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Geophysical Methods Commonly Employed for Geotechnical Site Characterization

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Preface

The purpose of this Transportation Research Board circular is to provide highway engineers with a basic understanding of how geotechnical geophysical tools are used to image or characterize the shallow subsurface of the Earth, typically to depths of less than several hundred feet. Geotechnical geophysical tools, by design, measure specific parameters that can be used to generate physical property models of the Earth. Gravity meters, for example, measure spatial variations in the gravitational field of the Earth, and are used to generate density models of the shallow subsurface. These density models, if properly constrained, can often be transformed into geologic models with varying degrees of sophistication.

Geotechnical geophysics is not a substitute for boring or testing, but it is often a very cost-effective and reliable means of imaging the subsurface between and below boreholes and for determining the in situ bulk properties of soil and rock. Reconnaissance geophysical investigations can also be used as the basis for making better selection of borehole locations.

Geotechnical geophysical investigations, in many instances, enhance the reliability and speed of geotechnical investigations, and reduce the cost of the investigation. However, geophysical tools are not always capable of meeting the objectives–requirements of highway engineers. The subsurface targets of interest may be too small or deep to resolve, or impossible to effectively image because its physical properties are too similar to those of the encompassing data. Moreover, if constraints (generally borehole control) are not available, geophysical interpretations may be inaccurate because of their inherent nonuniqueness.

Many geotechnical geophysics and nondestructive testing (NDT) tools are very similar and, in some instances, identical. Both sets of instruments measure specific parameters that are used to generate physical property models. The most significant difference is that geotechnical geophysical tools are used to investigate the Earth, where NDT methods are used to investigate manmade structures such as bridges, walls, pavements, and foundations.

This circular was initiated by Khamis Haramy, Central Federal Lands Highway Division, FHWA. The document was coauthored by several individuals: Neil Anderson, Missouri University of Science and Technology; Neil Croxton, Kansas Department of Transportation; Rick Hoover of Dawood Engineering; and Phil Sirles, Zonge Geosciences–Colorado. Critical reviews were provided by Kanaan Hanna, Zapata Incorporated; and Dennis Hiltunen, University of Florida. Special thanks are expressed to G.P. Jay Jayaprakash for his input and support.

—Vanessa Bateman
Chair, Exploration and Classification of Earth Materials Committee

Contents

Overview

This circular offers an overview of 12 geotechnical geophysical methods that are commonly applied to transportation projects. Geotechnical geophysics is the application of geophysics to geotechnical engineering problems; such investigations normally extend to total depths of less than 300 ft. Geotechnical geophysical surveys are performed on the ground surface, within boreholes and water, and from the air.

Using illustrations and brief examples, commonly employed geotechnical geophysical methods are described. Through summary tables and brief discussions, common applications of engineering geophysics are presented. Chapters are devoted to the selection of appropriate geophysical methods and geophysical contractors, respectively.

Use of geophysics by transportation agencies is reviewed through a summary of *NCHRP Synthesis 357: Use of Geophysics for Transportation Projects* (Sirles, 2006).

A detailed description of applications of geophysical methods to highway-related problems may be found at www.cflhd.gov/agm/index.htm.

Introduction to Geotechnical Geophysics

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WHAT IS GEOPHYSICS?

Geophysics is the application of physics principles to the study of the Earth.

The Earth is comprised of materials that have different physical properties. Clay and granite, for example, have different densities, acoustic velocities, elastic moduli, electrical conductivities, magnetic susceptibilities, and dielectric constants.

Geophysical instruments are designed to map spatial variations in the physical properties of the Earth (Table 1). A gravimeter, for example, is designed to measure spatial variations in the strength of Earth's gravitational field (Table 1). One limitation of most surface-based geophysical instruments is the inability to resolve relatively small-scale (but potentially significant) variations in the physical properties of the subsurface.

Geophysicists interpret these measured variations and use them to generate geologic models of varying sophistication (Table 1). If the subsurface target of interest can be differentiated from the encompassing strata on the basis of contrasting physical properties, the output geologic model can be of great utility to a highway engineer.

Perhaps the most significant limitation of geophysical data is its nonuniqueness. For example, in the absence of ground truth, a negative gravity anomaly could be attributed to a structural low at bedrock, to a small air-filled void within bedrock, or to a large water-filled cavity within bedrock. Therefore, in order for an output geologic model to be accurate, the interpretation of geophysical data must be constrained and verified by ground truth acquired using intrusive methods.

WHAT IS GEOTECHNICAL GEOPHYSICS?

Geotechnical geophysics is the application of geophysics to geotechnical engineering problems; such investigations normally extend to a total depth of less than several hundred feet but can be extended to thousands of feet in some instances. Geotechnical geophysical surveys are performed on the ground surface, within boreholes, and from the water and air. This Circular presents brief summaries of 12 geophysical methods that are commonly employed for geotechnical purposes. These methods, with the exception of seismic tomography, are primarily surface-based techniques. For the purposes of this Circular, the field of geotechnical geophysics will be differentiated from nondestructive testing (NDT), the field commonly associated with structural engineering applications.

Geotechnical geophysics is routinely used for many types of highway engineering investigations, including:

1. Subsurface characterization: bedrock depth, rock type, layer boundaries, water table, groundwater flow, locating fractures, weak zones, expansive clays, etc.;
2. Engineering properties of Earth materials: stiffness, density, electrical resistivity, porosity, etc.;
3. Highway subsidence: detecting cavities beneath roadways caused by sinkholes, abandoned mines, etc.; and
4. Locating buried manmade objects—buried utilities, underground storage tanks, etc.

TABLE 1 Summary of 12 Commonly Used Geophysical Surveying Methods for Geotechnical Investigations (After Anderson, 2006)

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model (Geotechnical Application)	Typical Site Model (Geotechnical Applications)
Shallow seismic refraction	Travel times of refracted seismic energy (p- or s-wave)	Acoustic velocity (function of elastic moduli and density)	Acoustic velocity–depth model often with interpreted layer boundaries	Geologic profile
Shallow seismic reflection	Travel times and amplitudes of reflected seismic energy (p- or s-wave)	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Acoustic velocity–depth model often with interpreted layer boundaries	Geologic profile
Cross-hole seismic tomography	Travel times and amplitudes of seismic energy (p- or s-wave)	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Model depicting spatial variations in acoustic velocity	Geologic profile
Multichannel analyses of surface waves (MASW)	Travel times of surface waves energy generated using an active source (e.g., sledge hammer)	Acoustic velocity (function of elastic moduli and density)	Acoustic (shear-wave) velocity–depth model often with interpreted layer boundaries	Geologic profile
Refraction micro-tremor (ReMi)	Travel times of passive surface waves energy	Acoustic velocity (function of elastic moduli and density)	Acoustic (shear-wave) velocity–depth model often with interpreted layer boundaries	Geologic profile
Ground-penetrating radar (GPR)	Travel times and amplitudes of reflected pulsed EM energy	Dielectric constant, magnetic permeability, conductivity and EM velocity	EM velocity/depth model with interpreted layer boundaries	Geologic profile
Electro-magnetics (EM)	Response to natural–induced EM energy	Electrical conductivity and inductivity	Conductivity–depth model often with interpreted layer boundaries	Geologic–hydrologic profile

continued

TABLE 1 (*continued*) Summary of 12 Commonly Used Geophysical Surveying Methods for Geotechnical Investigations (After Anderson, 2006)

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model (Geotechnical Application)	Typical Site Model (Geotechnical Applications)
Electrical resistivity	Potential differences in response to induced current	Electrical resistivity	Resistivity–depth model often with interpreted layer boundaries	Geologic–hydrologic profile
Induced polarization (IP)	Polarization voltages or frequency dependent ground resistance	Electrical capacitivity	Capacitivity–depth model	Model depicting spatial variations in clay content (or metallic mineralization)
Self potential (SP)	Natural electrical potential differences	Natural electric potentials	Model depicting spatial variations in natural electric potential of the subsurface	Hydrologic model (seepage through dam, levee, or fractured bedrock, etc.)
Magnetics	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility and remanent magnetization	Model depicting spatial variations in magnetic susceptibility of subsurface	Geologic profile or map (location of faults, variable depth to bedrock, etc.)
Gravity	Spatial variations in the strength of gravitational field of the Earth	Bulk density	Model depicting spatial variations in the density of the subsurface often with interpreted layer boundaries	Geologic profile or map (location of voids, variable depth to bedrock, etc.)

WHY USE GEOTECHNICAL GEOPHYSICS?

A geotechnical geophysical survey is often the most cost-effective and rapid means of obtaining subsurface information, especially over large study areas (Sirles, 2006). Geotechnical geophysics can be used to select borehole locations and can provide reliable information about the nature and variability of the subsurface between existing boreholes. An isolated geologic structure such as a limestone pinnacle might not be detected by a routine drilling program (Figure 1). An effective geophysical survey however, could detect the presence of the pinnacle and map the height and aerial extent of the same.

