Lesson 2

Geophysical methods for rock mass characterization

Emanuele Forte

3rd September 2016 - Naxos, Greece
Outline

Review of geophysical methods and their applicability to rock mass characterization:

- Gravimetry
- Magnetometry
- Electrical methods
- Electromagnetic methods (low frequency)
- Ground Penetrating Radar (GPR)
- Seismic methods

- Reflection
- Refraction
- Multichannel Analysis of Surface Waves (MASW)
Review of geophysical methods and their applicability to rock mass characterization

Gravity Method - Measurements of the gravitational field at a series of different locations over an area of interest. The objective in exploration work is to associate variations of gravity field with differences in the distribution of DENSITIES and hence material types.

What is important is the size of the difference in the gravitational acceleration near the “anomalous” body and away from that and the shape of the spatial variation (gravity profile or gravity map) in the gravitational acceleration.

⇒ DENSITY CONTRAST
Porosity (primary + secondary) 0-40% ⇒ high density contrast if filled with fluids
Useful at different scales: from regional characterization to local rock variations.
Optimal applicability for CAVITY detection due to the very high density contrast.

Overall low lateral and vertical resolution
Several correction must be applied in order to properly interpreting the data
To invert the data (2D or 3D) additional data are required → CONSTRAINED and/or JOINT INVERSION
Review of geophysical methods and their applicability to rock mass characterization

**Magnetic Method** - Measurements of the magnetic field or its components at a series of different locations over an area of interest.

Total Magnetic Field: **Principal field** (internal, with very low time variations) + **External field** (less intensity, time variable)

Objectives of the magnetic prospections are local variations of the TMF due to “magnetic anomalies” localized into the earth crust.

$$\vec{M} = k\vec{H}$$

Intensity of magnetization (Dipole moment per volume unit)

$$k_{SI} = 4\pi k'_{emu}$$

Magnetic susceptibility

$$B = \mu_o(H + M) = \mu_o(1 + k)H = \mu\mu_oH$$

$$B' = H' + 4\pi M' = (1 + 4\pi k')H' = \mu H'$$

$$[B] = \text{tesla}(T)$$

Mean intensity for the Earth Magnetic Field

$$H_{cmt} \approx 50 \mu T$$

### Table: Magnetic Susceptibility of Materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Susceptibility $\times 10^3$ (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary</td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td>0 – 0.9</td>
</tr>
<tr>
<td>Limestones</td>
<td>0 – 3</td>
</tr>
<tr>
<td>Sandstones</td>
<td>0 – 20</td>
</tr>
<tr>
<td>Shales</td>
<td>0.01 – 15</td>
</tr>
<tr>
<td>Av. 48 sedimentary</td>
<td>0 – 18</td>
</tr>
<tr>
<td>Metamorphic</td>
<td></td>
</tr>
<tr>
<td>Amphibolite</td>
<td>0.7</td>
</tr>
<tr>
<td>Schist</td>
<td>0.3 – 3</td>
</tr>
<tr>
<td>Phyllite</td>
<td>1.4</td>
</tr>
<tr>
<td>Gneiss</td>
<td>0.1 – 25</td>
</tr>
<tr>
<td>Quartzite</td>
<td>4</td>
</tr>
<tr>
<td>Serpentinite</td>
<td>3 – 17</td>
</tr>
<tr>
<td>Slate</td>
<td>0 – 35</td>
</tr>
<tr>
<td>Av. 61 metamorphics</td>
<td>0 – 70</td>
</tr>
<tr>
<td>Igneous</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>0 – 50</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>0.2 – 35</td>
</tr>
<tr>
<td>Dolerite</td>
<td>1 – 35</td>
</tr>
<tr>
<td>Augite-syenite</td>
<td>30 – 40</td>
</tr>
<tr>
<td>Olivine-diabase</td>
<td></td>
</tr>
<tr>
<td>Diabase</td>
<td>1 – 160</td>
</tr>
<tr>
<td>Porphyry</td>
<td>0.3 – 200</td>
</tr>
<tr>
<td>Gabbro</td>
<td>1 – 90</td>
</tr>
<tr>
<td>Basalts</td>
<td>0.2 – 175</td>
</tr>
<tr>
<td>Diorite</td>
<td>0.6 – 120</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>90 – 200</td>
</tr>
<tr>
<td>Andesite</td>
<td>160</td>
</tr>
<tr>
<td>Av. acidic igneous</td>
<td>0 – 80</td>
</tr>
<tr>
<td>Av. basic igneous</td>
<td>0.5 – 97</td>
</tr>
<tr>
<td>Minerals</td>
<td></td>
</tr>
<tr>
<td>Graphite</td>
<td>0.1</td>
</tr>
<tr>
<td>Quartz</td>
<td>– 0.01</td>
</tr>
<tr>
<td>Rock salt</td>
<td>– 0.01</td>
</tr>
<tr>
<td>Anhydrite, gypsum</td>
<td>– 0.01</td>
</tr>
<tr>
<td>Calcite</td>
<td>– 0.001 – 0.01</td>
</tr>
<tr>
<td>Coal</td>
<td>0.02</td>
</tr>
<tr>
<td>Clay</td>
<td>0.2</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>0.4</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>0.7</td>
</tr>
<tr>
<td>Cassiterite</td>
<td>0.9</td>
</tr>
<tr>
<td>Siderite</td>
<td>1 – 4</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.05 – 5</td>
</tr>
<tr>
<td>Limonite</td>
<td>0.25</td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td>0.3</td>
</tr>
<tr>
<td>Hematite</td>
<td>0.5 – 35</td>
</tr>
<tr>
<td>Chromite</td>
<td>0.45</td>
</tr>
<tr>
<td>Franklinite</td>
<td>3</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>1 – 600</td>
</tr>
<tr>
<td>Ilimenite</td>
<td>1800</td>
</tr>
<tr>
<td>Magnetite</td>
<td>1200 – 1900</td>
</tr>
</tbody>
</table>

**Water** ~0

**Air** 0
Magnetic Method

Principal field: (99%) inner origin, slowly varying with time

External field: (1%) low intensity but rapid changes and magnetic storms

We are looking for SPATIAL VARIATIONS of THE PRINCIPAL FIELD: localized, constant in space and time, due to magnetic anomalies within the earth crust (anomalous magnetic susceptibility values) → Objectives for the magnetic prospections

http://www.thisoldearth.net/
Magnetic Method

Useful for both regional...

https://www.uwgb.edu/dutchs/StateGeophMaps/IowaGphMap.HTM

...and local scale

Linear targets ➔ walls

High amplitude anomaly ➔ burnt materials

“Sterile” zone

http://www.gemsys.ca/archaeological-applications
Magnetic Method

Low processing required, fast and low cost data acquisition (offshore surveys, airborne acquisition).

Correction needed for time drifting or use of two combined sensors (Gradiometers).

Useful especially for igneous rocks characterization, caves detection and archaeological surveys

Very low resolution level (vertical and spatial) and no direct information about depth of anomalous rocks.

Difficult to applied in urban areas or zones with metallic structures and installations.
(Geo)Electrical Methods—Observation of electric fields caused by current introduced into the ground as a means of studying earth resistivity/conductivity

Since most of the minerals forming rocks are dielectrics, almost all rocks are also DIELECTRICS. The presence of WATER controls much of the conductivity variation. Measurement of resistivity can be considered, in general, a measure of water saturation and connectivity of pore space. Increasing water amount (saturation), salinity (and salt type), porosity of rock (water-filled voids), number of fractures (water-filled), TEMPERATURE all tend to decrease measured resistivity. Air, with naturally high resistivity increases subsurface resistivity.

⇒ HIGH SENSITIVITY TO WATER BUT IT IS DIFFICULT TO UNDESTAND WHICH IS/ARE THE MOST SIGNIFICANT MECHANISM(S)
(Geo)Electrical Methods

Resistivity STRONGLY DECREASES if there is WATER (with IONS) within the rock mass → IONIC CONDUCTION → ROCKS=SOLID ELECTROLITS

Ions movement (with lower velocity if compared to electrons) → MASS movement → Chemical Reactions → NET CONDUCTIVITY → Approximation to perfect (Ohmic) Conductors

**RESISTIVITY & WATER**

\[ \rho_e = a \Phi^{-m} S^{-n} \rho_w \]

Archie’s Law (1942)

\( \Phi = \) Porosity; \( S = \) saturation; \( \rho_w = \) resistivity of water within pores and parameters relate to the rock:

\( a = (0.5 \div 2.5); \quad m = \) compaction factor \((1.3 \div 2.5); \quad n \approx 2\)

**RESISTIVITY & TEMPERATURE**

\[ \rho_T = \frac{\rho_{18}}{1 + \alpha(T - 18)} \]

\( \alpha = \) Temperature coefficient (related to the resistivity of the electrolytes)  Mean value = \( 0.025/°C \)

![Graph showing resistivity vs temperature for different rock types](image-url)
(Geo)Electrical Methods

**Resistivity & Salinity**

- **Salinity (NaCl)** – [g/l]

- **Resistivity** – [Ωm]

**Resistivity & Permeability**

There are many empirical laws:
- e.g. for K in the range between \(5 \times 10^{-4}\) and \(1 \times 10^{-2}\) m/s and \(\Phi \sim 30\%\)

\[ K = 3.86 \times 10^{-1.3} \times \rho_a^{3.86} \]

**Since there are several parameter affecting the overall resistivity it’s almost impossible make a correlation**

**Resistivity ↔ Rock Type and Fluid Content**

Additional data are required.
Electric current can propagate within the rocks with 3 mechanisms:
1) Electronic Conduction (ohmic or metallic) - electrons
2) Electrolytic Conduction (ionic) - ions
3) Dielectric Conduction (Polarization)

Usually just ONE of the mechanisms dominates (based on rock characteristics and type of measures) ➔ Different geophysical methods

1) Electronic conduction ➔ RESISTIVITY METHODS (DC RESISTIVITY)

\[ \Delta V = RI \] \hspace{2cm} \text{Ohm law}

In differential form:

\[ E = -\frac{\partial V}{\partial r} \text{ or } \frac{\partial V}{\partial r} = -J\rho = \frac{I}{S} \rho \]

Therefore in a conductor with length "l" and cross-section "S":

\[ \Delta V = \frac{I}{S} \rho \int_0^l \partial l = \frac{I}{S} \rho l = RI \Rightarrow R = \rho \frac{l}{S} \text{ or } \rho = R \frac{S}{l} \text{ [Ωm]} \]

The RESISTIVITY \( \rho \) (or the conductivity \( \sigma \) i.e. \( 1/\rho \)) represents an INTRINSIC PROPERTY of the material relating the electric field \( E \) and the current density \( J \)

\[ J = E/\rho \text{ or } J = \sigma E \]
Faraday’s and Ampere-Maxwell’s laws can be combined as:

\[ \nabla \times E = -\frac{\partial B}{\partial t} = -\frac{\partial (\mu H)}{\partial t} \]
\[ \nabla \times H = \frac{\partial D}{\partial t} + I = \frac{\partial (\varepsilon E)}{\partial t} + \sigma E \]

\[ \nabla^2 E = \mu\sigma \frac{\partial E}{\partial t} + \varepsilon \mu \frac{\partial^2 E}{\partial t^2} \]
\[ \nabla^2 H = \mu\sigma \frac{\partial H}{\partial t} + \varepsilon \mu \frac{\partial^2 H}{\partial t^2} \]

2) Inductive regime (ELECTROMAGNETIC METHODS):

\[ f < 10^5 \text{ Hz} \Rightarrow \mu \varepsilon \omega^2 \ll \omega \mu \varepsilon \]
Conduction currents are more important.
Phase velocity is dispersive:

\[ v_{\text{phase}} = \sqrt{\frac{2\omega}{\mu \varepsilon}} \]

3) Propagation regime (Ground Penetrating Radar - GPR):

\[ f > 10^7 \text{ Hz and } 1/\rho = \sigma = 0 \Rightarrow \mu \varepsilon \omega^2 \gg \omega \mu \varepsilon \]
Displacement (polarization) currents are more important:
Phase velocity will be:

\[ v_{\text{phase}} \approx \frac{c}{\sqrt{\mu \varepsilon}} \approx \frac{\sqrt{\varepsilon_r}}{\sqrt{\mu \varepsilon}} \]
**DC Resistivity** - This is an active method that employs measurements of electrical potential associated with subsurface electrical current flow generated by a DC, or slowly varying AC, source. It's one of the most common methods with several possible options (1D: VES; 2D: ERT, Electrical sounding; 3D). Results in terms of **APPARENT SUBSURFACE RESISTIVITY → INVERSION**.

**Induced Polarization (IP)** - This is an active method that is commonly done in conjunction with DC Resistivity. It employs measurements of the transient (short-term) variations in potential as the current is initially applied or removed from the ground, or alternatively the variation in the response as the AC frequency is changed. It has been observed that when a current is applied to the ground, the ground behaves much like a capacitor, storing some of the applied current → **CHARGEABILITY**. Very useful for clay layers and metals detection. Low penetration depth.

**Self Potential (SP)** - This is a **passive method** that employs measurements of naturally occurring **ELECTRICAL POTENTIALS - ΔV**. Measurable electrical potentials have been observed for ore bodies, in association with groundwater flow and certain biologic processes. No depth information.
(low frequency) Electromagnetic (EM) - This is an active method that employs measurements of a time-varying magnetic field generated by induction through current flow within the earth. In this technique, a time-varying magnetic field is generated at the surface of the earth that produces a time-varying electrical current in the earth through induction. A receiver is deployed that compares the magnetic field produced by the current-flow in the earth to that generated at the source. Several physical parameters can be measured: $B$, $H$, $\rho$, $\sigma$, ...

Magnetotelluric (MT) - This is a passive method that employs measurements of naturally occurring electrical currents (telluric currents) generated by magnetic induction from electrical currents in the ionosphere. This method can be used to determine electrical properties of materials at relatively great depths (down to and including the mantle) inside the Earth. In this technique, a time variation in electrical potential is measured at a base station and at survey stations. Differences in the recorded signal are used to estimate subsurface distribution of ELECTRICAL RESISTIVITY.

Ground Penetrating Radar (GPR) - This is an active method based on EM waves injected into the subsurface. The REFLECTED WAVES are recorded at the surface as a function of time. It is a Ultra High Resolution method, but the maximum penetration depth is limited by conductivity.
DC electrical resistivity

This method is based on (DC) electric current injection into the ground by using two separated electrodes. Measuring the electric potential difference between two other electrodes it is possible to estimate the subsurface electrical resistivity distribution.

\[ \Delta V = \rho \frac{l}{S} I = \rho k I \]

K = geometric coefficient, constant for a certain electrode array and just depending by such geometry.

When the subsurface is not homogeneous (i.e. almost always!) we measure apparent resistivities. To recover the actual resistivity values an inversion process must be applied.

DATA INVERSION 1D ➔ Vertical Electric Soundings (VES)
2D, 3D ➔ Sections or volumes (Electrical Resistivity Tomography - ERT)

APPARENT RESISTIVITY (measured) ➔ REAL RESISTIVITY MODEL ➔ APPARENT RESISTIVITY (calculated)
**DC electrical resistivity: instruments**

Multielectrodes systems are available, both with **FIXED** (static) and **MOBILE** (dynamic) electrodes

**Fast data acquisition, high number of measurements ➔ more constrained subsurface models**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Instrument Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abem Instruments, Sweden (<a href="http://www.abem.se">www.abem.se</a>)</td>
<td>Static</td>
</tr>
<tr>
<td>Advanced Geophysical Instruments, USA (<a href="http://www.agiusa.com">www.agiusa.com</a>)</td>
<td>x</td>
</tr>
<tr>
<td>Campus Geophysical Instruments, UK</td>
<td>x</td>
</tr>
<tr>
<td>Geofyzika, Czech Republic (<a href="http://www.geofyzika.com">www.geofyzika.com</a>)</td>
<td>x</td>
</tr>
<tr>
<td>Geometrics, USA (<a href="http://www.geometrics.com">www.geometrics.com</a>)</td>
<td></td>
</tr>
<tr>
<td>IDS Scintrex, Canada (<a href="http://www.idsdetection.com">www.idsdetection.com</a>)</td>
<td>x</td>
</tr>
<tr>
<td>Iris Instruments, France (<a href="http://www.iris-instruments.com">www.iris-instruments.com</a>)</td>
<td>x</td>
</tr>
<tr>
<td>OYO, Japan</td>
<td>x</td>
</tr>
<tr>
<td>Pasi Geophysics, Italy (<a href="http://www.pasigeophysics.com">www.pasigeophysics.com</a>)</td>
<td>x</td>
</tr>
</tbody>
</table>

**MOVING ELECTRODES**

Not for rough terrains!

- 8 configurations 2 – 30 m
- Tail length 100 m
- Electrode weight 15 kg
- Small catapillar with instrumentations etc.
- 2 – 3 km per hour

**FIXED ELECTRODES**
DC electrical resistivity: Examples of applications

Salt (or brackish) water intrusion
Identification of the transition zone
Possible time monitoring
(4D analysis)

Evaluation of sea water intrusion below a dam
Lithologic and fracturing variations

Mantovani et al., 2012
DC electrical resistivity: Examples of applications

Localization and mapping of high fractured zones \(\Rightarrow\) usually lower resistivity values.

Seren et al., 2002

Vertical sections

Horizontal (depth) sections

Iso-resistivity volumes
DC electrical resistivity: strengths and limitations

• Virtually unlimited investigation depth, with limitation when very high resistivity materials (>1000Ωm) are present
• It is possible to monitor with time even rapid varying phenomena
  • Usually high sensitivity to water
  • Possible applicability to very different situations
• It is possible to acquire a lot of data in a relatively short time

• Low overall resolution, especially in depth
• Not unique models (indetermination principle) ➔ Constraints are essential
  • Problems when very rough topography is present
• Different geological environments can show similar resistivity distributions
• Dependency from the electrode array not easy to be eliminated ➔ not precise subsurface imaging.
Review of geophysical methods and their applicability to rock mass characterization

Ground Penetrating radar - GPR

- Electromagnetic waves injected into the ground by a transmitting antenna and recorded at the surface by a receiving antenna.
- The frequency range usually adopted for geological prospecting is between $10$ e $1500\text{MHz}$
  - Ultra Wide Band impulsive systems
- Bistatic, single channel (i.e. with just one receiving antenna) and constant offset devices

- Space interval (trace distance) usually between $0.5$ e $200\text{cm}$ depending by the target size.
- Maximum investigation depth extremely variable as a function of the materials and inversely proportional to the frequency of the used antennas.

$$v = f\lambda \quad R_{\text{max}} = \lambda / 4$$

- Vertical resolution directly proportional to the frequency of the used antennas and inversely proportional to the velocity of the investigated materials. Magnitude order: cm÷m.
Amplitude (intensity, energy) of the reflected waves
→ depends by the contrast of electromagnetic impedance
   \[ (\eta \approx E/H) \]
   (and by the attenuation and type of the used antennas)

Time (depth) of recorded reflections
→ depends by the subsurface geology

Data interpretation is based on “Horizons” considered as:
- Surfaces separating different layers
- Reflections from these surfaces
GPR: fundamental parameters

What can we see? \( \Rightarrow \) CONTRASTS OF THE SUBSURFACE ELECTRO-MAGNETIC PROPERTIES

Intrinsic EM impedance.

\[
\eta = \frac{E}{H} = \sqrt{\frac{-i\omega\mu}{\sigma - i\omega\varepsilon}} \approx \sqrt{\frac{\mu}{\varepsilon}} \quad [\text{ohm}]
\]

Reflection coefficient

\[
R = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}
\]

For waves perpendicular to the reflecting surface

\[
R \approx \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}}
\]

For low conductive media
The water content is an essential parameter!

\( \varepsilon_w \) one order of magnitude higher than \( \varepsilon_{\text{mezzi geol}} \)

\( \varepsilon \) determines the velocity of the EM waves

\[
v = \frac{1}{\sqrt{\mu \varepsilon}} \approx \frac{c}{\sqrt{\varepsilon_r}} \quad \text{in l.c.}
\]

For low loss media \( \Rightarrow \sigma < 1\text{mS/m} \)

\( \Rightarrow \varepsilon \) modifies the data resolution:
\( \Rightarrow \) the highest the velocity, the lower the resolution

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>( \varepsilon_r )</th>
<th>( K )</th>
<th>( \sigma ) (mS/M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>80</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>80</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Sea Water</td>
<td>80</td>
<td></td>
<td>3x10^3</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>3-5</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated Sand</td>
<td>20-30</td>
<td></td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Limestone</td>
<td>4-8</td>
<td></td>
<td>0.5-2</td>
</tr>
<tr>
<td>Shales</td>
<td>5-15</td>
<td></td>
<td>1-100</td>
</tr>
<tr>
<td>Silts</td>
<td>5-30</td>
<td></td>
<td>1-100</td>
</tr>
<tr>
<td>Clays</td>
<td>5-40</td>
<td></td>
<td>2-1000</td>
</tr>
<tr>
<td>Granite</td>
<td>4-6</td>
<td></td>
<td>0.01-1</td>
</tr>
<tr>
<td>Dry Salt</td>
<td>5-6</td>
<td></td>
<td>0.01-1</td>
</tr>
<tr>
<td>Ice</td>
<td>3-4</td>
<td></td>
<td>0.01</td>
</tr>
</tbody>
</table>
The maximum achievable penetration depth depends by several factors:

- Intrinsic attenuation of the material ($\alpha$)
- Frequency of the used antenna
- (Radiated energy, radiation pattern)

The global attenuation ($\alpha_t$) of an EM wave depends by:

- Geometrical spreading losses (spherical divergence)
- Antenna-ground coupling
- Partial reflections
- Scattering losses (diffractions)
- Efficiency/repetitivities of the system
- INTRINSIC ATTENUATION

### Approximated maximum depth

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Center Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1000</td>
</tr>
<tr>
<td>1.0</td>
<td>500</td>
</tr>
<tr>
<td>2.0</td>
<td>200</td>
</tr>
<tr>
<td>7.0</td>
<td>100</td>
</tr>
<tr>
<td>10.0</td>
<td>50</td>
</tr>
<tr>
<td>30.0</td>
<td>25</td>
</tr>
<tr>
<td>50.0</td>
<td>10</td>
</tr>
</tbody>
</table>

### Material properties

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$\epsilon_r$</th>
<th>$\sigma$ (mS/M)</th>
<th>$v$ (m/μs)</th>
<th>$\alpha$ (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0</td>
<td>0.30</td>
<td>0</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>80</td>
<td>0.01</td>
<td>0.033</td>
<td>2x10^{-3}</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>80</td>
<td>0.5</td>
<td>0.033</td>
<td>0.1</td>
</tr>
<tr>
<td>Sea Water</td>
<td>80</td>
<td>3x10^3</td>
<td>0.01</td>
<td>10^3</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>3-5</td>
<td>0.01</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated Sand</td>
<td>20-30</td>
<td>0.1-1.0</td>
<td>0.06</td>
<td>0.03-0.3</td>
</tr>
<tr>
<td>Limestone</td>
<td>4-8</td>
<td>0.5-2</td>
<td>0.12</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Shales</td>
<td>5-15</td>
<td>1-100</td>
<td>0.09</td>
<td>1-100</td>
</tr>
<tr>
<td>Silts</td>
<td>5-30</td>
<td>1-100</td>
<td>0.07</td>
<td>1-100</td>
</tr>
<tr>
<td>Clays</td>
<td>5-40</td>
<td>2-1000</td>
<td>0.06</td>
<td>1-300</td>
</tr>
<tr>
<td>Granite</td>
<td>4-6</td>
<td>0.01-1</td>
<td>0.13</td>
<td>0.01-1</td>
</tr>
<tr>
<td>Dry Salt</td>
<td>5-6</td>
<td>0.01-1</td>
<td>0.13</td>
<td>0.01-1</td>
</tr>
<tr>
<td>Ice</td>
<td>3-4</td>
<td>0.01</td>
<td>0.16</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Transmitting and Receiving (at the surface) of EM waves ⇒ RIFLECTIONS (and DIFFRACTIONS) are used to recover information of the subsurface.
Reflections are due to vertical and lateral variations of the EM properties of the materials
Fields of application of GPR

- **Geology**
  - Geological:
    - Detection of natural cavities and fissures
    - Subsidence mapping
    - Mapping and body geometry
    - Mapping of superficial deposits
    - Soil stratigraphy mapping
    - Glacial geological investigations
    - Mineral exploration and resource evaluation
    - Peat thickness mapping and resource evaluation
    - Permafrost investigations
    - Location of ice wedges
    - Fracture mapping in rock salt
    - Location of faults, dykes, coal seams, etc.
    - Geological structure mapping
    - Lake and riverbed sediment mapping

- **Environment**
  - Environmental:
    - Contaminant plume mapping
    - Mapping and monitoring pollutants within groundwater
    - Landfill investigations
    - Location of buried fuel tanks and oil drums
    - Location of gas leaks
    - Groundwater investigations

- **Glaciology**
  - Glaciological:
    - Ice thickness mapping
    - Determination of internal glacier structures
    - Ice movement studies
    - Detection of concealed surface and basal glacier crevasses
    - Mapping water conduits within glaciers
    - Determination of thickness and type of sea and lake ice
    - Sub-glacial mass balance determination
    - Snow stratigraphy mapping

- **Engineering**
  - Engineering and construction:
    - Road pavement analysis
    - Void detection
    - Location of reinforcement (rebars) in concrete
    - Location of public utilities (pipes, cables, etc.)
    - Testing integrity of building materials
    - Concrete testing

- **Archaeology**
  - Archaeology:
    - Location of buried structures
    - Detection and mapping of Roman Roads, etc.
    - Location of post-holes, etc.
    - Pre-exavation mapping
    - Detection of voids (crypts, etc.)
    - Location of graves

- **Forensic science**
  - Forensic science:
    - Location of buried targets (e.g. bodies and bullion)
GPR: applicability

1. Frequency of the antennas

- < central frequency \(\Rightarrow\) > dimensions
- < central frequency \(\Rightarrow\) > offset

200 MHz

- Shielded antennas \(\Rightarrow\) > size and weight

100 MHz

50 MHz
GPR: data processing

Data processing is essential but standards cannot be defined!

The processing flow should be tailored on the base of the objectives and expected results.

A typical flow could encompass:

1. Data conversion
2. Editing e geometry assessment
3. Drift removal (zero time correction)
4. Spectral analysis and filtering
5. Coherent noise (background) removal
6. Amplitude analysis and recovery (gain)
7. Velocity analysis
8. Depth conversion/migration

DATA INTERPRETATION
GPR: data processing

Original profile

Depth converted

“stack”
migrated
GPR: data processing

Single Fold

Multi Fold $\Rightarrow$ stack

$MF \Rightarrow Migrated \ in \ time$

$MF \Rightarrow Migrated \ in \ depth$
Seismic methods

Are ACTIVE (or passive) methods using seismic waves
Source: any “natural” or “artificial” system generating a “seismic perturbation” \(\rightarrow\) i.e. a ground motion \(\rightarrow\) SEISMIC WAVES

By using seismic waves travelling through the subsurface and recorded by dedicated sensors (R) we can recover information about the physical parameters of the materials and their geometry.

There are several waves generated, which can be used:

A) BODY waves
   - “P”
   - “S”
   - Direct
   - Reflected
   - Refracted
   - Diffracted
   - Multiple
   - …

B) SURFACE waves
   - Rayleigh
   - Love
   - …
By selecting different waves we can estimate different properties developing various “SEISMIC METHODS”
**Seismic Method** (REFERENCE SEISMIC) - It’s an ACTIVE method (artificial sources) measuring the energy reflected at subsurface boundaries with ACOUSTIC IMPEDANCE contrasts $\Rightarrow$ $v_p$ CONTRASTS. The density variation is less important as compared with VELOCITY.

<table>
<thead>
<tr>
<th>Material</th>
<th>P wave Velocity (m/s)</th>
<th>S wave Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>332</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>1400-1500</td>
<td></td>
</tr>
<tr>
<td>Petroleum</td>
<td>1300-1400</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>6100</td>
<td>3500</td>
</tr>
<tr>
<td>Concrete</td>
<td>3600</td>
<td>2000</td>
</tr>
<tr>
<td>Granite</td>
<td>5500-5900</td>
<td>2800-3000</td>
</tr>
<tr>
<td>Basalt</td>
<td>6400</td>
<td>3200</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1400-4300</td>
<td>700-2800</td>
</tr>
<tr>
<td>Limestone</td>
<td>5900-6100</td>
<td>2800-3000</td>
</tr>
<tr>
<td>Sand (Unsaturated)</td>
<td>200-1000</td>
<td>80-400</td>
</tr>
<tr>
<td>Sand (Saturated)</td>
<td>800-2200</td>
<td>320-880</td>
</tr>
<tr>
<td>Clay</td>
<td>1000-2500</td>
<td>400-1000</td>
</tr>
<tr>
<td>Glacial Till (Saturated)</td>
<td>1500-2500</td>
<td>600-1000</td>
</tr>
</tbody>
</table>
The Reflection Seismic Method allows (after a complex and multi step processing phase) to obtain a 2D or 3D high resolution SUBSURFACE IMAGING.

Due to extremely high density and velocity gases (like methane in the O&G industry) can be clearly localised on seismic data. Since the contrast is lower, fluids like water and oil can be found only with sophisticated analyses (AVO, AVA, Attributes, velocity analysis, data inversion).

This method can be applied both onshore and offshore at different depth scales (from few metres up to several tens of kilometres).
To extract the information embedded within the data a complex and time consuming processing is required.
Processing cannot be automated: it depends by several factors including the geological characteristics of the subsurface, i.e. the final objective of the survey.

A typical processing flow (onshore) is:

- Data Editing
- Sorting/geometry
- Filtering
- Amplitude recovery
- Static corrections
- Spectral shaping/deconvoluzione
- Velocity analysis- NMO correction
- Stacking
- Migration/depth conversion
- Optional specific analyses like AVO, AVA, Attributes
Possible application in any environment with scales from $10^0$m up to $10^6$m
Frequencies from Hz up to $10^2$ KHz
Investigation depths from a few m up to $10^5$m
Strong Dependency by the ENERGY of the used source
(and the attenuation characteristics of the materials)
The Reflection Seismic Method: applications

Is the most common method for geophysical prospecting, essential on both exploration and exploitation of the hydrocarbon reservoirs.

It gives information more detailed than any other non-invasive technique on the stratigraphy, the structures, and the properties of the materials.

It bases on travel times, amplitude and phase of the reflections due to the discontinuities of the elastic properties in the subsurface and allows to recover their position/shape and some physical properties like acoustic impedance, wave velocity, elastic parameters,…

It gives a realistic 2D or 3D representation (imaging) of the subsurface, similar to a geological section/volume.
Migration

Detail of the PSDM/TC section

The Reflection Seismic Method: applications and processing
Migration

Detail of the INTERPRETED TC PreSDM
Migration

Detail of a PreSDM section with the final v-z velocity macromodel superimposed
The Reflection Seismic Method: strengths and constrains

1. Detailed subsurface imaging in terms of geometries, shapes, positions of the acoustic impedance discontinuities \( \Rightarrow \) geology
2. Estimation of the petrophysical parameters of the rock masses and the fluids \((v, \sigma, E)\)
3. Estimation of the fluid characteristics and quantities with dedicated techniques (Amplitude Versus Offset Analysis - AVO; seismic attributes; Hydrocarbon indicators)
4. Virtually without depth limitations, but the detail level rapidly decreases with increasing depths
5. 2D, 3D (volumes), 4D (time comparisons) are possible
6. It is possible to adapt this technique to many different applications

1. High costs (1-10K€ Km)
2. A complex and time-consuming processing is mandatory
3. Complex logistic of acquisition. A trained acquisition team is requested.
The Refraction Seismic Method: theoretic overview
The Refraction Seismic Method:

STRENGTHS AND CONSTRAINTS

1. Moderated costs (from 500€ for a single 100m long profile)
2. Quite simple signal processing
3. Quite simple acquisition with limited energy sources (sledgehammers)
4. First Breaks usually easy to be detected and apparent
5. Tomographic reconstruction and joint inversions are possible
6. A small acquisition team is requested

1. It allows an approximated low resolution subsurface reconstruction ➔ position of the refractors and velocities between refractors
2. Wrong results if there are Velocity Inversions
3. Not interpretable data in case of a gradual incremental velocity trend
Objective:
Estimate the vertical distribution of the shear waves $V_s(z)$ and/or of the rigidity modulus $m(z)$

Possible techniques for their in situ estimation:

1) Borehole experiments (down hole, cross hole, well logs)
2) Seismic profiles (reflection, refraction) with peculiar sources and recorders
3) Analysis of surface waves
   a) ACTIVE methods: MASW
   b) PASSIVE methods: microtremors, H/V
The Vs velocity estimation: MASW

MASW is based on the analysis of the geometrical dispersion of the surface (Rayleigh) waves. From the conceptual point of view it encompasses 3 main phases:

1. Seismic data acquisition
2. Seismic data analysis (surface waves)
   Extraction of dispersion \((v(f))\) curves.
3. Inversion \(\rightarrow\) from \(v_R(f)\) to \(v_S(z)\)

---

**DATA ACQUISITION**

- Seismic dataset (CSG Gathers)

**DATA ANALYSIS**

- Dispersion curves

**INVERSION**

- Subsurface model:
  - \(h_1, Vs_1\)
  - \(h_2, Vs_2\)
  - \(H_{n-1}, Vs_n\)
The $V_s$ velocity estimation: MASW results

- $V_s$ increasing with depth (e.g., Soil-sand-hard rock)
- Surficial velocity inversion
- Complex stratigraphy without velocity inversion and with a hard bedrock
Objective: $Vs(x,z)$

It can be obtained:
1) By simultaneously inverting several Common Shot Gathers (joint inversions are indeed possible) $\Rightarrow$ 2D section

2) By separately inverting several Common Shot Gathers along a profile and then interpolating the results $\Rightarrow$ 1.5D section
The Vs velocity estimation: rock classifications

From: Eurocode 8 - Seismic Design of Buildings Worked examples


The average shear wave velocity $V_{s,20}$ is the leading parameter for the selection of the ground type. It should be used whenever possible and its value should be computed in accordance with the following expression:

$$V_{s,20} = \frac{30}{\sum_{i=1}^{N} \frac{h_i}{V_i}}$$  \hspace{1cm} (1.3)

where $h_i$ and $v_i$ denote the thickness (in metres) and the shear-wave velocity (at a shear strain level of $10^{-4}$ or less) of the $i$-th formation or layer, in a total of $N_i$ existing in the top 30 m.

When direct information about shear wave velocities is not available, the other parameters of Table 1.2.3 may be used to select the appropriate ground type.

<table>
<thead>
<tr>
<th>Ground type</th>
<th>Description of stratigraphic profile</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.</td>
<td>$V_{s,20}$ (m/s) &gt; 800</td>
</tr>
<tr>
<td>B</td>
<td>Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.</td>
<td>360 - 800</td>
</tr>
<tr>
<td>C</td>
<td>Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.</td>
<td>180 - 360</td>
</tr>
<tr>
<td>D</td>
<td>Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.</td>
<td>&lt; 180</td>
</tr>
<tr>
<td>E</td>
<td>A soil profile consisting of a surface alluvium layer with $V_s$ values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $V_s &gt; 800$ m/s.</td>
<td>&lt; 180</td>
</tr>
<tr>
<td>S1</td>
<td>Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silt with a high plasticity index ($IPi &gt; 40$) and high water content.</td>
<td>&lt; 100 (indicative)</td>
</tr>
<tr>
<td>S2</td>
<td>Deposits of liquifiable soils, of sensitive clays, or any other soil profile not included in types A – E or $S_1$.</td>
<td></td>
</tr>
</tbody>
</table>
The Vs velocity estimation: MASW

STRENGTHS and CONSTRAINTS

😊

1. Moderated costs (few hundred € for each survey)
2. Quite simple and automated signal processing
3. Simple logistic of acquisition with limited energy sources (sledgehammers)
4. Joint inversions are possible
5. Results useful for both geologist and engineers

😢

1. Low overall resolution
2. Uncertainties during the picking of the dispersion curves produces not accurate (or even wrong) results
3. Inapplicable with rough topography and strong heterogeneities
Remember: it's very important to **integrate** different geophysical methods and validate results also with direct data.
All is clear?