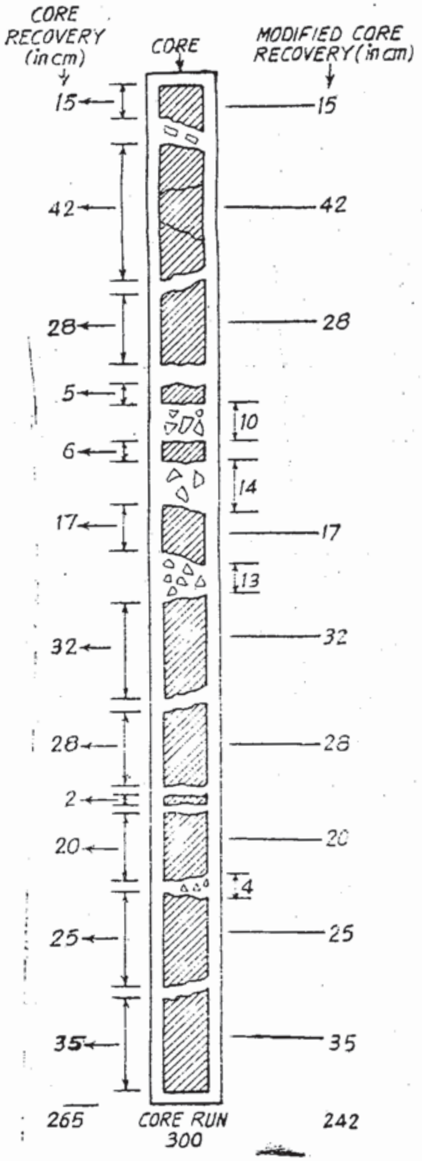
When a drilling has been done for a particular depth the cores coming out of it are accounted for. Then total length of core recovery (that is the rock which has come up) is measured. Then ratio of total length of core recovery and length of core run *i.e.*, drilling done, is expressed as core recovery ratio. The ratio is expressed in percentage.

$$\therefore \qquad \text{Core Recovery} = \frac{\text{Total length of core recovered}}{\text{Length of drilling done}}$$

In this procedure length of all the cores whatever be their length, are counted. But a new system was adopted in which the length of rock cores which are less than 10 cm are not counted and the core recovery ratio now expressed in percentage are known as Rock Quality Designation (R.Q.D.). In such a case the effect of rock weaknesses are taken into account. Because if the rock will be weak, then cores will not be of bigger length. At the same time due to joints, fracture etc. also the cores will be of lesser dimensions thus R.Q.D. gives a good assessment for the quality of rock. The cores might be broken during handling and drilling processes also. In such cases the surfaces may be having fresh irregular breaks. In such cases, fresh broken pieces are fitted together and counted as one piece provided they form the length of 10 cm or more. Natural joint surfaces can be identified looking at the broken core samples and generally in such cases pieces can not be fitted together to give an appearance of one piece. Per running metres the number of fractures may also be counted looking at the recovered core but the result may not be good. Hence R.Q.D. has been taken as yard stick to represent the quality of rock. Table 4·1 gives description of rock strength based on R.Q.D.

Fig. 4·1 explains determination of Rock Quality Designation (R.Q.D.) from the cores obtained from a bore hole.

Due to presence of bedding planes, some times correct inference is not obtained by this method for rock strata having sedimentary beds but for igneous and metamorphic rocks more exact inferance is made.



Total Core Recovery
$=265$ cm

Total Core Run
$=300$ cm

Modifien Core Recovery
$=242$ cm

Core recovery
$$=\frac{265}{300}=88{\cdot}3\%$$

R.Q.D.
$$=\frac{242}{300}=80{\cdot}7\%$$

As per table 4 1 Rock Quality Description
=Good (For R.Q.D.
=87%)

Note—

Cores for 10, 14, 13 and 4 cm resp. have come in small pieces. Hence not counted for R.Q.D.

Fig. 4·1.

Table 4·1

R.Q.D (Rock Quality Designation) (%)	*Rock Quality Description*
0—25	Very poor
25—50	Poor
50—75	Fair
75—90	Good
90—100	Excellent

4·4·4. Fracture Frequency

For description of quality of rock some times fracture frequency is used. Natural discontinuities in fracture per foot or per metre run is described as fracture frequency.

4·5. Large Diameter Calyx Holes

Although this method is costly, yet it gives a correct picture of the strata condition inside the hole. By this method the rock can be examined in-situ. With the help of camera, photographs are taken inside the hole for different sub-surface strata and inferance is drawn with those photographs. Sometimes, electronic equipments are also used as sub-surface probe.

4·6. Logging of Cores

Logging of cores means keeping the rock cores (which come out of the bore holes) in porper sequence with detailed descriptions. Cores are of no value unless properly logged In order to write a good log report the site incharge must understand drilling methods and comprehend the engineering purposes for which the work is to be undertaken. For example if bearing piles are to be located then determination of elevation of the depth of sound rock may be sufficient. If investigation for a masonary dam is being done, then location of faults, joints and fractures are also necessary.

Percentage of core recovery is to be determined after each pull and effort to be made to ascertain the cause of losses of the core. If the drill stem drops suddenly and circulation of drilling fluid is lost temporarily it can be inferred that core loss may be due to an open cavity. If drilling stem drops at faster rate than the normal while circulation of drilling fluid is normal but it becomes muddy then core loss may be due to grinding or washing away of the core, which means that in the zone, there might be fracture filled with silt which was washed away due to drilling fluid. For good reporting and preparation of good boring log, it is necessary that reporter should always be present at the site and must be able to make proper interpretations. A typical example of a boring log has been shown in Table 4·2.