Other advantages of geotechnical geophysics are related to site accessibility, portability, noninvasiveness, and operator safety. Geophysical equipment can often be deployed beneath bridges and power lines, in heavily forested areas, at contaminated sites, in urban areas, on steeply dipping slopes, in marshy terrain, on pavement or rock, and in other areas that might not be easily accessible to drill rigs or cone penetration test (CPT) rigs. Also, most surface-based or airborne geophysical tools are noninvasive and, unlike boring or trenching, leave little if any

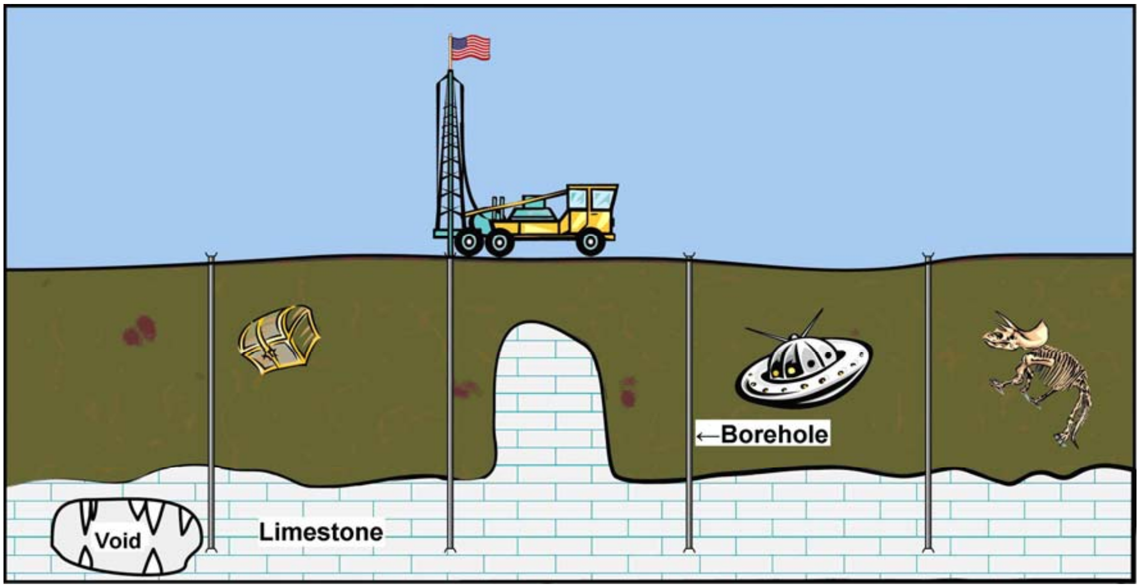


FIGURE 1 An isolated geologic structure such as a limestone pinnacle might not be detected by a routine drilling program.

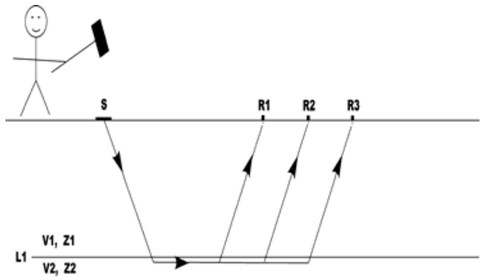
imprint on the environment. These considerations can be crucial when working in environmentally sensitive areas, on contaminated ground, or on private property. In addition, geophysical surveys are generally considered less dangerous than drilling since there are fewer risks associated with utility encounters and operations. Lastly, geophysical surveys can enable engineers to reduce the number of required boreholes.

GEOTECHNICAL GEOPHYSICS: A COMPONENT OF GEOTECHNICAL SITE CHARACTERIZATION

Geotechnical geophysics is not a substitute for boring and direct physical testing. Rather it complements a well-planned, cost-effective drilling and testing program, and provides a volumetric image of the subsurface rather than a point measurement. Geophysicists refer to borehole information and field geologic maps as “ground truth,” and rely on ground truth to constrain and verify all geophysical interpretations.

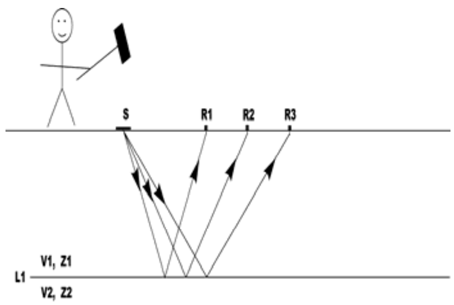
SOME COMMONLY EMPLOYED GEOTECHNICAL GEOPHYSICAL METHODS

Geotechnical geophysical tools are routinely used to image the subsurface of the Earth in support of transportation-related geotechnical investigations (Sirles, 2006). Commonly employed geophysical methods include seismic refraction, seismic reflection, MASW, ReMi, cross-hole seismic tomography, GPR, EM, electrical resistivity, IP, magnetics, SP, and gravity (Anderson, 2006; Wightman et al., 2004) (Table 1, Figures 2–4). Additional information on methods and applications is available at www.cflhd.gov/agm/index.htm.



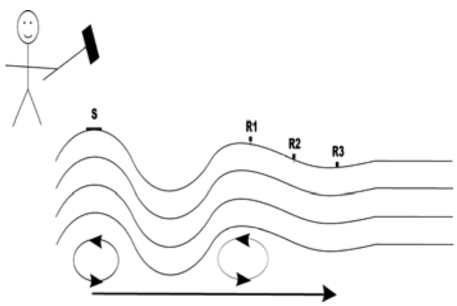
Seismic Refraction: Typically, acoustic pulses are generated at predetermined source locations (S) along the length of the refraction seismic profile. The travel times of acoustic energy that has been critically refracted at horizons of interest (L1) is recorded at predetermined receiver locations (R1, R2, etc.). The recorded travel time information is used to generate a velocity–structure profile of the shallow subsurface along the length of the refraction profile. If external constraints are available, the velocity–structure profile can be transformed into a geologic model.

(a)



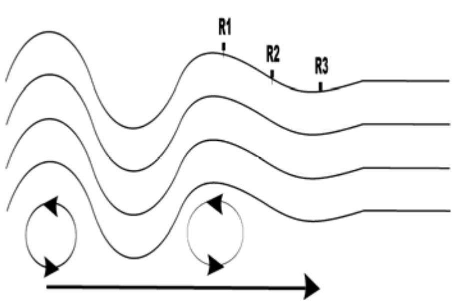
Seismic Reflection: Typically, acoustic pulses are generated at predetermined source locations (S) along the length of the reflection seismic profile. The travel times and amplitudes of reflected acoustic energy is recorded at predetermined receiver locations (R1, R2, etc.). The recorded travel time–amplitude information is used to generate a reflection seismic profile. These data can be transformed into a velocity–structure profile. If external constraints are available, the velocity–structure profile can be transformed into a geologic model.

(b)



MASW: Surface wave (Rayleigh wave) energy, generated using a nearby acoustic source, is recorded at predetermined receiver locations (R1, R2, etc.). A dispersion curve (phase velocity versus frequency), generated from the acquired field data, is inverted and used to generate a 1-D shear wave velocity profile (generally tied to the physical center of the receiver array). If additional MASW data sets are acquired at adjacent locations, 2-D or 3-D shear-wave velocity models can be created. If external constraints are available, the shear wave velocity models can be transformed into geologic models.

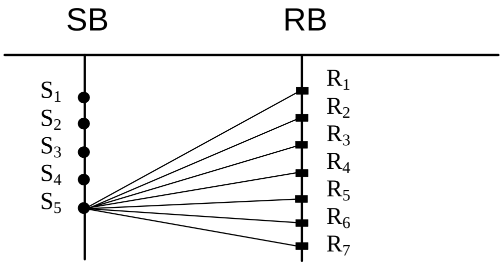
(c)



Refraction Microtremor (ReMi): Surface wave (Rayleigh wave) energy, generated using a passive (background) acoustic source, is recorded at predetermined receiver locations (R1, R2, etc.). A dispersion curve (phase velocity vs. frequency), generated from the acquired field data, is inverted and used to generate a 1-D shear wave velocity profile (generally "tied" to the physical center of the receiver array). If additional ReMi data sets are acquired at adjacent locations, 2-D or 3-D shear-wave velocity models can be created. If external constraints are available, these shear wave velocity models can be transformed into geologic models.

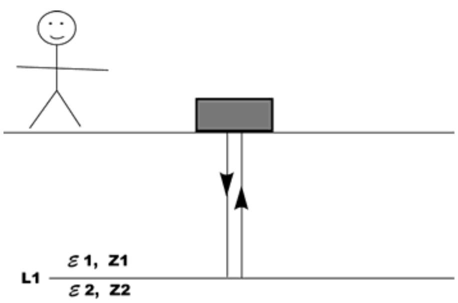
(d)

FIGURE 2 Overviews of the (*a*) seismic refraction, (*b*) seismic reflection, (*c*) MASW, and (*d*) ReMi methods (after Anderson, 2006).



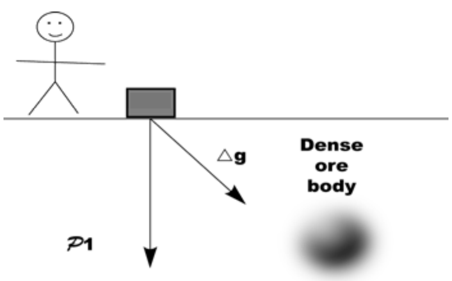
Cross-Hole Seismic Tomography: Typically, high-frequency acoustic pulses are generated at predetermined source locations (S) in the source borehole (SB). The amplitude and arrival time of direct arrivals (and others) is recorded at predetermined receiver locations in the receiver borehole (RB). The recorded travel time–amplitude data are statistically analyzed and used to generate a velocity–attenuation cross-sectional model of the area between the source and receiver boreholes. If external constraints are available, the velocity–attenuation profile can be transformed into a geologic model.

(a)



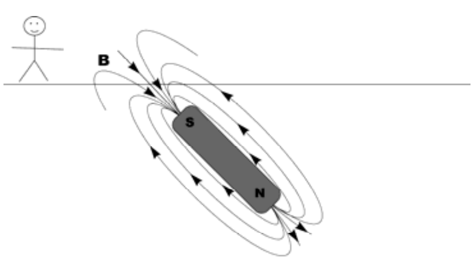
GPR: Typically, pulsed EM energy is generated at predetermined station locations along the length of the GPR profile. The travel times and amplitudes of reflected EM energy are usually recorded by a monostatic transmitter–receiver. The recorded travel time–amplitude information is normally used to generate a GPR profile (2-D time–amplitude image). These data can be transformed into a 2-D velocity–depth model. If external constraints are available, a geologic model can be generated.

(b)



Gravity: Gravimeters are designed to measure variations in the gravitational field of the Earth, and are typically used to generate 2-D or 3-D density–depth models of the subsurface. If external constraints are available, the density–depth models can be transformed into a geologic model.

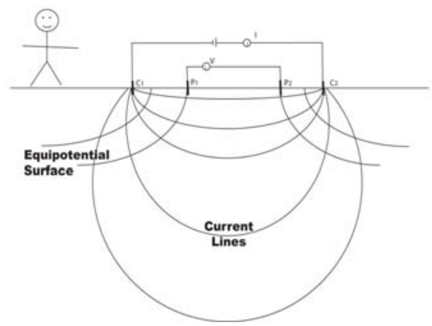
(c)



Magnetics: Magnetometers are designed to measure variations in the magnetic field of the Earth. These are usually caused by the presence of magnetically susceptible material of natural or human origin (typically magnetite or iron, respectively). In certain instances, magnetic data can be interpreted quantitatively, and transformed into constrained geologic models. More typically, however, magnetic data are interpreted qualitatively, and simply used to verify the presence or absence of magnetically susceptible materials.

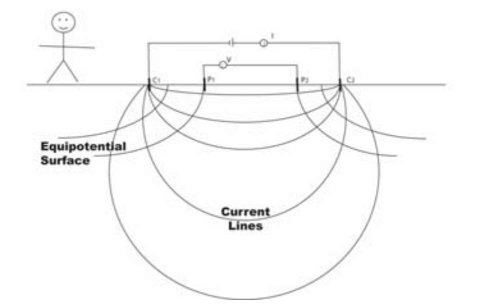
(d)

FIGURE 3 Overviews of the (*a*) seismic tomography, (*b*) GPR, (*c*) gravity, and (*d*) magnetic methods (after Anderson, 2006).



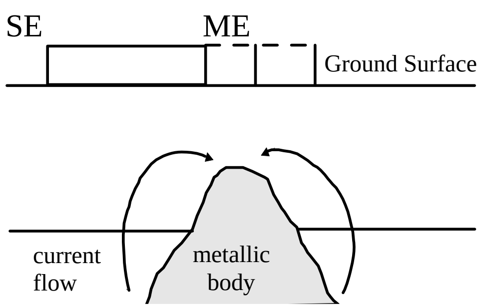
Electrical Resistivity: Typically, current (I) is induced between paired electrodes (C_1, C_2). The potential difference (ΔV) between paired voltmeter electrodes P_1 and P_2 is measured. Apparent resistivity (Δ_a) is then calculated (based on I, ΔV, electrode spacings). If the current electrode spacing is expanded about a central location, a resistivity–depth sounding can be generated. If the array is expanded and moved along the surface, 2-D or 3-D resistivity–depth models can be created. If external constraints are available, resitivity–depth models can be transformed into geologic models.

(a)



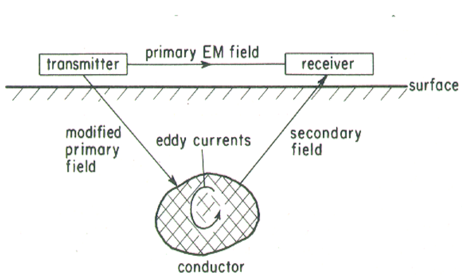
IP: Two types of IP data are acquired: frequency domain and time domain. Frequency domain IP data are generated by comparing the apparent resistivities determined for two variable frequency input currents. Time domain data are generated by measuring rate of decay of the measured potential difference after current flow is terminated. IP measures the capacitive properties of the ground, and is used to qualitatively–quantitatively estimate the concentration–distribution of clay or metallic mineralization.

(b)



SP: SP tools are used (mostly) to measure (*a*) natural potential differences arising from oxidization–reduction of metallic bodies straddling the water table and (*b*) streaming potential associated with flowing groundwater. SP data are usually interpreted in a qualitative manner, and are routinely used to locate zones of seepage in earth fill dams and levees.

(c)



EM: EM tools are used to measure the Earth's response to natural or anthropogenic EM energy. Measurements can be made in either the time or frequency domain. Some tools are used to locate metals or utilities; others are used to create conductivity–depth models of the subsurface. If external constraints are available, conductivity–depth models can be transformed into geologic models.

(d)

FIGURE 4 Overviews of the (*a*) electrical resistivity, (*b*) IP, (*c*) SP, and (*d*) EM methods (after Anderson, 2006).

Geophysical tools are designed to measure specific parameters, and are generally used to measure spatial variation in these specific parameters within a study area of interest (Table 1). GPR instruments, for example, are designed to measure the two-way travel times and magnitudes of reflected pulses of EM radiation (Figure 3 and Table 1). During the course of a typical GPR survey, these tools are used to measure spatial variations in the travel times and magnitudes of pulsed EM radiation that has been reflected from subsurface features (generally geologic boundaries) of interest. The example 2-D GPR profile presented in Figure 5 consists of multiple adjacent traces (reflection amplitude plotted as a function of two-way travel time) which were acquired at predetermined intervals along a 2-D traverse across a shallow stream. The GPR profile contains only one prominent reflection and hence can be considered to be simple two-layered (water overlying relatively uniform sand).

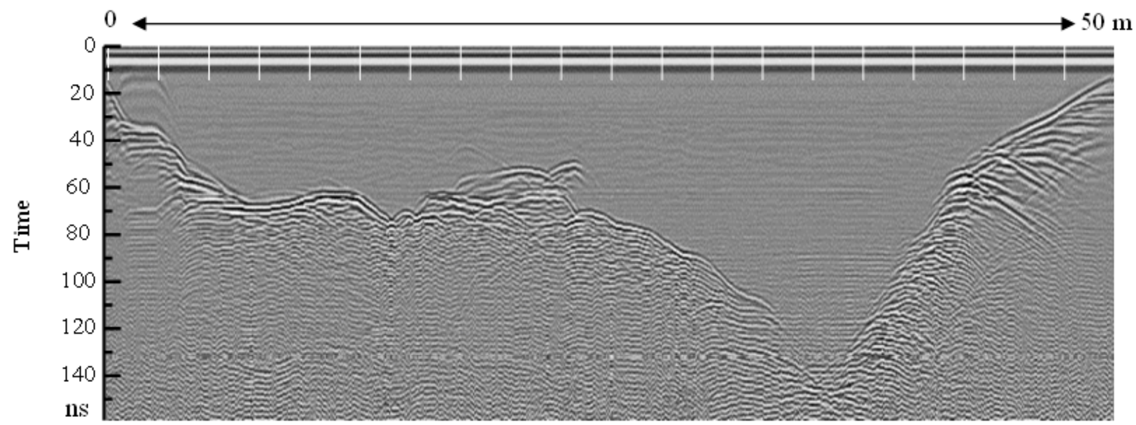
The specific parameters measured by geophysical tools (Table 1) are functions of the physical properties of the Earth's subsurface. For example, the travel times and amplitudes of the reflected pulsed EM radiation recorded during a GPR survey, are functions of the variable electrical and magnetic properties of the subsurface (including dielectric constant, magnetic permeability, conductivity, and EM velocity) (Table 1) along the respective ray paths (Figure 3). The EM velocities (dielectric constants) assigned to each of the two layers identified on the GPR profile in Figure 5*b* were estimated on the basis of in situ GPR field tests. The arrival time of the reflected event (water–sand interface) at any trace location on the GPR profile is a function of the EM velocity of water; and the amplitude of the GPR reflection at any trace location is a function of the contrasting dielectric constants of water and sand.

Properly acquired and processed geotechnical geophysical survey data can generally be transformed into a physical property model. GPR data, for example, are frequently transformed into corresponding 2-D or 3-D "reflection amplitude constant/depth" model (Table 1). The typical GPR physical property model in Figure 5*b* consists of one reflecting horizon (water–sand interface). In this "dielectric constant–depth" model, the vertical "time-depth" scale has been transformed into a vertical "depth" scale (time-to-depth conversion). Alternative physical property models could be in the form of "EM velocity–depth," "EM velocity–time-depth," etc.

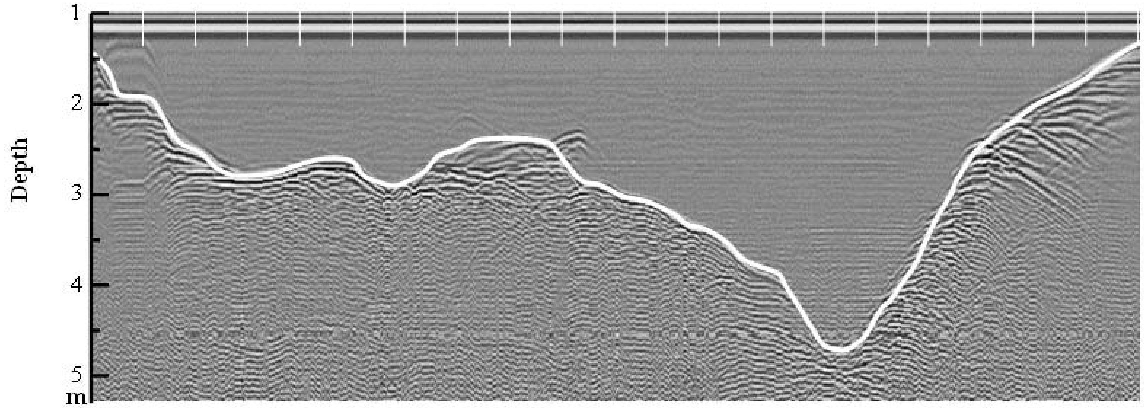
If additional geophysical or geological (including hydrologic, engineering, mining) constraints are available, physical property models can be transformed into "typical site models" (Table 1). A typical site model for a geotechnical geophysical investigation is a geologic model, complete with as many soil or rock properties as possible. In Figure 5*c*, the GPR physical property model has been transformed into a simple hydrologic–geologic model on the basis of site geomorphology and subsurface geologic control.

LIMITATIONS OF GEOPHYSICS

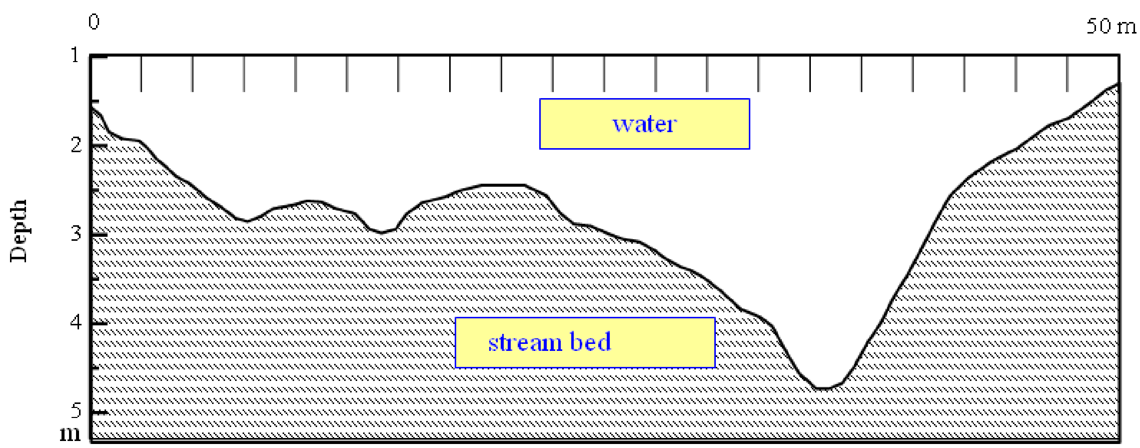
The most significant limitation of geotechnical geophysics is its non-uniqueness. In the absence of any external constraints (ground truth or basic conceptual model), a single geophysical data set can be transformed into an infinite number of "theoretically correct" output models (Table 1). Figure 6, for example, shows magnetic data acquired in Switzerland, and a corresponding subsurface interpretation that is theoretically accurate (consistent with field data), but not likely geologically consistent, since geologic features are not commonly shaped like question marks as is the case in Figure 6. Of the numerous theoretical interpretations that could be generated for



(a)



(b)



(c)

FIGURE 5 (*a*) GPR profile across a stream bed; (*b*) typical GPR physical property model (with interpreted layer boundaries); and (*c*) typical site model (geologic–hydrologic) (Anderson et al., 2007).

this magnetic data set, the most reasonable model is the one that is most consistent with all other geophysical data sets and available ground truth.

Other significant limitations are related to the intrinsic nature of the parameters geophysical tools are designed to measure, the spatial resolution such tools provide, and background noise levels. A gravimeter, for example, is designed to measure spatial variations in the earth's gravitational field (Table 1). Gravity data can be used to generate a density model of the earth, but is incapable of providing insight into variations in conductivity, acoustic velocity, magnetic susceptibility, etc. If the target of interest and the encompassing strata are not characterized by differences in density, the gravity tool will not image the feature of interest, although it may provide other useful secondary information about the subsurface.

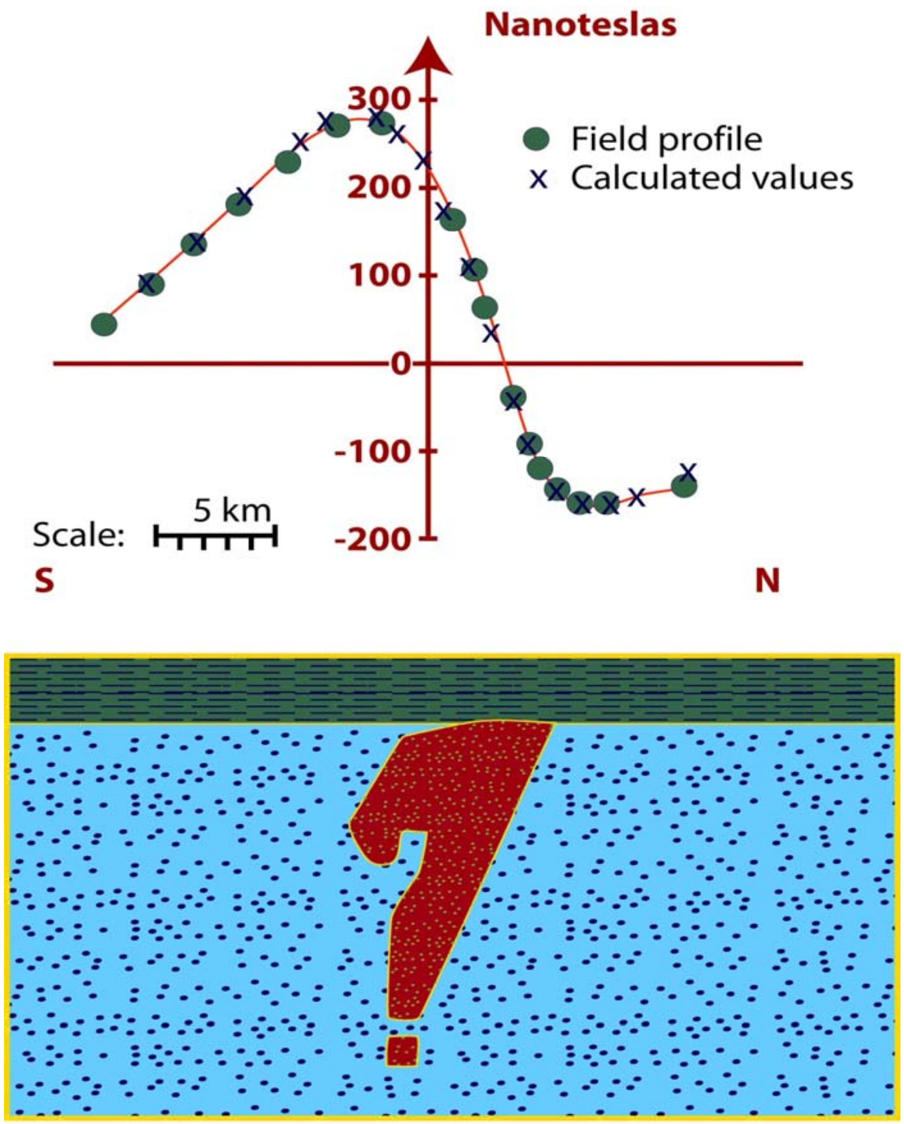


FIGURE 6 Magnetic data acquired in Switzerland, and a corresponding subsurface interpretation that is "theoretically accurate" but geologically absurd.

Additionally, because of inherent limitations in terms of how accurately a gravimeter can measure variations in the Earth's gravitational field (especially in the presence of random and coherent background noise), the tool provides increasingly reduced target definition and lateral and vertical resolution at depth. Basically, most geophysical instruments are capable of imaging small targets at shallow depths, but only large targets at greater depths. Geotechnical geophysical tools have practical maximum depths of investigations irrespective of the size of the target.

It is important to keep in mind that some targets are too deep or too small to be reliably imaged using any geotechnical geophysical tool. Other targets cannot be imaged because their properties do not differ sufficiently from those of the encompassing strata.

Common Applications of Geotechnical Geophysics

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Geotechnical geophysical tools are routinely applied to a broad spectrum of geotechnical problems. In Table 2, some of the more common applications of geotechnical technologies are listed. This table is not intended to be exhaustive. Rather it is intended to leave the reader with a feel for the depth and breadth of geophysical applications. (Note: For the purposes of this circular, the field of geotechnical geophysics specifically excludes structural engineering and borehole applications, with the exception of acoustic tomography).

TABLE 2 Some Potential Geotechnical Applications of Some Commonly Employed Geophysical Methods (Anderson, 2006)

Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
Mapping lithology (<30-ft depth)	M	X		M	X	X					M	M
Mapping lithology (>30-ft depth)	X	M	X		X	X					M	M
Estimating clay–mineral content					M	X	X				X	X
Locating shallow sand and gravel deposits				M	M						X	X
Locating sand and gravel deposits (that contain heavy minerals)									M			
Determining volume of organic material in filled-in lakes or karsted features	M	M			M					M	X	X
Mapping top of ground water surface	M (p-wave)	M (p-wave)		M	M	M						
Determining water depths (including bridge scour)				M								
Mapping groundwater cones of depression	X	X		M	X	X						
Subsurface fluid flow								M				
Mapping contaminant plumes				M	M	X		X				
Mapping crop land salination and desalination over time					M	M						
Locating underwater ferromagnetic objects				M					M			
Mapping bedrock topography (<30-ft depth)	M			M	X	X				X	M	M
Mapping bedrock topography (>30-ft depth)	X	M			X	X				X	M	M
Mapping sub-bedrock structure	X	M		X	X	X					X	X
Delineating steeply dipping geologic contacts (<30-ft depth)	M			M	M	M						

NOTE: M = Major Application; X = Minor Application.

continued

TABLE 2 (*continued*) Some Potential Geotechnical Applications of Some Commonly Employed Geophysical Methods (Anderson, 2006)

Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
Delineating steeply dipping geologic contacts (>30-ft depth)	X	M	X		X	X			X			
Mapping fracture orientation (near-surface bedrock)	M			M								
Identifying regions of potential weakness (e.g., shear zones and faults; <30-ft depth)	M		X	M	X	X			X			
Identifying regions of potential weakness (e.g., shear zones and faults; >30-ft depth)	X	X	M		X	X			X			
Identifying near-surface karstic sinkholes and the lateral extent of their chaotic, brecciated, and otherwise disrupted ground	M	M		M	X	X				X		
Mapping air-filled cavities, tunnels, (<30 ft depth)	X	X	X	M	X	M				X	X	X
Mapping air-filled cavities, tunnels, (>30-ft depth)	X	M	M		X	X				X	X	X
Mapping water-filled cavities, tunnels	X (p-wave)	M (p-wave)	M	X							X	X
Mapping clay-filled cavities, tunnels	x	M	M		X	X						
Estimating rippability	M		X								X	X
Foundation integrity studies	M		X	M							M	M
Dam-site integrity studies	M	M	M	M	X	X		M			M	M
Landslide site evaluation	M		M	X	M	M					X	X
Locating buried well casings (metal)				M	M				M			

NOTE: M = Major Application; X = Minor Application.

continued

TABLE 2 (*continued*) Some Potential Geotechnical Applications of Some Commonly Employed Geophysical Methods (Anderson, 2006)

Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
Locating buried drums, pipelines, and other ferromagnetic objects			M	M				M				
Locating buried nonmagnetic utilities			M									
Locating buried nonmagnetic utilities				M								
Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M			
Mapping archeological sites (nonmagnetic—excavations, burials, etc.)				M								
Detection of voids beneath pavement				M								
Detection and delimitation of zones of relatively thin subgrade or base course material				M								
Detection and monitoring of areas of insufficiently dense subbase				M							X	X
Mapping fracture orientation	M		M									
Detection of bodies of subgrade in which moisture content is anomalously high, as a precursor to development of pitting and potholes				M								
Mapping–locating landfills	X			X	M	X			M		X	X
Determining in situ rock properties (bulk, shear, and Young's moduli)	M		M								M	M
Estimating in situ rock properties (saturation, porosity, permeability)					M	M					X	X
Determining in situ rock densities										M		

NOTE: M = Major Application; X = Minor Application.

continued

TABLE 2 (*continued*) Some Potential Geotechnical Applications of Some Commonly Employed Geophysical Methods (Anderson, 2006)

Application	**Refr.**	**Refl.**	**Seis. Tomo.**	**GPR**	**EM**	**Resist.**	**IP**	**SP**	**Mag.**	**Grav.**	**MASW**	**ReMi**
Determining in situ rock properties (dielectric constant)				X								
Mapping abandoned, in-filled open-pit mines and quarries	M	M		X	X	X			X	X	X	X
Mapping abandoned underground mines		M	X			X						
Detecting abandoned mine shafts		X	X	M	M	X			X			

NOTE: M = Major Application; X = Minor Application.

Selection of Appropriate Geophysical Methods

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The selection of the most appropriate geotechnical geophysical tool is generally a two-step approach. In Step I, potentially useful geophysical methods are identified on the basis of the nature of the engineering problem. This initial "high grading" can be done using updated reference tables (such as those presented on the FHWA website: www.cflhd.gov/agm/index.htm) and reference guides (such as ASTM D5753 and D6429). In Step II, the most appropriate geophysical tool, or tools, is selected based on site-specific criterion such as the depth of the target, required resolution, site accessibility, and cost.

STEP I: USE OF REFERENCE TABLES AND PUBLISHED GUIDES

In Table 2, some common highway engineering problems and potentially applicable geophysical technologies are listed. This table is useful in steering the potential user of geophysical services in the correct initial direction during the preplanning phase of a geotechnical investigation. During this preplanning phase the use of geophysical technology is considered and potentially useful tools are identified on the basis of their historical applications.

The published reference tables (such as Table 2) are useful but are not the sole basis for selecting a specific geophysical tool for a specific highway project. For example, magnetic and EM tools are listed in Table 2 as commonly used for utility investigation. However, these tools are useful only when the utility is magnetically susceptible or electrically conductive, respectively. These limitations of the magnetic and EM tools are identified and considered in the early stages of Step II.

Additional information about potentially suitable surface geophysical methods can be found in:

- FHWA Geophysics Manual (www.cflhd.gov/agm/index.htm);
- ASTM D6429: Standard Guide for Selecting Surface Geophysical Methods; and
- ASTM D5753: Standard Guide for Planning and Conducting Borehole Geophysical Logging.

The ASTM publications cited summarize the practice, identify the significance and use of the method, describe procedures, provide report components, discuss precision and bias, and provide references. Unfortunately, they cover only a limited number of geotechnical geophysical methods and related applications.

STEP II: SELECTION OF APPROPRIATE TOOLS BASED ON SITE AND TARGET SPECIFICS

Based on past experience it appears that the selection of appropriate geophysical tools, from the larger list of potentially useful techniques, is site specific and target specific (Anderson, 2006). Therefore, it is important that all available potentially suitable methods are critically evaluated. The following are key considerations when developing a geotechnical geophysics exploration program:

- What are the physical properties of interest?
- Which geophysical methods respond to the physical properties of interest?
- Which techniques can provide the required spatial resolution and target definition?
- Which geophysical tools can perform well under study-area conditions?
- Which techniques are most cost effective?
- Which techniques can provide complementary data?
- What nongeophysical control is required to constrain the interpretation of acquired geophysical data?
- Is the overall geophysical program cost-effective?

If these considerations are not addressed, unsuitable geophysical data may be acquired, unnecessary expenditures may be incurred and undesirable time delays may be experienced.

WHAT ARE THE PHYSICAL PROPERTIES OF INTEREST?

Geophysical surveys are usually conducted with specific objectives (subsurface targets) in mind. These targets and their physical properties typically are clearly defined during the earliest stages of the appropriate tool-selection process. For example, consider a geotechnical investigation conducted with the objective of mapping any and all shallow air-filled voids. Shallow, air-filled cavities within otherwise intact sedimentary rock are characterized by spatial variations in density, acoustic velocity, EM velocity, dielectric constant, electrical conductivity, and electrical resistivity. Collectively, these variable attributes represent the physical properties of interest.

WHICH GEOPHYSICAL METHODS RESPOND TO THE PHYSICAL PROPERTIES OF INTEREST?

The appropriate geotechnical geophysical tool is one selected from a list of methods that are designed to respond to one or more of the physical properties of the target. To detect an air-filled void, for example, several geophysical techniques might appear suitable, including seismic refraction, seismic reflection, seismic tomography, GPR, EM, electrical resistivity, and gravity.

The seismic refraction, seismic reflection, and seismic tomography techniques respond to subsurface variations in acoustic velocity and density (either directly or indirectly). The GPR tool responds to spatial variations in dielectric constant, magnetic permeability, electrical conductivity, and EM velocity. The EM tools respond to changes in electrical conductivity and inductance. The electrical resistivity tools respond to changes in electrical resistivity. The gravity tool responds to spatial variations in the density of the subsurface.

WHICH TECHNIQUES CAN PROVIDE THE REQUIRED SPATIAL RESOLUTION AND TARGET DEFINITION?

Different geophysical tools provide varying degrees of spatial resolution (vertical and horizontal) and target definition (shape, depth). A high-frequency GPR tool (e.g., 1.5 GHz), for example, can provide very high spatial resolution (on the order of 0.03 ft) but has limited depth penetration (generally less than 3 ft). A low-frequency GPR tool (e.g., 80 MHz) provides only intermediate spatial resolution (on the order of feet), but is capable of imaging targets at depths on the order of 50 ft or more under ideal circumstances.

The spatial resolution and target definition provided by each geophysical technique are functions of multiple variables including (but not limited to) the contrast between the physical properties of the target and host rock, the depth of the target, background noise levels, the attributes of the specific tool employed, etc. These variables are considered prior to the selection of a specific tool.

Consultation with an expert is desirable during the spatial resolution and target definition phase of tool selection because a knowledgeable geophysicist is able to determine (on the basis of experience and modeling) which specific geophysical tools are practicably capable of providing the required spatial resolution and target definition (given target properties, depth, shape, and size).

WHICH GEOPHYSICAL TOOLS CAN PERFORM WELL UNDER STUDY-AREA CONDITIONS?

The usefulness of a specific geophysical tool is a function of site conditions. Variables include (but are not limited to) accessibility, areal extent, density of vegetation, topography, soil thickness, lithology, and groundwater salinity. The consideration of site conditions during the preplanning phase generally has a reasonable probability of the technique selected working well in the study area.

WHICH TECHNIQUES ARE MOST COST EFFECTIVE?

The relative cost effectiveness of prospective geophysical tools is a function of both cost (planning, acquisition, processing, and interpretation) and the overall usefulness of the interpreted results (resolution and target definition). Consultation with an expert geophysicist is considered in development of the cost estimates that are based on appropriate acquisition and processing parameters. The projected utility of a particular geophysical tool is also very much a function of the acquisition and processing schemes employed. In an effort to trim costs, acquisition and processing efforts are sometimes minimized at the expense of data quality to the extent that projected deliverables cannot be obtained. However, compromising data quality is not cost effective.

WHICH TECHNIQUES CAN PROVIDE COMPLEMENTARY DATA?

Generally, if two or more geophysical techniques provide similar target definition and cost is the overriding concern, the less expensive method is selected. However, if accuracy of interpretation is the overriding concern, more than one geophysical technique often is employed because complementary data sets assist in interpretations. Another consideration is whether a geophysical tool can contribute information above and beyond defining–imaging a specific target. Interpreted GPR and electrical resistivity data for example, can provide information about bedrock topography, subsurface lithology, etc.

WHAT NONGEOPHYSICAL CONTROL IS CONSIDERED TO CONSTRAIN THE INTERPRETATION OF ACQUIRED GEOPHYSICAL DATA?

Geophysical data are inherently ambiguous. Interpretations are more rigorous if constrained and verified by ground truth. Accordingly, the next step in the process is to collect sufficient ground truth (for constraint and verification purposes) as part of the overall geotechnical effort. Ground truth is commonly acquired during the geotechnical site characterization process using test borings. In order to increase the reliability of any acquired geophysical data, the engineer typically acquires geophysical control data in proximity to borings locations or vice versa. Having at least some boring information prior to the acquisition of geophysical data can be very useful in aiding interpretation.

IS THE OVERALL GEOPHYSICAL PROGRAM COST-EFFECTIVE?

The last step is to assess the cost-effectiveness of the overall geophysical effort relative to nongeophysical alternatives such as a patterned invasive drilling program. The final “go–no go” decision is based on projected costs and deliverables, and probability of success (e.g., obtaining desired deliverables). Also, the engineer considers important nontechnical issues such as timing, the potential for litigation, and the cost of failure.

Selecting Geophysical Contractors

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REQUEST FOR PROPOSAL

A common approach to acquiring geophysical services is to solicit proposals from a number of consultants–contractors. A request for proposal (RFP) that includes the following components is considered well structured:

1. Survey objectives;
2. Site setting and conditions;
3. Survey method and acquisition parameters;
4. Geophysical data processing parameters;
5. Geophysical interpretations;
6. Quality assurance–quality control (QA/QC) requirements;
7. Deliverables;
8. Schedule;
9. Payment terms;
10. Available background information;
11. Site photographs; and
12. Field-release clause.

SURVEY OBJECTIVES

The survey objectives are spelled out very clearly. The consultant–contractor ensures that all specifications in the RFP (i.e., geophysical methods to be employed, acquisition and processing parameters, deliverables) are consistent with the survey objectives.

SITE SETTING

Site access (steeply dipping hillside, wooded area, farm field, construction site, etc.) will affect the speed with which the geophysical data can be acquired, the quality of the acquired data, and overall cost of the geophysical survey. Right of entry issues are addressed. Site photographs, topographic maps, and utility information are made available.

SURVEY METHOD AND ACQUISITION PARAMETERS

This section is frequently the most difficult part of an RFP. Unless the geophysical tools are precisely specified and acquisition parameters are carefully spelled out, highly variable RFP responses can be expected. The use of less than optimal tools or acquisition parameters will impact survey costs and utility of the deliverables. (An organization with limited geophysical experience may want to consider engaging a design geophysicist to help select the most appropriate method and acquisition parameters.)

GEOPHYSICAL DATA PROCESSING PARAMETERS

Geophysical data processing parameters can significantly affect the interpretability of the acquired data, and are specified as precisely as possible. (An organization with limited geophysical experience may want to consider engaging a design geophysicist to help select optimum processing parameters.)

GEOPHYSICAL INTERPRETATIONS

The geophysical data are interpreted in a manner that is consistent with state-of-the-art industry practices. The presentation (e.g., geologic cross-sections, contoured maps, explanations of the same) of the interpretations are consistent with the objectives of the geophysical survey. If special interpretation (e.g., timing software, modeling software, display software) is to be employed, it is specified in the report; if specific presentations are required, they are duly noted in the RFP. The generation of synthetic models in support of interpretations is often a good idea.

QA/QC REQUIREMENTS

Daily progress reports (including preliminary results) focused on prespecified QA/QC requirements for all identified key aspects of the geophysical survey encourages dialogue between the client and the consultant–contractor. A field-release clause is often inserted allowing the client to terminate the contract in the event that noninterpretable data are being acquired because of unanticipated conditions.

DELIVERABLES

Well-defined deliverables are beneficial for both the geophysical consultant–contractor and the end user of the geophysical data. A typical report will contain the following headings:

1. Executive summary, with objectives and generalized interpretation;
2. Purpose and scope of study;
3. Dates and location (including a site location map);
4. Personnel and organizations involved;
5. Summary of data collection procedures (methodology, quantity, and type);
6. Quality and reliability of the acquired data (basis for ratings);
7. Summary of field investigation (tools and acquisition parameters);
8. Summary of data processing (methodology);

9. Summary of interpretation procedure, including verification (ground truth or synthetic modeling);
10. Presentation of relevant interpretation in a form that is useful to end user; and
11. Summary and recommendations.

Brief summaries of data collection, field investigations, and interpretation procedures suffice for many projects. However, if the user of the geophysical data has limited experience, a more detailed report, including theory and limitations can be requested. Adequate information is provided to permit the relocation of measurement positions and the field location of geophysical features of interest or concern. Maps at an adequate scale are required.

SCHEDULE

A timeline is specified, complete with reasonable allowances for equipment-related and weather-related downtime. Financial penalties for excessive delays can be incorporated.

PAYMENT TERMS

Common geophysical contracts are let on a line-mile, per-station, or lump-sum basis. A field-release clause is inserted allowing the client to terminate the contract in the event that noninterpretable data are being acquired because of unanticipated conditions.

If additional geologic control is to be acquired on the basis of the initial geophysical interpretation, the cost of integrating such control into a revised report is specified. Less important, but critical, factors subject to negotiation are stand-by time, possible changed interpretation requirements, content of deliverables, terms of payment, right of entry, responsibility for locating underground utilities, deadlines, and inclement weather stand-by costs.

Geophysical daily rates are usually straightforward. However, the productivity of field crews is dependent on some or all of the following factors: terrain, vegetation, hazardous waste, insects or other biohazards, weather (particularly the season), logistics, commute time or access to the field location, presence of third-party observers, the experience and resourcefulness of the field crew, and interference with the geophysical measurements due to noise.

AVAILABLE BACKGROUND INFORMATION

Any and all additional relevant information regarding the site is included in the RFP. This could include information regarding previous construction activities, accessibility problems on access roads due to heavy rains, presence of livestock, location of fences, trespass issues, etc.

FIELD-RELEASE CLAUSE

This clause permits contract termination if preliminary results do not justify continuation of the survey. Reasons for termination could include: noninterpretable data, initial interpretations that indicate geological conditions are different than envisioned and do not justify the continuation of the geophysical survey, achievement of the main objective prior to completion of all planned field work, etc.

Use of Geophysics by Transportation Agencies

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In 2005, NCHRP, in conjunction with the Transportation Research Board, sponsored the completion of *NCHRP Synthesis 357: Use of Geophysics for Transportation Projects*. Over the last 5 to 10 years, it had become apparent to the sponsor organizations and FHWA that the use of geophysics among U.S. transportation agencies is increasing; thus, the synthesis was designed to determine by how much, by whom, and what work is being done. This chapter summarizes results from the NCHRP publication [Project 20-5, Topic 36-08, 2005 (Sirles, 2006)], by showing some representative statistics.

The synthesis presents the state of the industry regarding the use of geophysics on transportation projects, particularly for geotechnical investigations. Geophysics, for the purpose of the synthesis, was defined as the application of physical principles to define geology and study Earth (geo-) materials. Geotechnical geophysics is used to evaluate natural and artificial foundation materials: soil and rock. But the synthesis focused purely on its application toward geotechnical problems. NDT was not addressed, as it is used to evaluate manmade structures (e.g., bridges, shafts, mechanically stabilized earth walls, etc.).

The following subjects are presented in the synthesis: a review on the state of knowledge; an assessment on the amount and type of geophysical investigations being performed; what geophysical investigation methods and technologies are being used; what engineering applications geophysics is being used for; an assessment of annual budgets and in-house capabilities; identification of how to select geophysical methods; the most common practices regarding solicitation and contracting; the level of comfort with this technology among highway engineers; and, future research ideas, as well as educational and training needs.

GENERAL

To accurately capture how transportation agencies are currently implementing geophysics, data were generated through a 68-question electronic survey sent to U.S. and Canadian transportation agencies. The questionnaire went to 70 agencies. Representatives within the 50 state departments of transportation (DOTs), the District of Columbia, most of the Canadian transportation agencies, and seven federal transportation agencies were contacted. A total of 63 questionnaires were returned for a response rate of 90%. Respondents included all 50 U.S. state DOTs, District of Columbia, Port Authority of New York and New Jersey, eight Canadian, and three federal agencies. Four extra responses were received from different departments in three state DOTs. Thus, 67 responses were entered into the database for analysis. Nine of the 67 respondent agencies indicated they do not utilize geophysics; therefore the results presented in the NCHRP Synthesis are based on answers obtained from 58 respondent agencies that use geophysics in their geotechnical investigations. Figure 1 illustrates the number of respondents that use geophysics.

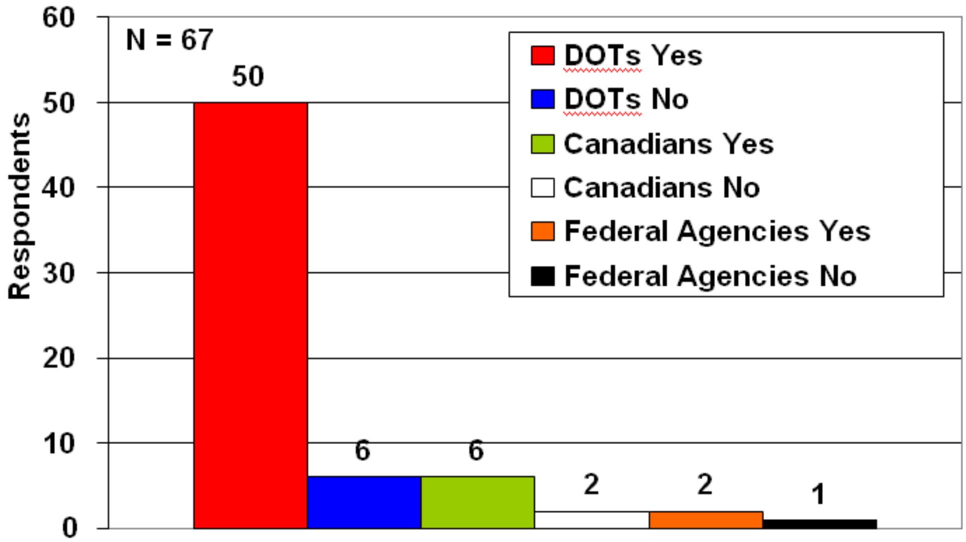

FIGURE 1 Agency response to survey on utilization of geophysics (after Sirles, 2006).

The majority of agencies pay for geophysical investigations through their design groups, but when it comes to soliciting and contracting service providers for geophysical investigations, the approach was varied. Figure 2 shows that the primary mode of solicitation is limited or sole-source solicitation (42% combined), indicating a lack of confidence in unknown (or not prequalified) geophysical contractors. The majority of contract work is done through procuring the contractors under bigger multiyear contracts to architectural–engineering (A/E) firms as part of their geotechnical program; however, when independent contracts are utilized 51% are set up primarily under lump sum–fixed price or time and materials subcontracts to firms specializing in geophysics (Figure 3).

Figure 4 indicates that about 45% of the respondents began implementing geophysics as part of their geotechnical investigations within the past 10 years, 26% within the last 5 years. Thus, the technology is relatively new as an investigation tool to most agencies. However, nearly 60% of the agencies indicate an increase in their use of geophysics in the past 5 years, and 21 agencies have increased its use by greater than 50% (Figure 5). Fourteen agencies conduct between 75% and 100% of their geophysical investigations using in-house capabilities. Out of 58 respondents, only two agencies indicate funds are allocated annually for geophysical investigations.

Figure 6 shows that contract values are predominantly less than $10,000 per geophysical investigation; however, there are a few agencies who utilize geophysics routinely that will spend more than $100,000 annually conducting geophysical investigations. These agencies tend to carry large on-call [indefinite delivery–indefinite quantity (IDIQ) type] contracts to easily access qualified service providers for projects. These contracts range from $300,000 per year to $5 million for 3 years (with two service providers). The typical number of geophysical investigations conducted each year ranges between one and five for more than 50% of the respondent agencies.

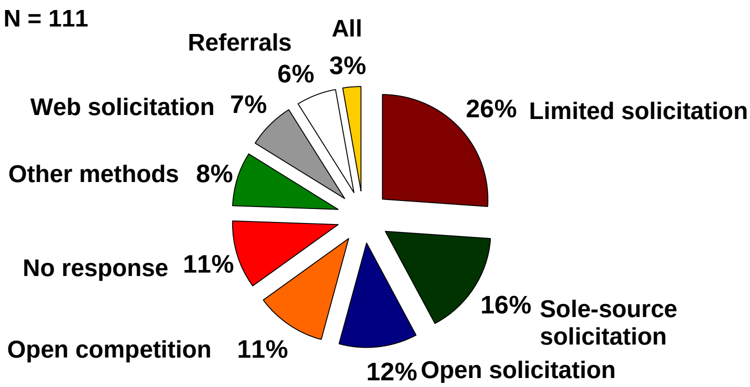

FIGURE 2 Survey response on means of acquiring geophysical services (after Sirles, 2006).

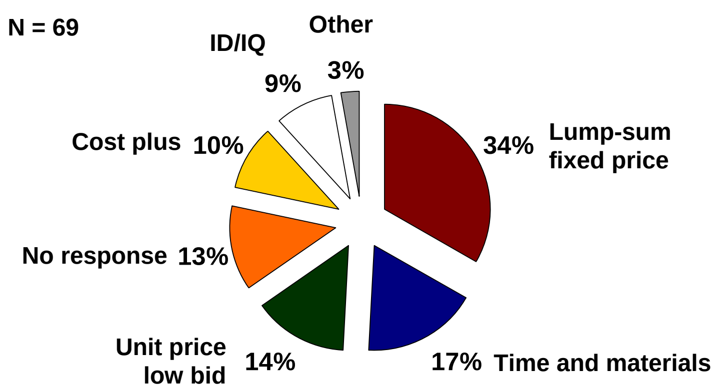

FIGURE 3 Survey response on contracting method for geophysical services (after Sirles, 2006).

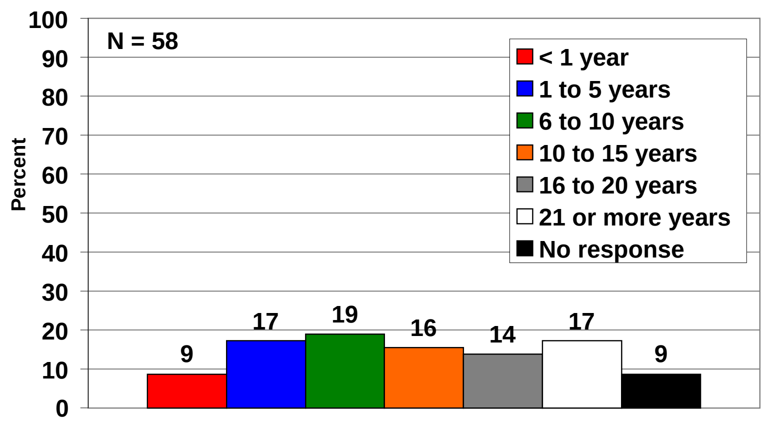

FIGURE 4 Survey response as to when geophysics was initially implemented by agencies (after Sirles, 2006).

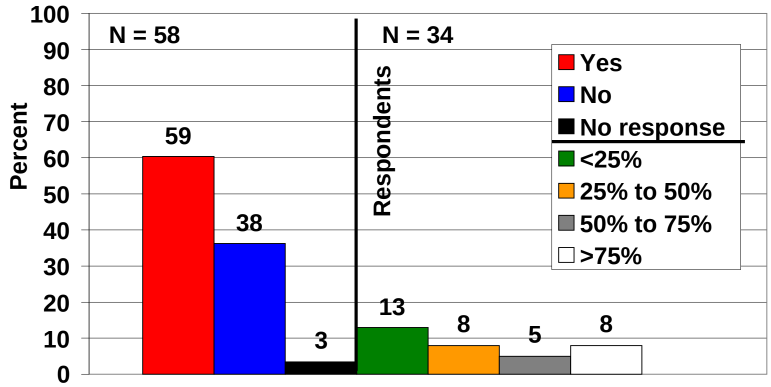

FIGURE 5 Survey response of the changes in the level of use in geophysics (after Sirles, 2006).

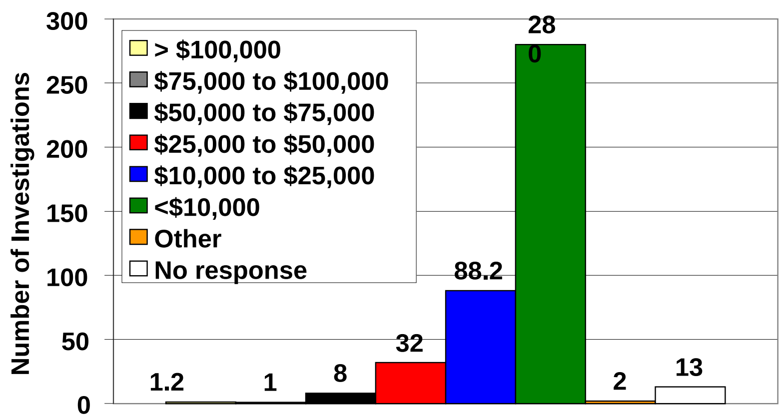

FIGURE 6 Survey response of typical cost per geophysical investigation and frequency (after Sirles, 2006).

Between 50% and 60% of the agencies and individuals completing the survey provided an experience rating of good to excellent for their use of geophysics. Yet, several limiting factors were identified as hindrances to the implementation of geophysics. These include: difficult field instrumentation and software for data interpretation, poorly qualified service providers, subjective and nonunique results; but, the majority of respondents indicated that a lack of understanding and knowledge was the greatest hindrance. Engineers continue to ask for easier to use instrumentation and turnkey software. Inherently, this is contradictory because geophysics, its applications, data, and interpreted results are by nature, very complex. Vendors produce systems that have become push-button as well as integrated software that is simple solution oriented. This may account for why poor results implicate the science and the technology, but not the uneducated end users.

The results of this synthesis support the conclusion that the majority of in-house geoscientists and engineers lack knowledge regarding the true value, the variety of benefits, or the advantages of geophysics. Figure 7 shows the items identified as the greatest value geophysics lends to projects; whereas Figure 8 shows the items that deter its use on projects. As experiences (e.g., case histories) are shared and educational opportunities provided for transportation engineers and agencies, these factors will be better understood which should lead to more routine use of this technology on their projects.

Because highway engineers acknowledge both the benefits and deterrents, the respondents unmistakably requested more training resources be made available, including the development of a national training workshop or course (e.g., National Highway Institute course). Figure 8 shows that although the FHWA recently published and distributed a manual, *Application of Geophysical Methods to Highway Related Problems* (Wightman, 2004), nearly 35% of the respondent agencies are not aware of it, greater than half of the agencies don't have it or are not sure if they do, and about 45% have not used it. Since publication of the manual in 2004 as a

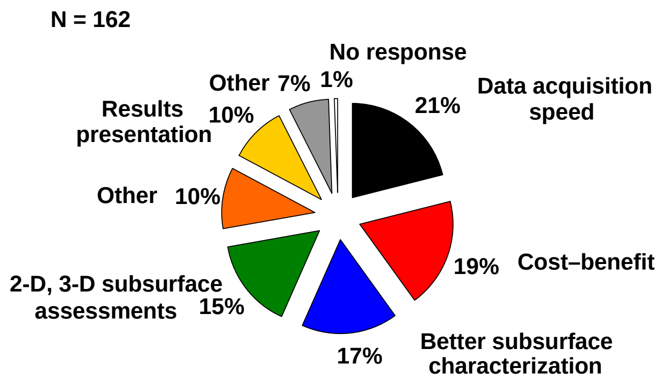

FIGURE 7 Survey response of the greatest value of geophysics use (after Sirles, 2006).

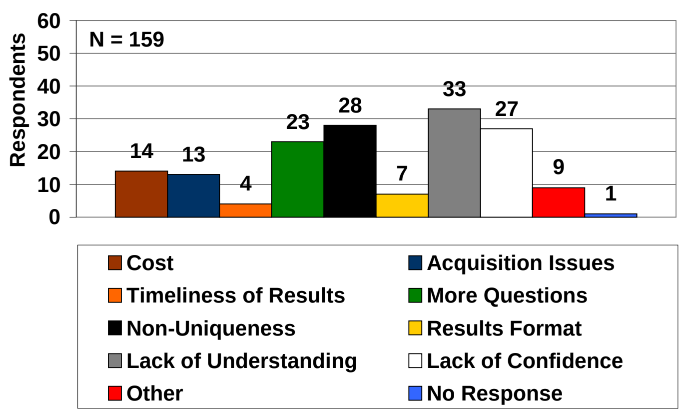

FIGURE 8 Survey response of greatest deterrent to geophysics use (after Sirles, 2006).

web-based document designed around problem solving and applications (not around geophysics), it is apparent that the effort to create the website and distribute the hard-copy is not being fully realized. The website can be accessed at www.cflhd.gov/agm/index.htm.

METHODS AND APPLICATIONS

A primary objective was to determine what geophysical methods were most commonly used. Figure 9 displays the results from the survey regarding which geophysical methods are most commonly used by these transportation agencies. It is apparent from this chart that NDT gets incorporated with geophysical methods, likely due to the overlap between the technologies (e.g., crosshole seismic for shear wave velocity versus crosshole sonic logging for drilled shaft integrity).

Results indicate seismic, GPR, and vibration monitoring are the most commonly used methods. Seismic and GPR methods make up nearly 50% of the overall usage of geophysics among transportation agencies. Significant results are (*a*) vibration monitoring represents a high percentage of use (22%); (*b*) electrical resistivity is fourth at about 10%; and, (*c*) there is an obvious lack of EM methods used. A number of other methods were designated by respondents that do not fit primary geophysical methods (as listed for the synthesis).

Additional information obtained indicates electrical resistivity, borehole logging, and a myriad of other methods are actively used. Magnetic methods have been used by 12 agencies and microgravity by five. Refraction and borehole seismic techniques (crosshole and downhole) are the most common seismic techniques. Two-dimensional profiling is well ahead of any other electrical technique commonly used. Time-domain and frequency-domain EM techniques are applied about equally, although very infrequently. Marine and airborne geophysical investigations appear to be very rarely conducted. Vibration monitoring is equally split by technique for construction monitoring (e.g., pile driving, dynamic compaction) and blast monitoring (e.g., rock mass excavation, quarry operations).

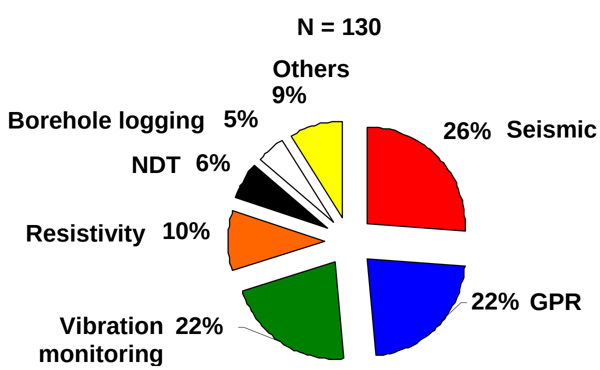

FIGURE 9 Survey response of the most common geophysical methods used (after Sirles, 2006).

To determine how these methods are being applied, several questions dealt with the specific applications that the geophysical investigations addressed. Figure 10 displays the most common applications for which geophysics is used by the respondent agencies. A footnote to this figure is required since nearly 25% of the applications described in the responses to this set of questions fall into the NDT category. NDT was not to be included as part of the synthesis. This figure clearly demonstrates that the difference between the application of NDT or geophysics continues to be confusing. Based on the variety and different descriptions of applications, responses were lumped into the general categories shown in the figure. For example, “mapping depth to rock,” “mapping topography of rock,” or “mapping bedrock strength” were all placed in the “bedrock mapping” category. The categorization permitted a better illustration of the responses to this question. The questions regarding method and applications all indicate that a third of the geotechnical applications are related to the use of geophysics to map bedrock characteristics such as depth, topography, or rippability. Numerous other applications (including the large representation of NDT applications) were provided by the respondents. As might be expected, roadway subsidence issues and soil mapping are dominant applications as well.

CONCLUSIONS

The top 10 results derived from the NCHRP synthesis are

1. 68% of the respondents don’t use geophysics very often (i.e., “occasionally”); 45% of the agencies have used geophysics only in the past 10 years, and only 26% in the last 5 years.
2. About 60% of the agencies indicate there is an increase in their implementation of geophysics, with approximately 25% indicating an increase between 50% and 100%.
3. The top three most commonly used geophysical methods are
   a. Seismic,
   b. GPR, and
   c. Vibration monitoring.
4. The top three geotechnical engineering applications for geophysics are

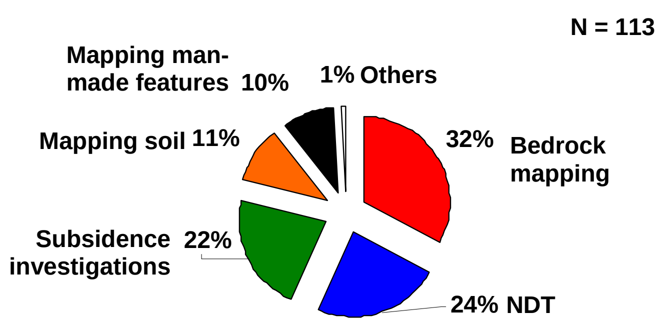

FIGURE 10 Survey response of the most common geophysical applications (after Sirles, 2006).

   a. Bedrock mapping;
   b. Mapping (characterizing) soil deposits, and
   c. Roadway subsidence. An interesting note is that NDT ranked second on the list, but it is not a qualified result since it is not part of this synthesis. This point emphasizes a general lack of understanding about the two technologies.
5. The top three “greatest values” for using geophysics are
   a. Speed of data acquisition,
   b. Cost benefits, and
   c. Better characterization of the subsurface.
6. The three greatest deterrents to using geophysics are
   a. Lack of understanding,
   b. Nonuniqueness of results, and
   c. Lack of confidence
7. The three items that can overcome the deterrents:
   a. Training,
   b. Experience (and sharing thereof), and
   c. Implementation of standards
8. Very few agencies allocate funds in their annual budgets specifically for geophysical investigations, and the majority of projects cost less than $10,000.
9. Limited or sole-source solicitations are the primary means of contracting geophysical providers, but seven agencies use large on-call, multiyear contracts (with the indication that more agencies will contract in this fashion).
10. A ratio of 7:1, successful-to-unsuccessful projects was shown to exist for the respondent agencies.

Based on a combination of results from this synthesis and discussions with hundreds of geotechnical engineers, as formal training gets developed and presented, and successful project experiences among transportation agencies increases (by utilizing either in-house or qualified service providers), geophysics will become more widely used in the transportation industry. The synthesis determined that design and construction engineers are beginning to appreciate the benefits of geophysics through limited use and exposure over just the past 5 years. Additionally, the majority of respondents, the synthesis author, and the technical panel believe that using geophysics has the potential to save money, time, and reduce the risk associated with unknown subsurface conditions for these transportation agencies.

Glossary of Selected Terms

Acoustic velocity	Acoustic velocity refers to the speed with which seismic waves propagate through a medium. Acoustic velocity is a function of the engineering properties of the medium and is not a vector quantity when used in this sense.
Elastic moduli	Acoustic velocity is a function of the elastic moduli of the medium through which it is propagating. These moduli include: bulk modulus, shear modulus, Young's modulus, Lame's constant and Poisson's ratio.
Dielectric constant	The dielectric constant of a material is a measure of its capacity to store charge when an electric field is applied.
Electrical conductivity	Electrical conductivity is a measure of the ability of a material to conduct electric current.
Inductivity	Inductivity is a measure of magnetic permeability.
Capacitivity	Capacitivity is a measure of permittivity, the property of a material which enables it to store electric charge.
Electromagnetic (EM) velocity	Electromagnetic velocity refers to the speed with which electromagnetic waves propagate through a medium. Electromagnetic velocity is a function of the dielectric property of the medium through which it is propagating and is not a vector quantity when used in this sense.
Geophysics	Geophysics is the study of the earth by quantitative physical methods, especially those described in this circular.
Magnetic permeability	The magnetic permeability of a material is the ratio of the induced magnetic field to the inducing field.
magnetic susceptibility	Magnetic susceptibility is a measure of the degree to which a material can be magnetized.
Natural electric potential	Natural electric potentials are voltages that are caused by natural processes such as flowing water or oxidization and reduction.
Remanent magnetization	Natural remanent magnetization the permanent magnetization within rocks. This is caused by natural causes such as cooling through the Curie point, chemical processes, alignment of magnetic mineral particles during deposition, pressure and exposure to an external magnetic field.

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