PD ISO/TR 21414:2016

BSI Standards Publication

Hydrometry — Groundwater — Surface geophysical surveys for hydrogeological purposes

bsi.

...making excellence a habit.™

National foreword

This Published Document is the UK implementation of ISO/TR 21414:2016.

The UK participation in its preparation was entrusted by Technical Committee CPI/113, Hydrometry, to Subcommittee CPI/113/1, Hydrometric methods and instrumentation.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Published by BSI Standards Limited 2016

ISBN 978 0 580 79191 8
ICS 07.060

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 April 2016.

Amendments/corrigenda issued since publication

Date	Text affected

PD ISO/TR 21414:2016

TECHNICAL REPORT

ISO/TR 21414

First edition
2016-02-15

Hydrometry — Groundwater — Surface geophysical surveys for hydrogeological purposes

Hydrométrie — Eaux souterraines — Relevés géophysiques de surface pour des besoins hydrogéologiques

Reference number
ISO/TR 21414:2016(E)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

The committee responsible for this document is ISO/TC 113, *Hydrometry*, Subcommittee SC 8, *Ground water*.

Introduction

Groundwater is available almost everywhere. Access to clean water is a human right and a basic requirement for economic development. The safest kind of water supply is the use of groundwater. However, its distribution is not uniform due to varying hydrogeological, topographical and climatic conditions. As a result, groundwater is not always available in the required quantity and/or quality, particularly in hard rock terrains where fractures and weathered zones are the primary conduits for groundwater storage and flow. Detailed knowledge on the extent, hydraulic properties, and vulnerability of groundwater reservoirs is necessary to enable a sustainable use of the resources. Therefore, collection of information on prospective groundwater zones, although costly, is essential. Geophysical methods are currently recognized as cost-effective techniques useful for collecting groundwater information. Measuring physical properties of the earth and their variation and then associating these properties with hydrogeological characteristics is the objective of groundwater geophysics.

Of the various geophysical techniques available today, the electrical resistivity method is probably most commonly used due to its relatively simple and economical field operation, its effective response to groundwater conditions and the relative ease with which interpretations can be made. This type of survey is occasionally supplemented by other techniques such as induced polarization, spontaneous potential, and Mise-a-la-Masse galvanic electrical techniques. Other geophysical methods in order of preference used for hydrogeological purpose are electromagnetic, seismic refraction, magnetic, gravity and seismic reflection surveys. More recently developed geophysical techniques include ground probing radar and nuclear magnetic resonance. Because surface geophysical surveys are carried out at the surface of the earth, the responses received from different precisional demarcations. Ambiguity exists in interpreted results and the effective application of these methods often depends on the skill and experience of the investigator, knowledge of local hydrogeological conditions, and the utility (and limitations) of the technique(s) themselves. The application of two or more geophysical techniques is a useful approach to reduce ambiguity. Integration of information from other disciplines, such as remote sensing, geologic mapping, hydrogeological characterization, chemical analysis of well water samples, etc., is also useful for interpreting geophysical field data.

Modern geophysical techniques are highly advanced in terms of instrumentation, field data acquisition, and interpretation. Field data are digitized to enhance the signal-to-noise ratio and computers are used to more accurately analyse and interpret the data. However, the present-day potential of geophysical techniques has probably not been fully realized, not only because such surveys can be expensive, but also because of the inadequate understanding of the application of relevant techniques in diverse hydrogeological conditions.

Hydrometry — Groundwater — Surface geophysical surveys for hydrogeological purposes

1 Scope

The application of geophysical methods is an evolving science that can address a variety of objectives in groundwater investigations. However, because the successful application of geophysical methods depends on the available technology, logistics, and expertise of the investigator, there can be no single set of field procedures or approaches prescribed for all cases. This Technical Report provides guidelines that are useful for conducting geophysical surveys for a variety of objectives (including environmental aspects), within the limits of modern-day instrumentation and interpretive techniques, are provided. The more commonly used field techniques and practices are described, with an emphasis on electrical resistivity, electromagnetic, and seismic refraction techniques as these are widely used in groundwater exploration. Theoretical aspects and details of interpretational procedures are referred to only in a general way. For full details, reference is intended to be made to specialized texts listed in the Bibliography.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
acoustic impedance
product of seismic velocity and density of a layer

2.2
anisotropy
variation in physical property with direction of measurement

2.3
apparent resistivity
ratio of measured voltage to input current multiplied by the *geometric factor* (2.16) for the electrode configuration

2.4
blind zone
layer having seismic velocity less than that in the layer overlying it

2.5
Bouguer correction
correction made in observed gravity data to account for the attraction (gravitational) of the rock between the datum and the plane of measurement

2.6
Bouguer anomaly
anomaly obtained after applying latitude, terrain, and elevation (free air and Bouguer) corrections to the observed gravity value and finally subtracting it from measured value at some particular station in the survey area

2.7
contact resistance
electrical resistance developed between an electrode planted in the ground and the ground material immediately surrounding it

2.8
Dar Zarrouk parameters
longitudinal unit conductance and transverse unit resistance of a geoelectrical layer

2.9
deconvolution
process of inverse filtering to nullify the undesired effect of an earlier filter operation

2.10
dipole-dipole electrode configuration
configuration in which the spacing between the current electrode pair and that between the potential electrode pair is considerably small in comparison with the distance between these two pairs

2.11
diurnal correction
correction applied to magnetic data to compensate for daily fluctuations of the geomagnetic field

2.12
drift correction
quantitative adjustment to account for a uniform change in the reference value with time

2.13
eddy current
current induced in a conductive body by the primary electromagnetic (EM) field

2.14
equivalence
function of product or ratio of two parameters (e.g. bed thickness and resistivity) where variation in the parameters keeping the ratio or product constant can yield almost the same response

2.15
geoelectrical layer
subsurface layer having characteristic of uniform electrical resistivity

2.16
geometric factor
numerical value dependent upon the arrangement of electrodes which, when multiplied by the measured voltage-to-current ratio, gives the *apparent resistivity* (2.3)

2.17
geophone
instrument which detects seismic energy and converts it into electrical voltage

2.18
gradient configuration
variation of the *Schlumberger configuration* (2.38) where the current electrodes are kept at a great distance from one another and central space is scanned by a small potential dipole

2.19
half–Schlumberger configuration
configuration in which one of the current electrodes is kept at infinity (large distance) and need not be collinear with the other three electrodes

2.20
homogeneity
characteristic of a formation with uniform physical property or properties

2.21
in-phase
component of a secondary electromagnetic (EM) field with the same phase angle as that of the exciting primary EM field

2.22
Lee-partitioning configuration
variation of the Wenner array where one additional electrode is placed at the centre between the potential electrodes

2.23
longitudinal conductance
ratio of the thickness of a geoelectrical layer (2.15) to its resistivity

2.24
magnetic permeability
ratio of magnetic induction (flux density) in a body to the strength of the inducing magnetic field

2.25
magnetic susceptibility
ratio of the intensity of magnetization produced in a body to the strength of the magnetic field

2.26
migration
part of processing of seismic reflection data required to plot the dipping reflections at their correct position

2.27
non-polarizing electrode
electrode which is not affected by electrochemical potential generated between the electrode and ground material in which it is planted

2.28
normal moveout
effect of variation of shot-geophone distance on time of arrival of seismic reflection

2.29
off-set Wenner configuration
modification in *Wenner configuration* (2.48) to remove or minimize the effect of lateral inhomogeneities

2.30
overburden
part of the host medium which lies above the target and is usually of no interest in exploration, but has physical properties that affect the measurements

2.31
phasor diagram
graph obtained by plotting *in-phase* (2.21) and *quadrature* (2.35) components of secondary electromagnetic (EM) field for different frequencies of primary EM field

2.32
polar diagram
method of plotting resistivity sounding data

2.33
porosity
ratio of the volume of pore space in a sample to the bulk volume of that sample

2.34
proton precession magnetometer
instrument to measure the magnetic field normal to the earth's magnetic field

2.35
quadrature
out-of-phase or imaginary component of secondary electromagnetic (EM) field

2.36
reflector
interface which separates two layers of contrasting *acoustic impedance* (2.1) giving rise to reflection

2.37
refractor
layer along which the refracted or head wave travels at a velocity that is higher than that in the overlying layer

2.38
Schlumberger configuration
collinear four-electrode configuration of current and potential electrodes in which potential electrodes are kept close to the centre of the configuration

2.39
skin depth
depth of penetration of electromagnetic (EM) field in a medium where the intensity of the EM reduces to about 37 % of its original value at the surface of the earth

2.40
Snell's law
laws applied when a seismic wave encounters a boundary between two media having different velocities

2.41
stacking
process of compositing data, for the same parameter, from various data sets for the purpose of eliminating noise

2.42
suppressed layer
layer lacking a response because of its small thickness and/or contrast in physical property with the surrounding environment

2.43
terrain correction
correction applied to measured gravity data to nullify the effect of irregular topographic relief in the immediate vicinity of the station of measurement

2.44
transition
linear or exponential variation of a physical property with depth

2.45
transverse resistance
product of the thickness and resistivity of a *geoelectrical layer* (2.15)

2.46
two-electrode (pole-pole) configuration
one current and one potential electrode are kept at infinity (more than ten times the distance between active electrodes) and perpendicular to the profile along which the other two active electrodes are moved

2.47
vibroseis
seismic survey in which a vibrator is used as a non-destructive source, instead of an explosive, to generate controlled frequency seismic waves in the ground

2.48
Wenner configuration
collinear four-electrode configuration of potential and current electrodes in which all the electrodes are equidistant

3 Units of measurement

Table 1 list the parameters and units of measurement in common use.

Table 1 — List of commonly used geophysical techniques and units of measurement

Method	Technique	Physical property involved	Unit for parameters measured
Electrical Resistivity	Sounding	Resistivity	Ohm-m
	Profiling		
Magnetic		Mag. susceptibility	
		Mag. field intensity	NanoTesla
Electromagnetic	VLF	Conductivity/ Resistivity	Inphase/quadrature Component (%)
	HLEM		Secondary/primary magnetic field (%)
	TEM		Current decay, ohm-m, µs
Seismic	Refraction	Wave velocity	m/s
	Reflection (High Res.)	Acoustic Impedance	Ns/m^3 or Pa s/m
Induced polarization		Chargeability	millisecond (ms)
Self-Potential (electro kinetic)		Natural potential	milliVolt (mV)
Mise-a-la-masse	Charged-body	Development of Potential	milliVolt (mV)
Gravity		Density (lateral variation)	milligal (mgal)

4 Purpose of geophysical survey

Geophysical surveys play a vital role in groundwater exploration. Surveys can be used to conduct either shallow subsurface investigation that may be needed for many environmental-related projects or for deeper investigations that may be required to identify productive aquifers. Also, surveys can be used to delineate bedrock topography, estimate the thickness of weathered zones, demarcate fracture geometry, identify the presence of limestone cavities and/or paleo-channels, and to assess quality of groundwater. Furthermore, surveys can be used to assess groundwater contamination and the movement of plumes, define vadose zone characteristics required for waste disposal or artificial recharge projects, demarcate sea water intrusion, differentiate between aquifers and aquitards, monitor the quality and direction of groundwater movement, etc.; geophysical measurements are also used to estimate hydraulic parameters of aquifers.

Geophysical methods can be grouped into two categories: natural field methods and artificial source methods. Commonly used natural field methods include gravity, magnetic, and self-potential methods, which measure variations in the earth's gravity field, magnetization of rocks and earth's natural kinetic potential. Microgravity techniques can detect changes in groundwater storage and identify saturated cavernous limestone features. Artificial source methods measure the response of the subsurface to artificially induced energy like seismic and electromagnetic waves and electrical currents. These methods include electrical resistivity, induced polarization, Very Low Frequency (VLF) electromagnetic, controlled-source electromagnetic, seismic refraction and, occasionally, seismic reflection.

5 Planning

Geophysical surveys need to be carefully planned in order to meet project objectives, particularly for surveys conducted in remote areas or harsh terrains. Planning should include the following.

5.1 General considerations

— Selection of appropriate method

— Effectiveness and accuracy of equipment and power supply

— Easy operation and maintenance

— Ready to use accessories

— Suitability of vehicle for transportation

— Safety of equipment

5.2 Access to the area

— Suitable access to the area/site

— Permission to work in the area

— Physical constraints in the area

— Clearance along profile line(s)

— Noise and cultural disturbances

— Overhead power line

5.3 Equipment

— Maintenance should be performed as required

— Should be stored in a stable, dust free, and dry environment

— Pre-operation checking should be carried out

— Power supply should be checked regularly

— Precautions given for each equipment are to be observed

— Any deterioration in equipment condition should be rectified immediately

5.4 Safety and precautions in operation

A safety code or plan should be developed prior to surveys to account for potential hazards in the field. Common hazards include working with high voltage power lines, in electrical storms, in extremely remote areas, and with explosives. If possible, surveys should be conducted in dry weather periods to avoid damage to equipment by lightening.

Unnecessary use of high voltage input should be avoided and care should be used when working with systems of 100 volts or more, or with systems having 120 mA or more of current. In the event of rain or lightening, the current and potential cable connections should be removed from the instrument and no one should be allowed to touch the terminals. Even at a distance of 5 km to 6 km, lightening can damage the circuit.

In seismic surveys, explosives should be handled by trained personnel and stored safely. Overhead power lines should not be located near the explosive shot hole, which should be dampened by water and covered with a blast blanket. Detonators should be always kept short circuited, even during transportation to the site.

5.5 Planning of survey

Field crews should be informed of operational procedures prior to the survey. Profile lines should be straight and the distances between transmitter and receiver should be accurately determined. Spacing should be repeatedly checked or confirmed. Other considerations are itemized below.

— Crew should not touch the electrodes or the cable until instructed to do so by the operator.

— Movement of the crew near the profile should be restricted and the cable should not be passed through water or near high voltage power lines. Also, the crew should not stand in water with bare feet.

— Data should be plotted at the site so that errors can be removed or readings repeated.

— Electrodes should not be located near lateral inhomogeneities such as boulders in rocky terrain or buried objects such as pipelines or telephone cables.

— Line should be checked regularly irrespective of the applied voltage.

— The charge (explosive) should not be placed in a highly-weathered zone so as not to overlay dissipate the energy.

— For shallow investigations, the depth of weathering should be estimated by special shooting so that charge can be placed below the weathered zone.

— For EM equipment with multiple frequency selections, frequencies should be changed only after switching-off the instrument.

— In magnetic surveys, ferrous objects should not be placed near the sensor.

5.6 Quality control in field data collection

Quality control considerations are a function of the selected equipment and the required level of accuracy. In any case, measurements should be repeated and profile orientations should be checked.

5.7 Site/area details

Investigators should become familiar with the local geologic and hydrogeological characteristics of a targeted site prior to conducting a survey. Characteristics may include, but not be limited to, lineament details, lithostratigraphic information, water-level information, and water-quality information. A well inventory should be conducted to identify sources of pertinent data and information.

Depending on the objectives of the survey, candidate sites for field surveys may be selected on the basis of existing information. Final site selection, however, should be based on a more rigorous study of geomorphic features and geological structures in the field. Local representatives may be consulted to help plan the surveys. Final site selection should be based on geophysical anomaly positions, accessibility, local conditions, and avoiding physical constraints such as electrical lines, metallic structures, crossing of roads, streams, or bridges, and topographic depressions.

6 Electrical resistivity

6.1 Purpose

To identify groundwater potential zones (whether granular or fractured), geometry, variations in the chemical quality of groundwater and the directions of groundwater movement.

6.2 Principles of measurement

The resistivity of soils and rocks is governed primarily by the amount of pore water, its resistivity, and the arrangement of the pores. To the extent that differences of lithology are accompanied by differences of resistivity, resistivity surveys can be useful in detecting bodies of anomalous materials or in estimating the depths of bedrock surfaces. In coarse, granular soils, the groundwater surface is generally marked by an abrupt change in water saturation and thus by a change of resistivity. In fine-grained soils, however, there may be no such resistivity change coinciding with a piezometric surface. Generally, since the resistivity of a soil or rock is controlled primarily by the pore water conditions, there are wide ranges in resistivity for any particular soil or rock type and resistivity values cannot be directly interpreted in terms of soil type or lithology.

Archie's law: An empirical law which relates, for clay-free sediment, the electrical resistivity ρ of a porous rock containing water and cement to the fraction of the pore space that is filled with water. It relates the in-situ electrical conductivity of sedimentary rock to its porosity and brine saturation, as given in Formula (1):

$$C_t = \frac{1}{a} C_w \varphi^m S_w^n \tag{1}$$

where

- a is the tortuosity factor;
- φ is the porosity;
- C_t is the electrical conductivity of the fluid saturated rock;
- C_w is the electrical conductivity of the brine;
- S_w is the brine saturation;
- m is the cementation exponent of the rock (usually in the range 1,8 to 2,0);
- n is the saturation exponent (usually close to 2).

Reformulated for electrical resistivity, the formula reads as given in Formula (2):

$$R_t = \frac{R_w}{\varphi^m S_w^n} \tag{2}$$

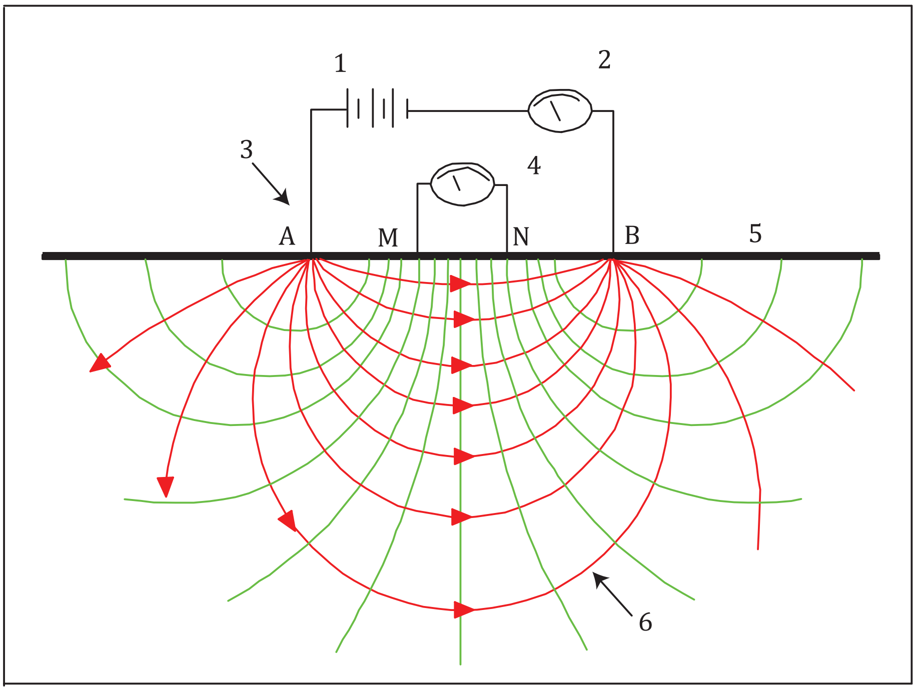
where

- R_t is the fluid saturated rock resistivity;
- R_w is the brine resistivity.

The factor $1/\varphi^m$ is also called **formation factor**.

It is a purely empirical law attempting to describe ion flow (mostly sodium and chlorine) in clean, consolidated sands, with varying intergranular porosity. Electrical conduction is assumed not to be present within the rock grains or in fluids other than water.

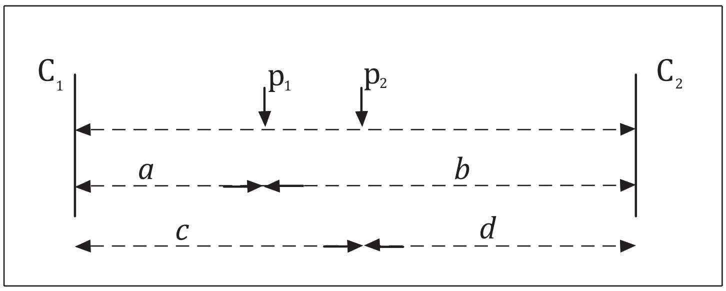
A known amount of electrical current is injected into the ground through a pair of electrodes. The electrical potential developed within the ground due to this current is measured across another pair of electrodes. The distribution of current and equipotential lines in an electrically homogeneous subsurface is shown in Figure 1.



Key

1	current source
2	current meter
3	electrodes
4	volt meter
5	ground source
6	current flow through subsurface
A, B	location of current electrodes
M, N	location of potential electrodes
(red line)	current
(green line)	voltage

Figure 1 — Current from a point source and the resulting equipotential distributions



Key

C_1, C_2 location of current electrodes

p_1, p_2 location of potential electrodes

a distance between current electrode C_1 and potential electrode p_1

b distance between current electrode C_2 and potential electrode p_1

c distance between current electrode C_1 and potential electrode p_2

d distance between current electrode C_2 and potential electrode p_2

Figure 2 — Current and potential inter-electrode distances

The potential difference, *V*, between any pair of electrodes at the ground surface, p_1, p_2, as shown in Figure 2, is then calculated as given in Formula (3):

$$V = \frac{\rho I}{2\pi}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right) \quad (3)$$

where

ρ	is the electrical resistivity of the homogeneous ground;
I	is the electric current with which the ground is energized;
a, b, c and d	are the inter-electrode distances, as shown in Figure 2.

Usually, the current and potential pair of electrodes is placed in a straight line with the potential pair being placed inside the current pair to maintain symmetry with respect to the inter-electrode distances. Conventional electrode configurations commonly used in geoelectrical resistivity surveys with their corresponding geometric factors as shown in Figure 3. In the Wenner array, the electrodes are equally spaced while in Schlumberger array, the potential electrodes are relatively close to one another as compared to the current electrodes. For the Wenner configuration of electrodes, Formula (3) becomes Formula (4):

$$\rho = 2\pi a \frac{V}{I} = KR \quad (4)$$

where

K	is the spatial or geometric factor;
R	is the resistance.

For Schlumberger configuration, it becomes Formula (5):

$$\rho = \frac{\pi}{2} MN \left[\left(\frac{L}{MN}\right)^2 - 1\right] \frac{V}{I} = KR \quad (5)$$

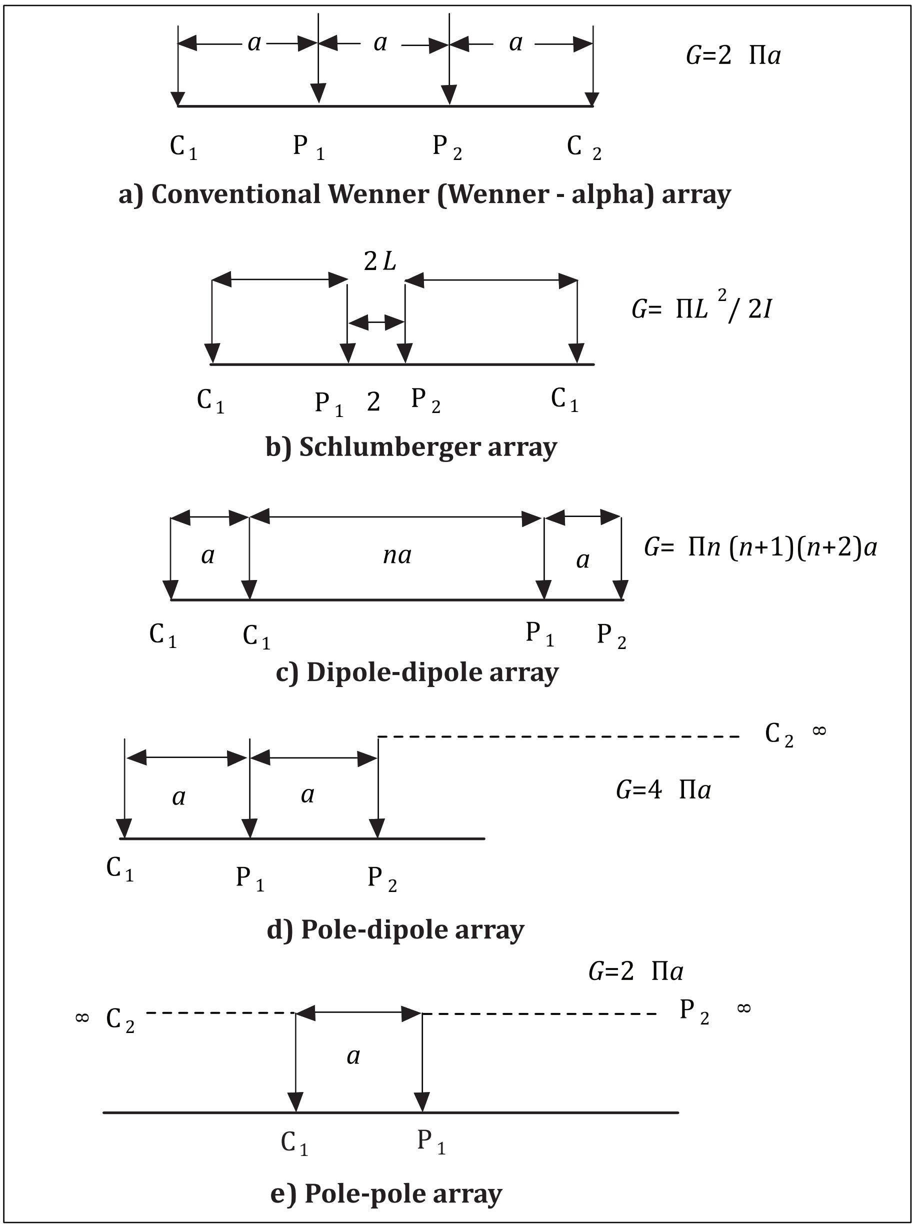
where

MN	is the distance between potential electrodes;
R	is the resistance;
K	is the spatial or geometric factor.

As shown in the above formulae, when the resistance *R* is multiplied by *K* (a constant called the “spacing or geometrical factor” which depends upon the spacing between current and potential electrodes), it gives the value of ρ, the resistivity of the ground. If the ground is homogeneous, the value of ρ gives the true resistivity of the medium or the ground. However, since the earth’s subsurface is generally multilayered, the value of ρ_a provides what is called the ***apparent resistivity*** value. Along with the electrode spacing, the apparent resistivity value is a function of the thicknesses and true resistivities of the individual layers and deducing the true resistivity value of any individual layer is a complex task. In practice, as the separation of the current electrodes is increased, the current penetrates and becomes more focused deeper into the ground. A plot between the current electrode separation and the resultant electrical resistivity value yields a curve known as ***vertical electrical sounding curve*** (VES).

In dipole-dipole configuration, the spacing between current electrode pair and that between potential electrode pair is considerably small in comparison to the distance between these two pairs. As the current and potential electrode pairs are moved further apart, the depth of exploration is progressively increased. The dipole-dipole configuration can be azimuthal, equatorial, radial, parallel, axial and perpendicular. The basic advantage of dipole-dipole array is to get the deeper information even in the areas where there is no straight line space are available. Less wire is needed than for some arrays.

Resistivity imaging is an advanced development of resistivity method for hydrogeological investigations. Enhanced data quality and resolution provide continuous two-dimensional resistivity models. Fifty or more electrodes can be set out in a regularly spaced array, connected to a resistivity meter through multi cables. Unit electrode spacing is determined by parameters such as profile length, desired resolution and targeted depth penetration. The separation between sampled electrodes is then widened to increase the effective depth penetration and the procedure is repeated down to increasing depth range.



Key

C_1, C_2 location of current electrodes

P_1, P_2 location of potential electrodes

a inter electrode distance

na *n* multiples of inter electrode distance

Figure 3 — Different electrode configurations in electrical resistivity surveys

There are two ways of interpreting the VES data. The first involves matching the field curve with master curves that have been prepared for multi-layered system with different combinations of resistivity and thickness. The second method is computer aided inversion where the VES curve is calculated for an initial "best guess" model of the system and then adjusted by successive iterations to match the observed field data. The matched model curve is assumed representative of a subsurface with the same layering and resistivity as indicated in master curve.

In resistivity profiling, an electrode array (the symmetric Wenner array is generally preferred) is moved in a line from one point to another to record variations in resistivity along a profile. The technique is helpful in locating lateral inhomogeneities owing to the presence of resistive or conductive bodies such as dykes, fractures, saline water bodies, etc. Significant resistivity contrasts occur between dry and water-saturated formations, and formations with fresh and brackish or saline water. Sands of various grain sizes, clays, weathered and fractured granites and gneisses, sandstones, cavernous limestones, vesicular basalts, etc. all have defined but overlapping ranges of resistivity. The resistivity ranges shown below for different materials are generalized and may vary significantly based on local hydrogeological conditions.

Table 2 — Resistivity of different materials (modified from Reference [22])

Dimensions in ohm-m

Material	Resistivity
Soil	<20 to >100
Dry sand and gravel	>200
Saturated sand and gravel	<50
Clay	5 to 100
Sandstone	50 to 1 000
Shale	5 to 50
Limestone, dolomite	>1 000
Igneous rock	>1 000
Metamorphic rock	>1 000

6.3 Instruments

A resistivity survey is carried out using an instrument known as a resistivity meter. These meters typically employ either a direct current or a very low frequency alternating direct current type of suitable wattage and may also be equipped with noise filters and digital displays of current input and measured voltage. Measurement accuracies for many resistivity meters typically fall within the micro-volt range. Meters with multi-selection constant voltage or constant current input are desired. Required accessories include rugged winches/reels with 200 m to 500 m of insulated single conductor cable, multi-strand thin wires of low electrical resistance, a rechargeable or non-rechargeable direct-current power source, small diameter stainless steel rods/stakes, hammers, non-polarizing electrodes, connectors, hand-held walkie-talkie sets, and surveying equipment.

6.4 Field procedures

There are a variety of electrode configurations used in resistivity surveys. The co-linear, symmetrical quadripole spread of the Schlumberger configuration for sounding and the Wenner configuration for profiling are the most popular. In the Schlumberger configuration, the practice is to move current electrodes outward while keeping the closely spaced potential electrodes fixed at the centre so long as a measurable potential difference is obtained. When the potential difference becomes so small that it cannot be accurately measured, the potential electrodes are expanded, always with the proviso that their separation does not exceed one-fifth that of the current electrode separation. Conventional sounding commences when the potential electrode spacing is equal to one-fifth of the current electrode spacing. Successive spacing of electrodes is usually increased in geometric progression, with each current electrode spacing being 1,414 times the preceding one. As such, there should be equal distribution of six to eight points in each log cycle of double log graph paper used for plotting the apparent resistivity curve. Spacing can be increased by 2 m to 5 m to study minor changes. In Wenner sounding, the potential electrode spacing is set at one-third the current electrode spacing throughout the survey (i.e. all four electrodes are equidistant and moved outward for successive measurements). In hardrock areas, radial soundings (soundings taken at a site along four to eight different directions) may be useful for studying fracture orientation and for correcting depth estimates.

The Schlumberger and Wenner configurations each have advantages. The Schlumberger configuration requires less manpower and cable and, because electrode movement is relatively small, the effects of near surface lateral inhomogeneities on the signal are minimized. Also, shifting of the curve with potential electrode changes is smoothened. The Wenner configuration has the advantage of giving higher potential values because the potential electrodes are equally spaced with the current electrodes.

For sounding curves, apparent resistivity values are plotted against half current electrode separation for the Schlumberger configuration, against inter-electrode spacing for the Wenner configuration, and against the distance between the current and potential dipoles for the dipole-dipole configuration. For radial soundings, polar diagrams are also prepared. In profiling with Wenner/Schlumberger/Dipole-Dipole electrode arrangements, the configuration (of fixed electrode distance) is moved along a straight-line profile taking measurements at fixed spacing's (station intervals). In gradient profiling, current electrodes are planted well apart, e.g. 800 m to 1 200 m, and the central one-third space is scanned by a potential dipole of 10 m to 20 m in length, at a station spacing of 5 m to 10 m. Gradient measurements can also be made along closely spaced (50 m apart) parallel profiles within the central one-third space without changing the positions of the more distant current electrodes.

In profiling, apparent resistivity values are plotted against stations on arithmetic graph paper. The centre of the potential electrode spacing is the point of measurement for the Wenner and gradient configurations. For the dipole-dipole configuration, the point of measurement is between the current and potential dipoles. When attempting to trace a fracture zone, because low resistive readings in a single profile may be erroneous and misleading, profiling should be taken along 2 to 3 parallel profiles located 50 m to 100 m apart. Also, profiling should be accompanied by test soundings to select optimum electrode spacing. At least one profile should be conducted with small electrode spacing (5 m to 10 m) to understand the effects of near-surface resistivity variations on deeper information and to reduce ambiguities. In the Wenner configuration, the effects of near surface inhomogeneities can be reduced by an offset arrangement of electrodes and by taking averages.

Selecting a site for a survey should serve its purpose. In the event that a geophysical anomaly is identified at a point, which is not accessible for drilling, its extension should be identified by observing some parallel profiles. If a site is near a concrete structure like a road, building or bridge, the profile should be laid in such a way that potential electrodes do not fall within 10 m of the structure and are on homogeneous ground. Rock debris and building materials lying in vicinity of the electrodes should be removed.

Locations of the current electrode positions should be identified before starting the survey. Electrode locations are accurately measured from the centre and small pits/holes are made compatible to the size of potential electrode base and moisture condition of soil. In dry soil conditions, sufficient water should be put in pits/holes before placing the electrodes in the ground. Care should be taken to ensure that the electrodes are in proper contact with the ground. Where electrode locations fall on dry, compact soil and sand, sufficient water should be put in the hole by removing the electrode and placing again to minimize contact resistance at the electrode. For small electrode spacing, the electrodes should not be driven more than 4 cm to 5 cm to maintain it as a point electrode. For large spacing, the entire length of the current electrodes can be driven into the ground.

Because minor variations in potential induce noise in the apparent resistivity curve, the potential values should be higher than 5 milliVolts and in no case below 1 milliVolt. Small potential values are generally observed with large electrode spacing for which the "geometric factor" is quite large. In such cases and relatively small inaccuracies with the geometric factor induce relatively large variations in apparent resistivity.

Ideally, the current circuit should not increase path resistance. Therefore, in practice, it should be ensured that cable resistance, as well as contact resistance, is minimum at both of the current electrodes. Contact-resistance can be reduced by driving the current electrodes deeper and by putting saline water in electrode pits. If necessary, additional one or two electrodes could be planted near the current electrode, about a metre apart, and connected in parallel to the main electrode. Alternatively, a sheet of tin foil placed in a watered pit can be a very effective current electrode.

With the Schlumberger array, when potential electrode positions are changed, repeat measurements should be made for at least two of the earlier current electrode positions (with new potential electrode position) for overlapping curve segments. It is necessary to plot data during operation so that the trend of the curve is evident and data points with noise can be repeated and also, the spacing to terminate measurements can be properly chosen (for instance, when bedrock is indicated by a steeply ascending portion of the VES curve). Accuracy of the data depends on the sensitivity of the instrument to measure potential differences, ability to filter out noise by stacking and by displaying the standard deviation of measured values, and by correct measurement of electrode distances and their alignments.

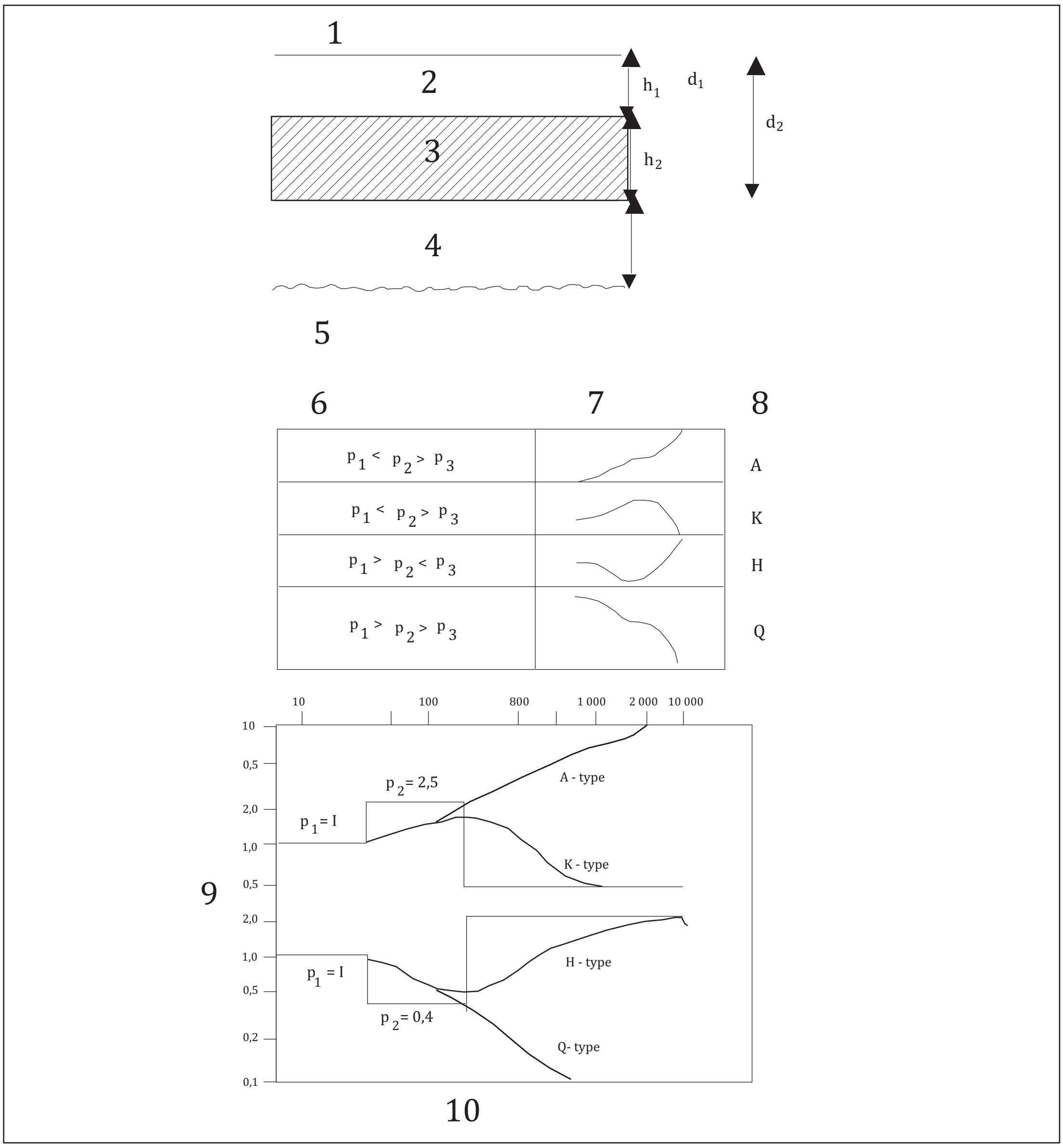
6.5 Processing of data

Sounding curves obtained by the Schlumberger configuration are generally discontinuous with upward or downward shifting of curve segments because of the shifting of potential electrodes. Shifting should be in a prescribed manner if there is no lateral inhomogeneity. Sounding curves can be smoothed by shifting the curve-segments up or down, depending on the type of curve (whether ascending or descending). Conventional shifting of the curve depends on the relative resistivities of the layer sequence. When the potential electrode spacing is increased, the depth of investigation is somewhat reduced, producing a curve that ascends upward and not downward. Difficulties involving the shifting of curve segments can be overcome by observing the trends of nearby soundings. Shifting of curve-segments could also be due to surface inhomogeneities near the potential electrodes.

Surface inhomogeneities near the current electrodes can also be recognized by distortion in the sounding curve. A sharp curvature of the maximum value in the sounding curve is not indicative of a resistive layer of regional extent, but rather a lateral surface inhomogeneity. Curves that suddenly rise or fall with changes in the position of the current electrode indicate the presence of a lithological contact. In such areas, other nearby sounding curves can help smooth the distorted curve and identify which current electrode has caused the shifting.

6.6 Interpretation

Qualitative interpretation of sounding curves can be made visually to identify the “type” of curve and to demarcate areas with similar types of curves [e.g. ascending/descending type or H, A, K, or Q type curves for various combinations of multi-layered subsurface resistivity variations (see Figure 4)].



Key

1 ground surface
2 layer I resistivity p_1 thickness h_1
3 layer II resistivity p_2 thickness h_2
4 layer III resistivity p_3 thickness h_3
5 geoelectrical parameters of a three layer model
6 layer resistivity
7 curve shape
8 type
9 apparent resistivity in ohm-m
10 electrode spacing AB/2

Figure 4 — Types of resistivity sounding curves

Quantitative graphical interpretation of resistivity sounding data is based on empirical or semi-empirical methods in which the field curves are smoothened and matched with a variety of 2-layer and 3-layer theoretical master curves along with the auxiliary point charts. This graphical technique involves a sequence of partial curve-matching, where two or more homogeneous and isotropic (assumed) layers are combined in a single anisotropic (introduced) layer, which is equivalent to another fictitious single homogeneous and isotropic layer. Interpreting results from soundings made this way is difficult and to some extent depends on the skill and experience of the interpreter, and on the availability of local geological information.

Development of computer-based inversion techniques has greatly aided investigators in interpreting results. With these techniques, parameters values for targeted layers can be obtained from the iterative adjustment of estimated "guessed" values to match the curves observed in the field. The equivalence and error analysis are done and also some of the layer parameters can be fixed (through borehole information), while inverting. A number of VES from an area can be interpreted simultaneously as "batch interpretation" required for a regional consistency in results. In some of the inversion programs, a guess model is not required. It is advisable to interpret curves by forward modelling, as well as automatic inversion, as the former provides the means to incorporate geological information, while the latter provides unbiased results, as well as an estimate of the error in final parameter values.

Resistivity profiling data are interpreted qualitatively. From gradient profiling data, the ratio of the resistivity 'low' (indicating saturated fracture zone) to the background 'high' is computed and calibrated with borehole results, if available. Similar ratios in the same hydrogeological environment can indicate fracture zones. Besides the ratio of a low anomaly to background value, actual values, as well as the steepness of the anomaly, are also considered for an indication of the depth to the anomaly source. Quantitative interpretation should also include essential parameters available from borehole information. The interpretation is modified with the inflow of drilling data.

6.7 Advantages

The electrical resistivity method is cost-effective and employs non-destructive field techniques. It is effective in assessing the quality of groundwater and therefore can be used to locate the saline/fresh groundwater interface or saline water pockets. Resistivity contrasts associated with presence or absence of groundwater can be used to delineate the geometry of aquifers and zones favourable for groundwater accumulation. This method also provides useful information on lithologic characterization, depth to resistive bedrock, direction of groundwater flow, orientation of fracture zones, and the locations of faults and paleo-channels, as well as cavities in limestone. The method can also be used for specific environmental applications such as delineating the areal extent of groundwater pollution, identifying zones suitable for artificial groundwater recharge, soil salinity mapping, and reclamation of coastal saline aquifers.

6.8 Disadvantages

Overlapping resistivity ranges and a very wide range of resistivity makes it difficult to uniquely characterize groundwater targets by their resistivities unless calibrated locally. Also, the accuracy and resolution of the response decreases with increasing depth and decreasing contrasts in resistivity. Finally, like other methods based on potential theory, is limited in its predictive application.

6.9 Limitations

The presence of very high or very low resistivity surface soils can affect interpretation. While the former increases contact resistance and reduce input current, the latter results in current channelling that mask the response of deeper layers. The resistivity low that may result from the presence of a conductive top soil/overburden may be mistaken for a suitable target. A profile with very small electrode spacing can be performed to identify the topsoil conductivity effect.

Because the response of a resistivity profile is dependent on two parameters, that is, on the geometry and resistivity of the targeted layer, there is no unique solution and a number of equivalent models are found. While conducting soundings on a multi-layered earth, it is observed that the parameters of intermediate layers could be altered to a certain extent, keeping either the ratio of thickness-to-resistivity or the product of thickness and resistivity constant. This would not produce any appreciable/detectable change (within the accuracy of the observation) in the shape of the resistivity sounding curves. This phenomenon is known as equivalence, the effect of which is pronounced if the layers are thin. It cannot be resolved by a single technique but requires the support of independent information for fixing either of the interpreted parameters or by obtaining the same parameters through joint interpretation with other techniques. The response is dependent on the depth and resistivity contrast of the target. Thin layers or layers with less resistivity contrast with the surrounding are suppressed.

In a layered sequence, the interfaces between successive layers having monotonously increasing or decreasing orders of resistivity cannot be distinguished accurately, particularly at greater depths, because of the transitions in resistivity. Dipping layers distort the measurements and produce ambiguities. The presence of inhomogeneities, either at the potential or current electrodes, produces distorted or shifted curves, which can be difficult to interpret. Induction of pseudo-anisotropy due to repetition of resistive and conductive layers results in an error in depth estimation, requiring corrections by calculating the coefficient of anisotropy through transverse resistance and longitudinal conductance (Dar Zarrouk parameters).

7 Self-potential

7.1 Purpose

To obtain information on the direction of natural or induced groundwater movement or seepage and fracture zones or stratigraphic contacts.

7.2 Principles of measurement

Measuring natural self-potential is one of the oldest and simplest methods in geophysics. The natural electrical potential [also known as Self-Potential or Spontaneous Potential (SP)] has two components: electro-kinetic and electrochemical component. The streaming potential component of SP is linked to the flow of groundwater, making its use effective in groundwater exploration. Streaming potentials increase in the direction of groundwater flow and the gradient of anomaly is related to the magnitude of flow. That is, a contour map of equal SP values can reflect the direction and magnitude of groundwater flow. The magnitude of streaming potential is generally low, being of the order of millivolts.

7.3 Instrument

Because the amplitudes of the anomalies produced by the streaming potential can be quite low, a high impedance potentiometer with high impedance more than 40 MΩ or resistivity meter capable of measuring in the millivolt range is required. Also, a micro-processor based stacking utility helps stabilize measurements and reject noise.

7.4 Field procedures

An SP survey is carried out along 20 m to 50 m spaced parallel profile lines or along radial lines originating from a borehole in eight to twelve directions. Station intervals can be kept at 2 m to 10 m, depending on the objective of the survey. Non-polarizing electrodes should be used. If not available, water-filled electrode pits can be constructed in advance of the survey so that potentials are stabilized. If possible, inhomogeneities located near the potential electrode should be removed while making the pits, or the pits should be constructed at an adequate distance away from inhomogeneities. While taking measurements, the presence of inhomogeneities should be recorded. The electrodes should be firmly placed into the pit. If porous pot-type potential electrodes are used, they should be kept connected in a tub containing a copper sulphate solution for 8 h to 12 h prior to their use in order to minimize potential differences due to the electrodes themselves.

There are two techniques used in SP field measurements: the total field measurement technique and the gradient or “leap-frog” measurement technique. In the total field measurement technique, one of the potential electrodes is kept fixed as a base or “reference electrode” at a site geologically suitable (i.e. without much variation in potential), while the other electrode is moved along the profile lines. If the reference electrode is shifted, a new reference electrode is tied in with the previous one and measurements are overlapped. In the gradient measurement technique, both electrodes are moved along profiles lines with a fixed separation. The distance between the electrodes is kept very small. The total field measurement technique is preferred, as it gives large values of potential difference and the error associated with electrode polarization is less in comparison to that in the gradient configuration. All measurements should be completed in the minimum time possible to avoid drift due to polarization.

To study the direction of groundwater movement induced by pumping, measurements are usually taken around the well before pumping and then repeated after pumping for a reasonable duration, after switching-off the pump.

7.5 Processing of data

In the total field measurement technique, the data are reduced to a common datum point and corrected for drift. Polarization effects are reduced by linearly interpolating between the measurements. Corrected data can be plotted as profiles or as iso-potential contour maps.

7.6 Interpretation

Interpretation of SP data can be complicated by a number of factors, including noise, which may distort the streaming potential anomaly. Also, the order of magnitude of the noise may be same as that of the anomaly (±5 milliVolts to 10 milliVolts). Qualitative interpretation is done by studying the amplitude and wavelength of the anomaly and then matching the anomaly with patterns for known source geometries. Smooth anomalies with longer wavelengths indicate a deeper source mechanism. Shorter wavelengths and higher amplitudes indicate a shallower source. Vertical lithologic contacts or structural discontinuities give steep, asymmetrical anomalies with an amplitude dependent on the resistivity ratio. Streaming potentials are reduced with increasing clay content. Interpretation of SP profile data is often facilitated by comparison with geoelectrical and/or geological sections and topographic profiles.

7.7 Advantages

Self-potential is a relatively inexpensive method for obtaining useful information on the lateral, as well as the vertical movement of groundwater flow or seepage. In areas of contaminated groundwater, flow induced by pumping can be traced to plan preventive measures. The method is also useful for locating shallow water-filled cavities in limestones with appreciable groundwater flow.

7.8 Disadvantages

Interpretation of results may be difficult because SP anomalies are often complex and of low amplitude.

7.9 Limitations

In long profile lines, SP anomalies are affected by telluric current variations which may be of much higher order. Also, SP anomalies are affected by magnetic storms and may yield erroneous anomalies on sloping ground. The presence of near surface inhomogeneities, conductive overburden, variations in soil moisture, electrochemical effects, conductive/ resistive bodies in the subsurface, overhead power lines, and corroded pipe lines will obscure the anomalies due to the streaming potential. Measurements are also affected by the location of the reference electrode and the watering of electrodes during measurement. Another major drawback of the self-potential method is that it cannot detect the presence of multiple, stacked aquifers. It is only useful for the uppermost aquifer and the effective depth of investigation is perhaps 100 m. At greater depths of investigation, self-potential anomalies, which are usually small and contain noise, become too diffuse to interpret.

8 Frequency domain electromagnetic (horizontal loop)

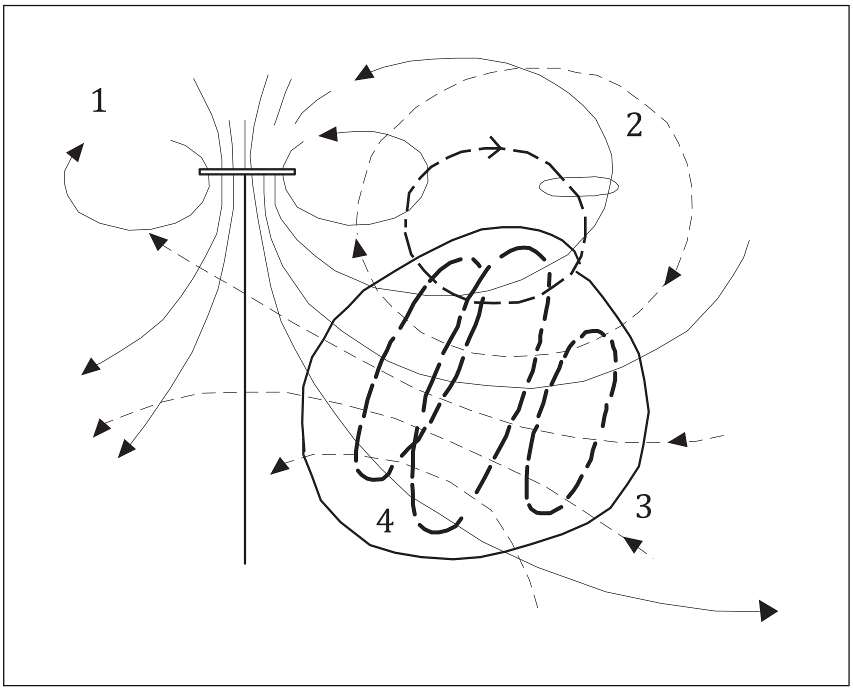
8.1 Purpose

To delineate saturated fracture zones in hard rocks and to estimate the thickness of weathered zones.

8.2 Principles of measurement

In conventional electromagnetic (EM) surveys, a transmitter radiates electromagnetic waves (primary field) that penetrate the ground. When the primary field encounters a conductor, that is, a body of limited extensions with an electrical conductivity higher than its surroundings, eddy currents are produced in the conductor. A secondary electromagnetic field (in a direction opposite to the primary field at the conductor) is produced by the eddy currents and the resultant field is measured by a receiver, placed at a given distance, in the form of in-phase and quadrature components (Figure 5). The receiver also measures the primary field. The resultant field is either measured as a percentage of the primary field or its direction relative to the vertical is recorded. The magnitude, direction and phase angle (which is the time delay of the resultant field in relation to the primary field) of the resultant field can be used to locate a conductive body and obtain its parameters.

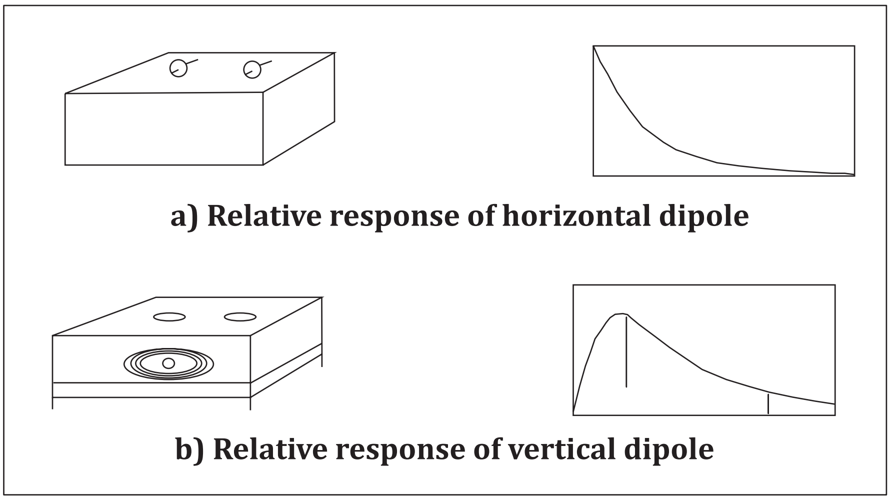
There are several ways to conduct EM surveys by varying the position and orientation of receiver and transmitter loops, viz., vertical loop, horizontal loop, Turam, etc. (Figure 6). Overall, in EM exploration, it is generally assumed that there exists a conductivity variation in the subsurface and that the conductive target is located within a non-conducting (resistive) surrounding or that the conductivity of the target is much higher than the surrounds.



Key

1	transmitter
2	receiver
3	conductor
4	eddy currents
—	primary field
---	secondary field

Figure 5 — Principles of electromagnetic induction in ground conductivity measurements



a) Relative response of horizontal dipole

b) Relative response of vertical dipole

Figure 6 — Relative response of horizontal and vertical dipole coil orientations

The EM method has advantages over the resistivity method in that the latter has difficulties in sending a current through a highly resistive surface layer, such as those often found in deserts or in hard rock terrains. Also, the change in penetration depth can be obtained by changing the frequency of the transmitted electromagnetic wave, as well as the transmitter-receiver coil separation. Because anomalies on groundwater targets in hard rocks are frequently caused by conductivity contrasts between the saturated zone and the surrounding dry medium, a higher contrast provides a better response.[68] The electromagnetic method has been used widely in groundwater exploration, occasionally to compliment the resistivity method and help resolve ambiguities in interpretation.

A commonly used technique is the Horizontal Loop Electromagnetic (HLEM) method, also known as the Slingram method. HLEM surveys are controlled-source surveys in which the transmitter can be operated at a number of frequencies and transmitter-receiver coil separations. The transmitter and receiver coils are placed in the same horizontal plane. HLEM profiling with a number of frequencies and transmitter-receiver separations gives a depth-wise distribution of electrical conductivity. That is, a reduction in the frequency of EM waves and/or an increase in the transmitter-receiver separation would provide deeper information. As in resistivity surveys, a conductive overburden of varying thickness can create a problem in quantitative interpretation and in detecting the target. The primary (incoming) field suffers attenuation, etc. and the depth to the target is sometimes over estimated as in the case of the electrical resistivity method.

In-phase and quadrature components of resultant magnetic field expressed as percentage of primary magnetic field are measured. Resultant field is a function of conductivity, frequency and coil separation. Hence, measured values depend on the response parameter $\alpha = \mu\ \sigma\ \omega\ L^2$, where μ is magnetic permeability, σ is ground conductivity, ω is angular frequency and L is transmitter receiver coil separation. In electromagnetic surveys, the term "conductivity" is preferred as response is generally proportional to conductivity.

8.3 Instrument

The instrument is comprised of a transmitter, a receiver, and the console. The transmitter can be operated at a number of frequencies, usually in the range of 100 Hz to 10 000 Hz. The instrument should have the ability to repeat readings. Insulated cables of 50 m, 100 m and 200 m lengths are often used for connecting the transmitter to the receiver.

8.4 Field procedures

HLEM surveys are usually conducted in profiling mode in combination with electrical resistivity surveys. At a minimum, a few resistivity soundings should be conducted in a study area to define the geoelectrical layering prior to detailed HLEM profiling.

Profile lines are oriented perpendicular to the probable strike of the target conductor. Profile lengths should be much longer than the expected lateral extent (geometry) of the anomaly. Station intervals are typically 10 m to 25 m apart, depending on the objective of the investigation and likely target dimensions. Spacings between the transmitter and the receiver should be accurately measured. Transmitter and receiver coils should be placed on the ground horizontally and properly aligned. In practice, the transmitter and receiver coils are moved in unison to successive stations, keeping inter-coil spacing fixed. In-phase and quadrature components of the resultant field are measured at available frequencies. Changes in frequency are indicative of various depths of penetration. Therefore, each station with in-phase and quadrature data measured at four to eight frequencies provide an EM depth sounding. Measured values represent the information obtained from the centre of the transmitter-receiver coil separation. Profiling may be conducted at two or more separations of receiver-transmitter coils.

8.5 Processing of data

Data can be plotted for inphase and quadrature components together or separately for different frequencies. Noise in the data can be eliminated by averaging or visual inspection. Phasor diagrams can be prepared to estimate the layer parameters.

8.6 Interpretations

Interpretation of the target anomaly can be done qualitatively, as well as quantitatively. The width of the anomaly is approximately equal to sum of the thickness of the conductor and the coil separation. Quantitative interpretation includes curve matching with available or generated theoretical models that have been previously developed for various subsurface conductivity distributions, depth-to-thickness ratios, and conductor attitudes.

The presence of conductive overburden increases the amplitude of the anomaly. At higher frequencies, the quadrature component response produces a base level shift and may reverse or become negative. The conductor appears to be buried deeper and more conductive.

Sounding data can be presented as a phasor diagram and interpreted with available sets of such diagrams that have been prepared for various layered earth models. The presence of a conductive surface layer rotates the phasor diagram clockwise.

Using an initial guess model and certain assumptions, the sounding data can be inverted by software to give layer models at each point. Interpretation becomes more useful if some borehole information is available to identify the character of geologic structures producing the response. Depth sounding by changing the transmitter frequency is called `frequency sounding' which measures the target response at various frequencies to image the hydrogeological structures.

8.7 Advantages

EM field operations are fast and cost-effective and can produce voluminous data. The instrument can be operated at a number of frequencies and coil separations for depth wise information. There is no need for ground (galvanic) contact, so no operating problem of current injection or of contact resistance in areas of highly resistive surface layer and also no noise introduced in the data because of near surface inhomogeneities.

The method requires less coil separation for deeper information than do resistivity soundings. As a rule of thumb, penetration depths for HLEM are 1,5 times the transmitter-receiver coil separation distance, compared with a maximum penetration of about one quarter of the current electrode separation required in the Schlumberger resistivity sounding. Consequently, given a favourable subsurface conductivity distribution, deeper information can be obtained in a smaller area. Also, multi-frequency data give deeper information, i.e. depth of penetration is not constrained by coil/electrode spacing as in the resistivity method.

8.8 Disadvantages

Success of the method depends on meaningful interpretation of the data, which in turn depends on the conductivity characteristics of the overburden through which primary field penetrates and returns, introducing two phase lags. That is, the HLEM technique is preferred to detect a conductive target through less conductive overburden, which may not be always available.

For layered earth interpretations, models are highly simplified which may not be the true condition. Detection of deeper layer is difficult. Skin-depth plays a significant role, as depth of exploration depends on relative conductivity of deeper layers.

In phase component is affected by topographic variations and it is always essential to standardize the response of the model through known borehole information in the area.

8.9 Limitations

The problem of equivalence exists. Presence of conductive overburden or surface layer induces phase lag and ambiguity. It is difficult to differentiate anomalies due to overburden variation and those due to variation within the bedrock.

Interpretation of layer model is not very accurate for highly conductive and resistive surface layer, i.e. for the high contrast in conductivities.

9 Transient (time domain) electromagnetic

9.1 Purpose

To delineate aquifer zones in a conductive surrounding and delineate conductive saline groundwater zones.

9.2 Principles of measurement

The transient electromagnetic (TEM) method is related to the frequency domain (continuous wave) electromagnetic methods by the Fourier transform. Instead of making measurement at different frequencies, in TEM methods, the decay of an induced EM field is measured at a number of sampling times. A constant current is passed through the transmitter loop which produces a static primary magnetic field. When the transmitter current is abruptly switched off, the static magnetic field decays and, due to the associated flux changes, currents are induced in conductors in the ground. This current flowing in a horizontal closed path below the transmitter loop produces a secondary magnetic field. The change in amplitude of secondary magnetic field with time induces a voltage in the receiver coil. Response normalized by the primary field is measured at selected time intervals after switching-off the primary field. Because response depends on resistivity of the ground, measurements can yield geoelectrical characteristics of the ground. Immediately after switching off, i.e. at early time stage, induced current is concentrated near the surface of the earth. Since the maximum amplitude of induced current diffuses downward and outward, deeper geoelectrical information can be obtained as time increases, i.e. at later stages. The transient field decays quite fast. The shape of transient curve (voltage decay against square root of time or apparent resistivity against square root of time) does not represent depth wise resistivity variations as it could be assessed from conventional dc apparent resistivity curve. Actually, the depth of exploration is a function of time (and current flowing in the transmitter loop) and does not depend on transmitter-receiver separation.

9.3 Instrument

Transient Electromagnetic system comprises of a receiver and a transmitter loop unit. Transmitter loops of different sizes are used for exploring different depth ranges. TEM instrument uses constant current waveform consisting of equal periods of time-on and time-off. A variety of TEM equipment is available with stacking facility. The TEM measurements are made in a time range of 6 µs to 1 s after switching off the primary current. The latest measurement time is determined by level of noise. For shallow groundwater exploration, measurement up to 10 ms to 30 ms is done.

9.4 Field procedures

The technique can be employed for sounding, as well as profiling. For profiling, a moving transmitter-receiver configuration is used. Three types of transmitter-receiver configurations are employed in TEM soundings, viz., grounded line, central loop and loop-loop configurations. The grounded line configuration is used for deep soundings, while central loop and loop-loop configurations are used in shallower applications. The dimension of the transmitter loop in central loop configuration depends on the depth to be explored and is selected based on field testing.

The transmitter loop dimensions range between about 30 m by 30 m to 500 m by 500 m to explore shallow zones to depths of about 2 500 m. For better resolution at early time, a small loop size is desired. Large loop size at later times provides better signal. A peak current of 2 A could be sent through the loop of 30 m by 30 m for shallow exploration. Higher amperage (20 A) and large loop size is used for deeper exploration. The receiver measurements can start at 6 µs after switching off and therefore shallow zones can be investigated. The latest time could be up to 10 ms to 30 ms depending on the level of noise. The minimum detectable signal ranges from 10 $V/A.m^2$ to 6 $V/A.m^2$ to 10 $V/A.m^2$ to 12 $V/A.m^2$. A group of four to six persons are required as crew.

9.5 Processing of data

The voltage decay against time observed data are converted to apparent resistivity against time data.

9.6 Interpretation

Induced voltage decay curve does not present direct picture of the subsurface geoelectrical condition as in case of electrical resistivity. Data are normalized for transmitter and receiver parameters and converted to apparent resistivity. Apparent resistivity against square root of time is plotted on double log graph paper. Curves are interpreted either by curve matching or by software packages for inversion and forward modeling.

9.7 Advantages

The method is relatively insensitive to lateral variations in resistivity as the induced current flows in rings around the receiver and also transmitter loop size is not changed frequently. Resolution is high in shallow central loop soundings. It has better resolving capability for S (h/ρ) equivalence and can be used with other techniques that respond better to resistive layers (i.e. direct-current electrical sounding) to help resolve ambiguity. Compared to electrical resistivity sounding, smaller area/smaller loop size is required for survey to achieve same order of depth. Thus, it can be conducted easily in confined areas. To probe deeper, transients at later times are recorded. It is highly sensitive to conductivity changes, i.e. a highly conductive layer underlying conductive clay overburden is detected better than a resistive layer.

9.8 Disadvantages

— TEM equipment is quite expensive. The transmitter loop size should be increased to investigate deeper targets.

— A good estimate of first and the last layer may not be possible due to equipment constraints. To get information for near surface layer very early stage time data is required.

— Target of limited lateral extents may not give a good match in inversion (due to 3-D effects).

— Resistive freshwater aquifers underlying thick clay overburden may not get detected.

— If the first layer is quite thick and resistive, the deeper relatively conductive layer may not get detected.

9.9 Limitations

Thin resistive layers cannot be detected. Transient EM noise at later time stage restricts the length of time during which transient can be sampled and thus deeper information cannot be obtained unless transmitter loop size or primary current flow is increased. Transient sounding for deeper exploration requires a large area for loop layout compared with the straight strip required for co-linear electrical resistivity arrays. However, for similar depths of exploration, DC sounding methods sample a much larger volume of ground and the data are therefore more susceptible to inhomogeneities and reduced resolution.

Information on ambient noise at the measurement location is necessary.

Technique may not be useful if resistivity-thickness contrast is comparable with measurement uncertainty.

10 Very low frequency (VLF) electromagnetic

10.1 Purpose

To delineate conductive water bearing fracture zones in resistive hard rock and to determine approximate thickness of overburden.

10.2 Principles of measurement

The VLF method is a type of electromagnetic method in which only the receiver is in control of the operator. Transmitters are fixed stations located at great distances (up to several thousand kilometres) from the survey area. There are several such transmitting stations around the world, which are continuously emitting electromagnetic waves in frequency range of 15 kHz to 30 kHz for navigation purposes. Though the term VLF indicates Very Low Frequency, the technique uses quite a high frequency for geophysical applications.

At large distances from the transmitter, radiated EM waves travel into the ground as plane wave with a horizontal magnetic and electric field and a vertical electric field all mutually perpendicular. These plane waves (primary field) penetrate the earth surface and in case a conductor (relatively conductive saturated fracture zones) is present, eddy currents are created in it. A secondary field with arbitrary orientation is generated due to the current induced. The resultant magnetic and electric fields are not in phase with the primary and so are elliptically polarized. In VLF surveys, secondary fields due to eddy currents are measured by a sensitive receiver.

The technique has directional advantages, as well as limitations. Saturated fracture zones in hard rocks oriented parallel to the radial direction of the transmitter are favourable survey targets.

VLF has good resolving power because of the high frequencies used, but is most effective in detecting shallow fracture zones. The high frequencies used are attenuated rapidly with depth. Also, in the presence of conductive overburden, attenuation increases and the technique becomes ineffective in detecting deeper fracture zones. Thus, VLF response becomes very susceptible to unwarranted near surface inhomogeneities and apparently presents a plethora of anomalies. VLF receivers can measure tilt of the major axis of polarization ellipse and the ratio of minor to major axis (known as ellipticity). VLF receivers can measure in-phase part, which is approximately equal to tilt and the out-of-phase (quadrature or imaginary) part, which is approximately equal to the ellipticity of vertical component of secondary field expressed as a percentage of the horizontal primary field. The electric field normal to the primary magnetic field is measured to obtain apparent resistivities.

10.3 Instrument

Several types of instruments are available at present. Besides instrument, conventional surveying accessories are required to lay out profiles along desired orientations.

10.4 Field procedures

The VLF method is easy to use in the field. A transmitter with a strong and clear signal is selected. Use of multiple transmitting stations is preferred, keeping the orientation of fracture zones in mind, to obtain the optimal response.

Parallel profile lines are laid perpendicular to the direction of transmitting station, i.e. along the direction of primary field.

Profiles are laid 25 m to 100 m apart and station interval is kept at about 10 m. The length of the profile is generally kept large (more than a kilometre) to study the regional trend. Selection of station interval becomes quite significant where anomalies show high rates of curvature.

Operational procedure varies with the type of VLF instrument. In some of the instruments, data are direct, digitally displayed, while in other, they are recorded by obtaining a minimum intensity of sound signal adjusting the instrument in various positions/orientations.

The orientation of the receiver with respect to the transmitter is adjusted by a method given for the instrument selected.

The apparent resistivity of the surface layer can also be measured by some of the instruments, using two sensors connected to instrument and placed on ground about 5 m to 10 m apart at each station along the profile.

The position of the transmitting station with respect to the movement of operator, i.e. to his right or to his left should be noted for interpretation of the “crossovers” of in-phase and quadrature components.

The accuracy of data depends on the signal-to-noise ratio and proper selection of the transmitter with reference to the orientation of the target.

In field operation, repeated readings are required. For instruments in which minimum sound is observed, accuracy may vary with operator skill and experience.

10.5 Processing of data

In-phase and quadrature components are plotted along profile line. Noise in the profile is identified and removed. If data on parallel profiles are available, contour maps can be prepared for in-phase and quadrature components.

10.6 Interpretation

Data can be interpreted qualitatively, as well as quantitatively. Being a reconnaissance survey method, it is mostly used for qualitative assessment. Anomalies are identified and interpretation of depth and lateral extents of targets and their conductivities are assessed. Mostly, the technique is used to demarcate lateral extent of a target.

Anomalies being affected by the presence of thick conductive overburden, assumption and simplifications are required in interpretation. The effect of conductive overburden and conductive host rock surrounding should be studied in detail from the available literature, before making any inference.

Quantitative interpretation is also attempted, in which experience of interpreter plays a significant role. In highly resistive terrain, ratio of in-phase to out-of-phase response is proportional to conductivity of the target. For quantitative interpretation, data can be filtered using the Fraser and Karous-Hjelt filters. The Fraser filter is used for in-phase data which show cross-over response. The Fraser filter turns cross-overs into ‘peaks and troughs’ and reduces sharp noise.

The Karous-Hjelt filter is used to determine the subsurface distribution of current, which is responsible for the measured magnetic field. Current density pseudo-depth sections are obtained for the purpose. Quantitative interpretations can also be attempted for layered earth model.

10.7 Advantages

— VLF survey is fast and economical in field operation and used for reconnaissance in delineating saturated fracture zones in hard rocks. Surveys can be made in areas where surface layer is highly resistive and high contact resistance would be encountered in galvanic resistivity surveys.

— Lateral disposition of conductive zone is delineated accurately.

— It gives fast estimation of surface soil/overburden resistivity.

— Use of higher frequency range enhances resolving power in detecting closely spaced conductivity discontinuities.

— Detectability of target increases in resistive surrounding.

10.8 Disadvantages

— The amplitude (or even the continual presence) of the VLF primary field cannot be always guaranteed at the receiver.

— To get proper response and detection, there is restriction on orientation of the target zones.

— Depth of investigation depends on resistivity of the surrounding media and is drastically reduced if surface layer is highly conductive.

— Instrument is expensive and may not deliver as much information of the subsurface as resistivity method can, except for reconnaissance.

— Because of high frequency used, measurements are highly susceptible to variation in resistivity and thickness of overburden. Most of the anomalies are generated by the variations in overburden alone and can be mistaken for the underlying fracture zones. So, the data profiles are noisy. Data obtained is a function of operational procedure and hence ambiguities are induced.

10.9 Limitations

— Because of high frequency, the fields are attenuated and phase shifted.

— Conductivity resolution is effective over a frequency range.

— Secondary field attenuates fast and skin-depth is small in highly conductive formations.

— In conductive terrain, maximum depth of penetration is half skin-depth for the medium surrounding the target or overlying it.

11 Seismic refraction

11.1 Purpose

Seismic refraction investigates the subsurface by generating arrival time and offset distance information to determine the path and velocity of the elastic disturbance in the ground. Refraction seismic technique is quite useful to map areas suitable for existence of potential aquifers. It is used to determine thickness and differentiate compactness of sediments, subsurface layering, delineate weathered zone thickness, bedrock topography, identify fracture zones and paleo-channels. Sometimes, the technique is very effective in differentiating saturated and un-saturated zones.

11.2 Principles of measurement

Seismic vibrations (waves) are created artificially on the surface of the earth either by explosives (high energy), impact at the ground surface either by heavy and accelerated weight drop (medium energy) or by hammer. (low energy). Induced vibrations radiate spherically in all directions and their arrival at different distances at the surface of the earth are detected by sensors, planted on the ground, known as Geophones. The responses of the geophones are recorded using multi-channel seismographs to time the arrival of seismic waves, originating at the shot point, where the vibrations are created to the geophones planted at different distances. The greater the rigidity and compactness of the medium, the higher the velocity.

In sedimentary or loose alluvial formations, the velocity of seismic wave propagation increases as the medium becomes saturated with water. Similarly, seismic wave velocity in weathered rock is less than intact unweathered rocks. Of the various seismic waves, compression waves (also known as the primary or P wave) move fastest and are the first to be detected. Thus, in refraction seismic work conducted for groundwater exploration, propagation of the P wave through different subsurface layers is of primary interest.

The subsurface consists of different layers and is not homogeneous. The compactness of the layers generally increases with depth and as a result, the deeper layers are expected to have seismic wave velocity greater than that in the overlying material. This condition, which is necessary for the refraction method to be successfully applied, creates refraction of the down moving seismic wave, incident to the interface of the two layers at a particular angle, called critical angle. At the interface, the refracted wave, sometimes called the head wave, moves with velocity of the deeper layer. As a result, after some distance between the source and the receiving geophones, the refracted wave overtakes the direct wave and is first to reach the geophone detector.

Snell's law is highly relevant to the seismic refraction method. Here, we assume that seismic wave propagation can be approximated by rays oriented perpendicular to the wave front. If an incident ray enters the first medium with P wave velocity V1 at an angle α with the vertical and emerges as refracted wave in the second medium with P wave velocity as V2 at an angle β with the vertical (Figure 7), it can be shown based on simple principle of optics that

$$\frac{\sin\alpha}{\sin\beta} = \frac{V_1}{V_2} \tag{6}$$

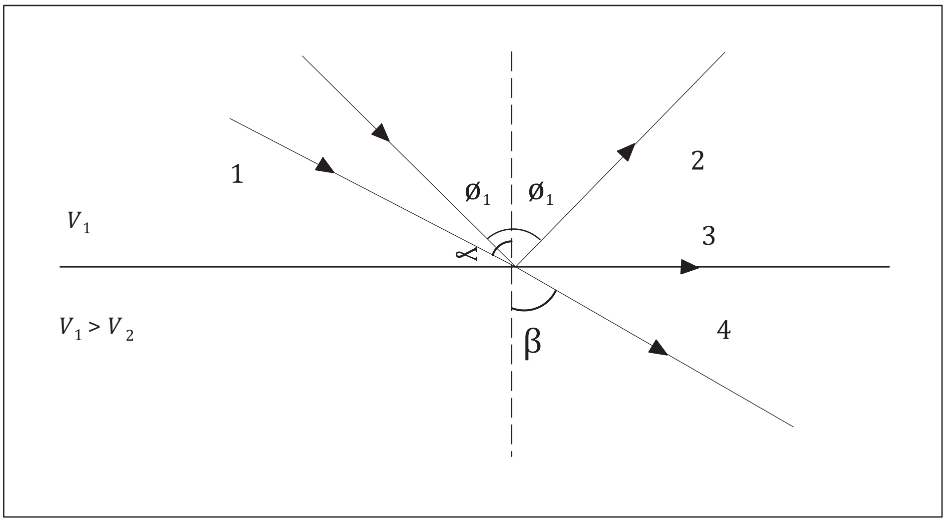
When angle α and the velocity contrast between two media, that is, difference between V1 and V2 becomes such that angle β becomes 90 degrees, the above formula simplifies to Formula (7) or Formula (8):

$$\frac{\sin\alpha}{\sin 90^\circ} = \frac{V_1}{V_2} \tag{7}$$

$$\sin\alpha = \frac{V_1}{V_2} \tag{8}$$

NOTE Necessary condition for critical refraction is $V_1 < V_2$.

At the critical angle (α), when total refraction occurs as the refracted wave grazes the interface, every point of the interface becomes active and, according to Huygens Principle, acts as a secondary source to generate waves that are transmitted back to the first medium as head wave.

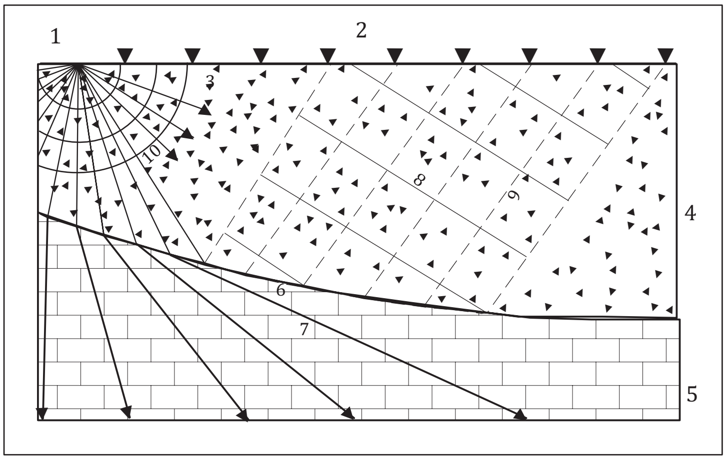


Key

1 incident ray
2 reflected ray
3 critically refracted
4 refracted ray

Figure 7 — Relation between the angle of incident ray (*i*) and angle of refracted ray (*r*)

In seismic refraction technique, head wave propagation and detection at the ground surface are of main concern. The principle as explained is illustrated in Figure 8.

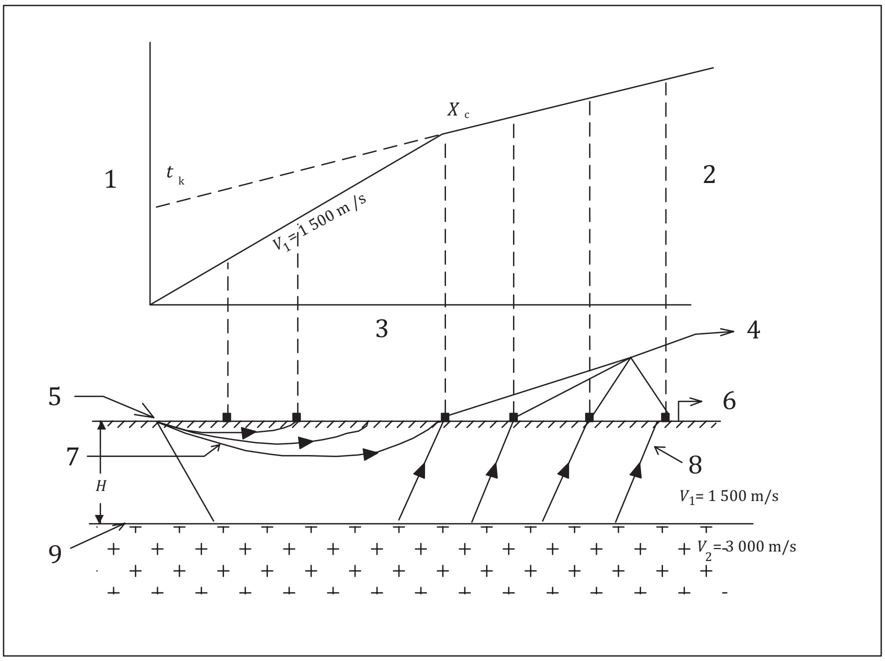


Key

1 shot point
2 geophones
3 direct wave and ground roll raypath
4 overburden
5 bedrock
6 critical refracted ray
7 refracted ray
8 hard wavefront
9 refracted ray
10 wave front

Figure 8 — Seismic refraction geometry

The wave front analysis is the best way to understand the refraction phenomenon and an illustration is shown below to appreciate Huygen's principle for the generation of head wave. A schematic presentation of refraction seismic survey and plot of travel-time curve is shown in Figure 9.



Key

1 time of first arrival
2 travel-time graph
3 shot-detector distance
4 geophones
5 shot point
6 ground surface
7 direct wave
8 refracted wave path
9 interface

Figure 9 — Seismic refraction survey and travel-time curve

Plot of time of arrival of P wave versus shot-detector distance makes it possible to determine P wave velocity in different layers (medium) and either from the value of t_{ic} or X_c, depth to interface or thickness of first layer can be determined with following formulae.

The calculation of depth to the refractor from the intercept time is given by Formula (9):

$$H = \frac{t_{ic}}{2\sqrt{\frac{1}{V_1^2} - \frac{1}{V_2^2}}} \qquad (9)$$

Values of compressional wave velocity indicate the compactness, degree of water saturation in layers, degree of weathering and fracturing in rocks, etc. The depth to different subsurface layers and seismic velocities in them (multi-layered system) can be calculated in the same way as indicated above for two layered earth. There are simple mathematical derivations with which dip of different layers can also be calculated. Reciprocal time method techniques have been adopted by various authors based on time distance discrete analysis techniques to find out depth of interface at different detector points and these are highly relevant to accurately decipher discontinuity in the refractor interface, like presence of fractures, faults, etc. Approximate plus-minus technique in refraction survey, based on wave front techniques are also especially effective in mapping interface discontinuities, especially in solving hidden layer problems.

Finally, a tentative range of seismic P wave velocities in various lithologies is shown in Table 3.

Table 3 — Range of seismic P wave velocities

Sl. No.	Formation	P wave velocity	Velocity range				
			100 to 500	500 to 1 000	1 000 to 2 500	2 500 to 5 000	>5 000
1	Loose alluvial sedime nts (dry/partially saturated)	300 to 800					
2	Loose and saturated alluvial sediments	1 200 to 1 500					
3	Sandstone	1 500 to 3 000					
4	Quartzitic sandstone	3 000 to 5 000					
5	Limestone	3 000 to 6 000					
6	Cavernous limestone	2 000 to 3 500					
7	Deeply weathe red rock (granite/khondalite/charnockites)	1 000 to 2 000					
8	Partially fractured granite	2 000 to 3 500					
9	Compact granite/gneiss	4 500 to 6 500					
10	Charnockites	3 000 to 4 500					
11	Khondalites	2 000 to 3 000					

11.3 Instruments

A seismic data acquisition system comprises a seismic energy source, geophones, and a seismograph for amplification, filtering and recording of seismic waves. For seismic refraction surveys, geophones of natural frequency of about 10 Hz are used. Typically, 12 to 24 geophone channels are employed to study several hundred metres of depth. The seismic sources are explosives, weight drops, and hammers. The hammer and weight drop are used for shallow exploration.

11.4 Field procedure

Surveys are carried out along straight profiles laid by surveying. In refraction surveys, total length of profile will be much greater (generally, three to five times) than the depth to be investigated. A series of 12 or 24 geophones are planted at regular interval along the profile.

The equal spacing up to 10 m between the geophones is kept for shallow investigation and 30 m to 50 m for investigating depth of 300 m to 400 m. Surveys are to be carried out in the areas of minimum cultural noise and vibrations or during the period when the noise becomes minimum, e.g. during nights in the urban areas. Surveys are to be avoided along roads with traffic, railway lines and during high winds, etc.

Profiles are shot from both the ends to ascertain the dip of the interfaces and for reciprocal time information.

11.5 Processing of data

Differences in elevation of shot point and geophone is corrected by bringing them to a common datum by subtracting or adding the travel time, if the velocity is known. The presence of near surface low velocity layers of varying thickness will produce an apparent variation in the depth to the underlying interface.

11.6 Interpretation

A preliminary interpretation is done in the field after a shot is fired. There are a number of quantitative interpretation methods, out of which the intercept time method and plus-minus methods are commonly applied. The intercept-time method is based on Snell's law. Travel time curves available for the shots from both ends of the profile are analysed to check the reliability and dip of the layers. The plus-minus method of Hagedoorn is an approximate method but fast and simple, based on the reconstruction of wave front. The intercept-time and plus-minus methods can be combined for practical solutions. The detailed literatures on all the quantitative interpretation methods are available. Advanced computer software like Seisrefa or Q Seis, are available to directly process digitized data obtained from seismographs. Very sophisticated seismographs with digital record facilities are available where various kinds of signal processing techniques are available which earlier was not possible with analog recorders.

11.7 Advantages

A stratigraphic sequence could be established if the stratigraphic breaks are associated with velocity contrast. Accurate depth can be estimated as a support to electrical resistivity interpretations. It has better resolution in vertical section. Bedrock topography and fracture zones can be deciphered with reasonable accuracy.

11.8 Disadvantages

Field operations are complex and cannot be conducted in seismically noisy areas or urban environments. Use of explosives limits its general application. Also, the overall cost of surveys (equipment, field operation, field arrangements and explosive, etc.) sometimes prohibits its application for groundwater exploration.

11.9 Limitations

The physical assumptions made are highly simplified. The effect of lateral seismic velocity changes within a layer can result in an overestimation or underestimation of depth. Also, anisotropy in seismic velocity can induce refractor depth errors.

Presence of "low velocity layer" (the blind zone) contradicts the necessary assumption for seismic refraction. It can cause overestimation of depth to the layers underlying the low velocity layer. Presence of 'thin layer' (thin with respect to its depth of occurrence) induces error in depth estimation. However, both of these conditions may be detected and compensated for in some of modern method of interpretation like Palmer's Generalized Reciprocal Method. The presence of dipping layers and their effect will induce error in estimation of velocity and therefore profiles are shot from both the ends for correction.

12 Seismic reflection

12.1 Purpose

To delineate subsurface layering, channels and thin layers, geological structures and bedrock topography, etc.

12.2 Principles of measurement

Seismic reflection in its simplest form uses a near surface source to generate seismic wave which travels through the subsurface formations and get reflected at interfaces (reflectors) having a density-velocity contrast. The velocity of seismic wave and the time taken to reach the reflector and return to the surface yield the depth to the reflector after putting some corrections to the data. In seismic reflection, for an angle of incidence less than the critical angle, the seismic ray is reflected back towards the ground surface and is received by a large number of receivers or detectors known as geophones.

12.3 Instrument

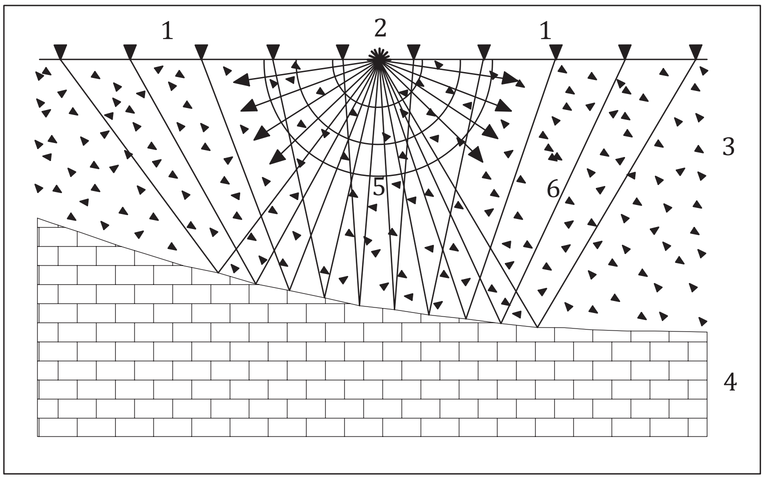
A variety of seismic reflection equipment is available for measurements in standard frequency range. For high frequency-high resolution seismics, special types of equipment and receivers are used. Several types of energy sources are available, viz., explosive, vibroseis, weight dropping, etc. For explosive source, a shot hole is required to place it below the water table. Best quality of data is obtained by it. Vibroseis generates vibrations in an oscillatory manner for a small duration instead of impulsive one. Weight dropping is a low energy and less expensive source. Non-explosive sources are useful in populated area.

Receivers, also known as geophones, convert ground motion into electrical signal. The signal from each geophone station is amplified and passed through cable to the instrument. For high resolution surveys, high frequency geophones are used.

12.4 Field procedures

The geophones are planted in the ground along profiles at regular interval and are connected by cable to the instrument. The layout of geophones is also known as spread. There are a variety of geophone geometry or spreads, viz., off-end, centre-spread asymmetrical, broad side and crooked, depending on relative positions of the source and the geophone-spread. The spread geometry is decided on the basis of depth to be explored. Spread-geometry for deeper information cannot yield shallow level information. The distance between two adjacent geophone stations depends on the seismic wave length and for the best removal of surface wave. This is determined by conducting test measurements.

Prior to detailed survey, a reconnaissance spread is laid to orient the field lay out. Information already available from other survey results may be useful in this regard. Accordingly, the spacing between two spreads is to be decided. An array of geophones for common-depth-point shooting or multiple coverage is used to cancel the noise. The optimum depth for placing the explosive source may be obtained by test measurements with varying depth of the source. The Seismic Reflection principle as explained is illustrated in Figure 10.



Key

1 geophones
2 shot point
3 overburden
4 bedrock
5 wave front
6 reflected ray

Figure 10 — Seismic reflection geometry

12.5 Acquisition and processing of data

Acquisition of seismic reflection data requires experience and skill. It involves a number of steps including amplification and filtering. Data processing is done to improve the quality of data, i.e. to enhance the signal to noise ratio. Software is available to process the data in a sequence. Processing parameters include resampling, filtering, determination of field statics, stacking, deconvolution and migration, etc. The end product is a seismic time-section.

12.6 Interpretation

Interpretation involves velocity determination and time to depth conversion and identification of reflectors. Useful interpretation of seismic-time section includes identification of litho-facies, structures and inferences on hydrogeological conditions. Deducing hydrogeological inferences and stratigraphic boundaries from seismo-geological depth section needs integration with geological information and depositional environment of the sediments. Computer software are available for interpretation of data.

12.7 Advantages

It is most accurate method to determine depth to the lithological interfaces and locate geological structures accurately. Thin layers can be detected by high resolution seismics.

12.8 Disadvantages

Field operation and processing of data are highly expensive. A large number of crew is required for the surveys. It needs a great deal of planning and local/legal clearance. In using source as weight dropping, a high level of noise is generated. Inappropriate selection of processing parameter may give wrong information. Though seismic reflection techniques have better accuracy and resolving power, because of high cost of seismic equipment and field operation, they do not enjoy wide applications in groundwater exploration.

12.9 Limitations

It cannot usually be operated in areas where noise, cultural disturbance or wind velocity is high. During field operation, weather should be good and wind velocity should be low. In high-resolution seismic reflection surveys, i.e. high frequency surveys to identify thin layers the weathered layer (overburden) of varying thickness attenuates the amplitude, and for this source, as well as the receivers are to be buried. Complexities in velocity distribution may indicate structures incorrectly.

12.10 Comparison of seismic refraction and reflection methods

The differences between seismic refraction and reflection are summarized in Table 4.

Table 4 — Seismic method comparison

	Refraction	Reflection
Typical targets	Near-horizontal density contrasts at depths less than ~100 feet	Horizontal to dipping density contrasts and laterally restricted targets such as cavities or tunnels at depths greater than ~50 feet
Required site conditions	Accessible dimensions greater than ~5× the depth of interest; unpaved greatly preferred	None
Vertical resolution	10 % to 20 % of depth	5 % to 10 % of depth
Lateral resolution	~1/2 the geophone spacing	~1/2 the geophone spacing
Effective practical survey depth	1/5 to 1/4 the maximum shot-geophone separation	>50 feet

Note that in situations where both could be applied, seismic reflection generally has better resolution, but is considerably more expensive. In those situations, the choice between seismic reflection and refraction becomes an economic decision. In other cases (e.g. very deep/small targets), only reflection can be expected to work. In still other cases, where boreholes or wells are accessible, neither refraction nor reflection may be recommended in favour of seismic tomography.

13 Magnetic

13.1 Purpose

To delineate subsurface structural features associated with contrasting magnetic susceptibilities, viz., basic dykes, quartz reefs, shear zones, etc. in hard rocks that may contain useful supplies of groundwater or influence its flow. Also, it is employed for regional reconnaissance to narrow down the zone of interest, reducing the cost of labour associated with intensive detailed geophysical surveys. Magnetic surveys may also reveal shallow paleo-channels that can form useful aquifers.

13.2 Principles of measurement

Variation in the magnetic susceptibility of rocks causes variation in magnetic field intensity. Measurement is made of local variations in the Earth's magnetic field intensity, direction and gradient (the magnetic anomalies) caused by lateral variation in magnetic susceptibility of subsurface formation having magnetic mineral of different amount and nature. Measurement of magnetic field intensity along profiles is primarily a reconnaissance method. Unit of magnetic field intensity used in magnetic survey is nanotesla (nT) or Gamma. Intensity of the Earth's magnetic field ranges from about 25 000 nT at the magnetic equator to 65 000 nT at poles.

Rocks containing varying quantities of ferromagnetic minerals may acquire both induced and permanent (remnant) magnetization. The intensity of magnetization is the resultant of these two components.

Magnetic anomalies depend on the magnetic properties and geometry of the causative body and the intensity and direction of Earth's magnetic field at the point of measurement. Anomaly amplitudes range from as low as a few nT to thousands of nT. The geometry (wavelengths) of anomalies can range from a few metres to hundreds of metres. In groundwater exploration, mostly local anomalies are of interest.

13.3 Instrument

The proton precession magnetometer is the most widely used instrument to measure the total magnetic field at 1 nT accuracy. It is lightweight and portable, consisting of a sensor and a console (Figure 11). It provides measurements in five-digit or six-digit digital display. Instrument should have repeatability of readings. The instrument should be capable of making repeated measurements. It should have multiple non-ferrous stands capable of holding the sensor at different heights. A total field intensity map for approximation of regional value should be available.

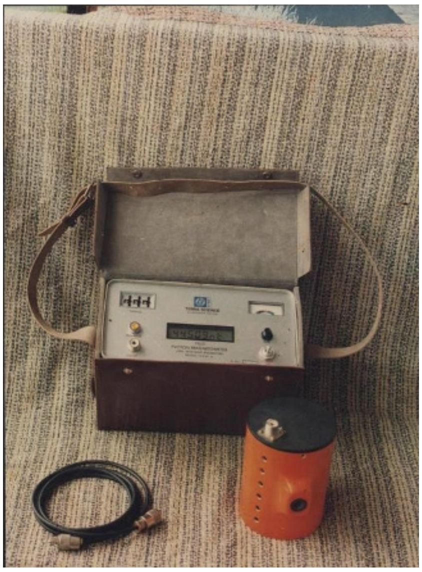


Figure 11 — Proton precession magnetometer

13.4 Field procedures

The magnetic method is a relatively straightforward and inexpensive field-operation geophysical survey for groundwater exploration. It is conducted mostly for reconnaissance and to support other methods, involving minimum time and money.

Values of total magnetic field intensity are not measured at isolated spots but are measured along selected profile line(s) at regular station intervals for a meaningful interpretation of variations in the field intensity.

Profile spacing and orientation, and measurement interval are based on the objectives of the survey, the size and depth of the body or anticipated size and amplitude of the anomaly, and availability of space. The closer the spacing, the greater the chance of detecting anomalies and accuracy in interpretation. Spacing and interval should be such that anomaly is not lost.

The reconnaissance survey may be conducted at large profile spacings and station intervals, while detailing should be done at finer resolution. In groundwater surveys, profiles should be conducted approximately 100 m to 200 m apart, while and station intervals should be 10 m to 50 m. Profile lengths should be approximately 500 m to 1 km.

Profiles should be run perpendicular to the geologic strike determined from local geological information.

The base station should be selected in an area of low magnetic gradient where it is unlikely to be disturbed during repeated base station measurements required for correction.

Before starting the survey, a few readings should be taken at a particular station to determine if there is any temporal magnetic disturbance (i.e. magnetic storm). If so, the survey should be delayed until the disturbance has subsided.

The profile should not pass within approximately 100 m of any extraneous sources of magnetism such as buildings, power or telephone lines, buried pipe lines, near standing vehicles, railway tracks, or metallic fencing.

Measurements should be repeated at the selected base station at convenient intervals (possibly every 2 h to 3 h) throughout the survey, depending on the length of the profile and the duration of the survey.

For large-scale surveys where repeat measurements at one base station become cumbersome, more than one base station may be established.

Frequent readings should be taken and recorded. A diurnal variation curve (plot of base readings with time) should be constructed daily and corrections to the readings should be linearly distributed. A diurnal correction will be more effective if the variation is recorded very frequently by another instrument deployed at the base station, as this correction is for external field and nothing to do with the instrument deployed.

Measurements should be made by keeping the sensor at a height of approximately 2 m to 3 m above ground. Measurements made by a sensor located on the ground surface will be full of noise because of the presence of varied material lying near it.

Ideally, some measurements of local rocks should be made with a susceptibility meter to assist in data interpretation.

Accuracy of the data depends on following factors.

Instruments with 1 nT sensitivity will give sufficiently accurate data for groundwater exploration purposes. Repeatability of reading is essential. Orientation of the instrument affects the accuracy of the measurements and the reliable anomaly of interest can be obtained by separating it from ‘near’ surface features.

13.5 Processing of data

Magnetic measurements should be corrected to eliminate external effects not due to the body, and to identify anomalies which may be characteristic of the subsurface formation or body. Such corrections are relatively simple to make.

Corrections made are mainly for (a) diurnal and (b) geomagnetic variations. Diurnal (solar and lunar) variations are caused by ionospheric influences and of periodicity about a day. Diurnal variations are of two types, viz., the “quiet day” smooth, low amplitude (25 nT) regular variation and ‘disturbed day’ rapid, high amplitude (1 000 nT) irregular variation caused by magnetic storms, during which measurements are discontinued.

‘Quiet day’ diurnal variation is corrected and adjusted by recording variation throughout the day at one or two fixed base stations in the survey area, and then correcting all other measured values by interpolating/distributing the variation linearly over them. Closing or loop error in successive base readings of the order of 5 nT to 10 nT is also distributed amongst the readings. A diurnal correction should be made for a chosen reference time.

Geomagnetic variation relates the magnetic field variation with the geographic coordinates of the observation point. For surveys covering a small area, this correction is not required but is essential for interpreting the data.

13.6 Interpretation

Observed (corrected) values are plotted at stations along profile lines on a map and a contour map is prepared, showing lines of equal magnetic field intensity or different profiles of corrected values may be drawn.

Data are interpreted qualitatively in terms of geologic structures and associated lateral extents by visual inspection of the contour trend, the gradient of convergence or divergence, and the shape of the anomaly under consideration.

A tentative geological interpretation for the area is made.

Quantitative interpretation is complex because of the ambiguity, equivalence, and simplifying assumptions inherent in the model.

In case of total field measurements, anomaly component changes with latitude, e.g. horizontal component at equator and vertical component at pole.

Software is available for interpreting the data by iteratively matching the observed anomaly with that calculated for a defined geometric form and attitude.

The closer the body to ground surface, the steeper the gradient of the magnetic anomaly. Uncertainties in the interpretation increase with geometric complexity.

13.7 Advantages

Field survey is economical and coverage is fast. In hard rocks, it is an essential reconnaissance technique to delineate concealed, shallow, geological feature favourable or unfavourable to groundwater occurrences. Approximation of simple geometrical shape and size is possible.

13.8 Disadvantages

An equivalence problem (inverse potential) exists in interpreting results. The anomaly is a complex response of the body that involves several parameters, including a number of assumptions required for interpretation. The method is difficult to apply in urban areas or areas with reinforced concrete structures. Also, no information can be obtained on groundwater quality conditions.

13.9 Limitations

The sensor cannot be operated near power lines. It may not be possible to continue measurements during mid-day and measurements should be discontinued during magnetic storms. Also, the sensor cannot be placed on the ground surface or near ferrous objects.

14 Gravity

14.1 Purpose

To ascertain change in groundwater storage in valley fill aquifers, to locate dry or water filled cavities in limestone, or to map bedrock topography and subsurface structures where sufficient lateral density contrast exists.

14.2 Principles of measurement

The gravity method measures minor variations in the gravitational field of the Earth caused by lateral changes in density of near surface rocks. Like magnetics, the gravity method is also a natural source method (passive) and can be used as a reconnaissance method dealing mainly with the relative variations. The gravity anomaly is expressed in milligal (gal being derived from Galileo) where

1 gal = 1 cm/s^2 or 1 milligal = 10^{-3} gal. The mean value of gravity at the earth's surface is 9,8 m^2/s or 980 gals.

The density of rock typically varies over a range from about 1,5 g/cm^3 to 3,5 g/cm^3. Dry alluvium has a density of about 1,5 g/cm^3 while water-saturated alluvium has a density of about 2 g/cm^3. The density of sandstone and limestone varies from about 2 g/cm^3 to 2,8 g/cm^3, while the density of igneous rock varies from about 2,5 g/cm^3 to 3,3 g/cm^3.

14.3 Instrument

A gravimeter is used to measure the relative variations in rock densities. Basically, it is an extremely sensitive balance. The instrument is lightweight and transportable. Instruments with an accuracy of 1 micro gal are available for microgravity measurements.

14.4 Field procedure

The manner in which gravity survey stations are laid out and spaced depends on the type of investigation. Surveys can be conducted along a series of profile lines across the expected strike direction of subsurface features. Measurements can be made at small station intervals (5 m to 10 m) for more detailed studies such as locating cavities in limestone terrain. Otherwise, it can be conducted at a regular station interval of about 100 m to 500 m. Additional measurement stations can be located in areas having abrupt changes in gradient. In general, the survey can be conducted relatively fast and economically.

The measurement stations are best placed in flat areas without marked irregularity. Gravity base stations are conveniently located. Measurements are closed at the base stations. If required, more than one base station can be established. Topographic elevations of the stations should be accurately measured, a task that can be somewhat time consuming and expensive. Placing of the gravimeter is made by leveling to check its verticality. Times of measurement should be noted.

14.5 Processing of data

A number of corrections are made to deduce the gravity anomaly due to rock density contrast alone. They are instrumental drift, latitude, elevation and terrain corrections. Elevation correction comprises free-air correction and Bouguer correction. Bouguer anomaly is obtained after applying these corrections to the measured gravity values.

14.6 Micro-gravity measurements

Given the refinements achieved in measuring the variation in Earth's gravitational field to the micro gal range, it is possible now to determine changes in groundwater storage in a closed valley fill and to identify subsurface cavities in limestone which may act as a potential groundwater conduit in karstic terrains. The method is becoming widely used in engineering investigations to detect natural and man-made cavities. Time-varying differential micro-gravity is a powerful technique for detecting changes in mass distribution beneath an area, such as change in groundwater storage.

On Earth, the acceleration due to gravity varies between 9,78 ms^{-2} to 9,83 ms^{-2}. These units are much too large and unit gal is preferred to identify structural features and change in subsurface density (an alternative unit in use today is the "gravity unit" which is one-tenth of a milligal). Its unit is 1 gal = 0,01 ms^{-2}. Micro gal is a further reduction of this unit and is defined as 1 micro gal = 10^{-8} ms^{-2}. This unit, which is applied for search of voids, cavities, and changes in groundwater storage, gives anomalies of the range of few tens to hundreds of micro gals.

The microgravity survey technique is a relatively fast, accurate and cost effective geophysical technique for identifying natural cavities in limestone and other (man-made) cavities, and for monitoring changes in groundwater storage in a closed well defined valley. The principle of the technique is to locate areas of contrasting density in the subsurface by collecting surface measurements of the lateral variation in the Earth's gravitational field.

Whether the cavity is man-made or natural, it should have a way in and usually a way out; otherwise, there will be no outlet by which material may be removed. Consequently, the “effective” size of the target is dependent not only on the strict volume of the cavity, but also its connectivity, the secondary effects imposed by the cavity on the surrounding rocks which arise from the genesis of that cavity in its host rock. Literature is available where successful use of micro-gravity surveys has been made for engineering problems, detection of subsurface cavities and ascertain difference in groundwater storage. Presently, a wide scale application of micro gravity surveys are being made in groundwater survey and exploration by USGS in western arid tract of USA in valley fills to ascertain change in groundwater storage.

14.7 Interpretation

In gravity surveys, interest being in local anomalies (residuals) regional effect is eliminated from the Bouguer anomaly. The gravity effect of shallow and localized bodies could be enhanced and isolated from regional trend by a second derivative analysis. Subsurface structures are inferred from maps of Bouguer anomaly contours, residual anomaly, and second vertical derivatives. Gravity anomalies are positive in case of excess mass (i.e. shallow bedrock, anticline, horst or ridges, etc.) while negative anomalies indicate deficit of mass (i.e. deeper bedrock, syncline, graben and cavity in limestones, etc.). The shape of the anomaly manifests the trend of the subsurface geological structure. Gravity interpretation is ambiguous, as an identical anomaly could be obtained for a variety of subsurface bodies located at different depths (the inverse potential problem). When the causative body is shallow, the anomaly is sharp.

The gravity anomaly is interpreted by both indirect and direct methods. The anomaly could be matched and adjusted by iterations with the theoretical one for a model of known density contrast and geometry and depth of burial. Otherwise, the anomaly is interpreted directly to ascertain the shape and depth of the subsurface body. The accuracy and uniqueness of the interpretation depends on a reliable density estimates of the rock and information on geological and hydrogeological conditions. A number of computer programs are available for interpretation.

14.8 Advantages

The gravity survey is a cost effective and fast reconnaissance method. Detailed micro-gravity mapping can precisely locate the cavities in limestone and buried channels. Detailed information on topography is required.

14.9 Disadvantages

Some ambiguity exists in interpreting results due to the equivalence in interpreting the potential field. The resolution is generally poor. Several corrections are required prior to the actual interpretation.

14.10 Limitations

The survey cannot be conducted in areas with cultural disturbances (i.e. vibrations). Precise elevation of measurement stations is essential.

15 Other techniques

15.1 Induced polarization

15.1.1 Purpose

To differentiate conductive clay mixed sand layers from conductive saline water-saturated zones.

15.1.2 Principles of measurement

On connecting two grounded current electrodes to a battery, a voltage between two points on ground can be detected. If the current is switched-off, the voltage does not become zero immediately but takes some time. The residual voltage, also known as "over-voltage", is caused by the "induced polarization" effect. It is mainly concerned with surface polarization of metallic minerals induced by electric current and redistribution of positive and negative ions in the ground. The process of ion redistribution can be classified into two groups: electrode polarization (exploited for metallic mineral exploration) and membrane polarization (useful for groundwater polarization).

Membrane polarization occurs due to the presence of clay particles which partially block the ionic solution path. The surfaces of clay particles are negatively charged, which attracts free positive ions from electrolytes to form a double layer of charge at the surface. A positively charged layer repels other positively charged ions and acts as an impeding membrane. When applying an electrical potential, the positive membrane is disrupted and positively charged ions can pass through while negatively charged carriers accumulate. When the current is switched off, the subsequent redistribution of ions is manifested as a decay of voltage between the two electrodes. That is, the induced polarization effect is mainly the diffusion of ions. In either case, polarization is a surface effect and therefore, the greater the surface area of the mineral particle or clay, the stronger would be the effect. In groundwater exploration, membrane polarization is effective, and silty formations generally show maximum polarization.

Measurements of induced polarization can be made in either the time domain or the frequency domain. The physical property and parameters measured are chargeability, frequency effect, metal conduction factor, and apparent resistivity. The measurements are made for the decaying voltage and for the phase shift between the receiver voltage and transmitter current. In time-domain, the measured quantity at the receiver electrode pair [the chargeability (m)] is the total area under the voltage decay curve. In frequency domain, the change in resistivity at two different frequencies is measured. Frequency effect (f_e) is the difference in apparent resistivities at two frequencies normalized by the higher frequency apparent resistivity. The metal conduction factor is calculated by normalizing the percent frequency effect by the low frequency apparent resistivity.

15.1.3 Instrument

There are two types of instruments: time-domain and frequency domain. In time domain, a square pulse of current is passed through the grounded current electrodes and the decaying voltage is measured between non-polarising potential dipoles at pre-set time intervals during the current-off period. The output voltage is integrated over an interval and divided by the voltage applied to the current electrodes. The amplitude and duration of the pulse are selected in such a way that the voltage has decayed before the reverse pulse is transmitted. The standard cycle time is 8 s with each on-off period as 2 s.

While in frequency domain, the change in resistivity is assessed by measuring the voltage at different frequencies. Modern IP receivers work in both frequency and time domain modes and also provide multi-dipole simultaneous reading facility. Frequency domain IP receivers are designed to measure both amplitude and phase over a broad band of frequency (2^{-14} Hz to 2^{+16} Hz). Instruments are microprocessor based with storage, facilitating fast recording of data, stacking of signals, filtering of noise, and digital display.

15.1.4 Field procedures

For groundwater exploration, an IP sounding, as well as profiling, can be conducted. A variety of electrode configurations can be used in an IP survey. For routine field work, the Schlumberger, Wenner, two-electrode, dipole-dipole, pole-dipole and gradient configurations can be used. While the pole-dipole and dipole-dipole configurations have low electromagnetic coupling, the gradient configuration has high electromagnetic coupling. Gradient array surveys can be conducted relatively quickly. In time domain surveys, two parameters are selected, that is, the time-period for which a transmitter is switched on and off, and the sampling interval of the decay voltage.

15.1.5 Processing of data

Normally, data are plotted at the midpoint of potential electrodes or at the centre point of the electrode configuration. When a dipole-dipole electrode configuration with fixed inter-electrode distance is moved along a profile, the data are plotted for each position of the configuration at the intersection of two lines drawn towards the centre at 45°. This is repeated for each placement of configuration and for increasing separation between the current and potential dipoles.

