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Geophysical Characterization of Subsurface Barriers

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GEOPHYSICAL CHARACTERIZATION OF SUBSURFACE BARRIERS

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ABSTRACT

An option for controlling contaminant migration from plumes and buried waste sites is to construct a subsurface barrier of a low-permeability material. The successful application of subsurface barriers requires processes to verify the emplacement and effectiveness of barrier and to monitor the performance of a barrier after emplacement. Non destructive and remote sensing techniques, such as geophysical methods, are possible technologies to address these needs. The changes in mechanical, hydrologic and chemical properties associated with the emplacement of an engineered barrier will affect geophysical properties such a seismic velocity, electrical conductivity, and dielectric constant. Also, the barrier, once emplaced and interacting with the in situ geologic system, may affect the paths along which electrical current flows in the subsurface. These changes in properties and processes facilitate the detection and monitoring of the barrier. The approaches to characterizing and monitoring engineered barriers can be divided between (1) methods that directly image the barrier using the contrasts in physical properties between the barrier and the host soil or rock and (2) methods that reflect flow processes around or through the barrier. For example, seismic methods that delineate the changes in density and stiffness associated with the barrier represents a direct imaging method. Electrical self potential methods and flow probes based on heat flow methods represent techniques that can delineate the flow path or flow processes around and through a barrier. To some

extent, most of the geophysical methods, such as seismic, electromagnetic, and electrical imaging, discussed in this report can be configured either to address direct imaging or process detection. Flow probes based on heat flow methods possibly can address monitoring issues if the longevity of subsurface probes is significantly increased.

Of the two approaches, direct imaging addresses requirements for the verification and delineation of a barrier. However, direct imaging is impacted by the limits of resolution. Due to scale, time-dependency and distribution of variations in material properties of soils and barriers, direct imaging methods may have difficulty in achieving the required resolution (the order of 1 to 10 cm). The variation in material properties, such as seismic velocity and electrical conductivity, due to variations in saturation has major effects on the achievable resolution relative to the effects of technology of the imaging method and its instrumentation. The development of geophysical source and receiver technology and the development of data processing and interpretation methods utilizing evolving computer systems will not alone sufficiently increase the resolution of the geophysical methods. An understanding of the physical processes, such as time dependent moisture migration in fingers, within the vadose zone and processes, such as the chemical evolution of pore fluids associated with the emplacement of a barrier, is critical. The understanding derived from these studies permits the effects of these processes on geophysical properties to be accounted for in the final images.

Direct imaging methods also address requirements for the monitoring of barrier performance. Multiple images taken over time can be effective in removing original variations in physical properties. Methods, such as electrical imaging and self potential arrays, that detect flow processes and flow paths, offer an alternative approach. These methods can detect whether flow is occurring around or through a barrier. Similar methods have to been used to detect flow through earthen dams and leaks in lined storage ponds. Such methods will not map the continuity of a barrier within the resolution requirements of many site operators, but will provide a means to measure and monitor performance of a barrier. This monitoring capability can address post-closure compliance with a regulatory standard.

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INTRODUCTION

An option for controlling contaminant migration from plumes and buried waste sites is to construct a subsurface barrier of a low-permeability material (Heiser, et al., 1994). This barrier could either be "interim" or "permanent". In concept, the "interim" barrier can provide time for the evaluation and selection of remediation options. The "permanent" barrier would be a component of the engineered landfill or containment system and would have to meet some performance goal to reduce subsurface movement of fluids. The requirement arises of how to verify the emplacement and effectiveness of the barrier and to monitor the barriers' performance after emplacement. Non-destructive and remote sensing techniques, such as geophysical methods, are possible technologies to address these needs.

Previous Evaluations of Geophysical Methods

Both DOE and EPA have sponsored several evaluations of geophysical methods as applied to environmental problems (example given, Olhoeft, 1988, Calef and Van Eeckhout, 1992). These evaluations give guidance as to the applicability of various geophysical methods, such as seismic, electrical, and electromagnetic, to different site conditions and targets. As already stated, geophysical methods represent important possible characterization and monitoring technologies. Detailed descriptions of geophysical methods that could be applied to subsurface barriers are available in several textbooks and publications (example given, Telford, et al., 1978; S. H. Ward, 1990). Heiser (1994) summarized geophysical methods that could be applied specifically to barrier emplacement.

Actual field demonstrations of geophysical methods as applied to barrier emplacement have occurred. Voss, et al., (1994) report for a grout barrier emplacement in arid alluvial soils that (1) borehole electrical and moisture logging during and after grout emplacement show a decrease in resistivity and increase in moisture content at the emplacement horizon, and (2) for this site, ground penetrating radar (GPR) was not effective in many localities due to attenuation with depth and near surface clutter or objects. At the same arid alluvial site, Dwyer (1994) obtained similar results with an overlapping set of geophysical methods: ground penetrating radar; surface electromagnetic induction; downhole electromagnetic induction; downhole neutron probe; and downhole temperature logs.

Approach of this Report

The approach taken in this report is not to supply a summary of methods (see Heiser, 1994) or a tutorial on geophysical methods, which can be obtained from, for example, Telford, et al., 1978 and S. H. Ward, 1990. The approach herein will be to:

- Describe possible barriers and emplacement methods
- Describe how the barriers may affect the physical properties measured;
- Describe what the methods measure and how these measurements relate to the physical properties;
- Identify methods/technologies to address three basic tasks:
  Process control during barrier emplacement
  Verifying barrier emplacement
  Monitoring barrier performance post emplacement
- Describe resolution; and
- Describe other limits of performance

This approach will focus primarily on geophysical imaging methods, for example, ground penetrating radar or electrical, electromagnetic, and seismic tomography. These imaging methods permit mapping of subsurface geophysical properties over broad regions while minimizing the number of boreholes that may affect the barrier. Therefore, chemical tracer methods (Heiser, 1994) and borehole logging methods (such as neutron logging) are given minor consideration. The logic for this narrowed focus is in part that: (1) tracer methods, except radioactive, are not actually geophysical methods, and are covered in other studies (e.g., Heiser, 1994); (2) borehole logging methods interrogate only a region several borehole radii or less around a borehole and the boreholes, unless already existing for chemical monitoring, may affect the performance of the barrier. The borehole logging methods are also described in textbooks, such as Hearst and Nelson (1985).

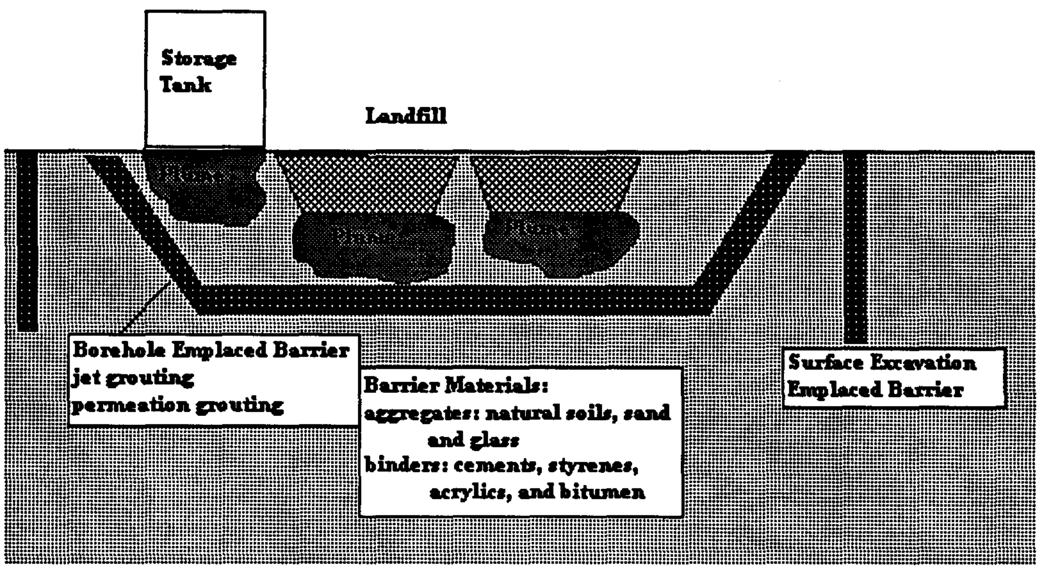

Figure 1: Conceptual Barrier Emplacement

Description of possible barriers and emplacement methods

The commonly envisioned approach (Heiser, et al., 1994; Johnson, et al., 1984) is to emplace the barrier in an excavation, such as a trench, or through a borehole method, such as jet grouting and permeation grouting (see Figure 1). There is a general relationship between permeability and groutability; and the ability of a grout to penetrate an earth material and form a barrier is a function of viscosity. Earth materials with higher permeability require higher viscosity grouts to form a barrier. The criteria and possible materials for these barriers are listed below:

Criteria for Barrier material from Heiser, et al. (1994)

a) As low an effective diffusivity as is reasonably achievable to minimize or inhibit transport of moisture and contaminants
b) Prefer to use conventional emplacement techniques (for example, jet grouting, permeation grouting, trenching)
c) Low permeability, resistance to aggressive chemicals. Special: radiation and thermal resistance
d) Possible binders: polyester styrenes, vinylsester styrenes, high molecular weight acrylics, sulfur polymer cement, polyacrylic acids, bitumen, and furfurl-alcohol based furan polymer
e) Aggregates of recycled glass stone, sand and natural soils
f) Effective control of the cure time that allows placement of the barrier but doesn't permit the grout to slump due to gravity loading

Frozen Barrier

The use of refrigeration for the freezing of soils and other geologic materials has been employed in large-scale engineering projects to give load-bearing strength during foundation construction, to seal subsurface structures against groundwater flooding, and to stabilize geologic materials during excavation. This engineering technology is proposed as method to prevent contaminant migration from storage tanks and disposal areas, such as landfills, trenches and pits. This frozen barrier will be formed by a network of underground piping in which a refrigerant (for example, calcium chloride brine) will be circulated. The barrier is formed by the conversion of water to ice in the pore space of the geologic material. The effectiveness of the frozen soil will in part be a function of the saturation state of initial material and the distribution of solid, gas and liquid phases of water in the pore space. An analog for the physical properties of the frozen barrier is permafrost soil (King, et al., 1988). This study looked at the seismic and electrical properties of unconsolidated permafrost. In this analog, an important observation is that a continuous ***unfrozen*** layer of water remains absorbed on the mineral grains of the soil (Figure 2). The remaining unfrozen water will increase in salinity and, therefore, decrease in electrical resistivity. Seismic velocities of permafrost decrease as a function of porosity and the water-to- ice ratio. The physical properties of the frozen soil will vary with the temperature attained during freezing (for example, the resistivity of the soil varies by a factor of five to ten from -2° to -15°)

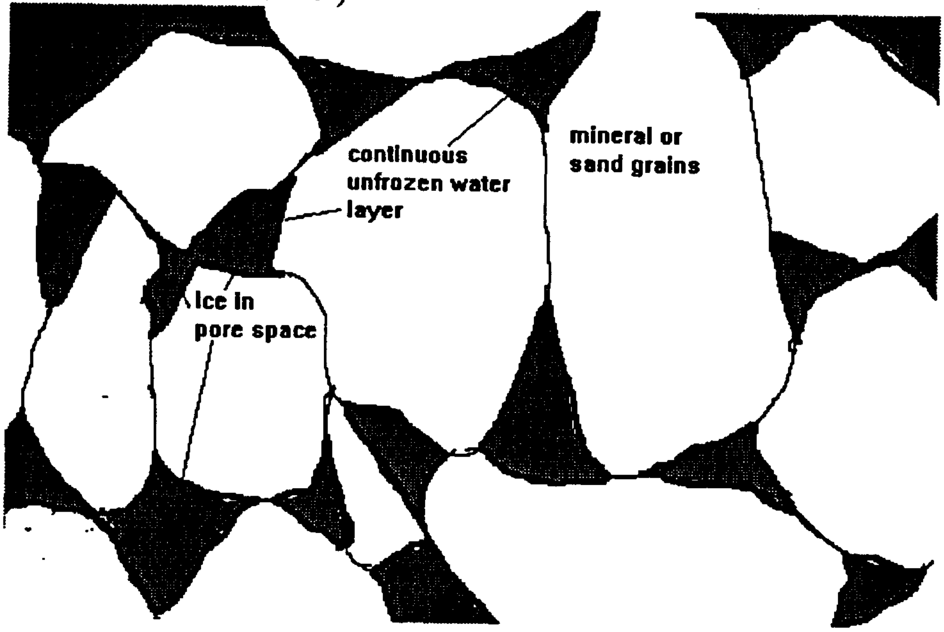

Figure 2. The structure of frozen soil, showing the continuous layer of adsorbed water on mineral grains (from King, et al., 1988)

Physical Description of Barriers

Post test samples of subsurface barriers (for example, Dwyer, 1994) show that the injected grout initially enters the pore space of the soil (Figure 3). Subsequent injections become displacive with a grout monolith forming around injection sites or lines. Further injections result in the fracturing of the monolith followed by filling of the fractures with grout. The dimensions of the grouted zone vary along the length of the injection line and away from the line.

New approaches are proposed to produced a more continuous and homogeneous barrier in the subsurface. An example of such a new technology is the "soil saw" as proposed by Halliburton. In this technology, a line of water jet cutters and following grout injectors is moved through the soil along a single slant borehole or between two approximately perpendicular directionally drilled boreholes. The effects of this system interacting with a heterogeneous geologic environment remains to be demonstrated. Certain effects, such as the introduction of water and grout, may have pronounced and local effects on soil properties.

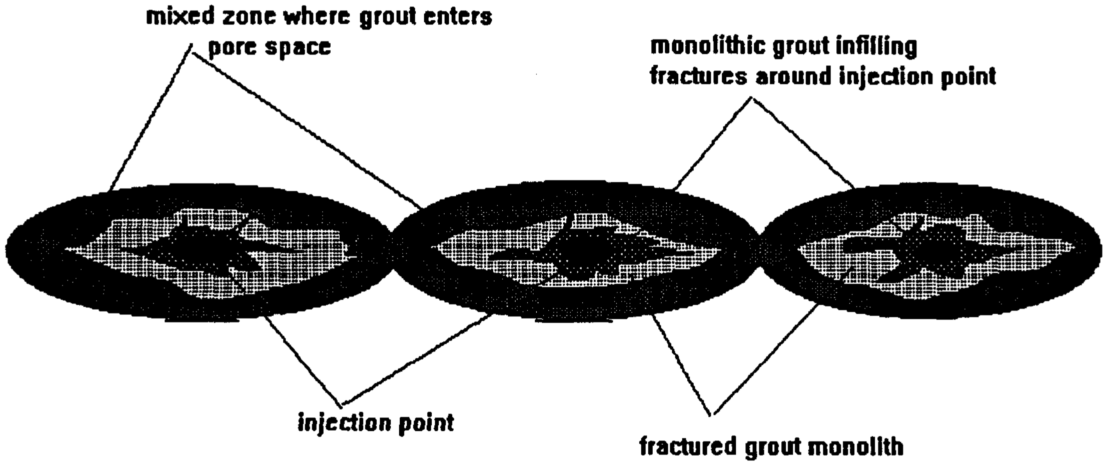

Figure 3: Conceptual Cross-Section of Subsurface Grout Barrier

Effects of Barriers on the Physical Properties Measured by Geophysical Methods

The emplacement of a barrier will change the physical behavior and properties of integrated host material in several ways. In part, the effects are based on the mode of emplacement, the material emplaced and the nature of the host material. These changes in physical properties are what makes the barrier detectable or capable of being monitored. Table 1 lists possible changes in material and hydrologic properties due to barrier emplacement. From this list, possible properties to be used for geophysical detection can be identified. In Table 2, the possible relationships of barrier materials and installation to changes in soil and geophysical properties are listed. These tables demonstrate that barrier installation can result in material and hydrologic changes that are detectable by geophysical methods. The questions remaining are the limits of resolution of the various geophysical methods and the magnitudes of change in soil and chemical properties required to be detectable by the various methods.

Some of the observed effects of barrier emplacement may be counter-intuitive. For example, with the reduction in permeability it has been suggested that a barrier leads to an increase in apparent resistivity. However, the barrier emplacement may actually result in a decrease in resistivity (for example, Heiser, et al., 1994; and Dwyer, 1994). This result may rise from several processes that affect electrical properties especially in the vadose zone. One is that the emplacement of the grout includes water as a transport medium or as a byproduct of the chemical reactions occurring after emplacement. Frozen barriers may also collect water relative to the surrounding unsaturated host material. Portions of this water may remain unfrozen along grain boundaries and promote the flow of electrical current (King, et al., 1988).

