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Basics in Geophysical Surveying

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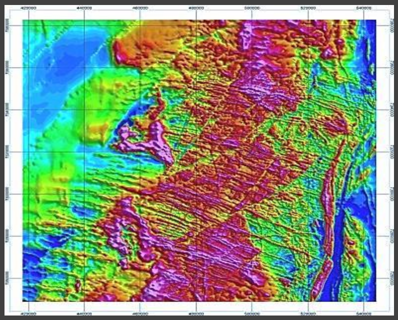

Introduction to Geophysical Surveying

Credits: 5 PDH

Course Description

Geophysical surveying is an applied branch of geophysics, which uses seismic, gravitational, magnetic, electrical and electromagnetic physical methodologies at the Earth's surface to measure the physical properties of the subsurface.

Geophysical surveying methods generally measure these geophysical properties along with anomalies in order to evaluate various subsurface conditions such as the existence of groundwater, bedrock, minerals, oil and gas, geothermal resources, voids and cavities, and much more.

Topics

- Geophysical properties
- Exploration, engineering & environmental geophysics
- Types of geophysical surveys
- Seismology, reflection seismology, seismic refraction, seismic tomography
- Seismoelectrical method
- Geodesy and gravitational surveys: gravity anomaly, gravimetry, gravity gradiometry
- Magnetic surveying: magnetometers, aeromagnetic survey, magnetotellurics
- (GPR) ground penetrating radar
- (TEM/TDEM) transient time-domain electromagnetics
- (MRS) magnetic resonance sounding
- Electrical resistivity tomography, (IP) Induced Polarization, (SP) Spontaneous Potential
- Borehole Geophysics (well logging), and remote sensing
- Geological analysis, UXO locating, hydrogeological applications
- Oil, mining, mineral exploration
- Environmental, geothermal, and marine applications
- Geotechnical engineering
- Dam and levee integrity studies
- Landfill boundaries, contaminant plumes, USTs, cavities and voids, archaeology

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Chapter 1: Geophysics

Intro of Geophysics

Geophysics

Geophysics is a branch of earth science dealing with the physical processes and phenomena which occur within the earth and in its vicinity.

It is a subject of natural science concerned with the physical processes and physical properties of the Earth and its surrounding spatial environment, and the use of related quantitative analytical methods.

Geophysics may refer strictly to the geological applications:

- Earth's shape
- its gravitational and magnetic fields
- its internal structure and composition
- its dynamics and their surface expression in plate tectonics
- the generation of magmas, volcanism and rock formation

Though modern geophysics tends to refer to a broader definition that includes:

- the water cycle (including snow and ice)
- fluid dynamics of the oceans and the atmosphere
- electricity and magnetism in the ionosphere and magnetosphere and solar-terrestrial relations
- conditions which are associated with the Moon and other planetary bodies, such as tidal properties

Geophysics Throughout History

Origins of Geophysics

Although geophysics was only recognized as a separate discipline of earth science in the 19th century, its origins began in ancient times.

The first magnetic compasses were made from lodestones, while more modern magnetic compasses played an important role in the history of navigation.

Ancient History

A natural explanation of volcanoes was first undertaken by the Greek philosopher Empedocles, who considered the world divided into four elemental forces: Earth, Air, Fire and Water.

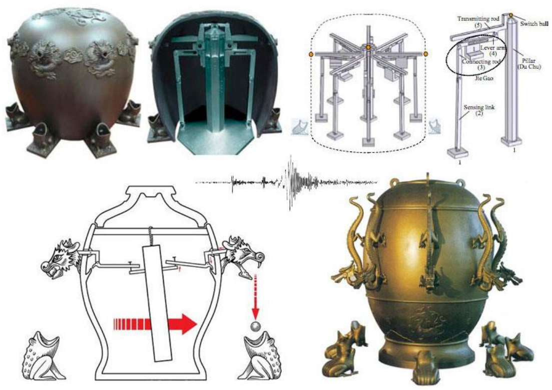
Around the time of 240 BC, Eratosthenes of Cyrene, Egypt (now located in present day Libya) measured the circumference of the Earth, using trigonometry along with the angle of the Sun.

There is also reference to the occurrence of earthquakes in Aristotle's “Meteorology”, in “Naturalis Historia” by Pliny the Elder, and in Strabo's “Geographica”.

Aristotle and Strabo were known to record observations on tidal behavior, as well.

132 AD - First Seismoscope

The first known seismic instrument was built in 132 AD. In the year 132, Zhang Heng of China's Han dynasty invented the first seismoscope, which was an "instrument for measuring the seasonal winds and the movements of the Earth."



Seismoscope invented circa 132 AD China
Image source: allshookup.org

This was a large bronze vessel, about 6 feet in diameter; at eight points around the top were dragon's heads holding bronze balls.

When there was an earthquake, one of the mouths would open and drop its ball into a bronze toad at the base, making a sound and supposedly showing the direction of the earthquake.

History – Early Modern Period

During this period in history, many of the physical laws which are the basis for modern day physics, and geophysics were discovered.

William Gilbert's experimental treatise, “De Magnete” written around 1600, deduced that compasses point north because the Earth itself is magnetic.

In 1687, Isaac Newton published his “Principia”, which not only laid the foundations for classical mechanics and gravitation but also explained a variety of geophysical phenomena such as the tides and the precession of the equinox.

Newton applied his theory of mechanics to a better understanding of the tides and of celestial movements; with subsequent instrumentation developed to measure the Earth's shape, density and gravity field, as well as the components of the water cycle.

These experimental and mathematical analyses were later applied to several areas of geophysics:

- Earth’s shape, density, and gravity field
- Earth’s magnetic
- Seismology
- Earth’s age, heat and radioactivity
- Hydrology - rainfall, runoff, drainage area, velocity, river cross-section measurements and discharge

Advances in the 18th century included Bernoulli's piezometer and Bernoulli's equation as well as the Pitot tube by Henri Pitot.
In the 19th century, groundwater hydrology was furthered by Darcy's law, the Dupuit-Thiem well formula, and the Hagen-Poiseuille equation for flows through pipes.
The thermoscope, or Galileo thermometer was constructed by Galileo Galilei in 1607.
In 1643, Evangelista Torricelli invented the mercury barometer.
In 1648, Blaise Pascal, rediscovered that atmospheric pressure decreases with height, and deduced that there is vacuum above the atmosphere.

Galileo thermometer
(the middle float shows the temperature)
Image source: Wikipedia

Modern Geophysics

Modern and Post Modern Era

Building upon laws of physics discovered in the preceding centuries, the 20th century was a revolutionary age for geophysics.

In areas such as:

- Oceanography
- Seismology
- Earth’s Interior
- Meteorology
- plate tectonics
- deep earth exploration

Oceanographic Breakthroughs

Advances in physical oceanography occurred in the 20th century. Sea depth by acoustic measurements of was first made in 1914. The German "Meteor" expedition gathered 70,000 ocean depth measurements using an echo sounder, surveying the Mid-Atlantic Ridge between 1925 and 1927.

“Physical Geography of the Sea”, the first textbook of oceanography, was written by Matthew Fontaine Maury in 1855.

The Great Global Rift was discovered by Maurice Ewing and Bruce Heezen in 1953 while the mountain range under the Arctic was found in 1954 by the Arctic Institute of the USSR.

The theory of seafloor spreading was developed in 1960 by Harry Hammond Hess.

The Ocean Drilling Program started in 1966. There has been much emphasis on the application of large scale computers to oceanography to allow numerical predictions of ocean conditions and as a part of overall environmental change prediction.

As an international scientific effort between 1957 and 1958, the International Geophysical Year or IGY was one of the most important for scientific activity of all disciplines of geophysics:

- aurora and airglow
- cosmic rays
- geomagnetism
- gravity
- ionospheric physics
- longitude and latitude determinations (precision mapping)
- meteorology
- oceanography
- seismology and solar activity

Industrial Applications for Geophysics

Industrial applications of geophysics were developed to meet the demands of petroleum exploration and recovery in the 1920s. As time went on, petroleum, mining and groundwater geophysics improved.

New industrial uses of geophysical engineering in the 1990s saw applications such as:

- for seismic analysis and prediction
- earthquake hazard minimization
- soil/site investigations for earthquake prone areas

Chapter 2: Geophysical Survey Methods

Geophysical Surveying Methods

This chapter provides an introduction to various geophysical surveying methods and principles.

Surveying using Magnetics

Survey measurements of the Earth's magnetic field will contain information about subsurface variations in magnetic susceptibility. These measurements record the Earth's field and fields induced in magnetic materials.

More magnetically susceptible materials will consist of stronger induced fields. Removing the Earth's field from the observations will leave the anomalous fields, which can be interpreted to discover where magnetic material lies, as well as its susceptibility and shape.

Magnetic data can be acquired:

- from the air (aircraft, drones, satellites)
- on the ground (stationary or mobile platforms)
- in the water (from floating or submerged vessels)
- subsurface (boreholes)

Processed data are presented as maps or profiles of the subsurface susceptibility distribution. Magnetic surveying is a highly versatile surveying process which can be applied to a variety of areas in the geosciences.

Surveying using Gradient Magnetics

Survey measurements of gradient of the magnetic field are made using two magnetometers, then taking the difference between the measured values.

Gradients can be measured in the X, Y or Z planes. Similar to magnetic surveys, gradient magnetic measurements are interpreted as variations in magnetic susceptibility.

Surveying using Gravity

Surveying measurements of the Earth's gravitational field can disclose subsurface variations in density, as gravitational attraction is based on the mass of material.

Measurements will vary with the latitude, elevation, and topography, requiring accurate recordings for each measurement.

Surveying using DC Resistivity

With this method, electric resistivity in subsurface materials is measured by sending an electrical current through the soil, between a pair of electrodes while the voltage across a second pair of electrodes is measured.

The resulting measurement is converted to an "apparent" resistivity. This value represents the weighted average resistivity over a given volume of earth.

Variations in measurements are caused by variations in the electrical resistivity of the soil, rock, and pore fluid.

Survey results are sometimes interpreted directly, or as 1, 2 or 3 dimensional models. These are estimated using inversion procedures.

- *One Dimensional model* - When the survey is conducted obtain a 1D model, it is called a sounding. Soundings are surveys that are arranged so that measurements reveal vertical variations in resistivity under one location. The ground is interpreted as flat lying layers.
- *Two Dimensional model* - Profiles are surveys that are arranged in order to be interpreted in terms of vertical and lateral variations under a line of measurements. Profiles are used to build 2D models of the earth. Results are interpreted in 2D and presented as a cross-section of the earth, that is, the assumption is that the structures extend without change either side of the survey line.

- *Three Dimensional models* - More complex electrode arrangements or multiple lines of electrodes are used to obtain a 3D interpretation.

Surveying using Induced Polarization (IP)

Certain earth materials act as capacitors, building up internal electrical charges when a current is passed through. The ability to accumulate this charge is “chargeability”.

An IP survey measures the secondary responses associated with chargeability. IP measurements can be made at the same time, with the same equipment, as those which are used with a DC resistivity survey.

Clays, graphite, and sulphide minerals have a high chargeability, however small changes in chargeability can be detected when groundwater is contaminated by salt-intrusion, or other materials such as hydrocarbons.

Surveying using Seismic Reflection

Compressional (P-wave) or shearing (S-wave) seismic energy will travel from its source, through the ground. This energy will be reflected by changes in the ground’s elastic properties and density.

Reflection surveys record signals with differing seismic velocities, depending on the ground’s density and elasticity, which have been reflected from boundaries between materials within the ground.

Data processing requirements are considerable, before the results can be used. Seismic reflection surveying represents over 90% of the geophysical surveys conducted, in support of oil and gas exploration.

Results can be interpreted in terms of subsurface layering if interfaces between layers are within roughly 10 to 20 degrees of being horizontal.

Those contacts between geologic units that are near to being vertically-aligned are difficult to image using seismic reflection, although breaks in horizontal features can often be found.

Oil exploration surveys may involve investigating the ground up to a few miles of depth, while engineering surveys may involve studying only the first 50 ft. or so of depth.

Surveying using Seismic Refraction

Refraction surveys are designed to record signals that have been refracted or bent within the ground so that they arrive back at the surface.

The refraction occurs due to increasing seismic velocity in the ground, which in turn is related to the ground’s elastic properties and density.

This survey method is commonly used for mapping sub-horizontal structure, but is not effective at characterizing features that are near to vertical.

Instruments used in refraction are similar to those used for seismic reflection surveys, but the field layouts differ. As with reflection surveying, results cannot be used without significant processing.

Surveys can be carried out at almost any scale; from lines less than a football field to lines which are miles long.

Surveying using GPR (ground penetrating radar)

GPR is similar method to seismic reflection, except it uses electromagnetic energy instead of acoustical energy. Radio energy pulses are emitted from an antenna, with echoes being received at a secondary antenna.

The results are then plotted and processed, similar to seismic reflection, although data processing is usually much less intensive in comparison to that required for seismic reflection.

The ground’s electrical resistivity controls the depth of the signal’s penetration. Penetration is usually less than 25 ft. Signals echo at boundaries where electrical resistivity and/or dielectric permittivity change abruptly.

Dielectric permittivity is a physical property related to the ability of the materials to become polarized in the presence of an electric field. It is mostly affected by the moisture level of the subsurface materials.

Surveying using Electromagnetic (EM) Terrain conductivity

Electromagnetic methods involve using oscillating electromagnetic energy which penetrates the ground which induce secondary EM fields in regions of heightened electrical conductivity or reduced electrical resistivity.

Terrain conductivity surveys usually involve a handheld instrument operating at a single frequency or at multiple frequencies.

In this system, one transmitter coil will generate EM energy, while a second receiver coil will detect the EM field generated by the transmitter, along with fields induced in subsurface conductive regions.

Large data sets can be collected efficiently, and plotted as maps or line profiles of apparent conductivity, to be analyzed to determine horizontal locations of conductive features. The results cannot be used directly to learn about variations of conductivity with depth.

Surveying using Frequency Domain EM

The EM terrain conductivity survey discussed previously is a simple form of frequency domain EM (FEM).

More sophisticated types of FEM surveys involve the use of multiple frequency or coil configurations. Surveys can be conducted on solid ground or in marine environments.

Each grouping of measurements for a location using a range of frequencies or coil configurations represents a "sounding". These results can be interpreted in terms of 1D layered earth models of electrical resistivity or electrical conductivity directly underneath the sensor.

Data can be obtained from very shallow depths to hundreds of feet in depth. FEM surveys can be conducted using grounded transmitters and receivers that measure magnetic or electric fields.

Interpreting data from multiple transmitters and receivers requires stitching together 1D inversion results or carrying out a full 3D inversion of the data.

Surveying using Time domain EM

Time domain EM (TEM) methods are similar to FEM methods, except that the current in a transmitter is a transient signal instead of being at a fixed frequency.

When the energy source is turned off, the TEM instruments record the secondary fields that still exist a few milli-seconds following the termination of the source signal. Although the physical principles for FEM and TEM surveys are similar, the instrumentation used to conduct the surveys differs.

As with FEM surveys, each TEM measurement is usually treated as a sounding. A number of measurements must be performed to produce a collection of soundings to be used for interpretation.

Borehole-type TEM surveys are commonly used for mineral exploration. As with all electrical and electromagnetic methods, TEM measurements yield datasets about variations in the earth's electrical resistivity or its reciprocal, electrical conductivity.

Surveying using VLF electromagnetics (EM)

The VLF (Very Low Frequency) band is a range of the electromagnetic spectrum that was originally used for very long distance communications from the pre-WWII era until the 90's.

Some of these radio transmitters are still operational, and these signals interact with shallow materials (within the upper 50 ft. to 150 ft.) in a way that can be measured with the proper instrumentation. This method can reliably detect buried metallic objects, and less reliably map the soil's variations in electrical resistivity.

Surveying using Resistivity cone penetrometer testing unit (RCPTU)

This technology involves the use of a system where an instrumented cone is pushed into the ground.

The electrical resistivity in the ground is measured using a system with four electrodes mounted behind the cone, which yields in-situ measurements of materials directly adjacent to the instrument.

Other useful geophysical parameters of the materials can be measured as well, such as shear strength, tip stress, fluid permeability, pore pressure, friction, shear wave velocity (using a surface source), and more.

Surveying using Other Methods

Other types of geophysical surveys include:

- *Borehole and crosshole geophysical methods* – involves using borehole readings as opposed to surface readings, in order to obtain deeper earth measurements
- *crosshole geophysical methods* - involves the use of multiple boreholes, with a seismic source, and multiple receivers (typically geophones), to obtain measurements in the soil regions between holes
- *Radiometric methods* – this method involves the investigation of radioactivity in ground materials

Surveying using Natural Source and controlled Source Magnetotelluric methods

This involves low frequency EM sources:

- *Spontaneous Potential methods* - involves the measuring of natural voltages occurring in the ground due to movement of fluids or chemical reactions between fluids and minerals.

Data Collection in Geophysical Surveying

Data Collection

Paying careful attention to the details in a survey, tailoring it to the target and to the environment, can avoid the collection of unnecessary data, and can also prevent drawing inconclusive or misleading interpretation of the data collected.

Quality control of the dataset performed onsite as part of the data collection methodology, with a careful review at the end of each site visit, is recommended.

Post Processing

The collecting of valid field data is only half of battle. The raw data must be carefully processed by an experienced geophysicist, in order to produce an accurate interpretation of the dataset, and to avoid misinterpreting false signals in the data.

Post-process of the data collected in one day in the field, can take days to complete in the office. The geophysical data collected, should be integrated with other sources of relevant site data, to produce an accurate interpretation meeting the needs of the client.

Data Collection and Visualization

Data interpretation and visualization software can be used in real time in the field to create a rough draft of the end result needed.

When combined with differential GPS for data location, delivering positional accuracy which exceeds a 0.25m tolerance, the software can eliminate the need to break the survey down into a number of rectilinear sub-areas, improving the efficiency of the data collected.

Quicker Surveying

Speed is often essential when collecting geophysical data. To speed up the collection process, often multiple types of geophysical datasets can all be collected simultaneously.

Using mobile instrument platforms mounted on versatile field vehicles such as ATV 4-wheelers, can also make the process go by much quicker.

GPS enabled, 4-wheel surveying
Image source: phoenix-llc

Chapter 3: Seismic Surveying

Seismic Waves

Seismic Methods

Seismic methods are the most commonly conducted geophysical surveys for engineering investigations. Seismic refraction provides engineers and geologists with the most basic of geologic data through simple procedures using common equipment.

Any mechanical vibration is initiated by a source and travels to the location where the vibration is logged (by the receiver). These vibrations are seismic waves. The vibration is merely a change in the stress state due to a disturbance. The vibration emanates in all directions that support displacement. The vibration readily passes from one medium to another and from solids to liquids or gases and in reverse.

Mechanical vs Electromagnetic Waves

Mechanical waves transport energy. This energy propagates in the same direction as the wave. Any kind of wave (mechanical or electromagnetic) has energy.

Mechanical waves can be produced only in media which possess elasticity and inertia. A mechanical wave requires an initial energy input. Once this initial energy is added, the wave travels through the medium until all its energy is transferred.

There are three types of mechanical waves:

- Transverse waves
- Longitudinal waves
- Surface waves

Transverse Waves

Transverse waves cause the medium to vibrate at a right angle to the direction of the wave or energy being carried by the medium. Transverse waves have two parts—the crest and the trough. The crest is the highest point of the wave and the trough is the lowest. The distance between a crest and a trough is half of wavelength. The wavelength is the distance from crest to crest or from trough to trough.

Longitudinal Waves

Longitudinal waves cause a medium to vibrate parallel to the direction of the wave. It consists of multiple compressions and rarefactions. The rarefaction is the farthest distance apart in the longitudinal wave and the compression is the closest distance together.

The speed of the longitudinal wave is increased in higher index of refraction, due to the closer proximity of the atoms in the medium that is being compressed. Sound is considered a longitudinal wave.

Surface Waves

This type of wave travels along a surface that is between two media. An example of a surface wave would be waves in a pool, or in an ocean, lake, or any other type of water body.

There are two types of surface waves, namely Rayleigh waves and Love waves:

- *Rayleigh wave* - also known as ground roll, are waves that travel as ripples with motion similar to those of waves on the surface of water. Rayleigh waves are much slower than body waves, roughly 90% of the velocity of body waves for a typical homogeneous elastic medium.
- *Love wave* - is a surface wave which has horizontal waves that are shear or transverse to the direction of propagation. They usually travel slightly faster than Rayleigh waves, about 90% of the body wave velocity, and have the largest amplitude.

Transmission of Waves in a Vacuum

Electromagnetic waves, in contrast to mechanical waves, require no medium but can still travel through one. A vacuum cannot support mechanical vibratory waves, while electromagnetic waves can be transmitted through a vacuum.

Direction of the Wave

The direction of travel is called the ray, ray vector, or ray path. Since a source produces motion in all directions the locus of first disturbances will form a spherical shell or wave front in a uniform material.