4·7. Geophysical Prospecting

Geophysical prospecting may be described as Geophysical exploration. This is a type of field investigation in which physical measurements are done at the ground surfare to obtain information about sub-surface. In this method of exploration, physical measurements which are based on principles of physics are interpreted in terms of sub-surface geological structure and lighology. In fact, an engineer is satisfied with bore holes only from which he gets a physical verification of the substrata condition. But making many bore holes for a project may be a costly affair. In such a case, geophysical methods are adopted which gives an qualitative idea of the sub-surface condition at comparatively lower cost and then, bore holes are done at determined places to have a correct picture. Hence bore holes and Geophysical methods may be considered as complementary to each other for an engineering project.

In a broad sense, geological prospecting is done for the following three purposes.

(*a*) Determination of extent of mineral deposits or a construction material.

(*b*) Determination of rock structure and lighology.

(*c*) Detection of underground metal or pipe lines etc.

4·8. Methods of Geophysical Prospecting

The properties of rocks which are mostly used in geophysical prospecting are density, magnetic susceptibility, elasticity and electrical conductivity. The four principal methods of geophysical exploration are :

(*i*) Seismic, (*ii*) Electrical, (*iii*) Magnetic, (*iv*) Gravitational.

4·8 1. Seismic Methods

Of all the methods seismic methods is highly developed and most of the details are obtained correctly where it is employed. Rocks have different elastic properties and densities therefore elastic waves are propagated through them with different velocities. At the interfaces, the velocities are reflected and refracted because properties of the rocks change at the interface. An elastic wave generated by an impulse at the surface travels in side the rock mass but when an interface is met with, some part of it is reflected back to the surface and some after refraction travels through the lower rock mass. Travel time of the wave is observed at different points at the surface. And with the help of graph or other methods the depth of interface is obtained.

Seismic exploration is done by two methods :

(*i*) Reflection

(*ii*) Refraction.

Reflection method is mostly used for deep exploration. Generally more than 600 metres.

Refraction methods are adopted for lesser depth. Since most of the engineering explorations are of shallower depth hence refraction method of seismic exploration are employed for engineering explorations.

4·8·1·1. Theory

Let at point *S* on the surface of ground a shock be created. At point *G* one geophone has been put to receive the signal. Distance between *S* and *G* is *x*. For waves there may be two possibilities to travel. One shown by *SAG* in which the wave travels through upper medium only. In which it has got velocity V_1. Another possibility is that it travels on path *SBCG*. Of course there might be other paths also. But path *SBCG* is also a possibility in which the wave passes through both upper and lower medium with velocity V_1 and V_2 respectively. Since V_2 is more than V_1, there is a possibility when signals at *G* is received at a time for the waves travelled by both the paths *SAG* and *SBCG*. Let *H* be the depth of upper strata.

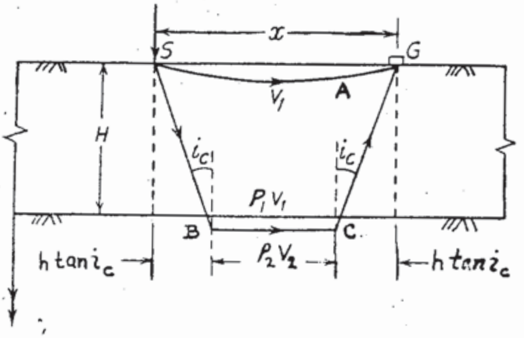


Fig. 4·2.

$$SB = CG = \frac{H}{\cos i_c}$$

where i_c is angle of incidence.

$$BC = x - 2H \tan i_c$$

If *t* is the time, taken by wave to reach at *C* through path *SBCG*

Then
$$t = \frac{1}{V_1}\left(\frac{H}{\cos t_c}\right) + \frac{1}{V_2}(x - 2H \tan i_c) + \frac{1}{V_1}\left(\frac{H}{\cos i_c}\right)$$

$$= \frac{1}{V_1} \cdot \frac{H}{\cos i_c} + \frac{x}{V_2} - \frac{2H \tan i_c}{V_2} + \frac{1}{V_1} \cdot \frac{H}{\cos i_c}$$

$$= \frac{x}{V_2} + 2H\left(\frac{1}{V_1 \cos i_c} - \frac{\tan i_c}{V_2}\right)$$

$$= \frac{x}{V_2} + 2H\left[\frac{1}{V_1 \cos i_c} - \frac{\sin i_c}{\cos i_c} \cdot \frac{1}{V_1/\sin i_c}\right]$$

$$\left[\because \quad \frac{V_1}{V_2} = \frac{\sin i_{c1}}{\sin i_{c2}} = \sin i_{c1}\right.$$

$$\left.\text{because } \sin i_{c2} = \sin 90^\circ = 1\right]$$

$$= \frac{x}{V_2} + 2H\left[\frac{1 - \sin^2 i_c}{V_1 \cos i_c}\right]$$

$$= \frac{x}{V_2} + 2H\frac{\cos^2 i_c}{V_1 \cos i_c}$$

$$= \frac{x}{V_2} + \frac{2H \cos i_c}{V_1} \qquad \ldots(4{\cdot}1)$$

Time t_1 taken by wave to reach from S to G through upper medium will be $\frac{x}{V_1}$.