Table 1: Properties Possibly Affected by Barrier Emplacement		
1. ***Material properties***		
	a)	density of integrated host material-barrier system
	b)	bulk modulus of integrated host material-barrier system
	c)	electrical properties
		(1) conductivity
		(2) dielectric constant
		(3) conductivity of pore fluid or filling
	d)	thermal conductivity
2. ***Hydrologic properties (for example, barrier material enters pores and fractures thus decreasing effective porosity and permeability)***		
	a)	effective porosity
	b)	saturation
	c)	permeability
	d)	relative permeability to gas and liquid
	e)	tortuosity

Table 2: How barrier materials, soil properties, and geophysical properties are related		
Emplaced in sand, silt, clay mixtures, saturated and unsaturated		
Barrier Material	Possible Change in Local Soil Properties	Geophysical Properties Affected
cementitous	stiffness- shear modulus bulk modulus electrical conductivity- permeability saturation effective porosity	seismic methods- velocity attenuation phase electrical methods- conductivity self potential electromagnetic methods- attenuation phase velocity conductivity dielectric constant
synthetic polymers	stiffness- shear modulus bulk modulus electrical conductivity- permeability saturation effective porosity dielectric properties of pores	seismic methods- velocity attenuation phase electrical methods- conductivity self potential electromagnetic methods- attenuation phase velocity conductivity dielectric constant
hydrocarbon waxes	stiffness-	seismic methods-

	shear modulus bulk modulus electrical conductivity- permeability saturation effective porosity dielectric properties of pores	velocity attenuation phase electrical methods- conductivity self potential electromagnetic methods- attenuation phase velocity conductivity dielectric constant
low temperature thermal	stiffness- shear modulus bulk modulus electrical conductivity- permeability saturation effective porosity	seismic methods- velocity attenuation phase electrical methods- conductivity self potential electromagnetic methods- attenuation phase velocity conductivity

Relationship between Geophysical Methods and Physical Properties of Soils and Rocks

Heiser (1994) summarized geophysical methods that are candidates for characterizing subsurface barriers. He also provided several case histories. Built upon Tables 1 and 2, the approach of this report is evaluate how the actual properties affected by barrier emplacement relate to the distinct families of geophysical methods (i.e., seismic methods and electromagnetic methods). Table 3 provides the linkage from the geophysical method to the hydrologic and material properties that are directly and indirectly measured by the method. This table is followed by several sections describing the basic principles of a given family of geophysical methods and existing applications of these methods to projects similar in technical needs as barrier emplacement.

Table 3: the linkage from the geophysical method to the hydrologic and material properties that are directly and indirectly measured by the method

Method	Property Measured Directly	Parameter Determined Indirectly
electrical and electrical imaging	resistivity or its inverse (conductivity)	porosity saturation ionic strength of the pore fluid permeability tortuosity
electromagnetic (imaging)	permitivity or dielectric constant resistivity or its inverse (conductivity)	saturation presence of non-aqueous phases porosity saturation ionic strength of the pore fluid permeability tortuosity
seismic imaging	seismic velocity attenuation phase	density bulk modulus saturation porosity fracture density rock quality
neutron logging	neutron flux	moisture content porosity
electromagnetic (borehole, and time domain reflectometry, TDR)	permitivity or dielectric constant resistivity or its inverse (conductivity)	saturation presence of non-aqueous phases over a restricted rock volume: porosity saturation ionic strength of the pore fluid permeability tortuosity
heat flow	anisotropy of heat flow around an isolated instrument	flow direction for gas and liquid fluxes

Seismic Methods

The principle of seismic methods is to initiate elastic waves at one point (the transmitter) and to determine at another point (the receiver) the arrival time, phase and attenuation of the transmitter impulse. These seismic impulses can be directly transmitted point-to-point or refracted and reflected. Therefore, seismic methods can be conducted from the surface, surface to borehole, and borehole-to-borehole. Seismic methods have proven to be of great use in the petroleum industry and large-scale engineering application. Due to the success of seismic methods in these applications, this family of methods is favored candidate for environmental applications such as barrier detection (Dwyer, 1994; Harding, 1994; Elbring, 1992; Lankston, 1990 Steeples and Miller, 1992, Calef and Van Eeckout, 1992).

The borehole-to-borehole tomographic imaging approach provides the maximum resolution of the subsurface. This configuration avoids surface noise sources and attenuation problems associated with near surface materials. In addition, the source and receiver are both near the area of interest giving shorter travel paths and less loss of high frequency energy. Both compressional (P) and shear (S) waves are used. In environmental applications, S waves will have somewhat better resolution capabilities than P-waves for the same source frequency. This is a result of the lower S-wave velocities that result in shorter wavelengths than P waves.

SEISMIC PROPERTIES

The imaging capabilities of seismic methods are based on the observation that elastic waves travel with different velocities in different rocks, soils and engineered materials. The elastic wave velocity and other seismic properties of these materials are functions of the rigidity (shear modulus- μ), incompressibility (bulk modulus- k), and density (ρ) of the material (Equations 1 and 2). Considering models and empirical relationships, we use seismic data in certain applications to estimate porosity, saturation and other rock properties. In the application to barrier characterization and monitoring, the introduction of binder and aggregate to the soil or rock matrix will affect the local rigidity, incompressibility, and density. These changes will make the barrier detectable to the seismic method within certain limits of resolution. This detectability has been demonstrated in the field (Dwyer, 1994; Harding, 1994)

COMPRESSIONAL WAVE

$$V_p = \left(\frac{k}{\rho}\right)^{\frac{1}{2}} \qquad [1]$$

or

$$V_p \approx \left(\frac{(\frac{4\mu}{3})}{\rho}\right)^{\frac{1}{2}}$$

where:
V_p = the compressional wave velocity
k = the bulk modulus
μ = the shear modulus
ρ = the density

SHEAR WAVE

$$V_s = \left(\frac{\mu}{\rho}\right)^{\frac{1}{2}} \qquad [2]$$

Electromagnetic Imaging:

Electromagnetic methods are sensitive to variations in electrical conductivity or dielectric constant in the soil or rocks. These properties are some of the most responsive geophysical indicators of metallic, acidic and water-based subsurface contaminants. These electrical properties as determined by electromagnetic (EM) methods are unique amongst geophysical measurements, since the electrical property is directly related to the hydrologic properties of the geologic medium and the chemical composition of the fluid passing through the geologic medium (Dobecki and Romig, 1985). The DOE Workshop on Non-invasive Geophysical Site Characterization rated electromagnetic methods as one of the most suitable technologies for waste site characterization (Calef and Van Eeckhout, 1992). These methods have been utilized in studying lateral variations in shallow aquifers and saltwater intrusion (Bartel, 1987). Ramirez and Daily (1987) have demonstrated the cross borehole electromagnetic tomography can provide high resolution images of fluid migration in unsaturated tuff. Stolarczyk (1987) showed similar success with high frequency electromagnetic imaging in coal mines. Another use of this imaging approach is the detection of fractures and fracture flow around tunnels in rock, such as at the WIPP (USA), Grimsel (Switzerland) and Stripa (Sweden) sites (Pfeifer et al., 1989; Lieb et al., 1989; Gale et al., 1983). The application of electromagnetic imaging to characterized disposal pits, hydrogeologic features, and plumes at landfill site has been demonstrated by Borns et al. (1993).

GPR and cross borehole radar methods are a subset (higher frequency) of the electromagnetic imaging methods. GPR, both pulsed and continuous wave system, is being extensively investigated for environmental applications in part due to its potential for high resolution (Berea and Haeni, 1991; Greaves and Toksoz, 1994; Pelton et al., 1994; Olhoeft, 1986; Roberts et al., 1994). A current approach is to apply the signal processing and imaging techniques developed for seismic methods to shallow radar images to greatly enhance resolution. However, as discussed by Dwyer (1994) and Voss, et al. (1994) in their barrier demonstrations, GPR systems are not applicable to many sites due to issues of ground clutter and limited penetration into the subsurface. With all the electromagnetic methods, there is a trade-off for the site engineer between resolution and coverage.

Electrical Imaging:

Direct current resistivity imaging methods have the advantages of ease of automation, low cost and expendable electrodes. These methods have been implemented to detect leaks in earthen dams (Hadley, 1983) and monitor ground water flow in fluvial sediments (White, 1993). The electrical resistivity tomography (ERT) method developed by Raimeriz and Daily at Lawrence Livermore Laboratory and LaBrecque at the University of Arizona is a commonly cited example of this family of methods. Schima, et al. (1993) tracked fluid flow in the vadose zone using cross borehole electrical imaging. The German nuclear waste program has used borehole electrode arrays to monitor underground seal performance (Flach and Yaramanci, 1989). For the University of Waterloo Borden field experiment, Schneider and others (1993) used an automated DC resistivity system to monitor migration of PCE and kerosene. We have been using another DC resistivity imaging method to monitor brine inflow around underground excavations at the DOE Waste Isolation Pilot Plant (Borns and others, 1990; Pfeifer and others, 1990; Truskowski and Andersen, 1993). The WIPP system is based on a series of surface arrays and has been operating since 1990 in an automated mode. The data has been used to calculate local changes in permeability and saturation (Truskowski and Andersen, 1993). Similar methods have to been used to detect flow through earthen dams (Hadley, 1983) and leaks in lined storage ponds (Frangos, 1994). For the post closure monitoring system, planar arrays of electrodes can be placed on the surface of the landfill, within different layers of the cap during closure, and beneath the landfill if we are starting with new trenches or if directional drilling is available (Fig. 4, Fig. 5). These arrays can be used in conjunction with electrodes placed below the landfill using monitoring wells.

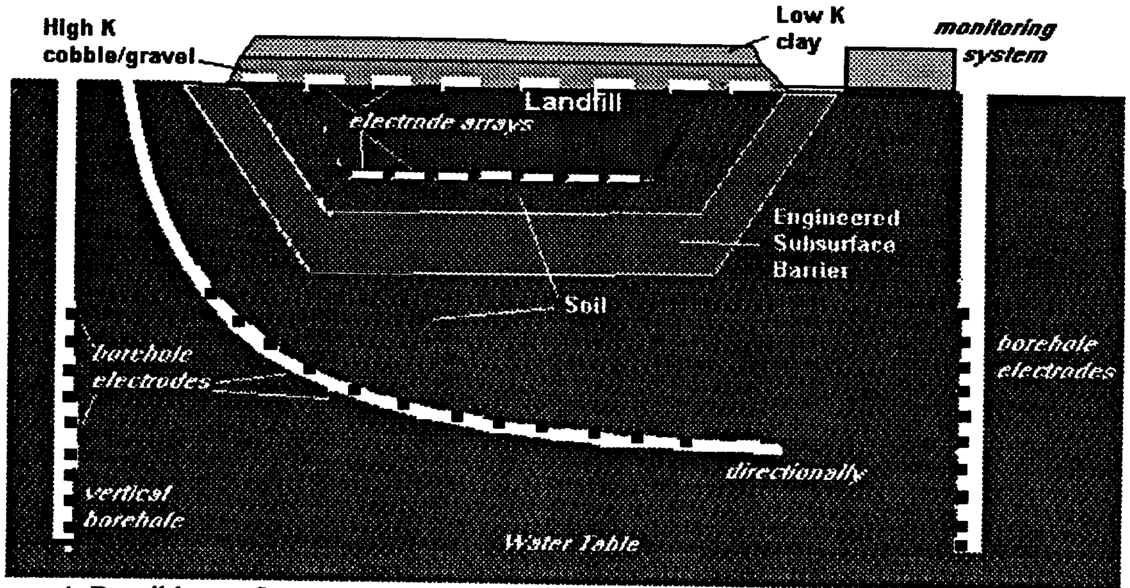

Figure 4: Possible configuration for electrical monitoring system

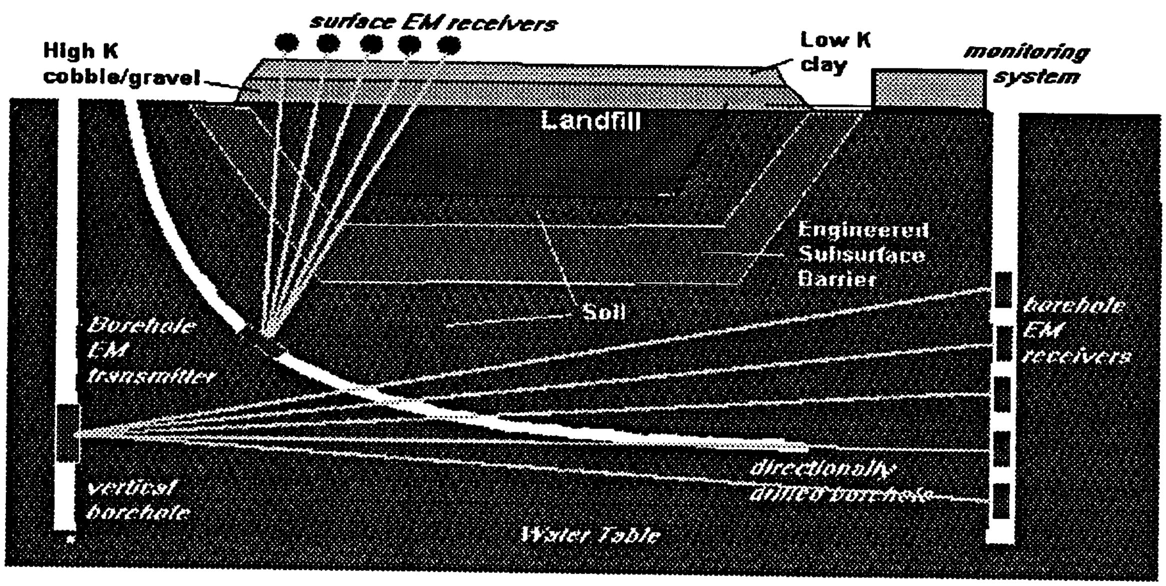

Figure 5: Possible configuration for electromagnetic or seismic system for monitoring or characterization

ELECTRICAL AND ELECTROMAGNETIC PROPERTIES

The relationship amongst barrier materials, the physical and chemical processes in and around a barrier, and the electrical properties measured is important in gauging the effectiveness of electrical and electromagnetic methods for characterization and monitoring of a barrier. Significant interrelationships are (1) how the electrical properties mirror the hydrologic system and (2) how the electrical properties reflect ongoing or completed geochemical processes. Characterization and monitoring of the hydrologic system and the possible chemical reactions around a barrier system are critical tasks in demonstrating barrier effectiveness.

(1) Electrical properties mirror the hydrologic system

The basic premise for the application of electrical and electromagnetic methods to environmental problems is that *electrical current mimics the fluid flow in the pore network.* The flow of electrical current in soils and rocks is supported through either ionic conduction in a pore network or mineral conduction in clays where they link as a continuous phase along the intergranular pore space. Hence, electrical properties of a soil, rock, or engineered material will be a function of pore fluid chemistry, matrix mineralogy, effective porosity, permeability and saturation. As with the seismic methods, the barrier material will locally alter these material properties and make the barrier detectable within certain limits of resolution. Also, ionic flow through the barrier, as is possible in a leak scenario, will affect the local conductivity and self potential, which may be detectable by these methods in a monitoring mode. A great uncertainty in this assessment is what are the actual physical and chemical processes that occur in the subsurface accompanying barrier emplacement (i.e., the increase in conductivity around some barriers, Dwyer, 1994).

Electrical and electromagnetic properties, which are measured in situ, can be related to hydrologic properties of soil, rock, and barrier. For example, based on Archie's Law (Equation 3) and the Poiseulle Equation (Equation 4), electrical conductivity/resistivity can be expressed as functions of porosity, saturation, and permeability .

Archies Law: the relationship amongst porosity, saturation, tortuosity, and resistivity

$$\rho = \rho_w \Phi^{-m} S^{-r} \qquad [3]$$

where:

$\rho =$ *the resistivity of the rock or soil*
$\rho_w =$ *the resistivity of the pore fluid*
$\Phi =$ *the porosity*
$S =$ *the saturation of the pores*
$m =$ *the "cementation factor"*
$r =$ *a constant* ≈ 2.0

Poiseulle Equation: the relationship of resistivity to permeability

$$k = \frac{\ell^2}{3}\frac{\rho}{\rho_w}^{-1.5} \qquad [4]$$

l = the width of the pore pathway or fracture

(2) Electrical properties reflect geochemical processes.

Reactions between soil minerals and pore fluid either in the barrier material or the waste, will affect electrical properties of the barrier and surrounding soil. The following chemical processes that affect electrical properties are oxidation-reduction, ion exchange reactions, and mineral-organic reactions (Olhoeft, 1985).

Oxidation-reduction: e.g., oxidation of iron to hematite

Change in electrical properties related to either (1) the reaction rate [kinetics limited] or (2) the speed of charged particle transfer to and from the interface [diffusion-limited].

Ion exchange reactions: commonly involving organic materials

Change in electrical properties in ion exchange systems related to (1) reaction rate [*kinetics limited*] at low frequencies and (2) high Hilbert distortion

Mineral-organic reactions: commonly clay-organic reactions

Change in electrical properties related to (1) reduced Hilbert distortion and high phase at low frequency, which represent organic molecules preferentially attaching to the surfaces of clay and inhibiting the cation exchange processes

Methods/technologies that Address Barrier Applications:

The application of geophysical methods to engineered barriers can be divided into three basic tasks: (1)process control during barrier emplacement; (2) verifying barrier emplacement; and (3) monitoring barrier performance post emplacement. Table 4 identifies geophysical methods that may apply to these three tasks. Considering field experience, we list the methods in Table 4 in bold that are the most applicable to barriers and the methods in italics that are possibly applicable. Table 5 lists specifically the advantages and disadvantages of the geophysical methods applicable to barrier characterization and monitoring as listed in Table 4.

Table 4: Geophysical Methods that Address the Three Basic Tasks		
process control during barrier emplacement	*verifying barrier emplacement*	*monitoring barrier performance post emplacement*
seismic reflection seismic tomography vertical seismic profiling electromagnetic imaging *electrical imaging* *frequency domain electromagnetic method (FEM)* *very early time domain electromagnetic method (VETEM)* *ground penetrating radar (GPR)*	seismic tomography electromagnetic imaging electrical imaging *self potential* *electrical resistance tomography (ERT)* *ground penetrating radar (GPR)* *frequency domain electromagnetic method (FEM)* *very early time domain electromagnetic method (VETEM)*	electrical imaging self potential electromagnetic imaging *seismic tomography* *frequency domain electromagnetic method (FEM)* *very early time domain electromagnetic method (VETEM)* *ground penetrating radar (GPR)*

Table 5: Advantages and Disadvantages of Selected Geophysical Approaches as applied to Subsurface Barriers		
Approaches	Advantages	Disadvantages
Seismic	affected by changes in shear and bulk modulus and density, major changes produced by barrier materials	• range of resolution relative to customer's requirements • probably will require boreholes • for borehole application, techniques will need to be develop for coupling source and receivers in ungrouted casing or holes which can not be filled with water due to regulatory concerns • variability of background geology and barrier itself. Some of the variability is accounted for by doing pre- and post-emplacement surveys. • does not measure hydrologic properties except relative saturation
Electromagnetic including radar	Sensitive to changes in permeability, porosity, saturation, and pore fluid chemistry. High frequency methods may detect dielectric changes due to organic binders in barrier.	• range of resolution relative to customer's requirements • probably will require boreholes. Ground penetrating radar (ground penetrating radar (GPR)) is an exception, but the depth limitations of ground penetrating radar (GPR) will limit its applications. • variability of background geology and barrier itself • changes in electrical properties of the barrier not completely understood, nor

		are the time dependent changes
Electrical	Sensitive to changes in permeability, porosity, saturation, and pore fluid chemistry. Self potential methods may delineate flow paths.	• range of resolution relative to customer's requirements • probably will require boreholes. • variability of background geology and barrier itself • changes in electrical properties of the barrier not completely understood, nor are the time dependent changes
Potential Methods 1. heat flow 2. magnetics 3. gravity	heat flow tools can detect and measure liquid and gas flow in the vadose zone. magnetics can detect objects gravity can detect density changes due to barrier materials.	• Heat flow tools will require borehole emplacement • Longevity of tools is currently limited • magnetics do not measure hydrologic properties or processes • density changes are small relative to lateral variations and instrument capabilities
Other borehole logging instruments sensors nuclear tracers absorbing sensors	neutron logs can detect moisture changes electrical log can detect conductivity changes induction logs can detect conductivity changes	• range of resolution relative to customer's requirements • will require boreholes. • must account for borehole effects

Resolution and its limitations

*...The [barrier verification] technologies should permit continuity verification of subsurface barriers on the order of **a few square meters** in dry vadose zones to **a depth of 10 meters.** We seek technologies which have as small a resolution as possible, but at least **on the order of decimeters...***

DOE-FY95 Needs Statement for Containment Assessment Technologies (ML-2)

Subsurface barriers are detectable by a variety of geophysical methods. The remaining question is whether the resolution of these methods meets the requirements of a site engineer or a regulatory agency (Durant, et al., 1993). The DOE needs-statement lays out the approximate criteria that barrier-emplacement engineers request: *size on the order of a few square meters; at a depth in the vadose zone up to 10 meters; and resolution on the order of decimeters*. For a given geophysical method and an individual waste site (e.g., conditions of soil type, saturation, electrical conductivity, and background noise), these criteria will raise basic questions: will the geophysical method function in the soil types and depths (issues of attenuation and background noise), and if the method can operate with the site conditions, what are the attainable limits of detection and resolution.

There are two basic components to resolution: (1) the minimum size of a object that can be detected (e.g., can a single 1 mm wide fracture be detected) and (2) the precision of locating this object in coordinate system, e.g., x, y, and z. The approach herein is heuristic by presenting some basic rules-of-thumb regarding resolution. The resolution attainable is a function of several aspects: (1) the physical principles of the method, (2) the conditions of the specific site, and (3) the compromises required to field a method at a specific site.

1. **The physical principles of the method**
    a) Rules of Thumb for Resolution
        i) ***Seismic (Parasnis, 1986)***
            a) lower limit of size and location is 1/4 of the wavelength used
        ii) ***Electromagnetic (cross-borehole; Nekut, 1994)***
            a) lower limit of size and location is 1/20 of borehole separation
2. **The conditions of the specific site**
    a) In general, the variation in material properties, such as seismic velocity and electrical conductivity due to, for example, variations in saturation, has major effects on resolution in terms of the technology of the imaging method and its instrumentation. The development of geophysical instrumentation, data processing and interpretation methods alone will not significantly increase this resolution. An understanding of the physical processes, such as moisture migration and chemical evolution of pore fluids, associated with barrier emplacement will improve resolution.
    b) 3D spatial variation within the vadose zone; variations in moisture content, fingering, caliche
    c) Variation in seismic and electrical properties laterally
    d) Issues concerning the actual material properties of barriers
        i) variability of material laterally with time
        ii) variation in electrical properties
        iii) variations in thickness of soil units and engineered units (see figure 2)
    e) Background Variability
        i) natural variations, facies layering, lateral and vertical variations in density and therefore velocity, variations in saturation
        ii) irregular interfaces

f) Man made objects in the subsurface and at the surface,
g) Stray electrical currents and electromagnetic signals

3. **The compromises required to field a method at a specific site**

a) Range of penetration and attenuation, for example, the penetration limits of high frequency electromagnetic methods including radar in soils of various resistivity (see Fig. 6, this figure shows the approximate attenuation of a signal for three resistivities (50, 100, 150 ohm-m) that are representative of arid alluvial soils over a range of frequencies representative of radar systems. The maximum penetration or two-way travel path at 100 and 200 dB attenuation ranges from 4.5 m at (60MHz, 150 ohm-m) to <1 m at (1 GHz, 50 ohm-m)).

b) Limited range of wavelengths or frequencies, for example, seismic methods in unconsolidated soils (Table 5 and Fig. 7, this table and figure show for a range of unconsolidated soils that possible resolution is dependent on the velocity of the soil and the frequency transmitted in the soil and higher frequencies, e.g., 1000 Hz, are required to approach resolutions of less than a meter.

c) Layout or geometry of the geophysical survey relative to the target (the barrier or contaminant). Generally, the target will be better defined the more it is surrounded by sources and receivers. Hence, the higher resolution surveys will be conducted from both boreholes and the surface. Also, the resolution of survey will be limited by the obtainable length and orientation of receiver and transmitter station (see Fig. 8), e.g., in a cross-borehole survey, if the depth of borehole containing either sources or receivers is roughly equivalent to the separation of the boreholes or the size of the target, then resolution will be diminished. Along similar lines, the spacing of receivers and transmitters affects the number of ray paths through a given pixel of the image or the current density through a given region of the image. Both affect the resolution of the imaging method.

d) the difference between reflected and transmitted energy for comparing surface to borehole methods

e) Calibration to account for three dimensional variation in geophysical properties and irregular interfaces(see Fig. 8, shows the effect of three dimensional structure on ray paths and current density)

f) Surface clutter and buried objects

g) Repositioning error

Chemical Waste Landfill: An example of the limitations of resolution

Demonstrations of electromagnetic and seismic methods to characterize an unlined chromic acid disposal pit (UCAP) at the Chemical Waste Landfill, Sandia National Laboratories, provide field example of the limitations of resolution (Borns, et al. 1993). The dimensions of this pit are approximately 5 by 12 meters on the surface and 4 to 5 meters deep. The soil units are stratified and channelized unconsolidated sands and cobble zones. The resistivity of the soil units ranges from 60 to 100 ohm-m, and the seismic velocities are less than 800 m/s. The pit, therefore, is similar in scale to possible barrier and presents similar resolution requirements. For use in the demonstrations, three boreholes were drilled to a depth of approximately 30 m. One borehole penetrated the pit, and other two boreholes straddled the pit. Separation between boreholes ranged from 4 to 10 m. Both seismic and electromagnetic cross borehole surveys were tried using these boreholes. These demonstrations at this site show that resolution attainable is a function of the three aspects outlined in the preceding section: (1) the physical principles of the method, (2) the conditions of the specific site, and (3) the compromises required to field a method at a specific site.

EXAMPLE OF ASPECT (1): THE PHYSICAL PRINCIPLES OF THE METHOD,

At the chosen frequency of 15 MHz, the cross-borehole electromagnetic imaging was able to map the base of the disposal pit and individual soil units on the scale of 0.5 m. This observed scale of resolution is consistent with the rule of thumb for electromagnetic surveys that the resolution is approximately 1/20 the of the borehole separation aspect (Nekut, 1993). For the UCAP site with a 10 m separation , the approximate resolution is [0.05*10] = 0.5 m.

EXAMPLE OF ASPECT (2): THE CONDITIONS OF THE SPECIFIC SITE AND ASPECT (3): THE COMPROMISES REQUIRED TO FIELD A METHOD AT A SPECIFIC SITE.

For comparison, we conducted a cross-borehole pulsed radar survey at 60 MHz in the same set of boreholes. The Radio Frequency Imaging Method (RIM) and the pulsed radar method resulted in similar images. Both images delineate four soil units in the 30 meters below the surface. These units are delineated probably by their varying moisture content resulting in variations in conductivity and dielectric constant.

Theoretically, the pulsed radar unit using a higher frequency of 60 MHz versus 15 MHz should result in higher resolution and should have the advantage of mapping variations in conductivity and dielectric constant. However, for the 50 to 100 ohm-m soils at this site, the radar method is highly attenuated even for direct ray paths over the ten meter borehole separation. This attenuation limits the raypath coverage, and therefore, the resolution (see Figure 8a and 8b).

The reproducibility of these images may be affected by lateral and vertical changes in the physical properties with the soil unit. A primary change that can affect the geophysical imaging is the change in moisture content mirroring seasonal or storm infiltration. The moisture content can also be affected by grout emplacement and aging of the grout materials. Voss et al. (1994) measured a change in soil moisture from approximately 0.05 g/cm^3 to 0.10 g/cm^3 at the grout injection intervals in a site adjacent to Chemical Waste Landfill. For electrical and electromagnetic surveys, soil moisture content, resistivity, dielectric constant, and attenuation are interrelated.

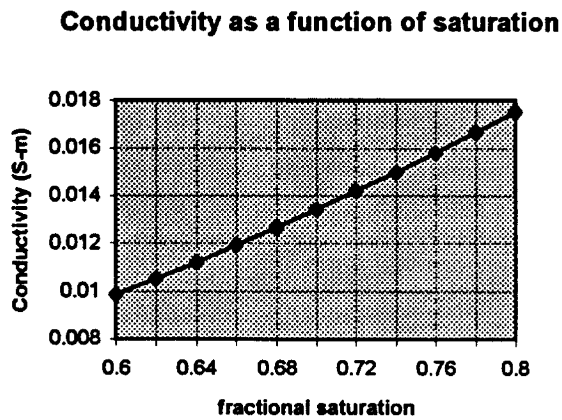

Figure 6: The relationship between soil saturation and electrical conductivity for a typical sandy soil of the Chemical Waste Landfill (assuming 30% porosity and a range of saturation from 0.6 to 0.8). A change in saturation from 0.7 to 0.6 would result in a reduction in conductivity from 0.013 to 0.010 S-m, which is on the order of the observed contrasts in the electromagnetic images of the site.

EXAMPLE OF ASPECT (3): THE COMPROMISES REQUIRED TO FIELD A METHOD AT A SPECIFIC SITE.

The seismic surveys were not completely tested since hurdles to implementation arose, both regulatory (limitations on the introduction of fluid into the borehole for coupling of source and receiver) and technical (coupling of the source and receivers with the style of completion (non-grouted)of environmental boreholes). These hurdles represent a fundamental consideration of whether the methods can be fielded at a specific field site. If the problems in fielding had been overcome, quarter wavelength resolutions of 0.1 m at 1000 Hz to 4 m at 50 Hz may have been attainable. In an site adjacent to Chemical Waste Landfill, Harding (1994) was able to detect a grout injection, approximately 0.5 to 1 m in cross-section, at 5 m depth. While the grout injection was detected, its position in the seismic survey was displaced by a half meter from the injection point in some images. This apparent displacement may be some artifact of the imaging process or a three dimensional effect not accounted for in a two-dimensional image. For the typical unconsolidated near surface sites, it remains difficult to propagate a 1000 Hz or greater signal over distances greater than a few meters.

Figure 7 (a, b, c): Attenuation of electromagnetic methods as a limitation of the methods

EM Attenuation (assuming $\mu = \mu_o$*)* [5]

$$\left|\frac{H_y}{H_o}\right| \approx e^{-2x10^{-3} z\sqrt{f/\rho}}$$

H_y = *the component of the magnetic field in the y direction*

f = *frequency*

z = *distance along the axis that the wave is propagating*

ρ = *resistivity*

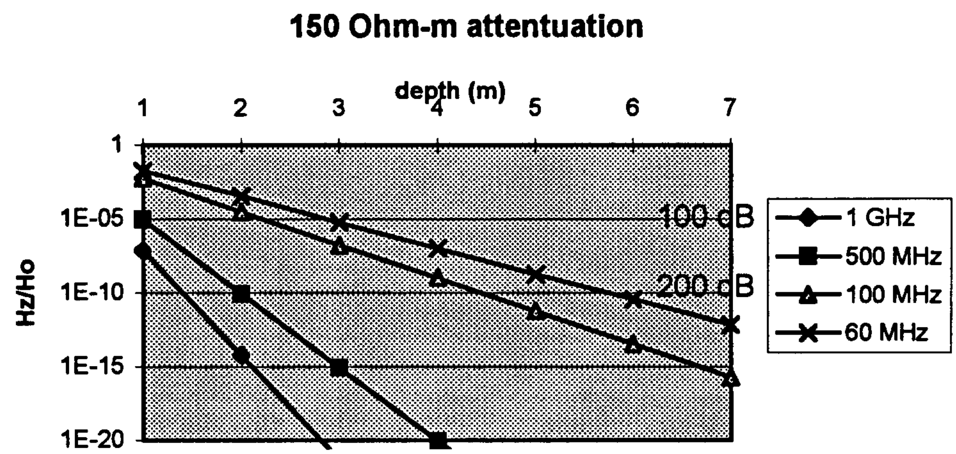

Figure. 7a: Attenuation for 150 ohm-m soil at four frequencies spanning the range utilized by current ground penetrating radar (GPR) systems.

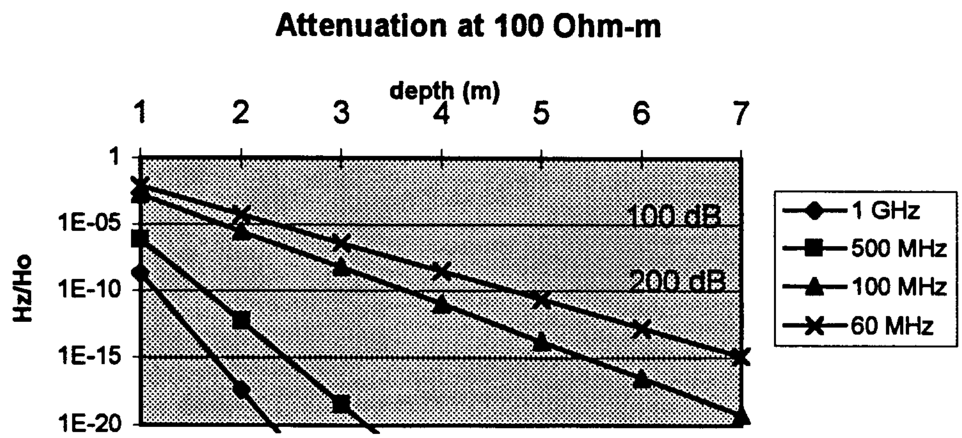

Figure. 7b :Attenuation for 100 ohm-m soil at four frequencies spanning the range utilized by current ground penetrating radar (GPR) systems.

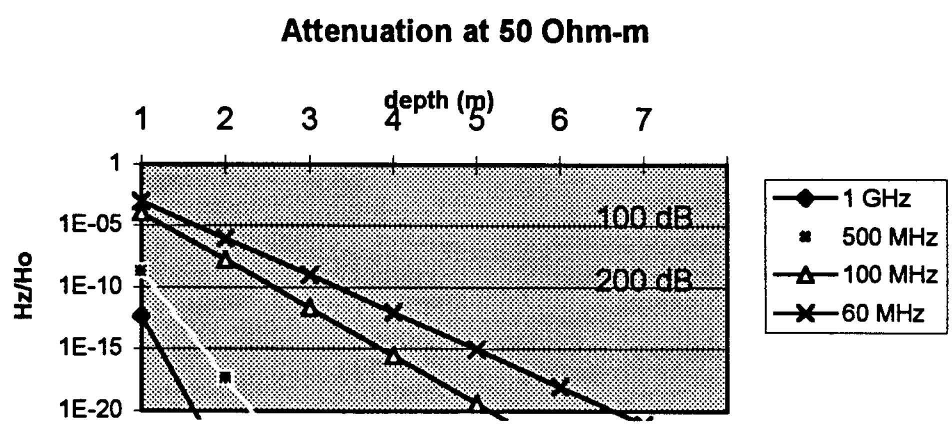

Figure. 7c :Attenuation for 50 ohm-m soil at four frequencies spanning the range utilized by current ground penetrating radar (GPR) systems.

	elastic velocities (m/s) (Parasnis. 1986)			
	compressional		shear	
medium	range		range	
air	330	330		
water	1450	1450		
sand	300	800	100	500
glacial till	1500	2700	900	1300

wavelength(m) @ frequency in Hz												
	compressional						shear					
	frequency 50 (Hz)		200		1000		50		200		1000	
range	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*
medium												
air	6.6	6.6	1.65	1.65	0.33	0.33	0	0	0	0	0	0
water	29	29	7.25	7.25	1.45	1.45	0	0	0	0	0	0
sand	6	16	1.5	4	0.3	0.8	2	10	0.5	2.5	0.1	0.5
glacial till	30	54	7.5	13.5	1.5	2.7	18	26	4.5	6.5	0.9	1.3

Table 5: Limits on Resolution; Range of Seismic Velocities and Wavelengths in Unconsolidated Sediments

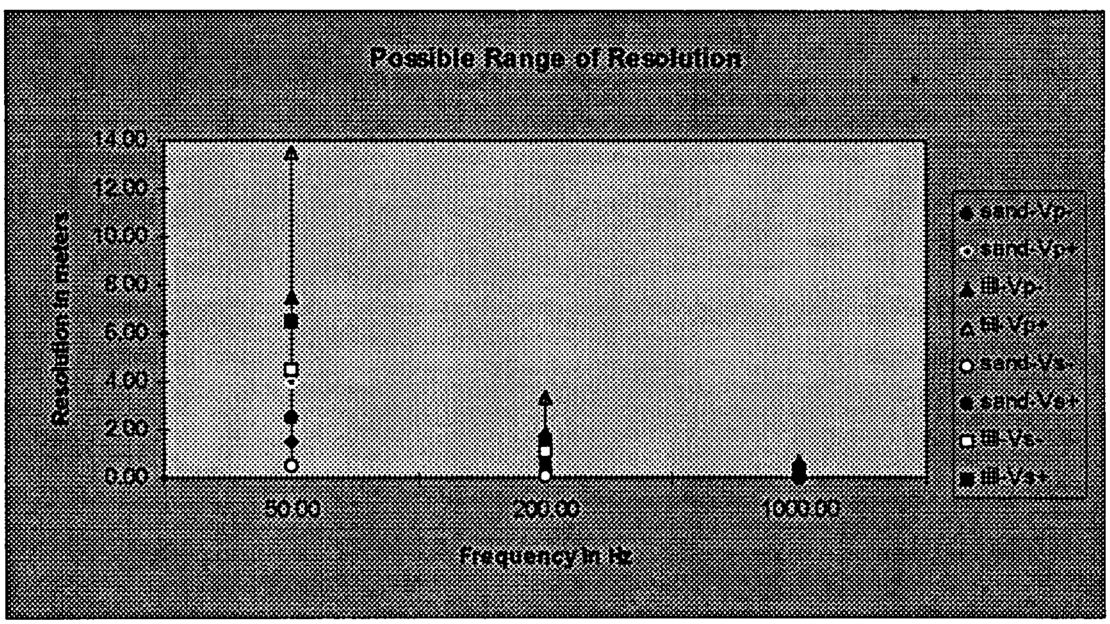

Figure 8: Limits of seismic resolution for different frequencies and sediment types

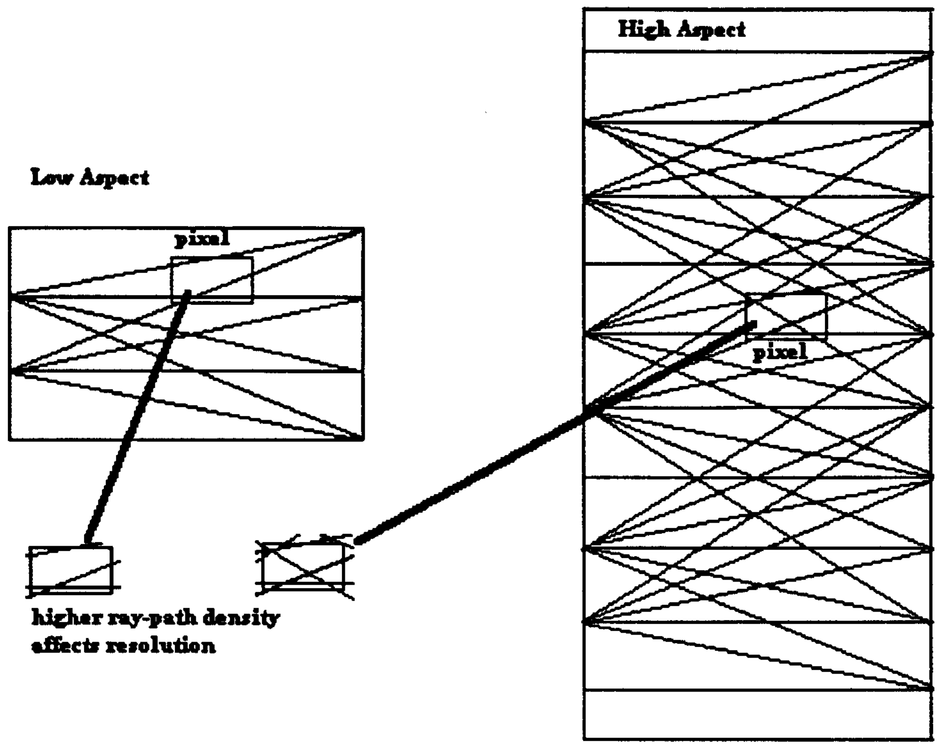

Figure 9a: Effects of survey aspect ratio on resolution

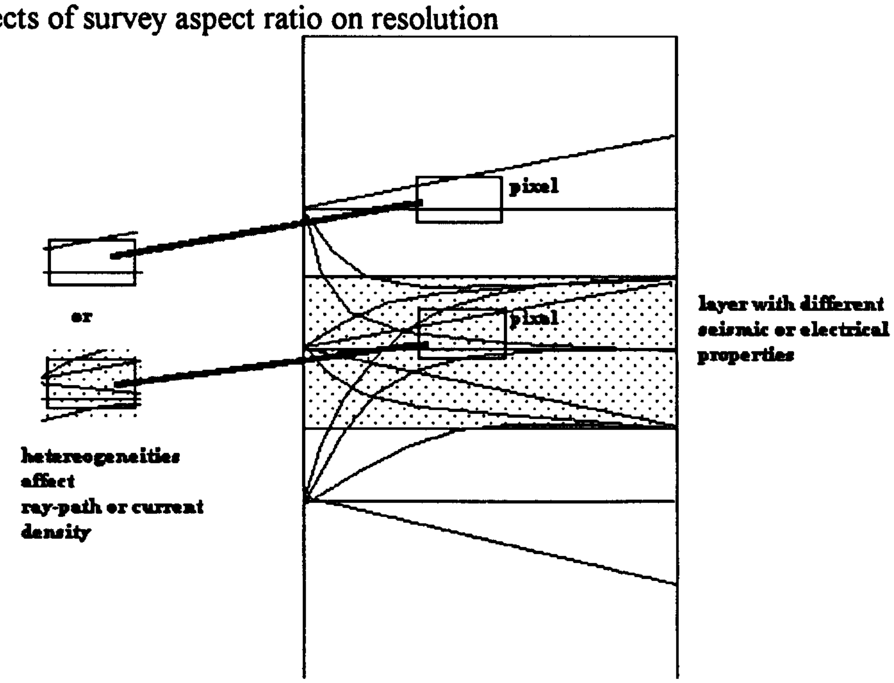

Figure 9b: Effects of subsurface heterogeneities on resolution

Summary

The changes in mechanical, hydrologic and chemical properties associated with the emplacement of an engineered barrier will affect geophysical properties such a seismic velocity, electrical conductivity, and dielectric constant. Also, the barrier, once emplaced and interacting with the in situ geologic system, may affect the paths along which electrical current flows in the subsurface. These changes in properties and processes facilitate the detection and monitoring of the barrier. The approaches to characterizing and monitoring engineered barriers can be divided between (1) methods that directly image the barrier using the contrasts in physical properties between the barrier and the host soil or rock and (2) methods that reflect flow processes around or through the barrier but not the barrier itself. For example, seismic methods that delineate the changes in density and stiffness associated with the barrier represents a direct imaging method. Electrical self potential methods and flow probes based on heat flow methods (Ballard, et al., 1994) represent methods that can delineate the flow path or flow processes around and through a barrier. To some extent, most of the geophysical methods discussed in this report can be configured either to address direct imaging or process detection. Flow probes based on heat flow methods possibly can address monitoring issues if the longevity of the subsurface probe is significantly increased.

As mentioned in the section on the limits of resolution, the observation that barriers are detectable by geophysical methods is not sufficient alone. Each site application will have criteria for resolution defined by the site engineer and performance standards set by the applicable regulations. An example of a resolution criterion is the DOE need statement: *size in the order of a few square meters; at a depth in the vadose zone up to 10 meters; and resolution on the order of decimeters.* An example of a regulatory standard is the requirement of RECRA (40CFR264, Subpart N, Landfills) that the engineered barrier achieve a permeability reduction of 10^{-7} cm/sec and a thickness of three feet. Of the two approaches, direct imaging addresses requirements for the verification and delineation of a barrier. Direct imaging methods also address requirements for the monitoring of barrier performance. Multiple images taken over time can be effective in removing original variations in physical properties. However, direct imaging is impacted by the limits of resolution. Due to scale, time-dependence and distribution of variations in material properties of soils and barriers, direct imaging methods may have difficulty in achieving resolution of the scales of 1 to 10 cm. The variation in material properties, such as seismic velocity and electrical conductivity due to variations in saturation, has major effects on resolution in terms of the technology of the imaging method and its instrumentation. The development of geophysical source and receiver technology and the development of data processing and interpretation methods utilizing evolving computer systems will not increase the resolution of the geophysical methods. An understanding of the physical processes, such as time dependent moisture migration in fingers, within the vadose zone and processes, such as the chemical evolution of pore fluids, associated with the emplacement of a barrier need to studied. The understanding derived from these studies permits the effects of these processes on geophysical properties to be accounted for in the final images.

Methods that detect flow processes and flow paths, such as electrical imaging and self potential arrays, offer an alternative approach. These methods can detect whether flow is occurring around or through a barrier. Similar methods have to been used to detect flow through earthen dams (Hadley, 1983) and leaks in lined storage ponds (Frangos, 1994). Such methods will not map the continuity of a barrier within the resolution requirements of the site operating but provide a means to measure and monitor performance of a barrier. This monitoring capability can be direct towards post-closure compliance with a regulatory standard.

Recommendations

The capabilities and limitations of geophysical methods have been described in this report and others. Table 6 addresses how the major families of geophysical methods (seismic imaging methods; electromagnetic imaging methods; and electrical imaging methods)capture barrier processes and what the considerations or caveats for the application of these methods are. The application of remote sensing methods to subsurface barriers is a complex task due to variability of the natural subsurface and barrier and the resolution requirement of site operators and regulators. A significant hurdle to implementation of remote sensing methods to barriers application is the incomplete understanding of the effects of the mechanical and chemical process that are associated with barrier emplacement and the effects of these processes on geophysical properties and measurements. Recommendations are as follows:

1. develop and utilize high-resolution three-dimensional imaging methods for electromagnetic, seismic and electrical methods.
2. develop an understanding of the physical and chemical processes around and within a barrier
    a) the three-dimensional distribution of mechanical properties around and within the barrier, including time dependent behavior
    b) chemical reactions during barrier emplacement and possible byproducts that are introduced or produced
    c) chemical reactions of barrier materials with the hydrologic system or the possible contaminant
    d) effects of a varying flow system in the unsaturated zone on electrical current methods such as self potential
3. pursue utilization of alternate drilling strategies such as directional and horizontal drilling to decrease borehole effects and increase resolution
4. increase longevity of flow probe technology
5. develope techniques to generate higher frequency seismic signals with greater range

Table 6a: Seismic Methods	
Barrier Processes Captured	*Considerations and Caveats*
• emplacement of barrier materials has a distinct effect on seismic properties • monitoring of the emplacement of barrier material has been demonstrated (Harding, 1994)	1. methods do not directly monitor hydrologic processes 2. boreholes required to reach optimum resolution 3. boreholes need to have appropriate aspect ratio (length of borehole relative to depth of barrier). The possible range for the borehole depth is 2x to 5x, such that a barrier at 10 m depth may require boreholes 20 to 50 m deep. 4. horizontal or directionally drilled boreholes and borehole-to-surface surveys may enhance the obtainable resolution. 5. resolution may not meet stated decimeter criteria, unless higher frequency sources can be developed. Still, the attenuation of the high frequency signals may require closely spaced boreholes (i.e., less than 5 m separation) 6. lateral variations in barrier properties and natural variations in the soil may mask zones where the barrier may be breached (i.e., single fracture)

Table 6b: Electromagnetic Imaging Methods	
Barrier Processes Captured	*Considerations and Caveats*
• changes in properties related to hydrologic properties (porosity, saturation, permeability, fluid chemistry) • reactions between contaminants and minerals in the soils may reflected by changes in electrical properties	1. changes in electrical properties are variable within the vadose zone and around the barrier. Such changes for a given barrier type are not completely understood 2. methods have not been demonstrated for barrier emplacement 3. boreholes required to reach optimum resolution 4. boreholes need to have appropriate aspect ratio (length of borehole relative to depth of barrier). The possible range for the borehole depth is 2x to 5x, such that a barrier at 10 m depth may require boreholes 20 to 50 m deep. 5. horizontal or directionally drilled boreholes and borehole-to-surface surveys may enhance the obtainable resolution. 6. lateral variations in barrier properties and natural variations in the soil may mask zones where the barrier may be breached (i.e., single fracture)

Table 6c: Electrical Imaging Methods	
Barrier Processes Captured	*Considerations and Caveats*
• these methods can monitor processes (e.g., fluid flow through a leak) in addition to changes in physical properties of the barrier • changes in properties related to hydrologic properties (porosity, saturation, permeability, fluid chemistry) • electrical current may mimic hydrologic flow (i.e., self potentials may delineate flow and flow rate). Electrical methods have been successful commercially in locating leaks in geomembrane liners) • reactions between contaminants and minerals in the soils may reflected by changes in electrical properties • these methods can be deployed in surface arrays thus minimizing boreholes	1. changes in electrical properties are variable within the vadose zone and around the barrier. Such changes for a given barrier type are not completely understood 2. boreholes required to reach optimum resolution 3. boreholes need to have appropriate aspect ratio (length of borehole relative to depth of barrier). The possible range for the borehole depth is 2x to 5x, such that a barrier at 10 m depth may require boreholes 20 to 50 m deep. 4. horizontal or directionally drilled boreholes and borehole-to-surface surveys may enhance the obtainable resolution. 5. resolution may not meet stated decimeter criteria, unless higher frequency sources can be developed. Still, the attenuation of the high frequency signals may require closely spaced boreholes (i.e., less than 5 m separation) 6. lateral variations in barrier properties and natural variations in the soil may mask zones where the barrier may be breached (i.e., single fracture)

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1190 St. Francis Drive
Santa Fe, NM 87503-0968

1 NM Bureau of Mines and Mineral Resources
Socorro, NM 87801

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