GEOPHYSICAL MONITORING TECHNOLOGIES

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Keywords: geophysical, electrical, electromagnetic, magnetic, gravity, seismic, ground penetrating radar

Contents

Summary

This chapter presents the different geophysical methodologies used in environmental monitoring. The methods highlighted include gravity, magnetic, seismic refraction, seismic reflection, electrical resistivity, spontaneous (self) potential, induced polarization, electromagnetics, and ground penetrating radar. For each method, principles, instrumentation, field procedures, interpretation, and case histories are highlighted. Most of the applications and case monitoring included volcanic hazards, detection of underground cavities and buried containers, landfill and earthquake studies, hydrogeology and groundwater contamination, contaminated land mapping, forensic uses, and others. This contribution is intended as a very good guide to students, teachers and professionals in the field of geological, engineering, and environmental sciences.

1. Introduction

Environmental monitoring and protection is a serious business when the rate of degradation is taken into consideration. In developed countries, monitoring and protection programs have been put in place. However, in the developing nations such facilities are lacking. It is therefore not uncommon to see youths protesting against the degradation of environment such as in the Niger Delta region of Nigeria.

Monitoring of environmental pollution necessitates dedicated instrumentation. Some pieces of equipment are very expensive and there is always the need to acquire and use cheap and relatively fast techniques. One possibility is the application of geophysical techniques. This chapter is geared towards introducing the different geophysical techniques as a tool in environmental monitoring.

Since the beginning of the 1980s, geophysical methods have been increasingly used to delineate polluted areas prior to more detailed investigations. One major advantage is that these methods are environmental friendly and a large area can be covered within a short time and at a low cost.

Geophysical method	**Dependent physical property**	**Applications (see key below)**									
		1	2	3	4	5	6	7	8	9	10
Gravity	Density	p	p	s	s	s	s	u	u	s	u
Magnetic	Susceptibility	p	p	p	s	u	m	u	p	p	u
Seismic refraction	Elastic moduli; density	p	p	m	p	s	s	u	u	u	u
Seismic reflection	Elastic moduli; density	p	p	m	s	s	m	u	u	u	u
Resistivity	Resistivity	m	m	p	p	p	p	p	s	p	m
Spontaneous potential	Potential differences	u	u	p	m	p	m	m	m	u	u
Induced polarization	Resistivity; capacitance	m	m	p	m	s	m	m	m	m	m

Electromagnetic (EM)	Conductance; inductance	s	p	p	p	p	p	p	p	p	m
EM-ground penetrating radar	Permitivity; conductivity	u	u	m	p	p	p	s	p	p	p

p = primary method; s=secondary method; m=may be used but not necessarily the best approach, or has not been developed for this applications; (u) = unsuitable.

Applications

1. Hydrocarbon exploration (coal, gas, oil)
2. Regional geological studies (over areas of hundreds of km^2)
3. Exploration/development of mineral deposits
4. Engineering site investigations
5. Hydrogeological investigations
6. Detection of subsurface cavities
7. Mapping of leachate and contaminant plumes
8. Location and definition of buried metallic objects
9. Archaeogeophysics
10. Forensic geophysics

Table 1. Geophysical methods and their applications

Geophysical methods respond to the physical properties of the subsurface media and can be classified into two types, the passive and active methods. The passive methods are those that detect variations within the natural fields associated with the Earth, such as the gravitational and magnetic fields. The active methods, in contrast, involve the generation of artificial signals that are transmitted into the ground, which then modifies the signals in ways that are characteristic of the materials through which they travel. The altered signals are measured by appropriate detectors whose output can be displayed and interpreted.

Geophysical methods may form part of a larger survey and geophysicists try to interpret their data and communicate their results clearly to the benefit of the whole team, and particularly to the client.

The various geophysical methods rely on different physical properties and it is important that the appropriate technique be used for a given type of application. The basic geophysical methods are listed in Table 1 together with the physical properties to which they relate and their main uses.

2. Gravity Method

Gravity surveying measures the variation in Earth's gravitational field created by differences in density of the subsurface rocks. The gravity method has been most widely used in the search for oil and gas in the twentieth century. However, today many other applications have been found. Subtechniques of this method include microgravity and airborne gravity. The microgravity surveys are those conducted on very small scale while the airborne gravity survey is concerned with obtaining gravity information from difficult terrain with the aid of aircraft.

2.1. Physical Basis

The gravity method is based on the two laws of Sir Isaac Newton namely; the Universal Law of Gravitation and his Second Law of Motion.

The Universal Law of Gravitation states that the force of attraction between two bodies of known mass is directly proportional to the product of the two masses and inversely proportional to the square of the distance between their centers of mass. It can be written as:

$$F = \frac{GMm}{R^2}$$

Where
F = force
G = gravitational constant = 6.67×10^{-11} Nm^2 kg^{-1}
M = mass of Earth
m = mass of body
R = distance between masses

Newton's Second Law of Motion states that a force (F) is equal to the mass (m) of a body multiplied by its acceleration (a), written as:
$F = ma$

Units: The unit of gravity measurement is the Gal (cm s^{-2}). Ten gravity units (gu) are equivalent to one milligal (1×10^{-3} Gal).

Gravity and rock types: Gravity surveying is sensitive to variations in rock density and therefore different rock types will affect the results of gravity measurements differently. Seven factors including composition, cementation, age and depth of burial, tectonic, setting, porosity, and type of parafluid affect the density of sedimentary rocks. The density of sedimentary rocks varies depending on the material of which the rock is made and the degree of consolidation. Sediments that remained buried for a long time consolidated and lithified and have low porosity and hence increased density.

Igneous rock tends to be denser than sedimentary rocks. For these rocks types (igneous), density decreases with increasing silica content whereas in metamorphic rocks, density tends to increase with increasing grade of metamorphism.

Instrumentation: The instrument used in gravity surveys is the *gravity meter* (gravimeter). Gravity measurements are affected by a number of factors. These include drift, Earth tides, Eötvös effects, latitude, terrain, and isostasy.

Bouguer anomaly: The main end product of gravity survey is the Bouguer anomaly, which should correlate only with lateral variations in the density of the upper crust. The Bouguer anomaly (g_B) is the difference between the observed value (g_{obs}), duly corrected, and a value at a given base station (g_{base}) such that:

$$g_B = g_{obs} + \Sigma\,(\text{corr}) - g_{base}$$

with

$$\Sigma\,(\text{corr}) = \delta g_L + (\delta g_F - \delta g_B) + \delta g_{TC} \pm \delta g_{EC} \pm \delta_{IC} - \delta g_D$$

where the subscripts refer to the following corrections:

L = latitude; F = free air; B = Bouguer; TC = terrain correction; EC = Eötvös correction; IC = isostatic correction; and D = drift (including Earth tides).

The variation of the Bouguer anomaly should reflect the lateral variation in density such that a high-density feature in a low-density medium should give rise to a positive Bouguer anomaly. Conversely, a low-density feature in a high-density medium should result in a negative Bouguer anomaly.

2.2. Interpretation Methods

There are two approaches to the interpretation of Bouguer anomaly data. One is direct where the original data are analyzed to produce an interpretation. The other is indirect, where models are constructed to compute synthetic gravity anomalies, which in turn are compared with the observed Bouguer anomaly.

3. Magnetic Method

Magnetic surveying, is the oldest method of geophysical exploration and is used for both oil and minerals. In prospecting for oil, it gives information which one can use to determine the depth to basement rocks and thus locate and define the extent of sedimentary basins. In mineral exploration, the magnetic survey is often used to prospect for magnetic minerals directly but it is also effective in the search for useful minerals that are not magnetic themselves but are associated with other minerals having magnetic effects detectable at the surface. Magnetic exploration was carried out mainly on land until the mid 1940s when the air-and seaborne magnetic surveys were introduced for reconnaissance surveys for minerals.

Magnetic methods can be used in a wide variety of applications and range from small scale investigations to locate pipes and cables very near the surface through a large scale regional geological mapping to determine gross structure, such as hydrocarbon exploration. In larger investigations, both magnetic and gravity methods are used to complement each other. Magnetics in some cases are used prior to seismic surveys and they can provide more information about the subsurface particularly the basement rocks.

3.1. Basic Concepts and Instrumentation

Around a bar magnet, a magnetic flux exists and converges near the ends of the magnet which are known as magnetic poles. If such a magnet is suspended in free air, the magnet will align itself within Earth's magnetic field. After alignment, the positive pole points towards the magnetic north pole and the negative pole points towards the magnetic south pole.

If two magnetic poles of strength m_1 and m_2 are separated by a distance r, a force exists between them. If the poles have the same polarity, the force will push the poles apart, and if they are of opposite polarity, the force is attractive and will draw the poles towards each other. The line of magnetic flux per unit area is the flux density B, and is measured in webers m^{-2} (teslas, T). The unit commonly used in magnetic surveys is the gamma (1 gamma = 1×10^{-9} Wb m^{-2} = 1×10^{-9} T). The magnetic field can also be defined in terms of a force field, which is produced by electric currents. The magnetizing field strength H is defined as the field strength at the center of a loop of wire of radius r through which a current I is flowing such that $H = I/2r$. The ratio of the flux density B to the magnetizing field strength H is called the absolute magnetic permeability (N).

Any magnetic material placed in an external field will have magnetic poles induced upon its surface. In the moderately magnetic materials and weak fields generally concerned with in geophysical work, this induced magnetization, sometimes called polarization, is in the direction of the applied field and its strength is proportional to the strength of that field. The intensity of magnetization J maybe considered to be the induced pole strength per unit area along a surface normal to the inducing field. It is also equivalent to the magnetic moment per unit volume. In the case of a homogenous external field H which makes an angle θ with the normal to the surface of a material capable of being magnetized the induced pole strength per unit area is:

$$I = kH \cos \theta$$

or for a field normal to the surface

$$I = kH$$

where k, the proportionality constant, is called the *susceptibility*.

3.1.1. Magnetic Properties of Rocks

Magnetic susceptibility is an extremely important property of rocks. Rocks that have a significant concentration of ferro- and/or ferri-magnetic minerals (for example magnetite, pyrite, illmenite, hematite) tend to have the highest susceptibilities. Consequently, basic and ultrabasic igneous rocks have the highest susceptibilities, acid igneous and metamorphic rocks have intermediate to low values, and sedimentary rocks have very small susceptibilities in general.

3.1.2. Magnetic Instruments

Magnetometers used specifically in geophysical exploration can be classified into three groups: the torsion (and balance), fluxgate, and resonance types, of which the last two have completely superseded the first.

Torsion and balance (Schmidt-type) magnetometer: In the early years of magnetic prospecting for petroleum, the magnetic field balance (magnetometer) was the standard instrument employed for magnetic field measurements. It was also extensively used in mineral exploration. The magnetometer originally developed by Schmidt comprise in essence a magnetic needle suspended on a wire (torsion type) or balance on a pivot. In the Earth's magnetic field the magnet adopts an equilibrium position. If the device is taken to another location where Earth's magnetic field is different from that of the base station, the magnet will align itself to the new field and the deflection from the rest position is taken as Earth's magnetic field. A modification to this magnetometer is the variometer, in which a magnetic beam was asymmetrically balanced on an agate knife edge and zeroed at the base station. Deflections from the rest position at other locations were then read using a collimating telescope. A further development of the variometer was the compensation variometer. This measured the force required to restore the beam to the rest position.

The fluxgate magnetometer: The fluxgate magnetometer was initially used for detecting submarines from aircraft during the Second World War. It has also been used, to a lesser extent, for magnetic surveys on the ground. This instrument makes use of a ferromagnetic element of very high permeability, in which Earth's field can induce a magnetization that is a substantial proportion of its saturation value. If Earth's field is superimposed upon a cyclic field induced by a large alternating current in a coil around a magnet, the resultant field will saturate the core. The place in the energizing cycle at which saturation is reached is observed, and this gives a measure of Earth's ambient field.

Resonance magnetometer: There are two main types of resonance magnetometer: the proton free-precession magnetometer and alkali vapor magnetometer. Both types monitor the precession of atomic particles in an ambient magnetic field to provide an absolute measure of the total magnetic field. The proton magnetometer is based on the phenomenon of nuclear magnetic resonance. The most widespread use of this instrument has been in airborne surveys but systems have also been developed for operation on land and for towing behind a ship.

The alkali vapor magnetometer or optical absorption magnetometer makes use of the development of a radio-frequency spectroscopy called optical pumping. This type of magnetometer is capable of measuring Earth's total field with a substantially greater precision than the proton magnetometer.

Cryogenic (SQUID) magnetometer: The most sensitive magnetometer available is the cryogenic magnetometer, which operates using processes associated with superconductivity. These magnetometers are known as SQUID (Superconducting Quantum Interference Device) magnetometer. They are used extensively in paleomagnetic studies and aeromagnetic surveying. In studies using SQUID magnetometer, two sensors need only be placed 25 cm or less apart, thus making it possible to have the entire sensor system in a very small place. This has great advantages in mounting the equipment in aircraft, in borehole probes and in submarine devices where space is premium.

Gradiometers: A gradiometer measures the difference in total magnetic field strength between two identical magnetometers separated by a small distance. In airborne work, typical separations between sensors is 2–30 m and 0.5 m for ground surveys. The gradiometer is used for high resolution surveys (e.g. mineral exploration).

3.2. Field Surveys and Interpretation

In ground surveys, it is important to establish a localized base station away from the suspected target or magnet noise and in a relatively flat area. A base station should be quick and easy to relocate and re-occupy. In airborne and shipborne surveys, it is not possible to return to a base station frequently.

The most significant correction is the diurnal variation in Earth's magnetic field. This is normally done by re-occupying the base station at least every 30 minutes. Also, a terrain correction may need to be applied when the ground over which a survey is conducted is susceptible to magnetic noise or is magnetically and topographically rough. In order to produce a magnetic anomaly map of an area, the data have to be corrected to take into account the effect of latitude and, to a lesser extent, longitude. This is because Earth's magnetic field strength varies from 25 000 nT at the magnetic equator to 69 000 nT at the magnetic poles. The data is normally corrected by subtracting the theoretical field value F_{th}, obtained from the international geomagnetic reference field, from the measured value, F_{obs}.

Once magnetic data have been fully corrected and reduced, they are displayed as either profiles or maps. Quantitatively, the essence of interpretation is to obtain information about the depth to a particular magnetic body, its shape and size, and details about its magnetization. This can be done in two ways. One is direct, where the field data are interpreted to give a physical model. The other is the inverse method, where models are generated from which synthetic magnetic anomalies are generated and fitted statistically against the observed data.

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Bibliography

Dobrin M.B. (1976). *Introduction to Geophysical Prospecting*.630pp. New York: McGraw-Hill. [This textbook presents essential principles and applications of geophysical techniques.]

McLean A.C. and Gribble C.D. (1979). *A Geology for Civil Engineers*.310pp. London: George Allen & Letwin .[This book deals with principles and applications of geology in civil engineering construction.]

Kearey P. and Brooks M. (1990). *An Introduction to Geophysical Exploration*.254pp. Oxford: Blackwell Scientific. [This book presents principles and application of geophysics in exploration.]

Parasnis D.S. (1973). *Mining Geophysics*.315pp. Amsterdam: Elsevier. [This book presents the principles and applications of geophysics in mining.]

Parasnis D.S. (1997). *Principles of Applied Geophysics*.278pp. London: Chapman & Hall. [This is a widely used textbook that presents essential principles of geophysics.]

Reynolds J.M. (1997). *An Introduction to Applied and Environmental Geophysics*. 796pp.New York: John Wiley & Sons. [This is a widely used textbook that presents essential principles and well documented application and case histories in applied and environmental geophysics from different sources.]

Sharma P.V. (1997). *Environmental and Engineering Geophysics*. 405pp.Amsterdam: Elsevier Science. [This book presents basic principles and application of geophysics in the field of environmental and engineering studies.]

Telford W. M., Geldart L.P., Sheriff R.E., and Keys D.A. (1990). *Applied Geophysics*. 770pp.Cambridge; Cambridge University Press. [This book presents basic principles and application of geophysics in the field of mining, engineering, petroleum, hydrogeology. and environment.]

Ward S.H. (1990). *Geotechnical and Environmental Geophysics*. 320pp.Tulsa: Society of Exploration Geophysicists. [This books deals with the principles and application of geophysics in the geotechnical and environmental fields.]

Biographical Sketch

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