High Frequency Impedance Measurements for Characterization, Monitoring and Verification Efforts

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Purpose

To develop high-frequency impedance methodology for non-invasive investigation of the near-surface utilizing frequencies between 1 and 100 MHz. The specific goal is high-resolution imaging of conductivity and permittivity to depths of a few meters.

Motivation

The physical integrity of clay caps ensures the isolation of hazardous waste at many sites. The caps may fail by two principal mechanisms: 1) loss of molding water by volatilization or transpiration can result in shrinkage and cracking, and 2) an excess of water can cause flocculation-induced weakening, leading to deformation or slumping. It is therefore desirable to have a means for estimating the water content of a remote clay region without disturbing either the clay or its covering material for verification and monitoring *(e.g.*, STCG #ID-S.1.04 and AL-09-01-03-SC-S, Subsurface Contaminants Focus Area).

There is a lack of advanced vadose zone geophysical techniques for adequately monitoring the movement of contaminants at Hanford and other DOE sites (STCG #.RL-WT045-S, Tank Focus Area). Electromagnetic geophysical methods can yield estimates of resistivity and permittivity that are useful for environmental investigations such as monitoring of contaminant plumes and characterization of buried waste.

Background

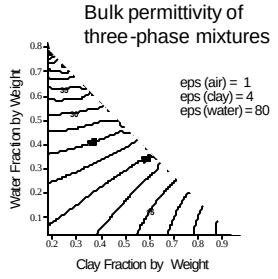
Soil and Clay Properties:

Water content controls both the mechanical properties (Atterberg limits, Proctor values) and the dielectric permittivity of the clay-air-water mixture.

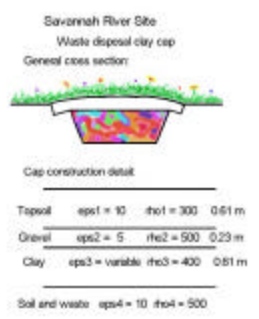
Permittivity Mixing Law:

$$\varepsilon = \left[\sum_{i=1}^{N} V_i \sqrt{\varepsilon_i} \right]^2$$

Bulk permittivity of three-phase mixtures



Model



Practical considerations lead to using near-field impedance, with its additional source dependence, rather than far-field impedance

Far-field Impedance:

$$Z_{xy}(\rho_i, \varepsilon_i, \omega) = E_x / H_y \Big|_{far\ source}$$

where ρ_i, ε_i are the component properties

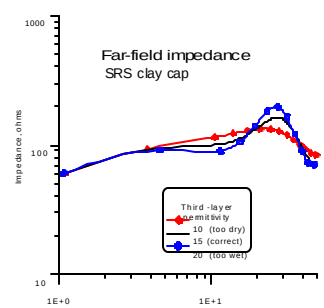
Near-field impedance:

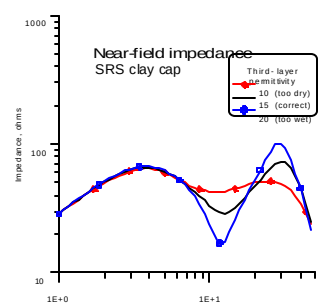
$$Z_{xy}(\rho_i, \varepsilon_i, \omega, R, S) = E_x / H_y \Big|_{near\ source}$$

where R is the location of source and receiver, and S describes the source type and orientation

Calculated layered-structure response:

The impedance response of a typical clay cap structure varies with permittivity of the clay layer and with the location (and orientation) of the source.



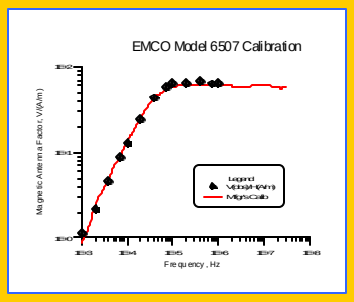


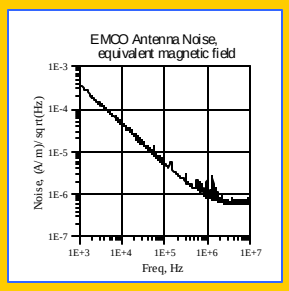
Sensors

Magnetic Loop Sensor

EMCO Model 6507 Magnetic Field Antenna

- 1 kHz to 30 MHz response
- Adequate sensitivity
- Directional sensitivity is typical dipole pattern
- Noise spectrum determined



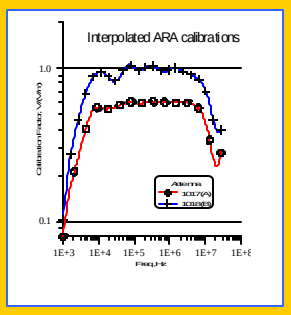


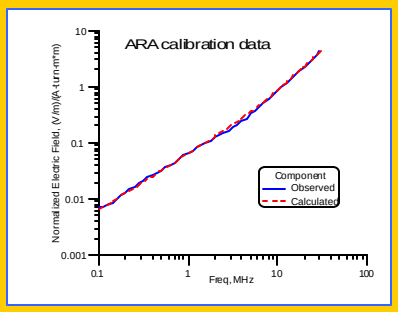
Magnetic Loop Antenna
Loop diameter is 30 cm

Stub Dipole Electric Sensor

ARA Model ADA-120/A Electric Field Antenna

- 1 kHz to 100 MHz useful frequency range
- Large Antenna Factor
- High source impedance
- Fragile construction





Comparison between observed and theoretical vertical electric field in a known environment

The stub dipole shown in horizontal orientation. Distance between the end plates is 66 cm.