Since both the signals are received at G at the same time.

$$\therefore \qquad t_1 = t$$

or
$$\frac{x}{V_1} = \frac{x}{V_2} + \frac{2H \cos i_c}{V_1}$$

or
$$x\left[\frac{V_2 - V_1}{V_1 \cdot V_2}\right] = \frac{2H \cos i_c}{V_1}$$

or
$$x = \frac{\dfrac{2H \cos i_c}{V_1}}{\dfrac{V_2 - V_1}{V_1 \cdot V_2}} = \frac{2H \cos i_c}{V_1} \cdot \frac{V_1 V_2}{V_2 - V_1}$$

$$= 2H \frac{V_2 \cos i_c}{V_2 - V_1} \qquad \ldots(4{\cdot}2)$$

$$\because \qquad \sin i_c = \frac{V_1}{V_2}$$

$$\therefore \qquad \sin^2 i_c = \frac{V_1^2}{V_2^2}$$

or
$$1 - \cos^2 i_c = \frac{V_1^2}{V_2^2}$$

or

$$\cos^2 i_c = 1 - \frac{V_1^2}{V_2^2}$$

$$= \frac{V_2^2 - V_1^2}{V_2^2}$$

$$\therefore \quad \cos i_c = \frac{\sqrt{V_2^2 - V_1^2}}{V_2} \qquad \ldots(4\cdot3)$$

Putting value of cos i_c in Eq. (4·2), we get

$$x = \frac{2H \cdot V_2 \dfrac{\sqrt{V_2^2 - V_1^2}}{V_2}}{V_2 - V_1}$$

$$= \frac{2H\sqrt{V_2^2 - V_1^2}}{V_2 - V_1}$$

$$= \frac{2H\sqrt{(V_2 + V_1)(V_2 - V_1)}}{V_2 - V_1}$$

$$= 2H\sqrt{\frac{V_2 + V_1}{V_2 - V_1}}$$

$$\therefore \quad H = \frac{x}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad \ldots(4\cdot4)$$

With the help of equation (4·4), thickness "*H*" of upper layer can be calculated.

4·8·1·2. Method of Exploration

The method is based on the variable velocity of wave propogation in different materials of the earth crust. Several seismic wave receivers, known as geophones or pickups, are set in a line on the ground at known distances as shown in Fig. 4·3 (*b*). The function of a pick-up is to convert the mechanical vibrations in the ground into electrical vibrations or pulses which are used to drive the recording mechanism. A small amount of electrical energy fed to the detector is amplified electronically in a manner similar to that employed in a radio receiver set. The energy supplied by the amplifier is fed to the recording device. Thus with the help of recorder, time of arrival of the wave is sensed, which is recorded also for future reference. At a distance, of course in the line of the pickups, a hole is made into the ground to keep some explosive. The point is known as shot point. The explosives are exploded by some electrical device and the seismic waves sent into the ground travel in different directions. The waves reaching at different, points 1, 2, 3 etc. are picked up by geophones kept at those points. After proper magnification, it is transmitted to the recording device. The time of shooting is recorded by a separate device. Thus time of shooting at the short point and time of arrival of seismic waves at points 1, 2, 3 etc. are recorded. The distance and time of arrival of wave front to reach a particular point is plotted on graph as shown in Fig. 4·3 (*a*). If points on the graph are jointed, two straight lines are obtained as shown in Fig. 4·3 (*a*). To the left of intersection point, geophones set at 1 and 2 receive the direct wave first, whereas as at the right of the intersection pt., *i.e.*, geophones at 4, 5 and 6, receive refracted waves first. Velocity of wave through lower strata is faster than that of the upper strata. At 3rd point the geophone receives both the direct and refracted waves at the same time, and this corresponds to the intersection point *C*.

With the graph presented in Fig. 4·3 (*a*), the distance *x* of the intersection point can be measured out and thus, thickness of the upper strata *H* can be obtained by Eq. 4·5,

$$H=\frac{x}{2}\sqrt{\frac{V_2-V_1}{V_2+V_1}}$$

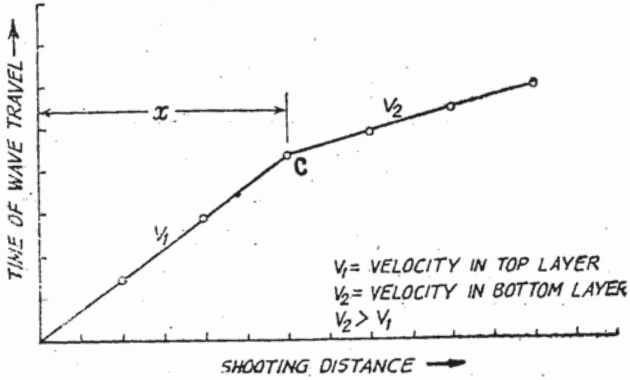
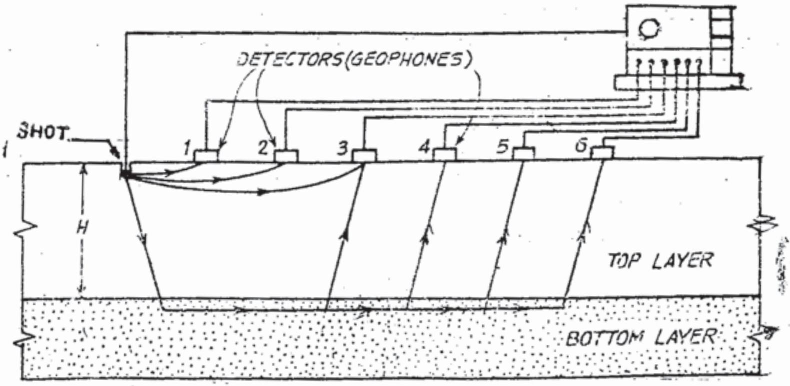


Fig. 4·3 (*a*)



Sketch showing principles of Seismic exploration.

Fig. 4·3 (*b*)

In the above equation V_2 and V_1 *i.e.* velocity of the seismic waves in upper and lower strata can be evaluated from the observations received by geophones kept at different points.

Signal at point 1 will be received earlier than point 2. At both the points, direct waves are being received. Distance between point 2 and 1 is known. Now difference in time intervals of signals received at point 2 and 1 gives the time of wave to travel from point 1 to 2. Therefore, velocity V_1 can be known as $\frac{D_1}{t_2-t_1}$;

where t_2 is the time when signal has been received by geophone at 2.

t_1 is the time when signal has been received by geophone at 1, and distance between point 2 and 1 is D_1 metres.

Similarly at point 4 and 5 refracted rays will be received earlier (since $V_2 > V_1$) than the direct wave. Therefore, velocity

$$\therefore \qquad V_2=\frac{D_2}{t_5-t_4}$$

where t_5 and t_4 are the times when signals are received at point 5 and 4 respectively, and distance between point 5 and 4 is D_2 metres. Distance between geo phones are kept about 20 metres to 30 metres. Shooting distance is kept 3 to 4 times the depth upto which probing is required.

If depth to be probed is not deep. then at shooting point, wave is generated by hitting the ground by a hammer instead of firing a dynamiee.

Theory of wave propogation is also used to estimate the strength properties of rocks.

4·8·1·3. **Limitations.** Although seismic method is best among the geophysical methods of site exploration, yet this method has got the following limitations.

1. If the lower strata is dense compared to the upper strata the velocity of waves will be faster and depth of upper strata can be predicted correctly. But if the upper strata is denser than the lower one; then this method may not be successful.
2. This method is successful only when the velocity contrast is great, which means that there is a sharp change in the density of the two layers. If there is a gradual transition from surface soil to bedrock, the velocity contrast will be relatively small and in such a case it becomes difficult to make definite conclusions.
3. If the surface terrain and the interfaces of the layers are steeply sloping or irregular instead of horizontal and smooth, then also seismic method may not be so successful.

4·8·2. Electrical Methods

Electrical methods of prospecting can be employed in three ways.

(*a*) Self-potential method,
(*b*) Surface potential method,
(*c*) Electromagnetic method.

Certain ore bodies tend to act as wet cell batteries and generate a feeble current which can be measured in their vicinity. And this property of the bodies are used to identify them in self potential method. Sometimes this method is used in ore prospecting.

When an electric circuit is grounded at two points, an electrical field is produced in the earth. Any sub-surface variation in conductivity alters the form of the current flow within the earth and this affects distribution ot electric potential. The measurement of potential helps in identification of the strata. This method is popularly known as resistivity method but sometimes it is known as surface potential method also.

In the electromagnetic method, electromagnetic field of the ground currents are measured in place of their electrical fields and interpretation of substrata is done.

Out of the three methods described above the surface potential method or the resistivity method is mostly used by engineers for subsurface explorations.

4·8·2·1. Resistivity Method

The electrical conductivity and its reciprocal, the resistivity of the earth materials which include soils or rocks, depend on the amount of dissolved electrolyte in pore water as well as on the volume of the pore water also. The amount of dissolved electrolyte in the pore water depends upon the chemical composition, whereas the amount and volume of pore water depend upon the porosity of the layer. Hence a layer having more porosity will have more pore water and thus, making the layer more conductive for electrical currents. The resistivity of the layer will be low. On the other hand if a layer of sand stone (which is composed of insoluble minerals) is there, it will have low concentrations of dissolved electrolytes in the interstices or pores. For such case the strata will be having less electrical conductivity and will have high resistivity. Thus, if the measurement of resistivity is done for passing current through the strata, it can help in identification of the strata.

The principle underlying the resistivity method is that two electrodes are placed in the ground and joined in a circuit to a source of electrical energy producing direct current. The current will flow from one electrode to the other passing through the ground. The difference in potential between the two points spaced at equal distance from the electrodes is measured by a potentometer from which resistivity of the strata can be known. Since, the resistivity thus obtained is an average value between the two points of electrodes spacing, it is called the "apparent resistivity".

Before going into the details of the method it is better to have some idea about the theory of current flow which will help in understanding the resistivity method.

4·8·2·2. Theory of Current Flow

If a current in parallel lines flows through a conductor of cross-sectional area A, then resistivity ρ is defined by

$$\rho = \frac{R.A}{L} \qquad \ldots(4\cdot5)$$

where R is the resistance measured between two equipotential surfaces separated by a distance L.

Ohm's Law states that

$$R = \frac{\Delta V}{I} \qquad \ldots(4\cdot6)$$

where I=current in the conducting body,

ΔV=potential difference between two surfaces of constant potential.

R=the resistance between the surfaces,

From Eq. (4·6)

$$I = \frac{\Delta V}{R} = \frac{\Delta V.A}{\rho L} \qquad \ldots(4\cdot7)$$

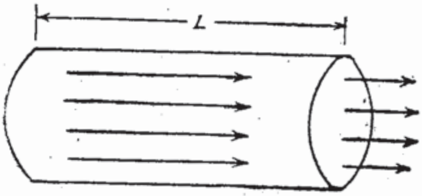


Fig. 4·4

The current density (current per unit area)

$$j = \frac{I}{A} = \frac{\Delta V}{\rho L} \qquad \ldots(4\cdot8)$$

If the current flow is not parallel, the current density will vary through the conductor. But the same argument can be applied to an infinitesimal element of the conductor bounded by equipotential surfaces which may be curved. The ratio $\Delta V/L$ becomes in the limit the maximum potential gradient dV/dL and then, the equation for current density can be written as,

$$j = -\frac{1}{\rho} \cdot \frac{dV}{dL} \qquad \ldots(4\cdot9)$$

Negative sign shows that the potential increases in the opposite direction to the current flow.

Next, let a current be flowing from a point which is known as 'source' and the negative pt., which is "sink", is at a infinite distance. If S is the strength of the source, the potential at a distance r from the source is given by

$$V=\frac{S}{r} \qquad ...(4{\cdot}10)$$

If the source is at the centre of a sphere of radius r, then the current flowing through unit area of the surface will be given by Eq. (4·9).

$$\begin{aligned} j&=-\frac{1}{\rho}\cdot\frac{\partial V}{\partial r} \\ &=\frac{1}{\rho}\cdot\frac{S}{r^2} \qquad ...(4{\cdot}11) \end{aligned}$$

$$\left[\because V=\frac{S}{r} \quad \therefore \frac{\partial V}{\partial r}=-\frac{S}{r^2}\right]$$

Surface area of the sphere

$$=4\pi r^2$$

$\therefore$ Total current = Surface area × Current density

$$=4\pi r^2\,\frac{S}{\rho r^2}$$

$$\therefore \qquad I=\frac{4\pi S}{\rho} \qquad ...(4{\cdot}12)$$

and
$$S=\frac{I\rho}{4\pi} \qquad ...(4{\cdot}13)$$

For resistivity surveying the following condition prevails. The medium is semi-infinite bounded by a plane surface. This plane surface separates it from air. Air is considered to be of infinite resistivity and the source is situated at the interface.

Since the surface is semispherical, hence from Eq. (4·13) we can write that

$$S=\frac{I\rho}{2\pi} \qquad ...(4{\cdot}14)$$

If the potential gradient is measured at a point distant r from the source at the surface, we can get equation for resistivity as follows

$$V=\frac{S}{r}$$

$$\therefore \qquad S = V\,r \qquad \ldots(4{\cdot}15)$$

Again
$$S = \frac{I\rho}{2\pi} \qquad \ldots(4{\cdot}16)$$

From Eqs. (4·15) and (4·16)

$$Vr = \frac{I\rho}{2\pi}$$

$$\therefore \qquad V = \frac{I\rho}{2\pi r} \qquad \ldots(4{\cdot}17)$$

and
$$\frac{\partial V}{\partial r} = -\frac{I\rho}{2\pi r^2}$$

$$\therefore \qquad \rho = \frac{2\pi r^2}{I}\,\frac{\partial V}{\partial r} \qquad \ldots(4{\cdot}18)$$

$(\partial V/\partial r)$ has opposite sign to I therefore ρ is finally positive.

If four electrodes are placed in line at equal distances apart and the inner being potential electrodes and the outer being current electrodes, the potential difference between the inner electrodes can easily be calculated with the help of the above equations. The configuration has been shown in Fig. 4·5.

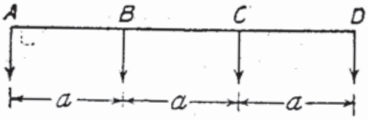


Fig 4·5

Potential at B due to A

$$V_{BA} = \frac{I\rho}{2\pi a}$$

$$\left[\because\ V = \frac{I\rho}{2\pi r},\ \text{Eq. (4·17)}\right]$$

Potential at B due to D

$$V_{BD} = \frac{I\rho}{2\pi\,(2a)}$$

$\therefore$ Net potential at B due to A and D.

$$V_B = \frac{I\rho}{2\pi}\left(\frac{1}{a} - \frac{1}{2a}\right) \qquad \ldots(4{\cdot}19)$$

Similarly potential at C due to A

$$V_{CA} = \frac{I\rho}{2\pi\,(2a)}$$

and
$$V_{CD} = \frac{I\rho}{2\pi a}$$

$\therefore$ Net potential at C due to A and D

$$V_C = \frac{I\rho}{2\pi}\left[\frac{1}{2a} - \frac{1}{a}\right] \qquad \ldots(4{\cdot}20)$$

Potential difference between *B* and *C*

$$V_B - V_C = \frac{I\rho}{2\pi}\left\{\left(\frac{1}{a} - \frac{1}{2a}\right) - \left(\frac{1}{2a} - \frac{1}{a}\right)\right\}$$

$$= \frac{I\rho}{2\pi}\left\{\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right\}$$

$$= \frac{I\rho}{2\pi}\left[\frac{2-1-1+2}{2a}\right]$$

$$= \frac{I\rho}{2\pi} \cdot \frac{2}{2a}$$

$$= \frac{I\rho}{2\pi a}$$

$$V_B - V_C = \Delta V$$

$$\Delta V = \frac{I\rho}{2\pi a}$$

$$\therefore \quad \rho = 2\pi a \frac{\Delta V}{I} \qquad \ldots(4{\cdot}21)$$

With the help of Eq. (4·21) resistivity of the strata can be known, if the difference of potential between two potential electrodes and current flowing between the outer two electrodes are known.

4·8·2·3. Measurements

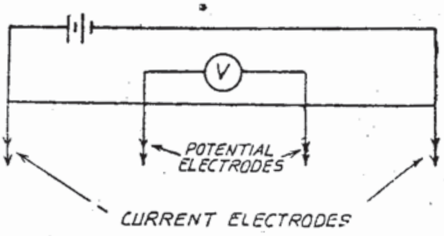


Fig. 4·6

The set up for the resistivity measurement is shown in Fig. 4·6. The instrument, which is a protable one is known as resistivitymeter. The two electrodes are placed in the ground and joinced in a circuit to a source of electrical energy which is usually dry cell. The amount of current flow is measured by a milliameter which measures the current in milliampere. The potential difference between the two inner potential electrodes is measured by a galvanometer. Sometimes, a potentiometer circuit is also used for the purpose. The current electrodes are steel pin electrodes which are driven into the ground. The potential electrodes are of non-polarising type. This is to avoid electrochemical effects. A non-polarising electrode consists of a porous pot containing a metal electrode immersed in an electrolyte of one of its own salts. For example a copper electrode is immersed in copper sulphate. It has been seen by experience that the average depth of penetration of the current is one fourth of the distance between the two current electrodes. If the four electrodes are kept in a line at the same distance "*a*" as shown in Fig. 4 6, then the configuration is known as Wenner configuration. Since the four electrodes are placed in a line at equal distances apart the calculation for resistivity becomes simple and easy. It can be stated that the depth of current penetration will be the same as the distances between electrodes (of course approximately). If greater depth is to be probed, then the electrodes spacing is to be increased. Sometimes Schlumberger arrangement is also used. In this configuration the electrodes are kept in a line, but the distance between potential electrodes are lesser.

The resistivity survey can be done by two methods.

(*i*) To get the horizontal variation of materials.

(*ii*) To get vertical variation of materials.

In the first method, the spacing between electrodes are kept equal to the depth to be probed. For example, if it is required to investigate the type of material upto 5 metres depth in a locality. Then the area is divided into traverse and electrodes spacing is kept 5 metres. The value of resistivity obtained is plotted on the traverse and equiresistivity curves can be drawn as contour lines and materials may be identified.

4·8·2·4. Interpretation of Result

A guide line about the strata condition can be obtained by resistivity values as given in Table 4·3. Since variation in the resistivity value is wide, exact inference can be made by experience and verification by a few bore holes in the area.

Table 4·3. Resistivity of different strata

Type of Stratum	*Resistivity (Ohm-m)*
Clay	1 – 10
Sand with saline water	5
Sand with fresh water	50 – 200
Gravel with fresh water	70 – 200
Weathered/fractured rock	90 – 200
Lime stone	300
Basalt	400
Granite	500
Schist	700 – 10,000

For vertical variations at a place the area is divided into different sections. At each section the resistivity values are obtained at different electrodes spacings. For example, electrode spacing of 5 m will give resistivity values of strata upto 5 m and 10 m spacing will give details up 10 m depth and so on. The result is plotted on graph. Electrode spacings on the x-axis and resistivity values on the y-axis are plotted.

An abrupt change in the curvature of the resistivity profile indicates a change of underlying material at a depth corresponding to the spacing of the electrodes. A rising curve indicates the presence of hard stratum, such as a rock, because rising curve indicates high value of resistivity which is possessed by rocks or a hard strata. A flat or descending curve indicates the presence of clays or other clayey type soils.

Resistivity method is widely used for the determination of water tables or water bearing strata. Civil engineers use it for the determination of depth of bed rocks for masonary or concrete dam construction. This method is employed for study of lithology also. This method also can be used for estimation of extent of a particular construction material such as sand, gravels etc. under ground.

4·8·3. Gravity Method

4·8·3·1. Theory

The basic theory involved in this method is the Newton's Law of Gravitation.

The law states that every particle of matter exerts a force of attraction on other particle, and the force between the two particles is given by the equation

$$F=G\,\frac{M_1 \cdot M_2}{R^2} \qquad \ldots(4{\cdot}22)$$

where M_1 and M_2 are the mass of the two particles

R the distance between them,

and G the gravitational constant.

From the second law of motion, we know that

$$F=aM_1$$

where a is the acceleration of the body of mass M_1

$$a=\frac{F}{M_1} \qquad \ldots(4{\cdot}23)$$

$$=\frac{G.M_1M_2}{R^2M_1}$$

$$=\frac{GM_2}{R^2} \qquad \ldots(4{\cdot}24)$$

Equation (4·24) gives the acceleration in the body of M_1 due attraction of a body of mass M_2. Equation 4·23 states that acceleration is equivalent to force per unit mass acting on the body.

If M_2 is taken as the mass of the earth and R equal to earth's radius, then the resulting acceleration will be equal to the gravitational acceleration on the earth's surface. Similarly acceleration due to a small burried mass m at a depth r can be obtained by the equation

$$a=G.\ \frac{m}{r^2}$$

Due to a variation in density of earth at different points laterally, there exists some difference between theoretical and observed gravity. This difference is known as Bouguer Anomaly.

These gravity anomalies are there which are detected by instrument and used for interpretation of sub-surface strata. Since gravity anomalies are very small compared with the average values of earth's field it follows that this direction is virtually constant and it is normal to the surface. Hence instruments used for detection of gravity anomalies measure the vertical component of the acceleration of gravity due to any local material inside the subsurface. Therefore, the vertical component a_z can be obtained by Eq. 4·25. Referring Fig. 4·7.

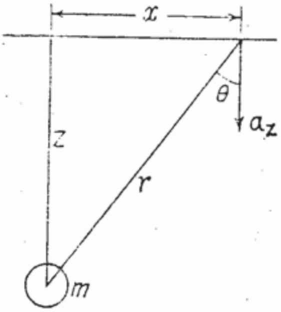


Fig. 4·7.

$$a_z=G.\ \frac{m\ .\cos\theta}{r^2} \qquad \ldots(4{\cdot}25)$$

$$=G.\ \frac{m\ .\ z}{r^2}\ .\ \frac{z}{r}=G.\ \frac{m\ .\ z}{r^3}$$

$$=G.\ \frac{m\ .\ z}{(x^2+z^2)^{3/2}} \qquad \ldots(4{\cdot}26)$$

If the body is large then

$$a_z=G\int\frac{m\ .\ z}{(x^2+z^2)^{3/2}} \qquad \ldots(4{\cdot}27)$$

If the mass is spherical and the difference in density of the mass and average earth crust is say "y" then for m in the Eq. 4·26, we can put $\frac{4}{3}\pi R^3 y$. Where R is the radius of the mass.

$$\therefore \qquad a_z=G.\frac{4}{3}\pi R^3 y\ \frac{z}{(x^2+z^2)^{3/2}}$$

$$=\frac{4\ G\pi R^3 y}{3.\ z^2}\ .\ \frac{1}{\left(1+\frac{x^2}{z^2}\right)^{3/2}} \qquad \ldots(4{\cdot}28)$$

Unit of acceleration in measuring gravity anomalies is milligal. One gal is equal to an acceleration of 1 cm/sec^2. Since 1000 m gal is equal to 1 gal, the acceleration due to gravity is about 980,000 m gal. In measurement of gravity anomalies in gravitational prospecting, data obtained is of the order of a few milligals.

4·8·3 2. Instrument and Measurement

The instrument used for measuring gravity anomalies are gravimeters. A brief description of its working principle is described. A beam which is hinged at H carries a weight, an shown in Fig. 4·8. The beam is connected to a spring and the other end of the spring is attached to a support at P which is directly above the hinge point H. Now tension in the spring is such that beam makes an angle θ_1 with the horizontal which is very small. The gravitational moment $m \cos \theta$ is balanced by a moment $F.x$. Where F is the force in the spring and x the perpendicular distance of the spring from the hinge point. If gravity increases, the beam deflects downward until the new equilibrium position is reached. The length of the spring increases. At point P some arrangement is made to bring the spring to the original length. This is done with the help of a micrometer to which the other end of the spring at P is attached. Provision is made to convert the micrometer reading to the force to bring the spring to the null position. Thus the force gives the vertical component of the gravitation anomally. The instrument is temperature compensated to neutralise the effect of temperature variations. Other instruments in use are pendulums and torsion balances. Pendulums also measure the relative values of gravity, but the torsion balance measures the gravity gradient *i.e.*, variation in gravity per unit horizontal distance.

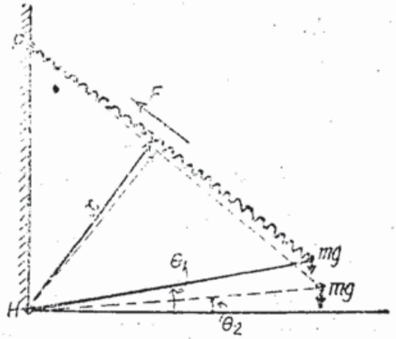


Fig. 4·8. Line diagram of a gravitymeter

4·8·3·3. Corrections

Since the observed gravity will depend upon a place where the measurement is being made, the following corrections are also required to be made.

(*a*) Latitude correction

(*b*) Elevation correction

(*c*) Terrain correction.

If g_o is the value of gravity at equater then g at a place is given by

$$g = g_o(1 + 0{\cdot}0052884 \sin^2 \phi - 0{\cdot}0000059 \sin^2 2\phi) \qquad \ldots(4{\cdot}29)$$

where ϕ is latitude of the place where observation is being taken.

If the observation is being taken at a height h above the sea level. Then

$$g = G.\frac{M}{(R+h)^2}$$
$$= \frac{GM}{R^2}\left(1 - \frac{2h}{R}\ldots\ldots\right)$$

Since for $\frac{GM}{R^2}$ we can write g_0, which means g at mean sea level

$$\therefore \quad g = g_0\left(1 - \frac{2h}{R}\right) \text{ (ignoring higher order)}$$

$\therefore$ Elevation correction

$$g_0 - g = \frac{2g_0 h}{R} \quad \ldots(4{\cdot}30)$$

Terrain correction depends upon nature of the ground. This is obtained by a graphical method.

Assuming uniform density distribution, it is now possible to correct for the above factors and value of gravity at any point on the surface of the earth can be computed. If these corrections are made and the computed value of gravity does not equal the observed value then the difference between the two is gravity anomaly. Such anomalies arise from irregularities in the distribution of mass in the earth's crust, and are closely connected with local geology. For this reason the gravity methods are good for subsurface geological exploration.

The anomalies or Bougur Anomalies after necessary correction are obtained as

[Observed gravity+elevation correction+topographical correction]
−[Theoretical gravity at the same latitude]

If the observed value of gravity is greater than computed value the anomaly will be positive and if observed value is less than computed value the anomaly will be negative. At a place if more dense material exist than the surrounding one, positive anomaly is obtained whereas negative anomaly will be obtained if less dense rock material exists than the surrounding one.

4·8·3·4. Interpretation of Rasult

The gravitational method makes possible to establish the boundaries between the masses of different densities. Anomalies of gravity *i.e.*, the difference between the theoretical and the corrected observed values are represented in plan by contours of equal gravity anomaly values called "isogams" and in section by anomaly profiles. One such profile describing a fault is shown in Fig. 4·9.

The gravity method, as other geological method, can be used for qualitative survey. This is a method to be used with suppliments of bore holes. It can reduce the number of bore holes at a plane. Generally this method is not so common for engineering projects. For mine exploration this can be used.

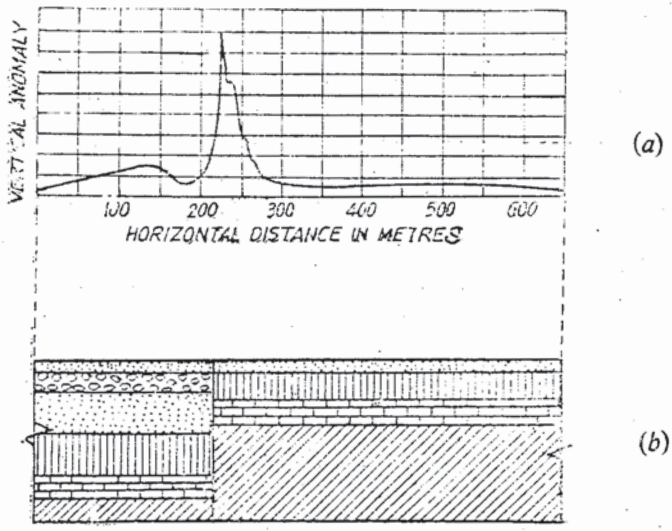


Fig. 4·9

4·8·4. Magnetic Method

4·8·4·1. Theory

The gravity method of geophysical prospecting is based on variation in density of rock masses, similarly the magnetic method of geophysical prospecting is based on variation in magnetic properties of rock masses. Similar to gravity anomalies, magnetic anomalies are also represented on maps and inference of the substrata under the surface is made.