Types of Seismic Wave

Seismic waves are elastic waves that propagate in solid or fluid materials.

There are two major classes of seismic waves:

- *Body waves* - which pass through the volume of a material
- *Surface waves* - that exist only near a boundary

P-waves (pressure)

These are the fastest traveling of all seismic waves and are called compressional, pressure or primary wave (P-wave). The particle motion of P-waves is extension (dilation) and compression along the propagating direction.

P-waves travel through all media that support seismic waves; air waves or noise in gases, including the atmosphere. Compressional waves in fluids, such as water or air, are referred to as acoustic waves.

S-waves (shear)

The second wave type is the secondary or transverse or shear wave (S-wave). S-waves travel slightly slower than P-waves in solids. S-waves have particle motion perpendicular to the propagating direction, like the obvious movement of a rope as a displacement speeds along its length.

These transverse waves can only transit material that has shear strength. S-waves therefore do not exist in liquids and gases, as these media have no shear strength.

S-waves may be produced by a traction source or by conversion of P-waves at boundaries. The dominant particle displacement is vertical for SV-waves traveling in a horizontal plane. Dominant particle displacements are horizontal for SH-waves traveling in the vertical plane. SH-waves are often generated for S-wave refraction evaluations of engineering sites.

Wave Speed

Surface waves travel slower than P-waves and S-waves, because they are guided by the Earth's surface and their energy is thus trapped near the surface, their strength can be much greater than body waves.

Surface waves are strongly excited when their source is close to the surface, as in a shallow earthquake or a near surface explosion.

Seismic Reflection

Seismic Reflection Method

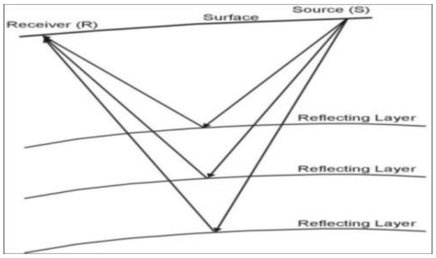
Reflection seismology (or seismic reflection) is a survey method that uses the principles of seismology to estimate the properties of the Earth's subsurface from reflected seismic waves.

The method requires a controlled seismic source of energy, such as a dynamite blast, a specialized air gun or a seismic vibratory instrument. Reflection seismology is similar to sonar and echolocation.

The reflection process

The physical process of reflection is shown below (image), as the ray travels through successive layers. There are usually several layers beneath the earth's surface that contribute reflections to a single seismogram.

The advantage of seismic reflection data is that it permits mapping of many horizon or layers with each shot.



Process of reflection
Image source: EPA

Applications

Reflection seismology is used extensively in a number of fields and applications; such as:

- Various near-surface engineering and environmental surveys
- coal and mineral exploration
- geothermal energy surveys
- hydrocarbon exploration
- crustal studies

Similar to GPR

Ground-penetrating radar which uses electromagnetics instead of elastic waves, and has a smaller depth of penetration, is similar in nature to reflection seismology.

Environmental impact

Seismic reflection surveying methods have some degree of impact on the environment, especially when used in marine applications.

The sonic waves can damage fish with air bladders, destroy marine wildlife eggs and larvae, and incite fish and other marine species to temporarily migrate away from the affected area.

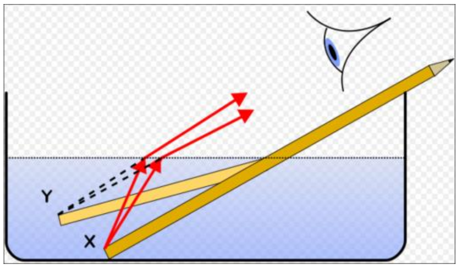
Seismic Refraction

Refraction

Refraction is the change in direction of wave propagation due to a change in its transmission medium (such as light wave travel from water to air).

The phenomenon is explained by the conservation of energy and the conservation of momentum. Due to the change of medium, the phase velocity of the wave is changed but its frequency remains constant.

This is most commonly observed when a wave passes from one medium to another at any angle other than 0° from the normal (see image below).



Pencil appears to bend at air/water interface
Image source: Wikipedia

Refraction of light is the most commonly observed phenomenon, but any type of wave can refract when it interacts with a medium, for example when sound waves pass from one medium into another or when water waves move into water of a different depth.

Seismic Refraction

Used in geophysical surveying, seismic refraction traverses (seismic lines) are conducted using one or more seismographs and/or geophones, in an array, with an energy source.

The seismic refraction method utilizes the refraction of seismic waves on geologic layers and rock/soil units in order to characterize the subsurface geologic conditions and geologic structure.

Subsurface analysis relies on the fact that seismic waves have differing velocities in different densities of soil or rock. In addition, the waves are refracted when they cross the boundary between different soil and rock stratum.

P-Wave Refraction (a.k.a. Compression Wave Refraction)

P-wave refraction evaluates the compression wave generated by the seismic source located at a known distance from the array.

The wave source is generated from various means such as vertically striking a striker plate with a sledgehammer, shooting a seismic shotgun into the ground, or detonating an explosive charge in the ground.

Since the compression wave is the fastest of the seismic waves, it is sometimes referred to as the primary wave and is usually more-readily identifiable within the seismic recording as compared to the other seismic waves.

S-Wave Refraction (a.k.a. Shear Wave Refraction)

S-wave refraction evaluates the shear wave generated by the seismic source located at a known distance from the array.

The wave is generated by horizontally striking an object on the ground surface to induce the shear wave. Since the shear wave is the second fastest wave, it is sometimes referred to as the secondary wave.

When compared to the compression wave, the shear wave is approximately one-half the velocity depending on the medium.

Downhole Seismic Testing

Downhole Seismic Testing

This technique measures vertical changes in seismic velocity by placing a seismic source at the top of a borehole and using a geophone to measure the travel times at different intervals in the borehole.

A geophone (image below) is a device that converts ground movement (velocity) into voltage, which may be recorded at a recording station.

The deviation of this measured voltage from the base line is called the seismic response and is used to analyze the structure of the subsurface.

SM-24 Geophone

Image source: Wikipedia

Common applications include:

- Bridge/dam foundation analysis
- Insitu materials testing
- Soil and rock mechanics
- Earthquake engineering
- Liquefaction analysis

Compared with the crosshole method

Although similar to the crosshole seismic method (covered in the following page of this chapter) in that a borehole is used, with this survey method the seismic source remains on the surface.

This means that the raypaths are mostly redundant from one geophone depth to the next, with a difference in travel time with depth. Thus the downhole method is a lower-resolution approach than crosshole.

On the other hand, the data analysis is relatively straightforward compared to crosshole, and much less prone to error.

Crosshole Seismic Method

Crosshole seismic method

The primary goal of obtaining crosshole data is to obtain the most detailed insitu seismic wave velocity profile for site-specific investigations and material characterization.

Crosshole velocity data are valuable for assessing man-made materials, soil deposits, or rock formations. Crosshole geophysical testing is generally conducted in the near surface (upper hundred yards) for site-specific engineering applications.

P and S waves

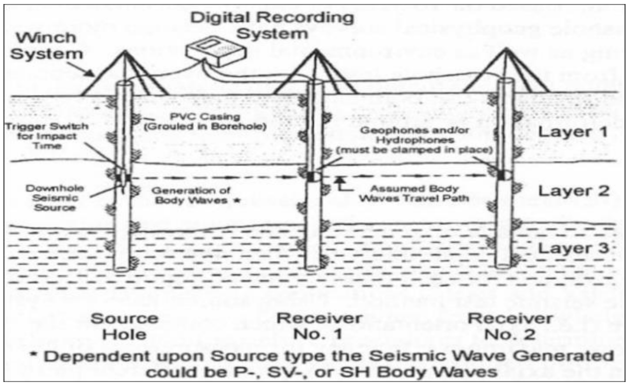
The seismic technique determines the compressional (P-) and/or shear (S-) wave velocity of materials at depths of engineering and environmental concern where the data can be used in problems related to soil mechanics, rock mechanics, foundation studies, and earthquake engineering.

Crosshole testing takes advantage of generating and recording (seismic) body waves, both the P- and S-waves, at selected depth intervals where the source and receiver(s) are maintained at equal elevations for each measurement. The image below shows a general field setup for the crosshole seismic test method.

Using source-receiver systems with preferential orientations in tandem (i.e., axial orientations, which complement the generated and received wave type/signal) allows maximum efficiency for measurement of in situ P- or S-wave velocity depending on the axial orientation.

Due to the different particle motions along the seismic ray path, it is crucial to use optimal source-receiver systems in order to best record crosshole P- or S-waves.

Because only body waves are generated in the source borehole during crosshole tests, surface waves (ground roll) are not generated and do not interfere with the recorded body-wave seismic signals.



Crosshole seismic method
Image source: EPA

Seismic Tomography

Science of Tomography

Tomography is imaging by sections or sectioning, through the use of any kind of penetrating wave. A device used in tomography is called a tomograph, while the image produced is a tomogram.

This investigative methodology has a wide range of scientific applications such as:

- Radiology
- Archaeology
- Biology
- atmospheric science
- geophysics
- oceanography
- plasma physics
- materials science
- astrophysics
- quantum information
- and many other areas of science

Seismic Tomography

Seismic tomography is a geophysical surveying method for imaging the subsurface of the Earth with seismic waves, produced by earthquakes or explosions.

P-, S-, and surface type waves can be used for tomographic modeling of varying resolutions based on seismic wavelength, wave source distance, and the seismograph array coverage.

The data received at seismometers are used to solve an inverse problem, wherein the locations of reflection and refraction of the wave paths are determined.

This solution can be used to create 3D images of velocity anomalies which may be interpreted as structural, thermal, or compositional variations. These images are used to better understand core, mantle, and plate tectonic conditions.

Applications

Seismic tomographic imaging can depict the following subsurface parameters:

- anisotropy (different properties in different directions)
- anelasticity (no definite relation between stress and strain)
- density
- bulk sound density

By observing thermal or chemical based variations in these parameters, subsurface processes such as mantle plumes (volcanic regions), subducting slabs (tectonic boundaries), and mineral phase changes can be identified.

Larger scale features that can be imaged with tomography include the high velocities beneath continental shields and low velocities under ocean spreading centers.

Limitations

Global seismic networks are still concentrated on continents and in seismically active regions. Most of the oceans throughout the world, particularly in the southern hemisphere, are under-covered.

The type of wave used in a model limits the resolution it can achieve. Longer wavelengths are able to penetrate deeper into the earth, but can only be used to resolve large features.

