Site Characterization & Hydrogeophysics

(Source: Matthew Becker, California State University)
Site Characterization

• Definition: quantitative description of the hydraulic, geologic, and chemical properties of a subsurface environment.

• Purpose: to support management decisions
Example Properties

• Hydraulic Properties:
  – Related to Geology
    • Permeability
    • Storage
  – Related to Fluid
    • Density
    • Viscosity
Example Properties

• Geologic Properties:
  – Geologic Structure
    • Hydrostratigraphy
    • Bedrock fracturing
  – Geologic History
    • Paleoenvironment (depositional history)
    • Recent disturbance
    • Biological interactions
How can we Characterize? The “Tool Box”

Initial:
- Historical review of site
- Geologic mapping
- Direct push sampling
- Soil gas survey
- Surface Geophysics

Complete:
- Drilling/Coring
- Borehole logging
- Chemical Sampling
- Hydraulic Testing
- Tracer Testing
Alle scale diverse

si usano strumenti di misura diversi
Alle scale diverse si usano strumenti di misura diversi
Cores

Cores are first drilled and then samples are obtained for hydraulic conductivity measurement by permeameters

High resolution but small support volume

Problems: i) the cores are disturbed; ii) the methodology is invasive (drilling); iii) small support volume; iv) require extensive drilling (unfeasible)
Alle scale diverse

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What is Hydrogeophysics?

• Application of physics to remotely sense hydrogeologic properties.
  – Borehole Logging
  – Geophysical Methods
What is Hydrogeophysics?

- Application of physics to remotely sense hydrogeologic properties.
  - Borehole Logging
  - Geophysical Methods
Borehole Geophysics for Ground-Water Investigations

- Technology borrowed from the oil industry
- Purpose to Characterize:
  - Borehole conditions
  - Formation
  - Fractures
  - Fluid Properties
Borehole Logging

- Geophysical borehole logging involves gradually lowering a probe down a borehole, while the probe measures a physical property of the surrounding rock or soil. Probes can be designed to measure any one of a variety of physical properties. Since the measured physical property is related to the composition of the surrounding rocks and soils, borehole logs can be used to map the subsurface.
Borehole Logging

• Conventional Logs (Often run as a suite soon after drilling):
  – Fluid Logs (Temperature, Fluid Conductivity)
  – Formation Logs (Caliper, Gamma, Neutron, Acoustic, Formation Resistivity, EM Induction)

• Borehole Imaging
• Flow Logging
Borehole Imaging

• Useful primarily in hard rock environments where wells are not cased.

• Methods Include:
  – Video logging
  – Acoustic Televiewer
Borehole Video

- Basic downhole camera
Flow Logging

• What is Measured and How?
  – Flow velocity along borehole is measured using impeller, heat pulse, or dissolved tracer
  – Flow is either natural or in response to pumping
  – May be use in single well or cross-hole mode

• Cautions
  – Measurements disturbed by borehole turbulence
  – Multiple well interactions may complicate interpretation as compared to packer testing
What is Hydrogeophysics?

• Application of physics to remotely sense hydrogeologic properties.
  – Borehole Logging
  – Geophysical Methods
Geophysical Methods

• Geophysics refers to the use of “remote sensing” of geologic properties
• Remote sensing is accomplished using electromagnetic of seismic energy propagation.
Petrophysics

• Science of relating geologic properties to geophysical properties
• Developed primarily for oil field applications
• Generally based upon physical relationships but rely upon empirical constants
Electromagnetic Properties

- Electric conductivity describes how free charges flow to form a current in presence of electric field:

\[ \bar{J} = \tilde{\sigma} \bar{E} \]

where

\( \bar{J} \) = electric current density vector
\( \bar{E} \) = electric field strength vector
\( \tilde{\sigma} \) = electric conductivity tensor
Electromagnetic Properties

- Dielectric permittivity describes how constrained charges (in poor conductors) are displaced in response to an electric field:

$$\mathbf{D} = \varepsilon \mathbf{E}$$

where

- $\mathbf{D}$ = electric displacement vector
- $\mathbf{E}$ = electric field strength vector
- $\varepsilon$ = dielectric permittivity tensor
Electromagnetic Properties

- Magnetic permeability describes how intrinsic atomic and molecular magnetic moments respond to a magnetic field:

\[ \bar{B} = \mu \bar{H} \]

where

- \( \bar{B} \) = magnetic flux density vector
- \( \bar{H} \) = magnetic field intensity
- \( \mu \) = magnetic permeability
Importance of Properties

- Conductivity is the most often used property for hydrogeophysical investigations.
- Electric permittivity is important for some GPR applications, particularly NAPL detection.
- Magnetic permittivity is rarely used in environmental applications.
Conductivity

• Conductive and capacitive properties of a material can be represented by complex conductivity:

\[ \sigma^* = i \omega \varepsilon^* \]

where

\[ \sigma^* \] = complex conductivity

\[ \varepsilon^* \] = complex permittivity

\[ \omega = 2\pi f \] = angular frequency
Conductivity

• Complex conductivity can be expressed in terms of magnitude and phase or as real and imaginary components:

\[ \sigma^* = |\sigma| e^{i\phi} = \sigma' + i\sigma'' \]

where

\[ |\sigma| = \text{magnitude of conductivity} \]

\[ \sigma' = \text{real component of conductivity} \]

\[ \sigma'' = \text{imaginary component of conductivity} \]
Dielectric Constant

- Most often permittivity is normalized to permittivity in a vacuum and called the dielectric constant:

\[ \kappa = \frac{\varepsilon'}{\varepsilon_0} = \frac{\sigma''}{\omega\varepsilon_0} \]

where

\( \kappa \) = dielectric constant (relative permittivity)

\( \varepsilon_0 \) = permittivity in a vacuum (8.85x10\(^{-12}\) Farads/m)
Refractive Index (CRIM) Model

- Predicts relative volume of two-phase mixtures. In an unsaturated geologic medium, the effective permittivity is given by:

\[ \sqrt{\kappa_{\text{eff}}} = \theta \sqrt{\kappa_w} + (n - \theta) \sqrt{\kappa_a} + (1 - n) \sqrt{\kappa_s} \]

- \( \kappa_a = \) permittivity of air
- \( \theta = \) volumetric water content
- \( \kappa_w = \) permittivity of water (~80)
- \( \kappa_s = \) permittivity of solids (4 to 8)
- \( n = \) porosity
Electric Conductivity Models

- Archie’ (empirical) Law is widely used to predict porosity in saturated geologic formations:

\[ \sigma_{\text{eff}} = \frac{\sigma_w}{F} = \sigma_w n^m \]

where \( F \) is the electric formation factor (related to tortuosity) and \( m \) ranges from 1.3 for unconsolidated sands to 2.0 for consolidated sandstones.
Permeability Estimation

- Kozeny-Carman equation predicts relationship between permeability, $k_s$, and formation factor, $F$.

$$k_s = \frac{1}{aF S_p^2}$$

where

$$a = \text{tube shape factor (1.7 - 3)}$$
$$F = \text{electrical formation factor}$$
$$S_p = \text{specific surface area}$$

- Of limited use in practice because $S_p$, related to pore size, varies much more than $F$. 
Electric Conductivity Models

- Archie’ (empirical) Law can also be used to predict water content:

\[ \sigma_{\text{eff}} = \sigma_w \theta^m \]

where \( m \) is determined empirically.
## Typical Electric Properties

**Table: 3-4 Typical Dielectric Constant, Electrical Conductivity, Velocity and Attenuation Observed in Common Geologic Materials**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>χ</th>
<th>σ (mS/m)</th>
<th>υ (m/ns)</th>
<th>a (dD/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>.01</td>
<td>103</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>Silt</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>2-10000</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>
Summary

• Site characterization requires estimation of hydraulic and geochemical property distribution in space.
• Geophysics offers indirect measures of geology and properties.
• Geophysical data must be related to properties of interest through petrophysical relationships.
What is Hydrogeophysics?

• Application of physics to remotely sense hydrogeologic properties.
  – Borehole Logging
  – Geophysical Methods
    • Surface Hydrogeophysics
Surface Hydrogeophysics

- Surface hydrogeophysics is remote sensing of hydrologic properties.
- Generally we use the influence of geologic and hydraulic properties on propagation of acoustic or electromagnetic waves to image subsurface.
# Common Surface Geophysics

<table>
<thead>
<tr>
<th>Method</th>
<th>Attribute Sensed</th>
<th>Hydrogeologic Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic Refraction</td>
<td>P-wave velocity</td>
<td>Mapping of bedrock or water table</td>
</tr>
<tr>
<td>Seismic Reflection</td>
<td>P-wave reflectivity and velocity</td>
<td>Mapping of stratigraphy, bedrock, fractures</td>
</tr>
<tr>
<td>Electric Resistivity</td>
<td>Electrical resistivity</td>
<td>Mapping of water table, bedrock, chemical zonation, hydraulic anisotropy, water content</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Electrical resistivity</td>
<td>Same as above</td>
</tr>
<tr>
<td>Ground Penetrating Radar</td>
<td>Dielectric constant and contrasts</td>
<td>3-D mapping of geologic, moisture, geochemical properties.</td>
</tr>
</tbody>
</table>
DC Resistivity

- Determines spatial distribution of low-frequency resistance of subsurface.
- Relatively inexpensive and widely used.
- Derived from oil exploration methods developed in the early 1900’s.
DC Resistivity

• What is Measured and How?
  – Resistance of subsurface measured by passing current and measuring voltage drop in a 4-electrode configuration
  – Voltage drop from a single electrode follows a $1/r$ relationship
DC Resistivity

• Voltage from an induce current

\[ V = \frac{\rho I}{2\pi} \frac{1}{r} \]

where

\[ \rho = \text{resistivity (1/}\sigma) \]
\[ I = \text{injected current} \]
\[ r = \text{distance from electrode} \]

Poisson equation:

\[ \nabla \cdot (\sigma \nabla V) = -I \delta(\mathbf{r}) \]
DC Resistivity

- Common Electrode Arrays
  - A and B induce current
  - M and N measure resistance
  - Choice of array depends on depth, power of system, resolution required
DC Resistivity

- Resistivity from multiple electrodes may be superimposed.
- In Wenner array, e.g., the apparent resistivity is:

\[
\rho_a = 2\pi a \frac{V}{I}
\]

where

\[
\rho_a = \text{apparent resistivity}
\]

\[
a = \text{electrode spacing}
\]
DC Resistivity Surveys

• Entire survey 100-200 m long at 20-30 m can be conducted in 2 hours, faster with “roll-along” devices
Pseudo-Section DC Resistivity

• Method of plotting resistivity measurements
• A pseudo section plots apparent resistivity, which is NOT a measurement of resistance of the medium at a point.
• To achieve actual resistivity profile, we must perform an inversion on the data
Building a Pseudo-Section

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Pseudo-Section DC Resistivity

a). Wenner array pseudosection

b). Pole-pole array pseudosection

c). Dipole-dipole array pseudosection

d). Pole-dipole array pseudosection

Apparent Resistivity Pseudosection

Pole-pole
Dipole - dipole
Pole-dipole

Resistivity in ohm.m

Unit electrode spacing 1.0 m.
Psuedo-Section

- Apparent resistivity bears little resemblance to actual resistivity
Inversion

- Inversion extracts actual from apparent resistivity
- True geometry still not recovered!

Archie’s empirical law:

$$\sigma_{\text{eff}} = \sigma_w n^m$$
Ground Penetrating Radar

• It is a method that transmits electromagnetic pulses from surface antennas into the ground, and then measures the time elapsed between when the pulses are sent and when they are received back at the surface.

• As the pulses are transmitted through porous media, their velocity will change, depending on the physical and chemical properties of the material through which they are traveling. When the travel times of the energy pulses are measured, and their velocity through the ground is known, distance (or depth in the ground) can be accurately measured.

• Reflections are recorded along transects using a variety of collection techniques.
GPR survey methodology

Reflection

Multiple Offset Gather

Transillumination

Zero Offset Profiling (ZOP)
Dielectric Constant

- Dielectric constant $k$ is ability of a material to store and allow passage of electromagnetic energy when a field is imposed upon it.

$$\kappa = \frac{\varepsilon'}{\varepsilon_0}$$

where

$\varepsilon'$ = electric permittivity

$\kappa$ = dielectric constant (relative permittivity)

$\varepsilon_0$ = permittivity in a vacuum ($8.85 \times 10^{-12} \ F/m$)
\[ \sqrt{K} = \frac{C}{V} \]

K = Dielectric Constant or Relative Dielectric Permittivity

C = Speed of light

V = Velocity of radar energy

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**CRIM Model**

\[ \sqrt{\kappa_{\text{eff}}} = \theta \sqrt{\kappa_w} + (n - \theta) \sqrt{\kappa_a} + (1 - n) \sqrt{\kappa_s} \]

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Figure 1. Measured values of RDP and resistivity [ohm-m] for sediments from the Coeur d’Alene River bed (Roth, 1996). There are two groups of samples, those from core 95PCK-1 (above) and those from elsewhere, ordered by depth. (!), high metal content; (&), pre-mining sediment. Values are for 80 MHZ.
GPR survey: an example

Figure 3. The 110 MHz GPR profile showing a compound bar deposit with an erosional base (thickest white line; arrowed) made up of a number of unit bar deposits. The top of the compound bar deposit has been truncated. Modified from Lunt et al. [2004a] with permission from Blackwell Publishing.
The seismic survey is one form of geophysical survey that aims at measuring the earth’s properties by means of physical principles such as elastic theories. It is based on the theory of elasticity and therefore tries to deduce elastic properties of materials by measuring their response to elastic disturbances called seismic (or elastic) waves.

Fig. 1. Schematic of overall field setup for a seismic survey.
Seismic Equipment

Seismometer

Thumper

Geophones
Acquiring wave data is important for determining the properties of the bedrock and glacial materials.

The material properties derived from P- and S-waves:

- Bulk Modulus
- Shear Modulus
- Young’s Modulus
- Bulk Density
- Poisson’s Ratio
- Velocity Ratio
Seismic survey

Seismic refraction
• Used to study large scale crustal layering: thickness and velocity

Seismic reflection
• “Imaging” of subsurface reflectors
• Difficult to determine accurate velocities and depths
Seismic survey: wave types

Figure 8.1. Types of waves: (a) Depiction of P-waves traveling in a solid medium; (b) the vertical component of S-waves traveling in a solid medium; (c) S$_P$-waves traveling in a solid medium (d) Rayleigh waves traveling along a section of the earth’s surface; and (e) Love waves traveling along a section of the earth’s surface; (a-e adapted from *Earthquakes*, by Bruce A. Bolt, 1993 [revised], Freeman and Co., with permission).
Seismic survey

A field record and interpretation of different seismic events based on the arrival pattern.
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