Magnetic property of rocks varies from place to place. The most common magnetic minerals are magnetite and pyrrhotite. A few other minerals also have magnetic properties but weaker in extent. In igneous rocks magnetic minerals are more abundant than in sedimentries. Magnetite and pyrrhotite are more abundant in basic rocks than in acid rocks. Magnetic minerals are also concentrated in fault zones.

The earth itself is considered to have two magnetic poles near its geographical poles. But the geomagnetic axis and geographic axis do not coincide. The effect of earth magnetic force is minimum at equater and maximum at the poles. Hence if a magnetic needle is suspended at equator it will be in horizontal position whereas at poles it will be vertical. Between equator and pole it will have some inclination which is defined as a dip. In magnetic method of geophysical prospectic vertical component of the magnetic intensity of a place is taken into account. While measuring magnetic intensity of a place declination also has to be taken into account. At the same time effect of diurnal changes in the earth's magnetism also is to be taken into account.

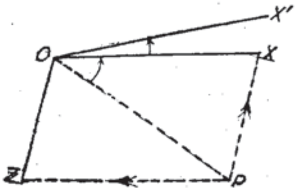


Fig. 4·10 (*a*)

OP represents in magnitude and direction the intensity of magnetic field due to earth and geological bodies. Angle *X'OX* represents the magnetic declination of the place. *OX* represents the horizontal and *OZ* the vertical component of the magnetic field. *XOP* represents the magnetic dip. The vertical component *OZ* of the vector *OP* is considered for magnetic anomalies. The difference between the theoretical and observed intensities is the magnetic anomaly. For magnetic measurements the unit is gauss which is numerically equal to 1 dyne. For expressing magnetic anomalies the unit is γ (gama) which is equal to 10^{-5} gauss.

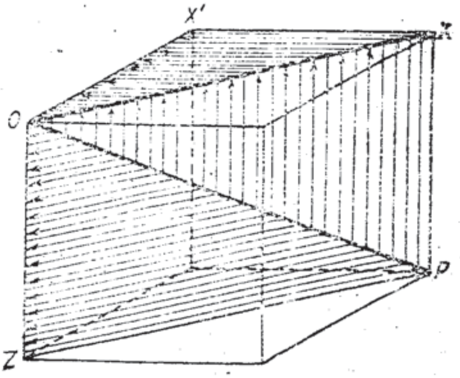


Fig. 4·10 (*b*) Earth Magnetic Field OF.

The anomalies plotted on plan are known as isonomaly lines. And in the sections are known as profiles.

4·8·4·2. Instrument used for magnetic prospecting are

(*a*) Magnetic balance. (*b*) Torsion magnetometer.
(*c*) Fluxgate magnetometer. (*d*) Proton magnetometer.

A magnetic balance measures the changes in horizontal or vertical component of the magnetic intensities of the earth's field. It does not measure the absolute strength of the components. It is known as vertical or horizontal force variometer depending upon wether it measures the vértical or horizontal component. The vértical force variometers are more common in use.

Torsion magnetometer is also a vertical force variometer. In this type of magnetometer, the restoring torque is applied to the magnet by a horizontal torsion fibre which also acts as the suspension for the system. The difference in angular torque needed to restore the magnet to the null position for different values of the vertical component of the field is a measure of the change of the component. It is unaffected by the horizontal component of the earth's field. Hence it is the most suitable method for the measurement of vertical component of the earth's field.

The flux gate magnetometer measures and records continuously the changes in total field strength. It records the component of the field along its axis with an accuracy of ±1 gamma, and can be used to record any component of the geomagnetic field depending upon the alignment of the sensitive element.

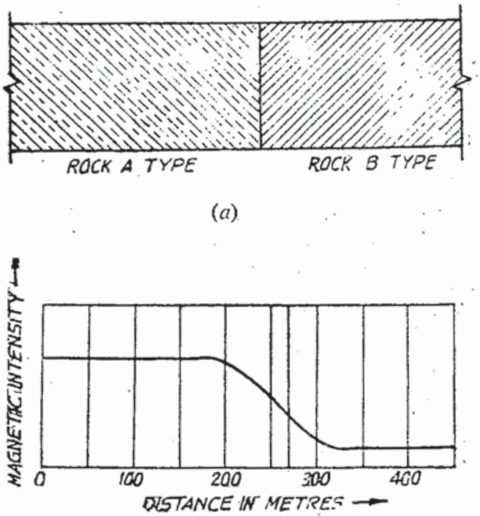
The proton magnetometer is a magnetometer which measures directly the strength of the total field. One great advantage with this type of magnetometer is that measurement can be done while they are in motion. Hence it can be used in air. This instrument is based on the principle of electronics.

Since the observed vertical force anomalies in the regions are related to the geological structure, measurement of vertical component is mostly done for prospecting. In magnetic prospecting, the anomalies measured are larger as compared to the gravity anomalies. In gravity prospecting measurements to an accuracy of 1 in 10^7 are common but in magnetic prospecting measurements are done to an accuracy of ±1 gamma, which is about 1 in 50,000.

4·8·4·3. Interpretation of result

As discussed in gravity prospecting in this case also engineers get only qualitative information of the substrata. Which helps in reducing the number of bore holes for site investigations. This method has got more application in mining. Ores such as magnetic and pyrrhotite are strongly magnetic, and hence these may be detected directly by magnetometers. Sometimes, this method can be used to detect underground pipe lines etc.

Where folds are existing, there may be sedimentary sequences consisting of ferruginous sandstones, shales or tuff. In such cases, anticlines will be nearer to the surface and will produce positive anomalies while synclines will produce negative anomalies. Thus geological structures can be inferred with this method. This method is used extensively in military engineering for locating mines and ammunitions. Since cost of survey work is low, this can be used as subsidiary method to give qualitative information.



(a)

(b)

Fig 4 11.

A typical profile of magnetic prospecting is shown in Fig. 4·11.