Finer resolution can be achieved with surface waves, with the tradeoff is that they cannot be used in models of the deep mantle layer of the Earth.

Seismic tomography provides only the current velocity anomalies, with tomographic solutions being non-unique.

Although statistical methods can be used to analyze the validity of a model, unresolvable uncertainty remains. This adds to the difficulty in comparing the validity of different model results.

Limitations in computing power inhibit the quantities of seismic data, unknowns, and iterations in tomographic models; with a reduction in mesh size.

This is of particular importance in ocean basins, which due to limited network coverage and earthquake density require more complex processing of distant data. Shallow oceanic models also require smaller model mesh size due to the thinner crust.

Tomographic images are typically presented with a color ramp representing the strength of the anomalies. This has the consequence of making equal changes appear of differing magnitude based on visual perceptions of color, such as the change from orange to red being more subtle than blue to yellow.

The degree of color saturation can also visually skew interpretations. These factors should be considered when analyzing images

Marine Seismic Surveying

Marine Seismic Methods

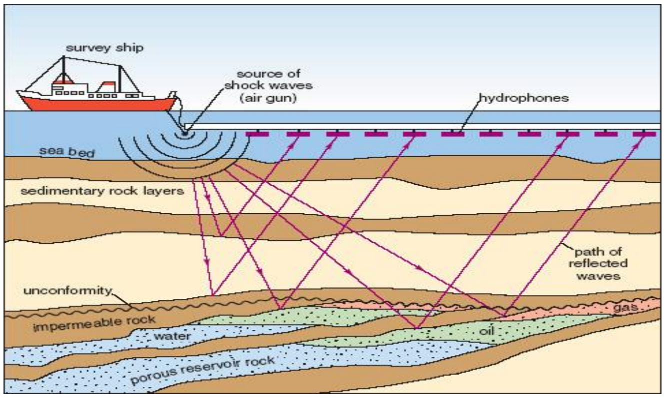
Seismic methods used in marine applications, have basically the same principals of operation as ground based seismic surveying.

The principals of operation being: a device which generates a sound wave is used to transmit the sound wave into a medium such as earth, while receiving devices measure the amplitude and arrival times of the returned (reflected or refracted) signals.

Differences between surface and marine methods

There are major variations between surface and marine surveys in the practical applications of field techniques, equipment, and geographic control.

With marine surveying, the instrumentation is generally a towed transmitter and array of geophones (see image below).



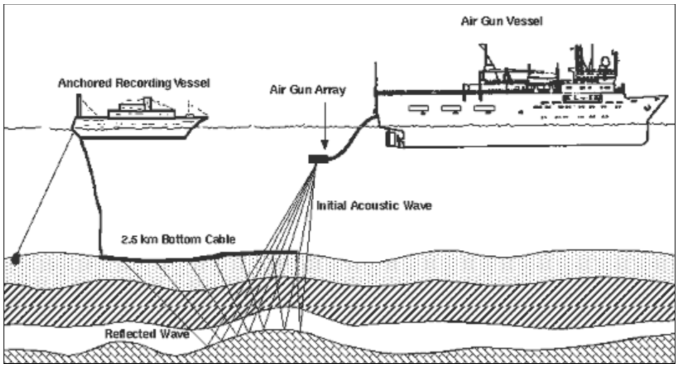
Basic application of seismic data acquisition in a marine application

Image source: EPA

Shallow water seismic surveying

In some shallow water applications, a specialized array that rests on the ocean floor during acquisition is used (see image below).

With the difficulty associated with establishing straight survey lines while in a vessel on a body of water, and with the necessity to image deep structures, this type of field equipment can be cumbersome.



Technique for ocean floor seismic data acquisition
Image source: EPA

Positional Control

Positional control is provided by GPS where the GPS sensor is mounted on the vessel towing the magnetometer, with a constant offset equal to the distance from the GPS sensor to the geophone array.

Types of Seismic Sources

A number of seismic sources are available for marine applications, with varying frequencies of operation:

- Water gun (20-1500 Hz)
- Air Gun (100-1500 Hz)
- Sparkers (50-4000 Hz)
- Boomers (300-3000 Hz)
- Chirp Systems (500 Hz-12 kHz, 2-7 kHz, 4-24 kHz, 3.5 kHz, and 200 kHz)

The greatest resolution of near surface structure is generally obtained from the higher frequency sources such as the Chirp systems, while the lower frequency source types tend to better characterize structure at greater depths.

Chapter 4: Gravitational Surveying

Gravitational Anomalies

Earth - The Imperfect Sphere

To understand gravitational surveying methodologies, one must first comprehend the concept of a gravitational anomaly.

If the Earth were a featureless, homogenously perfect sphere of constant density and shape, then gravity would be constant throughout the world.

However, this is not the case, as the Earth has a very imperfect mantle and crust.

Gravity Anomaly Maps and the Geoid

The Earth's gravity field is depicted in two principal ways:

- gravity anomaly maps
- maps of the Earth's geoid

Gravity anomaly maps (see image) show how much the Earth's actual gravity field differs from the gravity field of a uniform, featureless Earth surface.

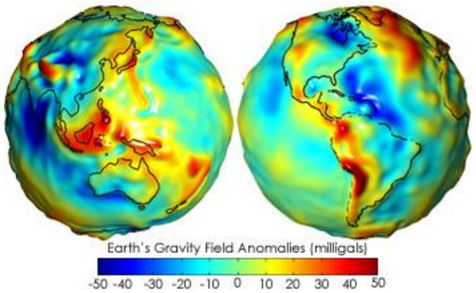
The anomalies highlight variations in the strength of the gravitational force over the surface of the Earth.

Gravity Anomalies

Gravity anomalies are often due to unusual concentrations of mass in a region. For example, the presence of mountain ranges will usually cause the gravitational force to be more than it would be on a featureless planet.

Observe in the map below, the areas of red in the Rocky Mountain region, of the Midwestern US.

Conversely, the presence of ocean trenches or the depression of the landmass that was caused by the presence of glaciers or by depressions from asteroid strikes occurring long ago can cause negative gravity anomalies.



Map of the Earth's gravitational anomalies
Image source: NASA

The "geoid" Hypothetical Model

The geoid is a hypothetical Earth surface that represents the mean sea level in the absence of winds, currents, and most tides.

The geoid is a useful reference surface, which defines the horizontal surface plane upon which gravity acts perpendicular.

Common alignment references to the Geoid:

- A carpenter's level aligns itself along the geoid's horizontal plane
- A carpenter's plumb bob aligns perpendicular (90 degrees) to the geoid
- Water will not flow in pipes which are perfectly aligned along the geoid
- Surveyors use knowledge of the geoid and the horizontal when they lay out highways and boundaries

Measuring Gravity and Gravimetry

Measuring gravity (absolute vs. relative)

To accurately measure gravity, requires an instrument called a gravity meter or gravimeter. There are two types of gravimeters: relative and absolute.

Absolute gravimeters

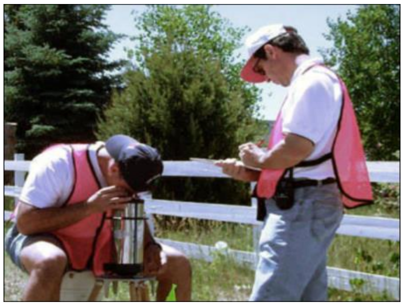
Absolute gravimeters (see image below) measure the local gravity in absolute units, called gals. These instruments tend to be large, cumbersome, and quite pricey.

Absolute gravimeter
Image source: NOAA

Relative Gravimeters

For field surveys it is more practical to use a relative gravimeter, which is cheaper, more rugged, and easier to handle in the field. However, they do not measure the absolute value of gravity, but can only measure the differences in gravity from one point to another.

Relative gravimeters must be calibrated at a location where the gravity is known accurately, and then transported to the location where the gravity is to be measured. They measure the ratio of the gravity at the two points.



Surveyors using a Worden relative gravimeter
Image source: New Mexico Tech

The Worden gravimeter (shown in the image above) is an entirely mechanical and optical instrument, which relies on a AA battery to illuminate the crosshairs.

It uses a fixed length spring and mass attached to a calibration spring and vernier scale to measure gravitational acceleration.

Relative gravity meters are essentially a mass hung on a spring: if you go to somewhere where gravity is a bit larger, the spring stretches a bit more. This stretch is miniscule, and in order to measure it, requires pulling on the spring with a micrometer screw to restore the mass to the original position.

Levers are used to make the system more sensitive and the whole mechanism is enclosed in a temperature-controlled housing to prevent changes in temperature from affecting the reading.

Gravimeters vs. Accelerometers

Gravimeters are a type of accelerometer, specialized for measuring the constant downward acceleration of gravity, which varies by about 0.5% over the surface of the Earth.

Though the essential principle of design is the same as in other accelerometers, gravimeters are typically designed to have a higher degree of sensitivity in order to measure minimal variations within the Earth's gravity of 1 g, caused by nearby geologic structures or the shape of the Earth and by temporal tidal variations.

This sensitivity means that gravimeters are susceptible to extraneous vibrations including noise that tend to cause oscillatory accelerations. In practice this is counteracted by integral vibration isolation and signal processing.

The constraints on temporal resolution are usually less for gravimeters, so that resolution can be increased by processing the output with a longer time constant.

Gravimeters display their measurements in units of gals (cm/s2), instead of more common units of acceleration.

Gravimetry

Gravimetry is the measurement of the strength of a gravitational field. Gravimetry may be used when either the magnitude of gravitational field or the properties of matter responsible for its creation need to be analyzed.

Gravimetry is used for petroleum and mineral prospecting, seismology, geodesy, geophysical surveys and other geophysical research, and for metrology.

Gravity Gradiometry

Gravity Gradiometry

This is the study and measurement of variations in the acceleration due to gravity, with the gravity gradient being the spatial rate of change of gravitational acceleration.

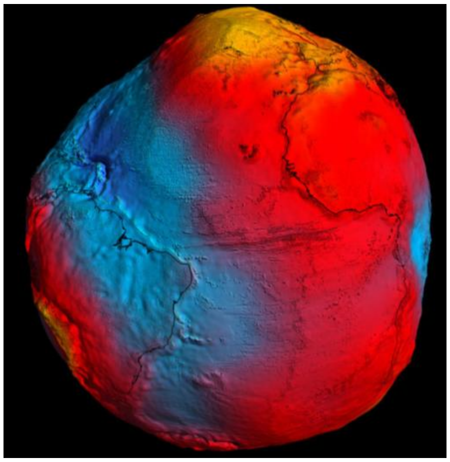
Applications

Gravity gradiometry is used in hydrocarbon and mineral exploration surveying to image the subsurface geology, and to measure the density of the subsurface and rate of change of rock properties.

From this information it is possible to build a picture of subsurface anomalies which can then be used to more accurately target oil, gas and mineral deposits. It is also used to image water column density, when locating submerged objects, or determining water depth (bathymetry).

These types of surveys highlight gravity anomalies that can be related to geological features such as Salt diapirs, Fault systems, Reef structures, Kimberlite pipes, etc.

Other applications include tunnel and bunker detection and a recent (ESA) European Space Agency GOCE mission, aimed at improving our understanding of ocean circulation.



ESA's GOCE mission delivered the most accurate model of the 'geoid' ever produced
Image source: ESA

Measuring the Gravity Gradient

Gravity measurements are a reflection of the earth’s gravitational attraction, its centripetal force, tidal accelerations due to the sun, moon, and planets, and other applied forces.

Gravity gradiometers measure the spatial derivatives of the gravity vector.

Chapter 5: Magnetic and Electromagnetic Surveying

Magnetometers

Magnetometers

A magnetometer is an instrument that measures magnetism, either magnetization of magnetic material like a ferromagnet, or the direction, strength, or the relative change of a magnetic field at a particular location.

A compass is likely the simplest form of a magnetometer, which measures the direction of an ambient magnetic field.

Magnetometers are widely used for measuring the Earth's magnetic field and in geophysical surveys to detect magnetic anomalies of various types. They are also used in the military applications for detecting submarines.

Some countries, have classified the more sensitive magnetometers as military technology, thus controlling their use and distribution.

Use in Integrated Circuitry

Recently, magnetometers have been miniaturized to the extent that they can be used in integrated circuits at very low cost, and are finding increasing applications as compass features built into everyday devices such as mobile phones and tablets.

Types of Survey Magnetometers

Survey magnetometers can be divided into two basic types:

- *Scalar magnetometers* - measure the total strength of the magnetic field to which they are subjected, but not its direction.
- *Vector magnetometers* - have the capability to measure the component of the magnetic field in a particular direction, relative to the spatial orientation of the device.

Scalar magnetometers:

- Proton precession magnetometer
- Overhauser effect magnetometer
- Caesium vapor magnetometer
- Potassium vapor magnetometer
- Vector magnetometers:
- Rotating coil magnetometer
- Hall effect magnetometer
- Magnetoresistive devices
- Fluxgate magnetometer
- SQUID magnetometer
- Spin-exchange relaxation-free (SERF) atomic magnetometers

Uses

Magnetometers have a wide range of applications, including locating of:

- submerged objects such as submarines and sunken ships
- hazards for tunnel boring machines
- hazards in coal mines
- unexploded ordnance and toxic waste drums
- ferrous mineral deposits and geological structures

They also have applications in heart beat monitors, weapon systems positioning, sensoring for anti-locking brakes, weather prediction (via solar cycles), steel pylons, drill guidance systems, archaeology, plate tectonics and radio wave propagation and planetary exploration.

Depending upon the geophysical surveying application, magnetometers can be:

- mounted on spacecraft or aircraft (fixed wing magnetometers)
- mounted on helicopters (stinger and bird)
- used on foot (backpack)
- towed at a distance behind quad bikes or snowmobiles (sled or trailer)
- lowered into boreholes (tool or probe)
- towed behind boats (towfish)

Aeromagnetic Survey

Airborne magnetic or gradiometric surveying

An aeromagnetic survey is a common type of geophysical survey conducted using a magnetometer mounted on or towed behind an aircraft. The principle is similar to a magnetic survey carried out with a common hand-held magnetometer, but is able to perform a survey of a much larger area.

The aircraft's flight path is typically a grid-like pattern with the grid's height and line spacing determining the resolution of the data and cost of the survey per unit area.

Aeromagnetic surveying is one of the most common types of airborne survey conducted for the exploration of mineral and hydrocarbon resources.

Regional and Detailed Surveying

Airborne methods are usually the most cost effective tools available for both large regional recon surveys for geological mapping and for locating target areas for more detailed follow-up.

Generally, aeromagnetic surveys are subdivided into two classes:

- Regional
- Detailed

Regional Surveys

Usually have a relatively wide traverse line spacing of 1500 ft. or more.

This type of survey is usually conducted for applications such as:

- Geological mapping
- Used to supplement in the mapping of lithology and structure in hard rock environments
- For mapping basement lithology and structure in sedimentary basins or for regional tectonic studies
- Depth to Basement mapping for exploration of petroleum, coal and other non-metallic resources in sedimentary basins.

Detailed Surveys

These consist of a line spacing of less than 1500 ft., and are conducted for various applications such as *direct* and *indirect* prospecting.

Direct Prospecting

For exploration of magnetic ores such as:

- magnetic iron ores
- chromium
- asbestos-bearing ultramafic rocks
- kimberlites

Indirect Prospecting

Used in combination with other methods or as a stand-alone method for:

- discriminating between metallic and non-metallic conductors
- aiding in interpretation of body geometry and depth
- determining the geologic environment of the source, locate specific "basement targets"
- for investigation using seismic methods in deep hydrocarbon exploration
- defining the "regional" field for gravity interpretation in sedimentary basins
- mapping of weak magnetic lineations related to faulting within the sedimentary section in some hydrocarbon plays

UAV and UAS-based Surveying

Unmanned Aerial Vehicles or Unmanned Aircraft Systems are quickly taking over most forms of airborne surveying practice.

Because of their low cost of operation and initial purchase, their programmability, improving payload capacities, and the ability to be operated from the safety of the ground, they are a highly desirable alternative to the use of small aircraft and helicopters for airborne surveying.

Magnetotellurics

Magnetotellurics

Magnetotellurics (MT) is an electromagnetic geophysical method for deriving the earth's subsurface electrical conductivity based on measurements of natural geomagnetic and geoelectric field variations at the Earth's surface.

MT is now an international academic discipline which is used in exploration surveys around the world.

Subsurface Depth Ranges

Investigative depths range from roughly 1000 ft. below the surface, down to 30,000 ft. or deeper by recording higher frequencies with long-period soundings.

Initial Development

The magnetotelluric technique was first introduced independently by Japanese scientists in the 1940s; then later, by Russian geophysicist Andrey Nikolayevich Tikhonov in 1950, and the French geophysicist Louis Cagniard in 1953.

With advances in instrumentation, processing and modelling, MT has become one of the most important tools in deep Earth research.

Since first being created in the 1950s, magnetotelluric sensors, receivers and data processing techniques, like other trends in survey electronics, have become less expensive, more advanced, and with more functionality with each subsequent generation.

Advances in MT instrumentation and techniques have mirrored advances in other survey technologies with:

- the shift from analog to digital hardware
- the advent of remote referencing
- GPS time-based synchronization
- 3D data acquisition and processing

MT can investigate where seismic can not
At its basic level of interpretation, resistivity correlates with varying types of rock.

High-velocity layers are typically highly resistive, whereas sediments, which are porous and permeable, are typically much less resistive.

While high-velocity layers are an acoustic barrier and make seismic exploration ineffective, their electrical resistivity means the magnetic signal passes through almost unimpeded.

This allows MT to investigate deep beneath these acoustic barrier layers, complementing the seismic data and assisting interpretation.

Resistivity data

MT exploration surveys are conducted to acquire resistivity data which can then be evaluated to create a 3D model of the subsurface.

Data is acquired at each sounding location for a given period of time, with physical spacing between soundings dependent on the target size and geometry, local terrain constraints and financial cost.

Reconnaissance surveys can be spaced in intervals of several miles, while more detailed work can have 500 ft. intervals, or even adjacent soundings (dipole-to-dipole).

Commercial applications include:

- hydrocarbon (oil and gas) exploration
- geothermal exploration
- carbon sequestration
- mining exploration
- hydrocarbon and groundwater monitoring

Research applications include:

- experimentation to further develop the MT technique
- long-period deep crustal exploration
- deep mantle probing
- earthquake precursor prediction research

Oil and Gas exploration

When used for hydrocarbon exploration, MT is normally used as a supplemental method for the principal technique of “reflection seismological” exploration.

While seismic imaging can image subsurface structure, it cannot detect the changes in resistivity which is associated with hydrocarbon and hydrocarbon-bearing formations.

MT is able to detect resistivity variations in subsurface structures, which can detect the differences between structures which bear hydrocarbons and those that do not.

Mining and mineral exploration

MT is useful in detecting various base metals such as nickel, diamonds and other precious metals, as well as for kimberlite mapping.

Other commercial and research applications
MT is also used for:

- crustal research
- earthquake precursor prediction research
- geothermal development
- groundwater exploration and mapping
- hydrocarbon reservoir monitoring
- deep investigation (60 miles and more) of the electrical properties of the bedrock for high-voltage direct current (HVDC) transmission systems
- carbon dioxide sequestration
- other environmental engineering applications such as nuclear blast site monitoring, and nuclear waste disposal site monitoring

Low Environmental and safety Impacts

The environmental and safety impacts of MT exploration are minimal, because of light-weight equipment, natural signal sources, and reduced hazards compared to other types of exploration such as with drilling, explosives, or high electrical current methods.

Survey Equipment

A typical full suite of MT equipment for a five component (sensor) sounding consists of a receiver instrument with five sensors (three magnetic sensors, which are typically induction coil sensors, and two telluric electric sensors.)

For long-period MT (frequencies below approximately 1–10 Hz), the three discrete magnetic field sensors can typically be replaced with a single compact triaxial fluxgate magnetometer. In many situations, only the telluric sensors will be used, and magnetic data borrowed from other nearby soundings to reduce acquisition costs.

Magnetotelluric suite
Image source: wikipedia

Deployment

A complete five-component set of MT equipment can be backpacked in by a small field team (2 to 4 persons) or carried by light aircraft, allowing deployment in many remote and rugged areas.

Most MT equipment is capable of reliable operation over a wide range of environmental conditions, with ratings of typically −20 °C to +45 °C, from dry desert to high-humidity (condensing) and partial immersion.

Ground Penetrating Radar (GPR)

GPR

Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface conditions.

This nondestructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures.

GPR unit - ground-based antenna
Image source: Ditch Witch

Mediums

GPR can have applications in a variety of mediums including rock, soil, ice, fresh water, pavements and structures.

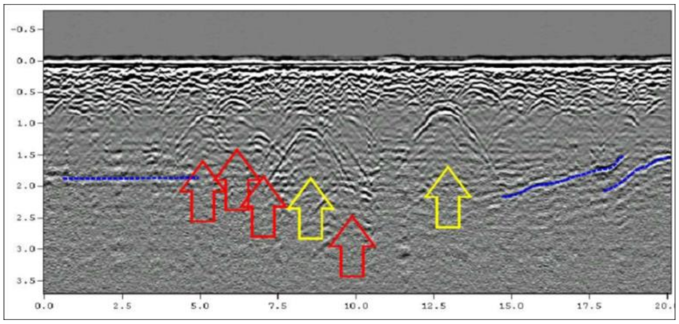
Under the right conditions, GPR can be used to detect subsurface objects, changes in material properties, and voids and cracks.

Principles of GPR

The principles of operation for a GPR are similar to seismology, except GPR methods implement electromagnetic energy rather than acoustic energy, and energy may be reflected at boundaries where subsurface electrical properties change rather than subsurface mechanical properties; as is the case with seismic energy.

GPR uses high-frequency, usually polarized radio waves, typically in the range of 10 MHz to 2.6 GHz. A GPR transmitter emits electromagnetic energy into the ground.

When the energy encounters a buried object or a boundary between materials having different permittivities, it may be reflected or refracted or scattered back to the surface. A receiving antenna can then record the variations in the return signal.



GPR radargram from a historic cemetery.
Image source: wikipedia

In the image above, hyperbolic arrivals (arrows) indicate the presence of diffractors buried beneath the surface; possibly associated with human burials. Reflections from soil layering are also present (dashed lines.)

Limiting Conditions

The electrical conductivity of the ground, the transmitted center frequency, and the radiated power all may limit the effective depth range of GPR investigation.

Increases in electrical conductivity attenuate the introduced electromagnetic wave, and thus the penetration depth decreases.

High vs low Frequencies

Because of frequency-dependent attenuation mechanisms, higher frequencies do not penetrate as far as lower frequencies. However, higher frequencies may provide improved resolution. Thus operating frequency is always a trade-off between resolution and penetration.

Optimal depth of subsurface penetration is achieved in ice where penetration can achieve several thousand meters in depth when used at low GPR frequencies.

Penetration Depths

Dry sandy soils or massive dry materials such as granite, limestone, and concrete tend to be resistive rather than conductive, and the depth of penetration could be up to 50 ft.

In moist and/or clay-laden soils and materials with high electrical conductivity, penetration may be as little as a few centimeters.

Antennas on the ground and in the air

Ground-penetrating radar antennas are generally in contact with the ground for the strongest signal strength; though GPR air-launched antennas can also be used above the ground.

Cross borehole GPR

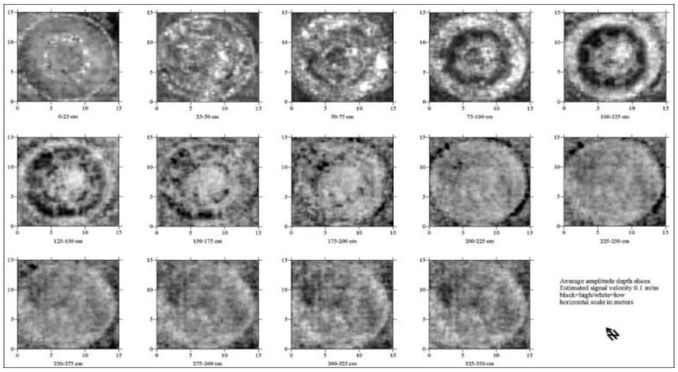
Cross borehole GPR has developed within the field of hydro-geophysics to become a valuable means of assessing the presence and amount of subsurface groundwater.

History of GPR

The first patent for a system designed to use continuous-wave radar to locate buried objects was submitted by Gotthelf Leimbach and Heinrich Löwy in 1910, following soon after the first patent for radar technology.

A patent for a system using radar pulses rather than a continuous wave was filed in 1926 by Dr. Hülsenbeck, leading to improved depth resolution. Further developments in the field were limited until the 70s, when military applications began driving the research.

Commercial applications followed with the first affordable consumer equipment being available in 1985.



GPR radar depth slices of an underground structure
Image source: Wikipedia

The image above, shows plan view maps isolating specific depths, constructed from many lines of data collected at close intervals. The structure depicted is a crypt at a historic cemetery.

Limitations of GPR

The most significant performance limitation of GPR is in high-conductivity materials such as clay soils and soils that are salt contaminated. Performance is also limited by signal scattering in heterogeneous conditions such as rocky soil types.

Other disadvantages of currently available GPR systems include:

- Interpretation of radargrams is generally non-intuitive to the novice.
- Considerable expertise is necessary to effectively design, conduct, and interpret GPR surveys.
- Relatively high energy consumption can be problematic for extensive field surveys.

Radar is sensitive to changes in material composition; detecting changes requires movement.

When looking through stationary items using surface-penetrating or GPR, the equipment needs to be moved in order for the radar to examine the specified area by looking for differences in material composition.

While GPR can identify items such as pipes, voids, and soil, it cannot identify the specific materials, such as gold and precious gems. It can however, be useful in providing subsurface mapping of potential gem-bearing pockets.

The readings can be confused by moisture in the ground, and they can't separate gem-bearing pockets from the non-gem-bearing ones.

Very-Low-Frequency (VLF) Methods

VLF Methods

VLF survey methods use a very low frequency, radio communication signal to determine electrical properties of shallow bedrock and near-surface soils. Used primarily as a reconnaissance tool, VLF profiles can be run quickly and affordably to identify areas with anomalies, which may call for further investigation by other types of surveys, or by drilling and sampling. This technique is especially useful for mapping steeply dipping structures such as faults, fractures and shallow areas of potential mineralization.

Ranges of depth of investigation vary, from:
4-5 meters in conductive soils
40-60 meters in highly-resistive soils

Basic Principle of VLF

A “very low frequency,” in relation to other radio communication ranges, is from about 15 to 25 kHz. In relation to other frequency ranges used in geophysical exploration, these are actually very high frequencies.

The VLF method uses powerful remote radio transmitters which have been established for military communications. The VLF method uses fairly simple instruments and serves as a useful recon surveying tool.

These radio transmitters are extremely powerful, inducing electric currents in conductive bodies, thousands of miles away. Under normal conditions, the fields produced are relatively uniform in the far field at a large distance from the transmitters.

The induced currents produce secondary magnetic fields that can be detected at the surface through deviation of the normal radiated field.

Signal Propagation

The radiated field from a remote VLF transmitter, propagating over a uniform or horizontally layered earth and measured on the earth's surface, consists of a vertical electric field component and a horizontal magnetic field component, each perpendicular to the direction of propagation.

Suitable Mediums

The high frequency of VLF transmitters means that in more conductive environments, the exploration depth is fairly shallow.

The presence of conductive overburden (upper soil stratum) can suppress the response from underlying conductors, and relatively small variations in overburden conductivity or thickness can themselves generate significant VLF anomalies.

Thus, VLF is more effective when the host rock is resistive, and the overburden is thin.

Some weaknesses of VLF surveys:

- may be biased by topographical effects that are difficult to cull from the data
- sensitive to interference from buried pipes, and other linear, conductive objects
- some ionospheric conditions might compromise the quality of the data
- military VLF transmitters can be subject to random outages

Transient Electromagnetics (TEM/TDEM)

Transient Electromagnetics

Transient electromagnetics, which is also called time-domain electromagnetics (TDEM), or pulse EM, is a geophysical exploration technique in which electric and magnetic fields are induced by transient pulses of electrical current; with the subsequent decay response being measured.

TEM methods are generally able to determine subsurface electrical properties, but are also sensitive to subsurface magnetic properties in applications like UXO detection and characterization.

TEM surveys are a commonly used surface EM technique for mineral exploration, groundwater exploration, and for environmental mapping, used throughout the world in both onshore and offshore applications.

Physical Principles

Two fundamental electromagnetic principles are needed to derive the physics behind TEM surveys:

- Faraday's law of induction
- Lenz's Law

A loop of wire is generally energized by DC current; then at a given time (t0) the current is quickly halted. Faraday's law dictates that a nearly identical current will be induced in the subsurface to preserve the magnetic field produced by the original current (eddy currents).

Due to ohmic losses, the induced surface currents dissipate, causing a change in the magnetic field, which induces subsequent eddy currents.

The net result is a downward and outward diffusion of currents in the subsurface which appear as an expanding smoke ring when the current density is contoured.

These currents produce a magnetic field by Faraday's law. At the surface, the change in magnetic field (or flux) with time is measured. The way the currents diffuse in the subsurface is related to the conductivity distribution in the ground.

This is a basic overview of the physical principles involved in TEM. When conductive bodies are present, the diffusion of the transients is changed. In addition, transients are induced in the conductive bodies as well.

TEM instrumentation and sensors

TEM systems consist of a transmitter instrument, transmitting coil or transmitting wire, receiver coil or antenna, and receiver instrument.

Depending on subsurface resistivity, current induced, receiver sensitivity and transmitter-receiver geometry, TEM measurements allow geophysical exploration from a few yards beneath the surface to several hundred yards of depth.

Power supply requirements:

- Low-power TEM instrumentation can operate using common C-cell batteries
- Mid-range systems (approx. 2.5 kW) can operate with automotive batteries
- High power systems (20 kW to around 150 kW) will require a generator to provide the necessary current for deep investigations

Commercial applications:

- Mining (mineral location and characterization)
- Groundwater characterization
- HVDC injection point mapping
- Oil and gas exploration

Magnetic Resonance Sounding (MRS)

Magnetic Resonance Sounding

This method works on the same principles as Magnetic Resonance Imaging (MRI). However, as opposed to scanning a human body for hydrogen nuclei, MRS stratifies the subsurface with respect to water content and hydraulic conductivity.

MRS has a maximum penetration depth to roughly 450 ft. and can potentially measure 1 or 2 sites in a day.

Principles of Operation

MRS technology relies on a property known as “spin”, which causes the hydrogen nuclei in water to behave like magnets. When influenced by the Earth’s magnetic field, the hydrogen nuclei will align themselves in a similar fashion as compass needles do, pointing in the direction of earth magnetic field.

An electromagnetic pulse is then induced within a cable loop, turning the magnetization of the hydrogen nuclei in the resulting field direction.

When the pulse is ended, the magnetization of the hydrogen nuclei turns back to the Earth’s magnetic field direction, while creating a secondary relaxation field.

Estimating water content in the soil

The relaxation signal is measured in the same loop, where the initial amplitude is directly proportional to the quantity of water in the ground, while the decay time is related to the ground permeability.

The depth of investigation is a function of the coil's diameter. By gradually increasing the pulse moment, water content and hydraulic conductivity distribution with depth can then be estimated.

Pros

The advantage of magnetic resonance sounding (MRS) in comparison to other types of geophysical methods is that MRS can directly measure the water content and estimate the hydraulic conductivity in the ground.

In addition, access to pumping test data makes it possible to estimate the transmissivity and storage coefficients of groundwater.

Cons

Electromagnetic noise, magnetic rocks and sediments tend to complicate the measurements; while the instrument is heavy and bulky (see image below), making it difficult to maneuver and transport in the field.

MRS suite
Image source: Geovista AB

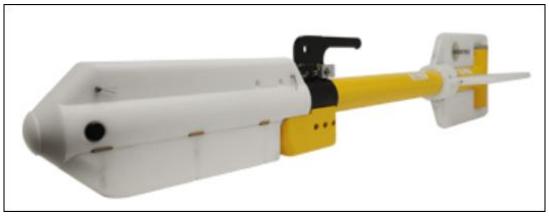
Marine Magnetic Methods

Marine Magnetic Methods

Magnetic methods which are used in marine applications have few differences in their theory of operation, from surface magnetic surveys.

The instrument measures the magnetic field of the earth at each measurement location. However, the practical applications of field techniques, field equipment, and geographic control can vary greatly between the two forms of surveys.

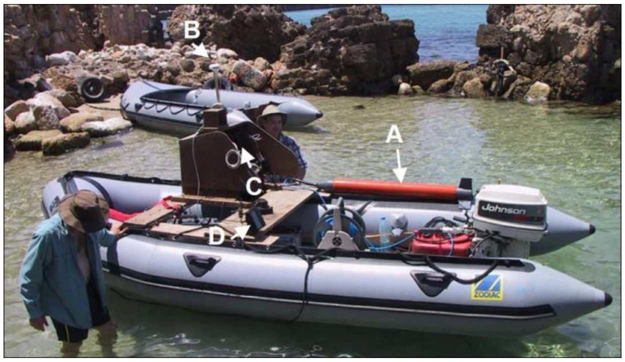
In marine surveying, the magnetometer instrument is usually a sensor towed behind a motorized vessel, which is housed within a waterproof shell (see image below) called a "towfish."



Geometrics G-882 marine magnetometer
Image source: EPA

Positional Control

Positional control is provided by GPS, where the GPS sensor is mounted on the vessel towing the magnetometer, with a constant offset equal to the distance from the GPS sensor to the magnetometer sensor.



Zodiac inflatable boat outfitted for collecting magnetic and bathymetric data
Image source: EPA

Components shown in the image above:

A) Marine magnetometer with an Overhauser-style sensor
B) GPS antenna for positional control
C) Data logging computer, used to gather raw datasets
D) Navigation and echo sounder display

Chapter 6: Other types of Geophysical Surveying Methods

Electrical Resistivity Tomography (ERT)

Electrical Resistivity Tomography (ERT)

Electrical resistivity tomography (ERT) or electrical resistivity imaging (ERI) is a geophysical surveying technique for imaging subsurface structures from electrical resistivity measurements made at the surface, or by electrodes in one or more boreholes.

ERT Unit
Image source: surfacesearch.com

The ERT method measures resistivity, which is the mathematical inverse of conductivity. It is a bulk physical property of materials that describes the difficulty in passing an electrical current through that specific material.

Resistivity measurements can be performed with either an AC or DC current. As resistivity measurements are frequency dependent, care must be taken in comparing resistivity values collected from different geophysical techniques.

Clay materials, metallic oxides, and sulphide minerals are the only common sedimentary materials that can carry significant electrical current through the material itself.

Thus, the resistivity of most near surface sediments is primarily controlled by the quantity and chemistry of the pore fluids within the material.

Any given material can have a wide range of resistivity responses which can be dependent on:

- level of saturation
- concentration of ions
- presence of organic fluids
- faulting
- jointing
- weathering
- etc.

Similar to IP

A related geophysical method, induced polarization, measures the transient response. The technique evolved from techniques of electrical prospecting that predate digital computers, where layers or anomalies were sought rather than images.

(IP) Induced Polarization

Induced Polarization (IP)

When an electrical current is applied to a given material, such as various earth materials, a phenomenon known as induced polarization occurs, with a charge being acquired by the material.

When the current is turned off the charge will dissipate with time, in a similar manner as a car battery slowly losing its charge when not in use.

Electrical Chargeability

An induced polarization survey is conducted to identify the electrical chargeability of subsurface materials, such as ore.

The method is similar to the electrical resistivity tomography method, in that an electric current is transmitted into the subsurface through two electrodes, and voltage is monitored through two other electrodes.

Combining testing methods (IP and Resistivity)
An induced polarization survey is generally conducted along with a resistivity survey.

The resistivity method can be adapted to an IP method by adding switches and minor modifications to the instrument. Combining the two surveys together saves both time and money.

Time Domain Measurements

Time domain IP methods measure considers the resulting voltage following a change in the injected current.

The time domain IP potential response can be evaluated by considering the mean value on the resulting voltage, known as integral chargeability or by evaluating the spectral information and considering the shape of the potential response, for example describing it with a Cole-Cole model.

Frequency Domain Measurements

Frequency domain IP methods use alternating currents (AC) to induce electric charges in the subsurface, and the apparent resistivity is measured at different AC frequencies.

Spectral induced polarization (SIP) or Complex resistivity is an extension of the IP method, which is itself an extension of measuring the Earth's resistance at a single frequency or under a DC current (resistivity method).

SIP measures the frequency-dependent (i.e. spectral) complex impedance, equivalent to the amount of resistance and phase shift between electric current and voltage.

The usual frequency range for alternating current (AC) applied during SIP surveys is tens of kHz to mHz.

As with other geophysical methods, SIP is used to distinguish material properties of the subsurface, such as salinity and saturation.

(SP) Spontaneous Potential

Spontaneous Potential

Spontaneous potential (SP), or self potential, is a naturally occurring electric potential difference in the Earth, which can be measured by use of an electrode, placed relative to a fixed reference electrode.

Spontaneous potentials are often measured down boreholes for formation evaluation in the oil and gas industry, and can be measured along the Earth's surface for mineral exploration or groundwater investigation, as well.

Schlumberger brothers

The phenomenon and its application to geology were first recognized by the Schlumberger brothers, Conrad and Marcel, along with E.G. Leonardon, in 1931.

Schlumberger Limited which was initially founded by these two brothers in 1926, is now the largest oilfield services company in the world.

Surface Method

Electrodes can be placed on the ground surface to map relative changes in the SP value (in millivolts, or mV), typically with the goal of identifying the path of groundwater flow in the subsurface, or seepage from an earthen dam.

A voltmeter measures the voltage between a fixed liquid-junction electrode and a mobile “rover”, which is moved along a dam face or over an area of investigation to collect multiple readings. Anomalies observed may indicate groundwater movement or seepage.

Borehole Method

Spontaneous potential can be measured by placing one probe of a voltmeter at the Earth's surface (called surface electrode) and the other probe in the borehole, which is the downhole electrode, where the SP is to be measured.

As other logging tools use this identical method, and this measurement is a relatively simple one, an SP downhole electrode is usually incorporated into other logging tools.

Factors which affect Interpretation

SP can be affected by a number of factors that complicate the interpretation. SP can be affected by the petrochemical component (through hydrocarbon suppression), as well as by electrokinetic potential and bimetallism.

SP is also affected by the following factors:

- Formation bed thickness
- Resistivities in the formation bed and the adjacent formations
- Resistivity and makeup of the drilling mud
- Wellbore diameter
- The depth of invasion by the drilling mud into the formation

SP data can be used to find:

- Depths of permeable formations
- The boundaries of these formations
- Correlation of formations when compared with data from other analogue wells
- Values for the formation-water resistivity

Hyperspectral Imaging

Hyperspectral imaging

Hyperspectral imaging, similar to other forms of spectral imaging, collects and processes information from across the electromagnetic spectrum.

The goal of hyperspectral imaging is to obtain the spectrum for each pixel of the image of a scene, with the purpose of finding objects, identifying materials, or detecting processes.

While the human eye is only able to see color of visible light in mostly RGB bands (red, green, and blue), spectral imaging splits the spectrum into many more bands, not visible by the human eye.

In hyperspectral imaging, the recorded spectra have fine wavelength resolution and cover a wide range of wavelengths. Hyperspectral imaging measures contiguous spectral bands, as opposed to multispectral imaging which measures spaced spectral bands.

There are two general branches of spectral imagers:

- push broom scanners and whisk broom scanners - which read images over time
- snapshot hyperspectral imaging - which uses a staring array to generate an image in an instance

Spectral Signatures

Hyperspectral sensors look at objects using a vast portion of the electromagnetic spectrum. Certain objects leave unique 'fingerprints' in the electromagnetic spectrum.

Known as spectral signatures, these 'fingerprints' enable identification of the materials that make up a scanned object. For example, a spectral signature for oil helps geologists find new oil fields.

Applications

Hyperspectral remote sensing is used in a wide array of applications. Although originally developed for mining and geology (the ability of hyperspectral imaging to identify various minerals makes it ideal for the mining and oil industries, where it can be used to look for ore and oil).

It has now spread into fields as diverse as ecology and surveillance, as well as historical manuscript research.

Publicly available Images

Imaging from this technology is becoming increasingly more available to the public. Organizations such as NASA and the USGS have catalogues of various minerals and their spectral signatures, and have posted them online to make them more readily available for download.

One advantage of hyperspectral imaging is that, because an entire spectrum is acquired at each point, the operator needs no prior knowledge of the sample, and post-processing allows all available information from the dataset to be mined.

Also, hyperspectral imaging can take advantage of the spatial relationships among the different spectra in a neighborhood, allowing more elaborate spectral-spatial models for a more accurate segmentation and classification of the image.

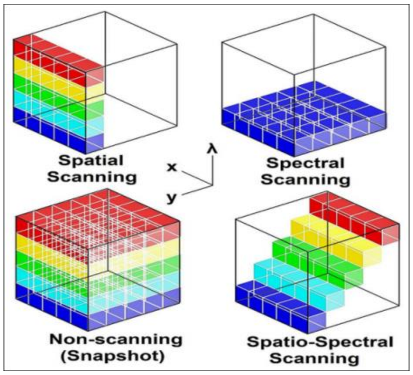
However, one of the obstacles researchers have had to face is finding ways to program hyperspectral satellites to sort through data on their own and transmit only the most important images, as both transmission and storage of that much data could prove difficult and costly.

Hyperspectral data acquisition

There are four basic techniques for acquiring the 3D dataset of a hyperspectral cube (see image below):

- Spatial scanning
- Spectral scanning
- Non-scanning
- Spatiospectral scanning

The choice of technique depends on the specific application, as each technique has context-dependent advantages and disadvantages.



Data acquisition techniques
for hyperspectral imaging
Image source: Wikipedia

Chapter 7: Geophysical Survey Applications

Geological and Geotechnical Engineering Applications

Geological and geotechnical engineering applications

Geophysical surveying methods play a very important part in subsurface investigations for a wide variety of geologic and geotechnical needs.

Rock Density

By using methods such as gravity types or seismic refraction, various rock density evaluations can be conducted:

- density of the rock
- locations of low density portions of the stratigraphy
- spatial density variations

Depth to Bedrock

By using methods such as seismic refraction, electromagnetics for geologic structure, DC resistivity, or gravity, these evaluations can be performed:

- distance from the surface is a rock layer
- location of a postulated fault, water table
- determining the subsurface elastic properties of a zone or layer
- determining where a channel cuts into the bedrock
- evaluating "top of rock" boreholes
- determining the locations of a weak zones, soft layers or fault gouge zones

Elastic Properties of Earth Materials

Using methods such as cross-hole seismic, surface-wave analysis, plus P and S wave refraction, the following can be achieved:

- determining the insitu values of the elastic constants: Young's modulus, shear modulus, bulk modulus, poisson's ratio
- the alluvial and rock strengths
- the shear wave (S-wave) velocity and compressional wave (P-wave) velocity of specific subsurface layers
- determining liquefaction and collapse risk factors for dams and levees
- evaluating foundation design parameters

Electric Properties of Earth Materials

Using methods such as DC resistivity, and electromagnetics for geologic structure, the following can be determined:

- ground resistivity for grounding mat design for facilities such as electrical substations
- determining the conductivity of soils along a pipeline route
- establishing design specifications for cathodic protection systems
- establishing geologic formation boundaries

Location of fault, cavities, and voids

Using methods such as DC resistivity and seismic reflection, the following can be determined:

- determining underground geology related to the fault location
- determining the direction of displacement of a fault
- determining the size of a fracture zone around the fault

Ground Motions (vibration analysis or blast monitoring)

Using methods such as seismic recording and monitoring, the following can be determined:

- ground motions due to the industrial blast
- 'safe' limits for blasting
- analyzing vibrations from surrounding industrial facilities and construction sites

Rippability

Using methods such as ground penetrating radar, cross-hole seismic, seismic reflection and refraction, and IP, the following can be determined:

- the strength of the bedrock
- sizing of heavy equipment required to rip rather than blast, a highway cut through a rock mass
- if there hard patches in the subsurface that cannot be ripped

Site Classification and Seismic Hazard Analysis

Using methods such as seismic refraction, long-term seismic recording, and surface wave analysis, the following can be ascertained:

- the probability of a seismic hazard for a proposed structure
- the acceleration that a structure will experience during its useful lifetime
- what are the acceleration design considerations for a structure, to prevent catastrophic collapse
- what is the UBC site classification that should be used for foundation design

Temperature

Using methods such as thermal gradient, and DC resistivity, the following can be ascertained:

- establishing temperature gradients of geothermal waters; temperature profiling with depth
- determining heat flow variations across the earth's surface
- locating the geothermal resource
- proper siting of a geothermal steam plant

Exploration Surveying

Exploratory Surveys

Geophysical surveying plays a vital role in various exploratory surveys, providing recon and analysis for archeological, mining, mineral, ore, and hydrocarbon resources.

Mining

Using methods such as seismic reflection, GPR, and gravity, the following can be ascertained:

- Locating of abandoned mine shafts
- Where are the surface air shafts
- Determining where subsidence may possibly occur
- locating rooms or pillars
- Locating areas and the extent of past subsidence (collapse)

Archeology

Using methods such as ground penetrating radar, resistivity, and EM, the following can be performed:

- Locating of deeply buried artifacts and structures
- reexaminations of previously excavated historical sites
- recon of suspected sites of interest
- non-intrusive analysis of sensitive sites

Aggregate exploration

Using methods such as seismic refraction, DC resistivity, induced polarization or other EM methods, the following can be ascertained:

- quantity of inground gravel deposits
- Are there significant quantity variations between drill holes
- The depth to the bedrock cutoff
- The property valuation
- quantity of clay is present in the gravel
- fines content variations between sample points
- quality of the groundwater

Ore exploration

Using methods such as EM, DC Resistivity, Magnetics, Radiometric Ore Bodies, Borehole Methods, and Seismic Refraction the following can be determined:

- locating of ore deposits, the drilling targets and determination of their ranking priority
- determination of the size and shape of the ore body
- locating the faults which control ore deposition
- determining where to drill for ores such as uranium, gold or copper:
- determining the types of rock (sandstone or siltstone, granite or pegmatite, limestone or coal)
- determining how the rock types change laterally

Hydrocarbon Exploration

Using methods such as IP, resistivity, seismic reflection, borehole logging methods, and other EM methods the following can be determined:

- drilling locations for natural gas and oil
- what is the geological structure
- in which direction does the strata dip

- location of faults and folds
- location of the contacts between formations
- the stratigraphy and geological boundaries

Environmental Engineering Applications

Contaminant and Spill Plumes

Using methods such as GPR, DC resistivity, and electromagnetics for geologic structure, the following can be determined:

- if there is possible ground contamination
- location and extent of the contamination plume
- contaminate dispersal rates with distance
- boundaries of the contaminant plume
- shape of the plume

Underground Storage Tanks or Drums (USTs)

Using methods such as time domain EM, GPR and magnetics, the following can be determined:

- locating of the underground tanks and drums, along with associated piping
- quantities of tanks and drums at a location
- proof of tank removal
- are there drums or tanks in this landfill
- establishing Phase II report specifications

Fly Ash Disposal

Using methods such as DC resistivity, and electromagnetics for geologic structure, the following can be determined:

- locating the limits of the fly ash disposal area
- thickness of the deposits
- detecting downstream migration of fly ash
- analysis of soil conditions

Locating underground chambers

Using methods such as GPR, the following can be determined:

- locating of lost gravesites
- locating of underground bunkers and other subsurface chambers
- locating of septic tanks, and cesspools

Landfill Boundaries

Using methods such as magnetics, DC resistivity, and electromagnetics for geologic structure, the following can be determined:

- locations of the landfill boundaries, and disposal trenches
- tracking of the leachate migration
- locating of the larger metallic objects in the landfill
- required depth for isolating an uncontrolled landfill facility
- required depth for the slurry wall containment trench

Hydrogeological Applications

Permeability

Using methods such as CSAMT, Borehole Methods, and IP, the following can be determined:

- permeability of the rocks
- direction of water flow
- zones of increased water production

Locating abandoned well casings

Using methods such as magnetics, and electromagnetics for metal detection, the following can be determined:

- locations of old, abandoned water wells
- if there is pollutant migration below the aquitard
- sources of pollutant migration
- where corroded brine production casings exist
- if there is a potential hazard from natural gas seepage

Water Quality

Using methods such as GPR, DC resistivity, streaming IP, and electromagnetics for geologic structure, the following can be determined:

- specific water quality at a given point
- lateral variations in the total dissolved solids (TDS)
- locations of freshwater and brine interfaces

Water table

Using methods such as seismic refraction, DC resistivity, and electromagnetics for geologic structure, the following can be determined:

- locations of water tables and plumes
- whether there are elevation changes across geologic boundaries
- where is the plume

Dam, Levee or Reservoir Leaks (earthen impoundment structure seepage)

Using methods such as self-potential, DC resistivity, and electromagnetics for geologic structure, the following can be determined:

- leak locations and water flow
- if the flow is concentrated or is sheet flow
- size of the zone that is leaking

Salinity Measurements

Using methods such as electromagnetics, and DC resistivity, the following surveys can be conducted:

- mapping of soil salinity levels
- mapping of saltwater intrusion into freshwater and brackish sources

Military Applications – Locating UXO's

Unexploded ordnances (UXO)

These are explosive weapons, which were either "duds" and were abandoned. Types of UXO include: bombs, shells, grenades, land mines, naval mines, cluster munition, etc.

These are essentially time bombs, which still pose a risk of detonation, many decades after they were deployed or abandoned.

Gas Munitions

World War one munitions filled with poisonous gases continue to be a serious hazard. The types of weapons employed ranged from disabling chemicals, such as tear gas, to lethal agents like phosgene, chlorine, and mustard gas.

This type of chemical warfare was a major component of the first global war. Aside from unexploded shells, there have been claims that poison residues have remained in the local environment for an extended period.

Over 16 million acres of France had to be cordoned off at the end of the war because of unexploded ordnance. About 20% of the chemical shells were duds, and approximately 13 million of these munitions were left in place. This has been a serious problem in former battle areas from immediately after the end of the War until the present.

Environmental contamination

In addition to the danger of an inadvertent explosion, buried UXO remains can cause environmental contamination.

In some heavily used military training areas, munitions-related chemicals such as explosives and perchlorate (a component of pyrotechnics and rocket fuel) can enter soil and groundwater. An additional difficulty is the current stringency of environmental legislation.

In the past, a common method of getting rid of unexploded chemical ammunition was to detonate or dump at sea; this is currently prohibited in most countries.

Detection technology

The time-domain electromagnetic (TEM or TDEM) method is the most common geophysical method used in detecting munitions and explosives of concern (MEC).

TEM is capable of detecting ferrous and non-ferrous MEC to a depth of over five ft., depending upon the size of the target.

When there is no geologic interference present, total-field magnetometers may also be used in multi-sensor arrays to detect deeper ferrous MEC.

To co-locate the sensor data for generating digital maps, sensors are equipped with a real-time-kinematic differential global positioning system (RTK-D GPS).

Handheld magnetic locators

Schonstedt Instrument Co. is the world's leading manufacturer of handheld Fluxgate magnetometers for locating unexploded ordnance (UXO) and other explosive remnants of war (ERW).

Handheld Fluxgate magnetometers are capable of finding ferrous metal targets such as cluster bombs, grenades, mortars, weapons caches and ammunition, and have been tested and proven by the US military, private contractors and NGOs in munitions response operations around the globe.

Bibliography

1) Numerous topics in this course are based on online articles within Wikipedia.org
2) Course materials concerning geophysical methods are based on technical publications released by the Environmental Protection Agency (EPA)
3) Some topics concerning geophysical applications are based in part on articles from Zonge International
4) Course materials on MRS techniques are based on information provided by Geovista AB Consulting.
5) Portions of the Aeromagnetic surveying topic were based on articles provided by New-Sense Geophysics
6) Portions of the surveying methods topic were based on articles provided by gpg.geosci.xyz