15.1.6 Interpretation

In saturated sediments, the IP effect is observed only when sands are mixed with some amount of clay. Coarser materials show less effect than finer materials. The effect is particularly prominent in silts while clean sand will not show any IP effect. A large quantity of clay segregation would show less polarization than the same amount of clay if dispersed. Polarization depends on the type of clay (i.e. polarization is more in montmorillonite than kaolinite) but the variation is complex. The membrane polarization of clay decreases with increases in the salinity of water. For sediments saturated with freshwater, membrane polarization can also be correlated with hydraulic conductivity.

Like apparent resistivity sounding curves, IP sounding curves can be interpreted by available theoretical sounding curves. Qualitatively, pure clay will have relatively low resistivities whereas sand will show higher resistivities. High resistivity associated with high chargeability reflects the presence of thick sand layers intercalated with thin clays. For saline water, zone chargeability may increase or decrease depending on the salinity.

15.1.7 Advantages

The Induced Polarization survey for groundwater exploration is generally used to supplement resistivity surveys. When it becomes difficult to identify the conductive clay mixed zones from the conductive saline water zones, i.e. when the contrast is small, IP chargeability measurements help resolve them.

15.1.8 Disadvantages

The IP effect is complex and it is difficult to interpret the lithology or groundwater condition only from IP measurements.

15.1.9 Limitations

A major limitation in the IP survey involves electromagnetic coupling, which is an electromagnetic response between the grounded receiver and transmitter wires used in the survey. The effect becomes prominent at large electrode separation. Also, the effect is significant for low ground resistivity and higher frequencies. It can be mathematically removed by observing the phase shift over three or more frequency decades. A long pulse time combined with measurements at long time delay can be used to reduce electromagnetic coupling effect. Electromagnetic coupling may also be minimized by careful selection of an electrode array.

15.2 Mise-a-la-masse

15.2.1 Purpose

To map on ground surface the extension of a shallow level saturated fracture zone in hard rock which has already been encountered in a borehole.

15.2.2 Principles of measurement

Schlumberger first attempted the mise-à-la-masse (charged body) method in 1920. Only very limited case histories are available for this method.[38][47] In groundwater exploration, when a saturated fracture zone in hard rock or a water-filled cavity in limestone is indicated by surface geophysical methods, a borehole is drilled to tap the fracture zone or cavity. Once the borehole has encountered the fracture zone or cavity, it may be necessary to demarcate its lateral extensions for drilling a few more boreholes into the zone of interest. To make the operation cost effective by avoiding failed boreholes, a technique of mapping is used to electrically charge the fracture/cavity and trace the developed potential on the ground surface. The technique is prevalent in mineral exploration where contrasts in conductivity between mineralized zones and host rock is high. In groundwater exploration, though the contrast in conductivity is usually not great, the technique can be used for lateral demarcation of such fracture zones and cavities occurring at shallower levels.

The overall objective is to map the developed potential distribution on ground surface due to the energization of fracture zone/cavity and thus determine its geometry. In this case, the absolute value of the potential is not significant.

15.2.3 Instrument

Any resistivity meter, preferably one with a multi-selection constant current input can be used to measure the potential. A microprocessor-based stacking facility is preferred to reduce noise.

15.2.4 Field procedures

In this technique, two types of electrode configurations are used, that is, the normal (potential) and the potential gradient. In the normal configuration, one of the potential electrodes is fixed at a large distance. The other potential electrode is moved from one station to another along profile lines. In the potential gradient configuration, the potential difference is measured by a potential dipole with a small spacing. The normal configuration is preferred as in gradient configuration very small potential difference is measured and error is added for both the electrodes. Also, speed of coverage is better in normal configuration.

Proper location of “infinite” or distant current and potential electrodes with local geological considerations is important. The active current electrode is placed against the fracture zone within the borehole. Current input should be sufficient for recording a considerable potential on the surface. Profile lines can be parallel with a spacing of 10 m to 50 m with a station interval of 5 m to 10 m surrounding the well. The profiles could be radial also, diverging out from the well in 8 to 12 directions. The pits or holes for planting the potential electrodes is made in advance and watered to avoid spurious potentials.

15.2.5 Processing of data

If a constant current source is not used, the potential data are normalized to a fixed current input, say 1A. The potential data can also be converted to apparent resistivity data. Data can be taken as profile or contour maps of iso-potential or iso-resistivity.

15.2.6 Interpretation

The potential developed depends on thickness of the fracture zone, its depth of burial, extent, dip, resistivity contrast with the surrounding and presence of conductive overburden. In a normal configuration, the potential profile broadens with increased depth of the fracture zone. That is, a deeper fracture zone may not show up on a potential distribution map. Asymmetry in potential distribution is introduced if the fracture zone is inclined. A dip of fracture zone is better indicated in gradient measurements. Negative peak amplitudes on the up dip side are greater than positive peak amplitudes on the down dip side. Whereas, in normal measurements up dip direction is indicated by steeper slope while down dip side is indicated by gentler slope. The presence of conductive overburden reduces the magnitude of the anomaly while a variation in its thickness would complicate the anomaly. Near surface inhomogeneities would also affect the anomaly. Fracture zones are better defined if these zones have higher conductivity contrasts with the surrounds. In contour maps, elongated contours indicate a trending fracture zone. The axis of the elongated contour with maximum value should be above the fracture zone.

The location of an active current electrode in a borehole (though it cannot be controlled) affects the anomaly pattern. If the current electrode in a dipping fracture zone is located in the upper part of the borehole, the anomaly will be relatively sharp in comparison to that if the electrode were located in the lower part of the borehole.

With this technique, the resolution between two closely spaced fracture zones is poor, i.e. tracing an unconnected fracture zone located close to one being electrically charged in the borehole is difficult. While interpreting, both resistivity and potential data should be studied jointly.

15.2.7 Advantages

It can be fruitfully used to ascertain lateral continuity of a saturated fracture zone or water filled cavity in limestone. The field operation is easy and inexpensive.

15.2.8 Disadvantages

A borehole which has encountered fracture zone is required to conduct the survey. It cannot be conducted in boreholes with pumps running.

15.2.9 Limitations

Deeper zones or zones with little contrast in resistivity with the surrounding will not be picked-up. Location of reference current electrode affects the potential profile seriously. Any other fracture zone in vicinity of the charged fracture zone would affect potential values. Also, near surface inhomogeneities affect the potential values.

15.3 Ground-Penetrating Radar (GPR)

15.3.1 Purpose

The objective of GPR surveys is to map near-surface interfaces. For many surveys, the location of objects such as tanks or pipes in the subsurface is the objective. Dielectric properties of materials are not measured directly. The method is most useful for detecting changes in the geometry of subsurface interfaces, bedrock configuration, location of pipes and tanks, location of the groundwater surface, borrow investigations, and others. Geologic and geophysical objectives determine the specific field parameters and techniques

15.3.2 Principles of measurements

The GPR technique is similar in principle to seismic reflection and sonar techniques. GPR is like taking an x-ray of the ground. Pulse mode GPR systems radiate short pulses of high frequency electromagnetic energy into the ground from a transmitting antenna. The propagation of the radar signal depends on the frequency-dependent electrical properties of the ground. When the radiated energy encounters an inhomogeneity in the electrical properties of the subsurface, part of the incident energy is reflected back to the radar antenna. Reflected signals are amplified, transformed to the audio-frequency range, recorded, processed, and displayed.

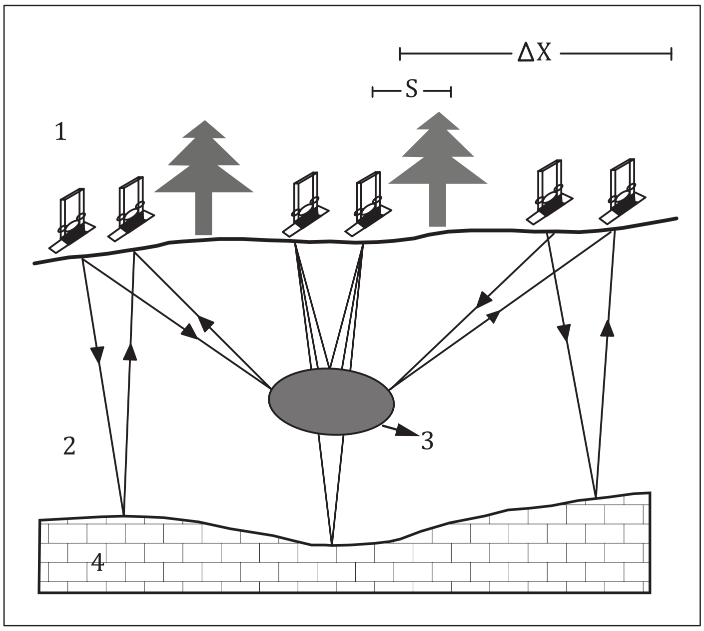
Ground-penetrating radar (GPR) uses a high-frequency (e.g. 40 MHz to 1 500 MHz) EM pulse transmitted from a radar antenna to probe the earth. The transmitted radar pulses are reflected from various interfaces within the ground and this return is detected by the radar receiver. Reflecting interfaces may be soil horizons, the groundwater surface, soil/rock interfaces, man-made objects, or any other interface possessing a contrast in dielectric properties. The dielectric properties of materials correlate with many of the mechanical and geologic parameters of materials. The radar signal is imparted to the ground by an antenna that is in close proximity to the ground. The reflected signals can be detected by the transmitting antenna or by a second, separate receiving antenna. The received signals are processed and displayed on a graphic recorder. As the antenna (or antenna pair) is moved along the surface, the graphic recorder displays results in a cross-section record or radar image of the earth. As GPR has short wavelengths in most earth materials, resolution of interfaces and discrete objects is very good. However, the attenuation of the signals in earth materials is high and depths of penetration seldom exceed 10 m. Clay materials with a high cation exchange capacity increase the attenuation and decreasing penetration.

There are two physical parameters of materials that are important in wave propagation at GPR frequencies. One property is conductivity (σ), the inverse of electrical resistivity (ρ). The relationships of earth material properties to conductivity, measured in mS/m (1/1 000 Ωm), are given in the section on electrical methods. The other physical property of importance at GPR frequencies is the dielectric constant (ε), which is dimensionless. This property is related to how a material reacts to a steady-state electric field; that is, conditions where a potential difference exists but no charge is flowing. Such a condition exists between the plates of a charged capacitor. A vacuum has the lowest ε and the performance of other materials is related to that of a vacuum. Materials made up of polar molecules, such as water, have a high ε. Physically, a great deal of the energy in an EM field is consumed in interaction with the molecules of water or other polarizable materials. Thus, waves propagating through such a material both go slower and are subject to more attenuation.

15.3.3 Field procedures and data acquisition

The useful item of interest recorded by the GPR receiver is the train of reflected pulses. The seismic reflection analogy is appropriate. The two reflection methods used in seismic reflection (common offset and common midpoint) are also used in GPR. The typical mode of operation is the common-offset mode where the receiver and transmitter are maintained at a fixed distance and moved along a line to produce a profile (Figure 12).

Note that as in seismic reflection, the energy does not necessarily propagate only downwards and a reflection will be received from objects off to the side. An added complication with GPR is the fact that some of the energy is radiated into the air and, if reflected off nearby objects like buildings or support vehicles, will appear on the record as arrivals. GPR records can be recorded digitally and reproduced as wiggle trace or variable area record sections. Figure 13 illustrates the presentation used when a graphic recorder is used to record analog data. Both negative and positive excursions in excess of the threshold appear as blackened portions of the record. This presentation is adequate for most tasks where target detection is the object and post-survey processing is not anticipated. Wide variations in the appearance of the record are possible, depending on the gain settings used.



Key

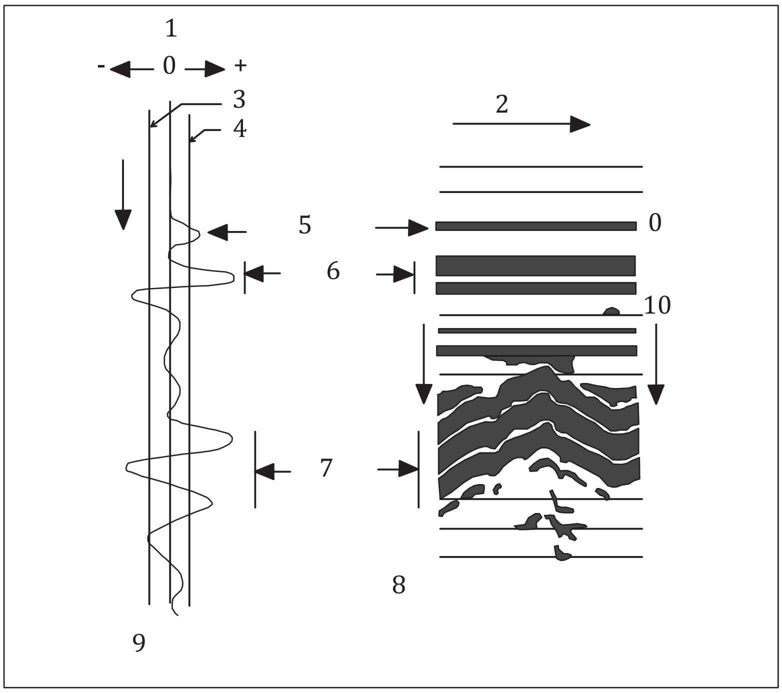
1 air

2 soil

3 anomaly

4 bedrock

Figure 12 — Schematic illustration of common offset single-fold profiling



Key

1	signal amplitude	6	surface
2	horizontal travel	7	interface signal
3	recorder print	8	graphic recorder representation of multiple waveforms along a profile
4	thresholds	9	sketch of typical signal waveform
5	transmitted pulse	10	depth

Figure 13 — GPR received signal and graphic profile display[67]

GPR crew consists nominally of two persons. One crew person moves the antenna or antenna pair along the profiles and the other operates the recorder and annotates the record so that the antenna position or midpoint can be recovered. Recent innovations have made the application of GPR to may scenarios a one person job, by allowing for cart based applications. The site-to-site variation in velocity, attenuation, and surface conditions is so large that seldom can the results be predicted before fieldwork begins. Additionally, the instrument operation is a matter of empirical trial and error in manipulating the appearance of the record. Often, a line will be done twice to be sure that all the features on the record are caused by the subsurface. Thus, the following steps are recommended for most fieldwork:

a) unpack and set up the instrument and verify internal operation;

b) verify external operation (one method is to point the antenna at a car or wall and slowly walk toward it; the reflection pattern should be evident on the record);

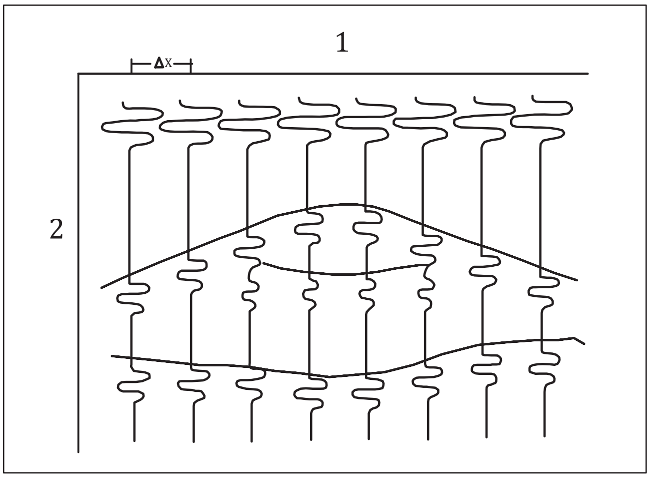
c) calibrate the internal timing by use of a calibrator;

d) calibrate the performance by surveying over a known target at a depth and configuration similar to the objective of the survey;

e) begin surveying the area of unknown targets.

15.3.4 Interpretation

Because of the strong analogy between seismic reflection and GPR, the application of seismic processing methods to GPR data is a fertile field of current research. The focus herein is on the most frequent type of GPR survey, i.e. location of specific targets. GPR surveys will not achieve the desired results without careful evaluation of site conditions for both geologic or stratigraphic tasks and target-specific interests. If the objectives of a survey are poorly drawn, often, the results of the GPR survey will be excellent records that do not have any straightforward interpretation. It is possible to tune a GPR system such that exceptional subsurface detail is visible on the record. The geologic evaluation problem is that, except in special circumstances (like the fore-set beds inside of sand dunes), there is no ready interpretation. The record reveals very detailed stratigraphy, but there is no way to verify which piece of the record corresponds to which thin interbedding of alluvium or small moisture variation. GPR surveys are much more successful when a calibration target is available. GPR can be useful in stratigraphic studies; however, a calibrated response (determined perhaps from backhoe trenching) is required for geologic work. Figure 14 indicates that localized objects will produce a hyperbola on the record. The hyperbolic shape is due to reflection returns of the EM pulse before and after the antenna system is vertically above the target. The shortest two-way travel distance is when the antenna (or centre of the antennae pair) is on the ground surface directly above the object. All other arrivals are at greater distances along a different hypotenuse with each varying horizontal antenna location. This hyperbola is also important for the determination of the radar velocity. Figure 15 shows the potential for the excellent detection of discrete targets by GPR; in this case, simulated air-filled subterranean voids (fractures, tunnels, caves).



Key

1 position

2 travel time

Figure 14 — Format of a ground penetrating radar reflection section with radar events shown for features depicted in Figure 12

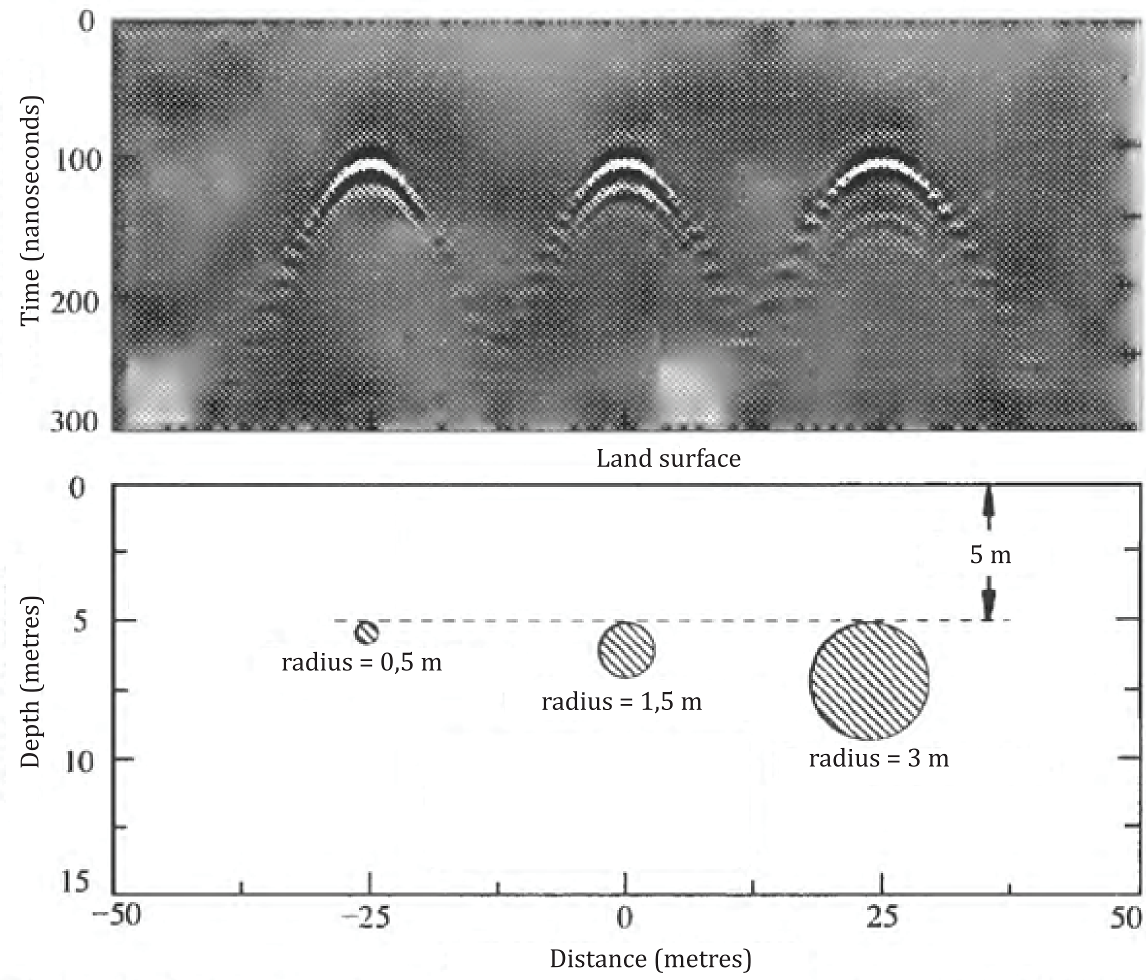


Figure 15 — Synthetic record over air-filled cylindrical voids of different radius, at 5 m depth in limestone[6]

15.3.5 Advantages

Nevertheless, GPR can be very useful when a thorough search of the site is required. GPR normally has accuracy of several feet or less when measuring the depth of a buried object.

15.3.6 Disadvantages

GPR surveys should be performed in the dry season if at all possible. Soil moisture, especially in high-clay soils, only increases the radar attenuation rates, further limiting the radar performance.

a) Soil attenuation may restrict the use of GPR to shallow depths.

b) The GPR antenna beamwidth is broad making it difficult for radar to discriminate between closely-spaced pipes.

c) In disturbed ground the radar may detect the walls of a trench but not the pipe it contains.

16 Report writing and presentation of results

The presentation of geophysical survey results in the form of report is very important, as it helps the planners to carry out follow-up actions effectively and unambiguously. The report should contain summary, introduction, objectives, hydrogeological information, geophysical approach, quantum of surveys carried out, results, discussions, conclusions and recommendations, and references. The language should be clear and simple without any vague inference.

The report should invariably contain the hydrogeological inferences and the recommendation on the objectives or purpose of the survey. It may contain technical and physical limitations and uncertainties in parameter estimation. Follow-up studies or surveys required should be mentioned.

There has to be a location map at an appropriate scale showing profile lines, geology and lineaments, etc. There should be figures showing representative data with interpretations. Also, figures to be given as per the objective, e.g. cross-sections, isopach maps, bedrock depth contours, fence diagram, depth slicings, correlation with available borehole data, etc., maps on aquifer thickness variation, depth to aquifer, thickness of protective clay, depth to saline/fresh groundwater interface, etc. The interpreted results are generally presented in a tabular form. It will not only include the geophysical parameters but also the hydrogeological inferences in brief and order of priority of the sites to be taken up for drilling, with reasons. If the geophysical parameters are correlated with hydrogeological parameters, the graphs as well as map for inferred hydrogeological parameters should be prepared. In this case, regression analysis and confidence limits may be shown. Overall, the aim should be to give maximum number of utility maps for the objective, in a clear and concise manner.

Table 5 — Overview of geophysical methods for their application to groundwater studies, advantages and disadvantages

Method	Application to GW Studies	Advantages	Disadvantages
Electrical resistivity	Weathered zone thickness Bedrock depth Fracture zones Fracture orientation Cavities in Limestone Granular zone in Sediments Clay zone demarcation Deep aquifer delineation Dyke/fault zone Water quality assessments GW hydraulic parameters	Direct response to occurrence and quality of groundwater	Overlapping resistivity range
Self-potential	Direction of groundwater movement/seepage Fracture orientation	Simple interpretation	Ambiguity between electrochemical and electro kinetic potentials
Frequency domain electromagnetic	Fracture zone Cavities in Limestone Sea water intrusion	Depth of investigations depend on frequency	Interpretations are difficult
Time domain electromagnetic	Water quality assessments Sea water intrusion	Not sensitive to coil alignment	Interpretations are difficult
VLF electromagnetic	Fracture zones Dyke/fault zone	Fast coverage and accurate lateral demarcation	Interpretations are mostly qualitative

Table 5 *(continued)*

Method	Application to GW Studies	Advantages	Disadvantages
Seismic refraction	Weathered zone thickness Bedrock depth Fracture zones Cavities in Limestone	Accurate depth determination and detection of fracture zone	Interpretations are cumbersome and shallow mapping
Seismic reflection	Deep aquifer delineation	Detection of hidden/thin layer by high resolution	Interpretations are cumbersome
Magnetic	Dyke/fault zone	Simple interpretations	No direct indication of groundwater
Gravity	Dyke/fault zone Deep aquifer delineation Cavities in Limestone	Useful for formation with density contrast	Ambiguities in interpretations
Induced Polarization	Clay zone demarcation	Differentiate clays from saline water layer	Interpretations are ambiguous
Mise-a-la-masse(charged body)	Fracture orientation Direction of groundwater movement/seepage Fracture orientation	Simple interpretation	Poor vertical resolutions and overlapping response

Bibliography

[1] Aaltonen J. Seasonal resistivity variations in some different Swedish soils. *European Journal of Environmental and Engineering Geophysics.* 2001, **6** pp. 33–45

[2] Abdelatif M.A., & Sulaiman W.N. Evaluation of groundwater and soil pollution in a landfill area using electrical resistivity imaging survey. *Environ. Manage.* 2001, **28** pp. 655–663

[3] Ademilua L.O., & Olorunfemi M.O. A geoelectric/geologic estimation of the groundwater potential of the basement complex area of Ekiti and Ondo State, Nigeria. *Journal of Technoscience*. 2000, **4** pp. 4–18

[4] Aki K., & Richards P.G. *Quantitative Seismology*. University Science Books, Sausalito, CA, 2002

[5] Al-Garni M.A. Schlumberger sounding and magnetic survey in Wadi Al-Damm, Makkah Al-Mukarramah, Saudi Arabia. *Journal of Petroleum and Mining Engineering*. 2004a, **7** pp. 45–60 [JPME]

[6] Munk J. and Sheets, R. A., 1997, Detection of underground voids in Ohio by use of geophysical methods: U.S. Geological Survey, Water-Resources Investigations Report 97-4221, pp. 28

[7] Baker S.S., & Cull J.P. Streaming potential and groundwater contamination. *Explor. Geophys.* 2004, **35** pp. 41–44

[8] Ballukraya P.N., & Sakthivadivel R. 1984, Analysis and interpretation of electrical resistivity data from hard rock areas for groundwater exploration. Tech. Report no.33, Centre of Water Resources, Anna Univ. of Tech. Chennai, India

[9] Barker R.D. The offset system of electrical resistivity sounding and its use with a multicore cable. *Geophys. Prospect*. 1981, **29** pp. 128–143

[10] Benson R., & Glaccum R. *Test Report: The application of ground penetratingradar to soil surveying for National Aeronautical and Space Administration (NASA).* Technos Inc, Miami, Florida, 1979

[11] Bhattacharya P.K., & Patra H.P. *Direct current geoelectric sounding*. Elsevier Publishing Co, Amsterdam, 1968

[12] Bhattacharya B.B. *Induced polarization method, lecture delivered at MEC*. Nagpur, India, 1975

[13] Bhattacharya B.B., & Dutta I. Depth of investigation studies for gradient array over homogeneous isotropic half-space. Geophysics. 1982, **47** (8) pp. 1198–1203

[14] Bhowmick A.N. 1985, *Twenty-five years of geophysical activity in the Central Groundwater Board*. Published in the seminar volume in the Golden Jubilee Celebration of Geological Survey of India.

[15] Bhowmick A.N. *Hydrogeophysical Eficacy and its Future scope in crystalline rocks- An Overview', presented as a key paper in the Regional seminar on 'Hydrology in Crystalline Rocks, organized jointly by Indian National Committee on Hydrology (INCOH), Water and Power Consultancy(WAPCO) and Indian Association of Hydrologists*. IAH, 1992

[16] Bishop I., Styles P., Emsley S.J., Ferguson N.S. The Detection of Cavities Using the Microgravity Technique: Case Histories From Mining and Karstic Environments in Modern Geophysics in Engineering Geology, McCann, Fenning, Reeves (Eds)., Geol. Soc.of London Special Publication No 12, 155-168. 1997

[17] Bogoslovsky V.A., & Ogilvy A.A. Natural potential anomalies as a quantitative index of the rate of seepage from water reservoirs. *Geophys. Prospect.* 1970, **18** pp. 261–268

[18] Breiner S. *Applications manual for portable magnetometers*. GeoMetrics, California, USA, 1973

[19] Chandra P.C., Tata S., Raju K.C.B. Geoelectrical response of cavities in limestones: an experimental field study from Kurnool district, Andhra Pradesh., India. *Geoexploration.* 1987, **24** pp. 487–502

[20] Daniels J.J. Ground Penetrating Radar, 2nd edn. The Institution of Electrical Engineers, London 2004

[21] Dobrin M.B. *Introduction to Geophysical Prospecting*. McGraw-Hill International Book Company, 1976

[22] Lucius J.E., Langer W.H., Ellefsen K.J. An Introduction to Using Surface Geophysics to Characterize Sand and Gravel Deposits. U.S. Geological Survey Circular, 1310, 2007, pp. 33

[23] Draskovits P., Hobot J., Vero L., Smith B.D. Induced polarization surveys applied to evaluation of groundwater resources, Pannonian basin, Hungary, publ. from Eotovos Lorand Geoph. Inst., Hungary

[24] Datta S., & Bhowmick A.N. Amplitude decay of Head Waves in three dimensional seismic models. *Geophysical Prospecing.* 1974, p. 1974

[25] Edward L.S. A modified pseudosection for resistivity and IP. *Geophysics*. 1977, **42** (5) pp. 1020–1036

[26] Fitterman D.V. Calculations of self-potential anomalies near vertical contacts. *Geophysics.* 1979, **44** (2) pp. 195–205

[27] Fitterman D.V., & Stewart M.K. Transient electromagnetic sounding for groundwater. *Geophysics*. 1986, **51** (4) pp. 995–1005

[28] Fitterman D.V., Meekes J.A.C., Ritsema I.L. 1988, Equivalence behavior of three electrical sounding methods as applied to hydrogeological problems, presented at 50th Annual meet. EAEG, The Netherlands

[29] Furness P. Gradient array profiles over thin resistive veins. *Geophys. Prospect.* 1993, **41** pp. 113–130

[30] Hagedoorn J.G., & Diephuis G. The seismic transmission volume. *Geophys. Prospect.* 2001, **49** pp. 697–707

[31] Hallenburg J.K. *Geophysical logging for mineral and engineering applications*. Penn Well Books, Tulsa, Oklahoma, 1984, p.

[32] Hoekstra P., & Blohm M.W. *Case histories of time-domain electromagnetic Soundings in environmental geophysics, SEG publ. on Geotechnical and Environmental Geophysics, Vol.II.* Environmental and Groundwater, 1990

[33] Hwang S., Shin J., Park I., Lee S. Assessment of Seawater Intrusion Using Geophysical Well Logging and Electrical Soundings in a Coastal Aquifer. – Youngkwang-gun, Korea. *Explor. Geophys.* 2004, **35** pp. 99–104

[34] Karous M., & Hjelt S.E. Determination of apparent current density from VLF measurements, Report, Dept. of Geophysics, Univ. of Oulu, Finland, Contr. No.89, 1977

[35] Kearey P., Brooks M., Hill I. *Introduction to Geophysical Exploration*. Blackwell, Oxford, Third Edition, 2002

[36] Keller G.V., & Frischknecht F.C. *Electrical Methods in Geophysical Prospecting*. Pergamon Press, 1982

[37] Kemna A., Binley A., Slater L. Crosshole IP imaging for engineering and environmental applications. Geophysics. 2004, **69** pp. 97–107

[38] Ketola M. Some points of view concerning *Mise-a-la-masse* measurements. *Geoexploration*. 1972, **10** pp. 1–21

[39] Koef*oed, O., 1979,* Geosounding Principles, Vol.1, Resistivity Sounding Measurements, Elsevier Scientific Publ. Co., Amsterdam

[40] Lampe B., Holliger K., Green A.G. A finite difference time-domain simulation tool for ground-penetrating radar antennas. *Geophysics*. 2003, **68** pp. 971–987

[41] Lowrie W., & West G.F. The effect of a conducting overburden on electromagnetic prospecting measurements. *Geophysics*. 1965, **30** pp. 624–632

[42] McNeill J.D. *Advances in electromagnetic methods for groundwater studies*. Geonics Ltd, Canada, 1988

[43] Meekes J.A.C., Ridder J., Scheffers B.C. Optimization of high resolution seismic reflection parameters for hydrogeological investigations in The Netherlands. *First Break*. 1990, **9** pp. 263–270

[44] Mwenifumbo C.J. 1980, Interpretation of Mise-a-la-Masse data for vein type bodies, Ph.D Thesis, Univ. Western Ontario, Canada

[45] Olorunfemi M.O., Fatoba J.O., Ademilua L.O. Integrated VLF-Electromagnetic and electrical resistivity survey for groundwater in a crystalline basement complex terrain of southwest Nigeria. *Global Journal of Geological Sciences*. 2005, **3** (1) pp. 71–80

[46] Palacky G.J., Ritsema I.L., De Jong S.J. Electromagnetic prospecting for groundwater in Pre Cambrian terrains in the republic of Upper Volta. *Geophys. Prospect.* 1981, **29** pp. 932–955

[47] Parasnis D.S. Three dimensional electrical Mise-a-la-masse surveys of an irregular lead-zinc-copper deposit in central Sweden. *Geophys. Prospect.* 1967, **15** pp. 407–437

[48] Patterson D.A., Davey J.C., Cooper A.H., Ferris J.K. The investigation of dissolution subsidence incorporating microgravity geophysics at Ripon, Yorkshire. *Q. J. Eng. Geol*. 1995, **28** pp. 83–94

[49] Prensky S. Recent Developments in Logging Technology. *Petrophysics*. 2002, **43** (3) pp. 197–216

[50] Roy K.K.B.G., & Mahatsente R. Combined resistivity and IP sounding for groundwater exploration. *Indian J. Earth Sci.* 1992, **19** (1) pp. 28–40

[51] Schiavone D., & Ouarto R. Self-potential prospecting in the study of water movements. *Geoexploration*. 1984, **22** pp. 47–58

[52] Schulz R. Interpretation and depth of investigation of gradient measurements in direct current geoelectrics. *Geophys. Prospect.* 1985, **33** pp. 1240–1253

[53] SEG. Geotechnical and Environmental Geophysics, Vol.II: Environmental and Groundwater, Edited by S.H.Ward, SEG publication, Tulsa, Oklahoma, USA. 1989

[54] Shaaban F. Vertical electrical for groundwater investigation in northwestern Egypt: a case study in a coastal area. *J. Afr. Earth Sci.* 2002, **33** pp. 673–686

[55] Sheriff R.E. *Encyclopedic Dictionary of Exploration Geophysics*. Society of Exploration Geophysicists, Tulsa, Oklahoma, 1991, pp. 376.

[56] Taylor R.W., & Fleming A.H. Characterizing jointed systems by azimuthal resistivity surveys. Groundwater. 1988, **26** (4)

[57] Telford W.M., Geldart L.P., Seriff R.E., Keys D.A. *Applied Geophysics.* IBH Publ.Co. Pvt. Ltd, Oxford, 1976

[58] Vacquier V., Holmes C.R., Kintzinger P.R., Lavergne M. Prospecting for groundwater by induced electrical polarization. *Geophysics*. 1957, **22** (3) pp. 660–687

[59] Van Overmeeren R.A. The plus-minus method for rapid processing by portable computer of seismic refraction data in multi-layer groundwater studies, First Break, Vol.5, no. 3, 1987

[60] Van Overmeeren I.L. Ritsema. Continuous vertical electrical sounding, First Break, Vol.6, no.10, 1988

[61] Villegas-Gracia C.J., & West G.F. Recognition of electromagnetic overburden anomalies with horizontal loop electromagnetic survey data. *Geophysics*. 1983, **48** (1) pp. 42–51

[62] Ward S.H., & Fraser D.C. Conduction of electricity in rocks, Chapter II part B, Mining Geophysics, SEG publication, Tulsa, Okl., USA, 1967.

[63] White P.A. Electrode arrays for measuring groundwater flow direction and velocity. Geophysics. 1994, **59** (2) pp. 192–201

[64] Wright J.L. *VLF interpretation manual*. Geonics Ltd, Canada, 1988

[65] Zohdy A.A.R. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics*. 1989, **54** pp. 245–253

[66] Zohdy A.A.R., Eaton G.P., Mabey D.R. 1974. Application of surface geophysics to groundwater investigation, U.S.G.S. Techniques of Water-Resource Investigation, Book 2.

[67] Benson R.C., Glaccum R.A., Noel M.R. 1983. Geophysical techniques for sensing buried wastes and waste migration. Environmental Monitoring Systems Laboratory, U. S. Environmental Protection Agency, Contract #68-03-3050, Las Vegas, NV, 1983, pp. 236

[68] McNeill J.D. Advances in electromagnetic methods for groundwater studies. Geoexploration. 1991, **27** pp. 65–80

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Copyright

Useful Contacts:

Customer Services
Tel: +44 845 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 845 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK