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# Hydrometry — Groundwater — Surface geophysical surveys for hydrogeological purposes

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## National foreword

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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.

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Published by BSI Standards Limited 2016

ISBN 978 0 580 79191 8
ICS 07.060

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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 |
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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)

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# Foreword

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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).

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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*.


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# 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.

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# 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

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**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


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**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

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**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


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## 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.

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# 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.


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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.

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## 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 $\rho$ 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;
- $\varphi$ 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.


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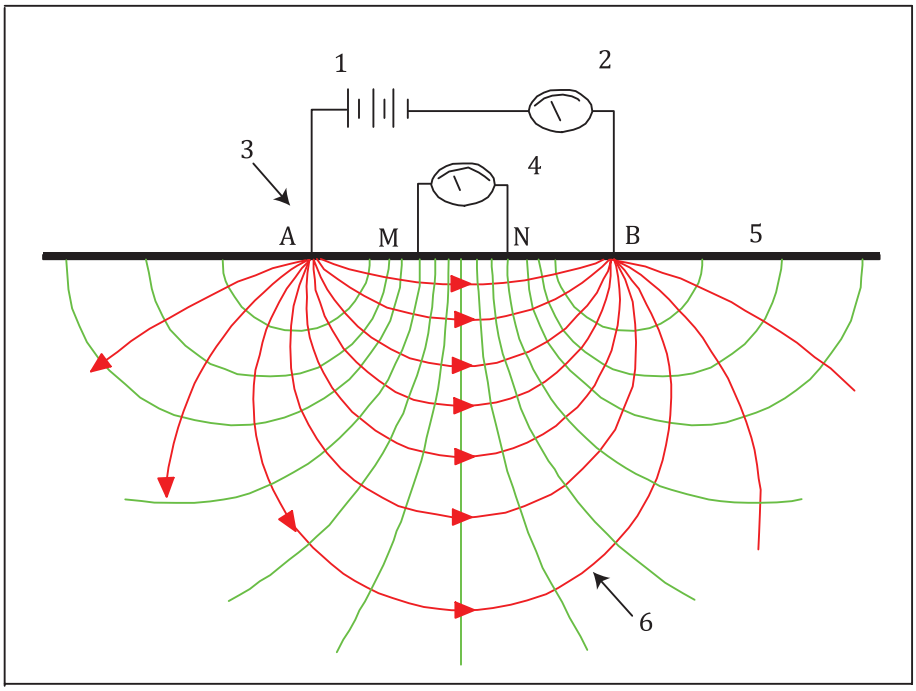
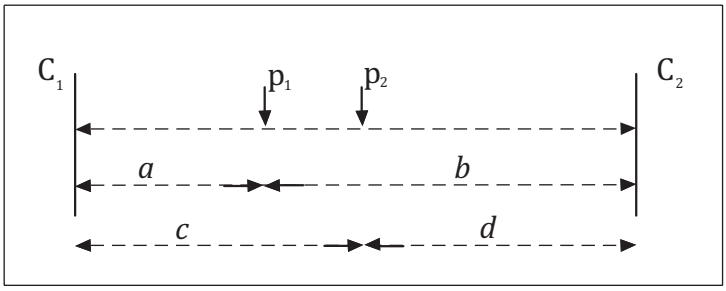



**Key**

| | |
|---|---|
| 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 |
| —— | current |
| —— | 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 $p_1$

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*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):

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

where

$\rho$ 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):

$$\rho = 2\pi a \frac{V}{I} = KR \tag{4}$$

where

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

For Schlumberger configuration, it becomes Formula (5):

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

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 $\rho$, the resistivity of the ground. If the ground is homogeneous, the value of $\rho$ gives the true resistivity of the medium or the ground. However, since the earth's subsurface is generally multilayered, the value of $\rho_a$ 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).


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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.

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