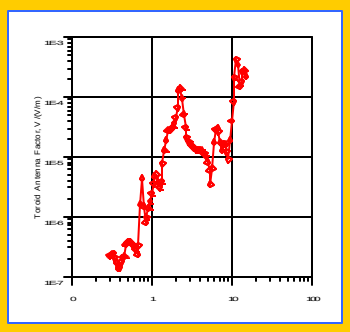
Toroid Electric Sensor

Small size, robust design
Small antenna factor, increases with square of frequency:

$$AntennaFactor = V/E = 2NADk^2$$

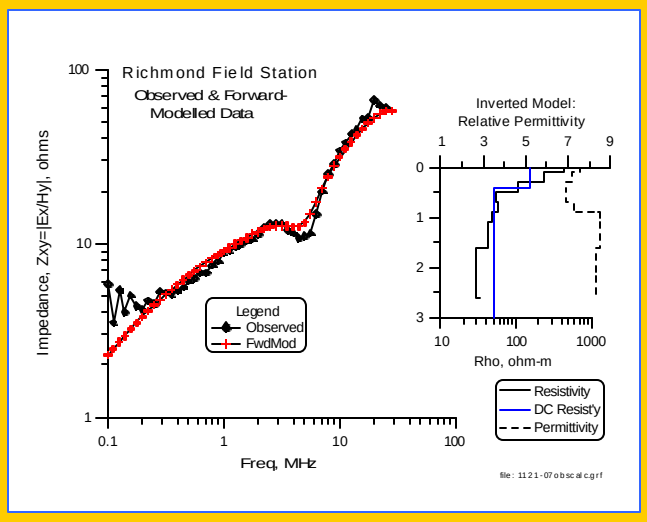
$$k = \sqrt{\varepsilon\mu\omega^2 - i\,\mu\sigma\omega}$$

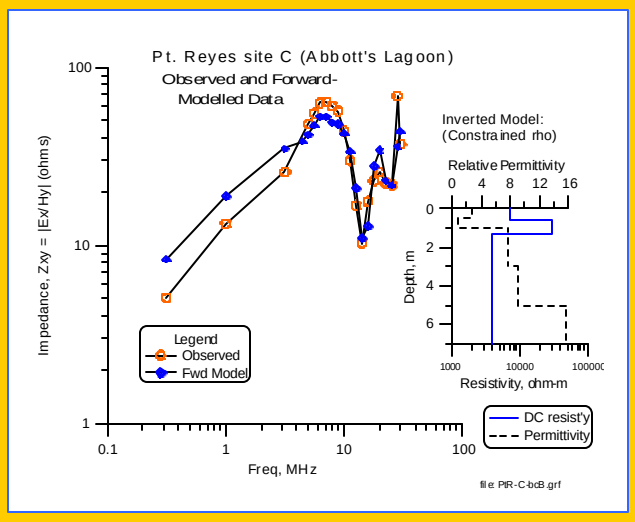
High source impedance



Prototype toroid sensor.
Diameter is 3 inches (7.5 cm)

Field Results





Observed data in a conductive regime, where resistivity controls electrical response, fit well with independently measured resistivity.

Permittivity controls electrical response in a resistive regime. Constraining resistivity, the observed data invert to a plausible permittivity.

Summary

A working prototype, proof-of-concept high frequency impedance (HFI) system has been built and tested

- stub dipole electric sensors work
- toroid sensor requires further development
- magnetic sensor good to 30 MHz
  - need to extend range
- data acquisition system implemented

HFI data have been measured at several sites

- conductive site data agree well with independently determined resistivity
- resistive site data invert to yield reasonable permittivities

Clay moisture, which relates to engineering properties, may be determined from interpreted permittivity

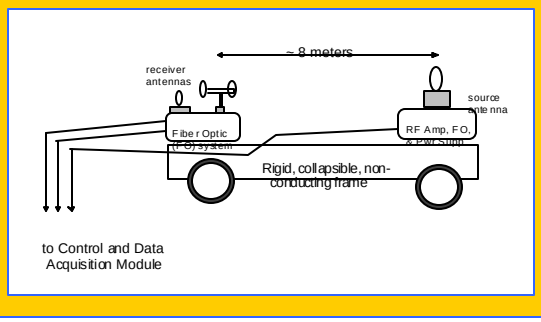
Future Work

Investigate additional applications

Further development of the toroid electric field sensor

Extend frequency range of magnetic sensor

Development of improved interpretation software

- faster, constrained inversion methods
- 3-dimensional analysis

Construction of a field-worthy prototype system: