

A PROTOCOL FOR SELECTING APPROPRIATE GEOPHYSICAL SURVEYING TOOLS BASED ON ENGINEERING OBJECTIVES AND SITE CHARACTERISTICS

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Abstract

Engineering geophysical tools provide specific information about the physical properties of the site (includes materials and/or structures) investigated, and are routinely applied to highway-related problems. The transportation engineer responsible for site characterization should ensure that geophysical technique(s) employed provide useful and cost-effective information about physical properties of interest at the required level of spatial resolution and target definition.

As an aid to the highway engineer, we present tabularized information about ten commonly employed geophysical methods and a generalized approach for evaluating their utility as site characterization tools. Our discussions are intended to be informative - not exhaustive. The reader is referred to the selected bibliography for more rigorous treatments of the geophysical techniques. The engineer engaged in geophysical survey design is strongly encouraged to work with a knowledgeable geophysicist.

Introduction

Geophysical techniques measure specific physical parameters (Table 1) and are routinely applied to highway-related problems. Commonly employed methods include seismic refraction, seismic reflection, seismic tomography, ground-penetrating radar (GPR), electromagnetics (EM), electrical resistivity, induced polarization (IP), magnetics, self potential (SP) and gravity (Figures 1 and 2).

In the normal course of an engineering site investigation, one or more geophysical data sets may be acquired for the purpose of determining physical properties of interest (Table 1). Typically, non-geophysical information (borehole, geohydrologic, surficial geology, concrete thicknesses, etc.) is also acquired, all contributing to the interpretation of the geophysical data and the development of an integrated site model.

To ensure that the most appropriate geophysical techniques are employed, the highway engineer should critically evaluate the potential utility and cost-effectiveness of available methods. There are several "questions" that should be considered including:

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

Herein we present tabularized information about ten commonly employed geophysical methods, and a generalized approach for evaluating their utility as site characterization tools. To illustrate the ideas presented, we consider a hypothetical site characterization situation and address the "questions" (posed above) sequentially.

Geophysical	Measured	Physical Property or	Physical Property	Typical Site
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Method	Parameter	Properties	Model (Highway Application)	Model (Highway Application)
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.	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.	Geologic profile.
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.
Ground-Penetrating Radar (GPR)	Travel times and amplitudes of reflected electromagnetic energy.	Dielectric constant, magnetic permeability, conductivity and EM velocity.	EM velocity/depth model.	Geologic, material or structure profile.
Electro-magnetics (EM)	Response to natural/induced electromagnetic energy.	Electrical conductivity and inductance.	Conductivity/depth model.	Geologic/hydrologic profile.
Electrical Resistivity	Potential differences in response to induced current.	Electrical resistivity.	Resistivity/depth model.	Geologic/hydrologic profile.
Induced Polarization (IP)	Polarization voltages or frequency dependent ground resistance.	Electrical capacitance.	Capacitance/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 beneath dam or through 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 (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.	Geologic profile (location of voids, variable depth to bedrock, etc.).

Table 1: Summary of ten geophysical surveying methods commonly employed for highway site investigations. Each geophysical technique measures different physical properties. A physical property model is developed from single method data only. Site models are generated using multiple geophysical data sets and available non-geophysical constraints.

In our hypothetical situation, a transportation engineer wants to identify, locate and map potentially unstable, air-filled voids (near-radial cavities with extended horizontal axis; modeled as horizontal cylinders; oriented N-S, effectively parallel to predominant fracture system) in otherwise uniform limestone (moist, devoid of clay) at a bridge site (40m x 100m; Figures 3 and 4). There are no physical constraints

with respect to site accessibility. Limestone bedrock is near-horizontal, overlain by a thin veneer of soil (<1m of unconsolidated fine-grained sand), and underlain by lower-velocity shale (contact at a depth of 50m). The geophysical techniques employed need to be capable of detecting: 1) air-filled cavities with minimum diameters of 1m centered at sub-bedrock depths shallower than 3m; 2) cavities with minimum diameters of 3m centered at depths shallower than 5m; and 3) cavities with minimum diameters of 8m centered at depths shallower than 15m. Cavities centered at depths greater than 20m are water-filled and do not constitute a significant risk to overlying structures.

**What Are the Physical Properties of Interest?
Which Geophysical Methods Measure These Physical Properties?**

The first step in designing a geophysical survey is to identify the *physical properties* of interest (Table 1). In our hypothetical situation, the highway engineer would recognize that limestone containing shallow, air-filled cavities would/could be characterized by spatial variations in density, acoustic velocity, EM velocity, dielectric constant, electrical conductivity and electrical resistivity (Figure 4). The second step is to determine which geophysical method(s) measure one or more of these parameters. Based on the data provided in Table 1, several geophysical techniques would appear potentially suitable site investigation tools, including seismic refraction, seismic reflection, seismic tomography, GPR, EM, resistivity and gravity.

**Spatial Resolution and Target Definition
Which Geophysical Tools Will Perform Well in the Study Area?**

The third step is to determine which geophysical technique(s) can provide the required spatial resolution and target definition. The fourth step is to assess which tools have a reasonable probability of performing well in the study area, given the nature of the target, the target environment, and the related strengths and weaknesses of the various methods. (Information relevant to our hypothetical example is summarized in Table 2. The reader is referred to the selected bibliography for more thorough and rigorous treatments of tool resolution, definition and performance.)

Based on *spatial resolution/target definition/site utility* considerations (as provided in Table 2 and 3 only), the engineer would rank the various geophysical techniques in a manner consistent with Table 4. GPR would be rated optimal for investigating cavities at shallow to intermediate depths. Resistivity is a potentially viable tool for investigations at all requisite depths. Gravity and seismic tomography are potentially suitable for investigations at intermediate or greater depths. Seismic reflection could be a viable tool for delimiting larger cavities at depths on the order of 15m.

**Which Techniques Are Most Cost-Effective?
Which Techniques Will Provide Complementary Data?**

The fifth and sixth steps are to consider the cost-effectiveness and complementary nature of each geophysical tool. Cost-effectiveness is a function of both cost (planning, acquisition, processing and interpretation) and the overall usefulness of the interpreted results (target definition). In our hypothetical case study, tool options have been narrowed down to GPR, resistivity, gravity, seismic tomography, and seismic reflection. In Table 4, we summarize (given the nature of target and site accessibility) the cost-effectiveness of each tool still under consideration.

Generally, if two or more geophysical techniques provide similar target definition and cost is the overriding concern, the less expensive method is generally selected. However, if accuracy of interpretation is the overriding concern, more than one technique is often employed because complementary geophysical data sets will further constrain interpretations. Another consideration is whether a geophysical tool can contribute information above and beyond the definition of the specific target. Seismic surveys for example, can provide in-situ estimates of engineering rock properties.

Based on the information presented in Table 4, GPR is ranked as the most accurate (in terms of spatial resolution/target definition) and cost-effective tool for mapping voids at shallow to intermediate depths. With respect to the identification of larger cavities at greater depths, resistivity is ranked first in terms of cost and overall cost-effectiveness. (Note that seismic tomography was ranked first in terms of target definition and spatial resolution, but a distant second in terms of overall cost-effectiveness. If the

determination of elastic moduli in-situ had been a significant secondary interest, seismic tomography would have been rated as most cost-effective.)

Assume that cost-effectiveness is the primary concern (based on an evaluation of strategic needs), and that the plan is to use GPR to investigate shallow to intermediate depths and resistivity to evaluate the subsurface at greater depths.

Non-Geophysical Data Constraints? Is the Overall Geophysical Program Cost-Effective?

The seventh step is to plan for the acquisition of non-geophysical constraints. Our engineer understands that geophysical data is inherently ambiguous, and realizes that interpretations will be more rigorous if constrained and verified by ground truth. With this consideration in mind, two anchor boreholes will be drilled on-site prior to the interpretation of the geophysical data. This boring control will ensure that geophysical interpretations are calibrated and constrained. Our engineer also plans to drill two confirmation boreholes at sites designated as anomalous (or otherwise), in order to verify geophysical interpretations.

The last step is to assess the cost-effectiveness of the overall geophysical effort relative to non-geophysical alternatives such as invasive drilling (as per hypothetical example). The final decision is based on cost-effectiveness, confidence, and engineering judgment.

Summary

The engineer designing or responsible for a geophysical investigation should raise several pertinent questions, and select methodologies based on the responses. Questions could include:

- *What are the physical properties of interest?*
- *Which geophysical methods measure the physical properties of interest?*
- *Which techniques will likely provide the required spatial resolution and target definition?*
- *Which geophysical tools will perform well in the study area?*
- *Which techniques are most cost-effective?*
- *Which techniques will provide complementary data?*
- *What non-geophysical control is required to constrain the interpretation of acquired geophysical data?*
- *Is the overall program cost-effective?*

It was not our intent to discuss these “questions” in detail in this paper. Rather, we have tried to raise and summarize pertinent related issues, in an effort to assist the engineer involved in designing geophysical surveys, and inform the engineer charged with decision responsibilities.

The reader is referred to Table 6 for a general summary of some applications of the ten geophysical methods considered in this paper. For more in-depth discussions of these geophysical methods, the reader is referred to Table 6. This bibliographical list is not exhaustive, nor is it comprised of the most theoretically rigorous papers. Rather, it is intended to serve as a resource for the highway engineer requiring information about methodology above and beyond that presented in this paper. References to well logging techniques are also included in Table 6.

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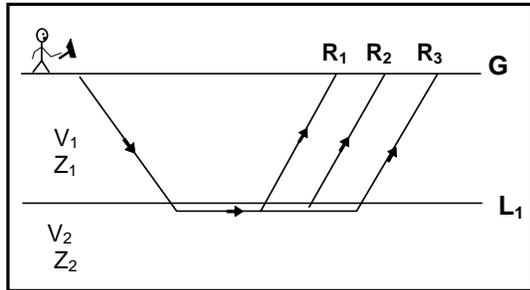
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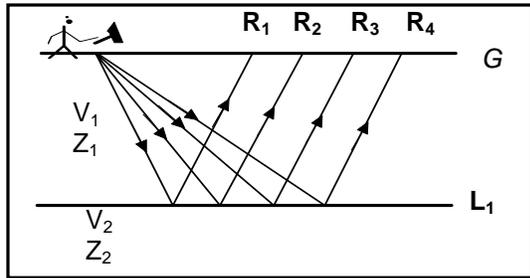
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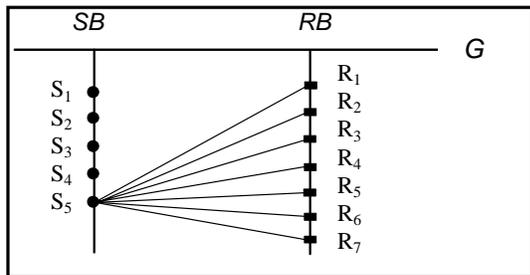
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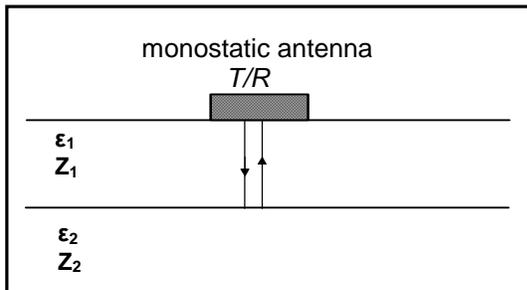
Seismic Refraction: Typically, acoustic pulses are generated at predetermined source locations (S) along the length of the refraction seismic profile. The travel times of acoustic energy that has been critically refracted at horizons of interest is recorded at predetermined receiver locations (R). The recorded travel time information is used to generate a velocity/structure profile of the shallow subsurface along the length of the refraction profile.



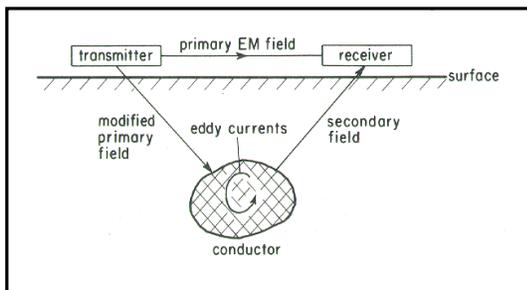
Seismic Reflection: Typically, acoustic pulses are generated at predetermined source locations (S) along the length of the reflection seismic profile. The travel times and amplitudes of reflected acoustic energy is recorded at predetermined receiver locations (R). The recorded travel time/amplitude information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



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.

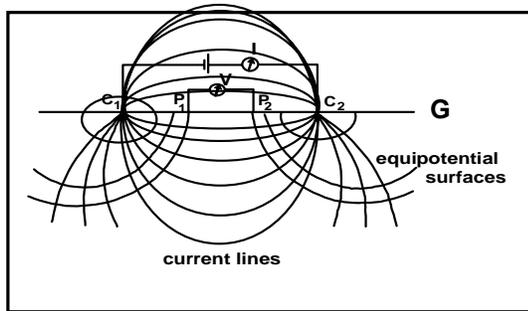


Ground-Penetrating Radar (GPR): Typically, pulsed electromagnetic energy is generated at predetermined station locations (S) along the length of the GPR profile. The travel times and amplitudes of reflected EM energy is recorded by a monostatic transmitter/receiver. The recorded travel time/amplitude information is used to generate a reflection GPR profile. These data can be transformed into a velocity/depth profile.

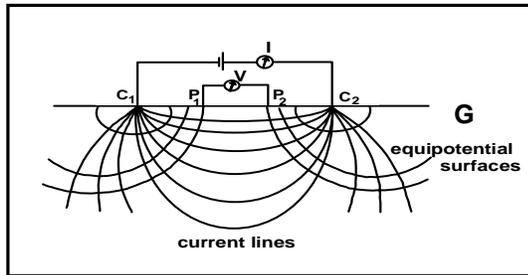


Electromagnetics (EM): Typically, a receiver is used to measure the earth's response to natural or artificial, primary EM energy. The secondary EM field (generated by causative body) can be expressed in terms of an in-phase component and an out-of-phase component. These data can be interpreted, and in some instances, used to generate a conductivity/depth model of the subsurface.

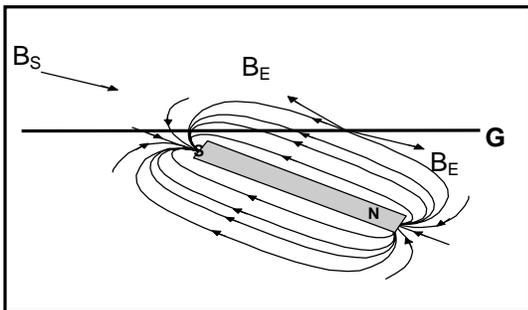
Figure 1: Generalized overviews of five commonly employed geophysical tools: seismic refraction, seismic reflection, seismic tomography, ground-penetrating radar (GPR) and electromagnetics (EM). The reader is referred to the selected bibliography (Table 6) for more in-depth summaries.



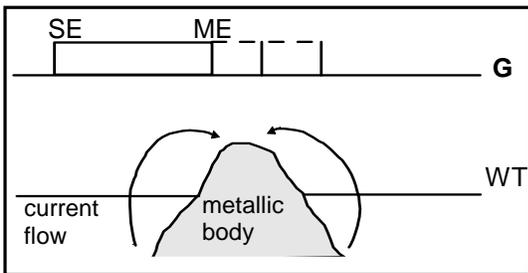
Electrical Resistivity: Typically, current (I) is induced between paired electrodes (C_1, C_2). The potential difference (ΔV) between paired voltmeter electrodes P_1 and P_2 is measured. Apparent resistivity (Δ_a) is then calculated (based on $I, \Delta V$, electrode spacings). If the current electrode spacing is expanded about a central location, a resistivity/depth sounding can be generated. If the array is expanded and moved along the surface, a resistivity/depth profile can be created.



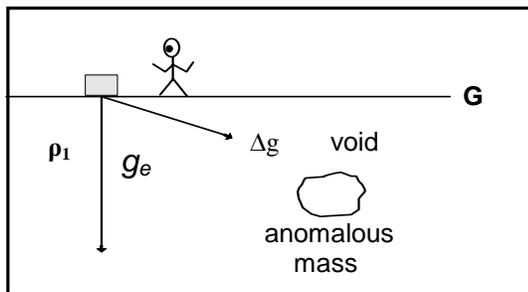
Induced Polarization (IP): Two types of IP data are generated: frequency domain and time domain. Frequency domain IP data are generated by comparing apparent resistivities as determined for variable frequency input currents. Time domain IP data are generated by measuring rate of decay in potential difference after current flow is terminated. IP measures capacitive properties of the ground. Often acquired simultaneously with resistivity data.



Magnetic: Magnetometers are designed to measure either the vector or scalar sum of the earth's magnetic field (B_E) and superposed secondary magnetic fields (B_S) created by causative, magnetically susceptible materials. Generally, the secondary field is isolated and interpreted with a view to elucidating the nature of the secondary causative body.

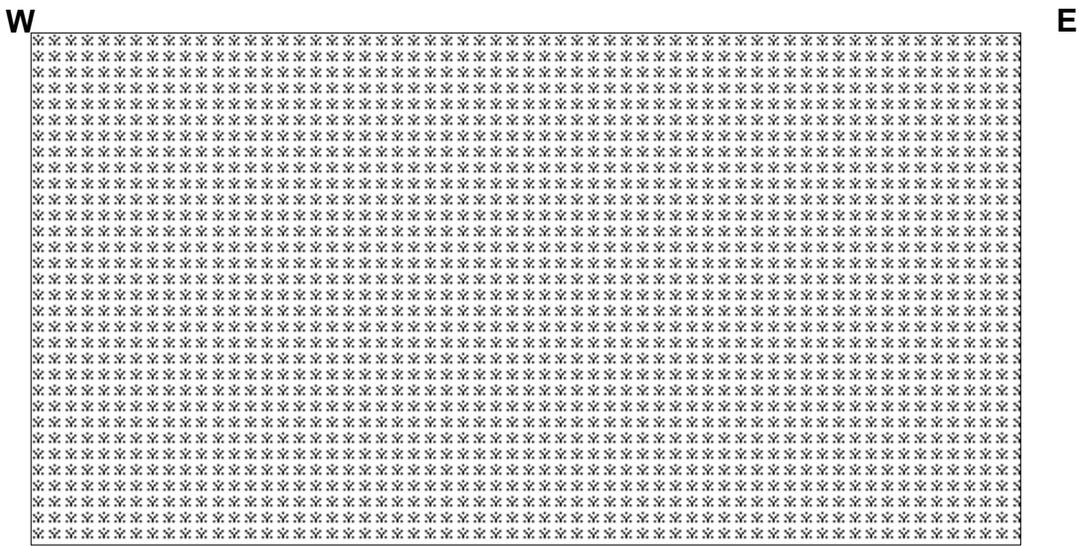


Self Potential (SP): Self (spontaneous) potential anomalies are generally caused by natural potential differences arising from either current flow associated with metallic bodies straddling the water table or groundwater flow in the subsurface. SP data are usually interpreted in qualitative manner.

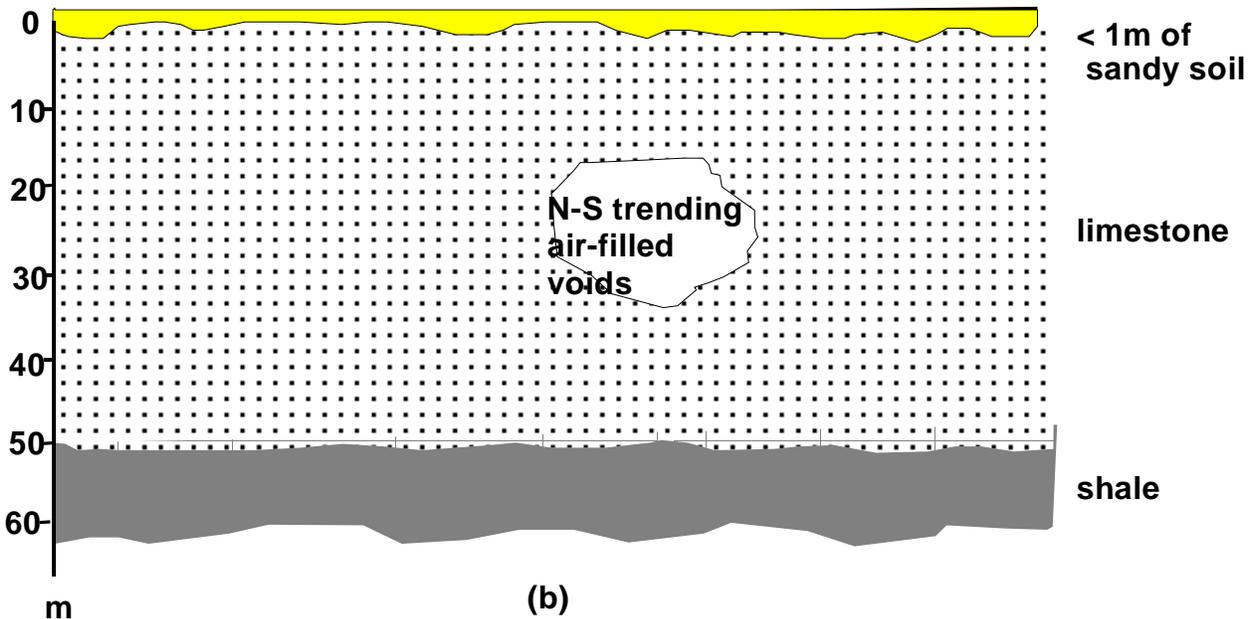


Gravity: Gravimeters are designed to measure the vertical component of the vector sum of the earth's background gravitational field (g_E) and superposed secondary fields (Δg) created by localized, causative bodies of anomalous density. Generally, the secondary field is isolated and interpreted with a view to elucidating the nature of the secondary causative body.

Figure 2: Generalized overview of five commonly employed geophysical tools: electrical resistivity, induced polarization (IP), magnetics, self potential (SP) and gravity. The reader is referred to the selected bibliography (Table 6) for more in-depth summaries.

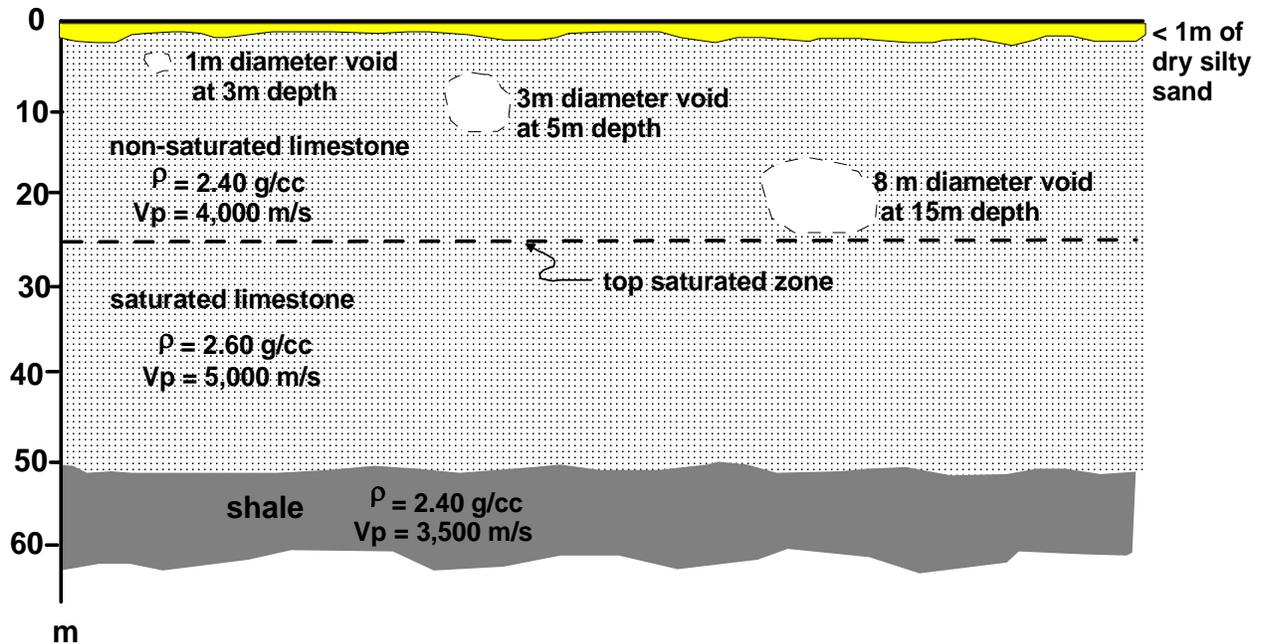


(a)



(b)

Figure 3: (a) Plan view of 40m x 100m study area; (b) The engineer is wanting to identify, locate and map north-south trending, near-horizontal, near-cylindrical solution voids that constitute potential threats with respect to foundation stability.



		AIR-FILLED VOID
	$\sim 2.4 \text{ g/cc}$	0
	$\sim 4000 \text{ m/s}$	$\sim 350 \text{ m/s}$
	10^8 m/s	$3 \times 10^8 \text{ m/s}$
	~ 9	~ 1
	10^{-8} mho	0
	$3 \times 10^7 \Omega\text{m}$	$\sim \text{infinite}$
	0.3	~ 0
	10 – 20 ms	~ 0

Figure 4: (a) Schematic west-east geologic profile through study area; (b) Physical property table for non-saturated limestone and void. The engineer wants to use non-invasive geophysical techniques to identify, locate and map north-south trending, near-horizontal, near-cylindrical solution voids that constitute potential threats with respect to foundation stability.

Method	Spatial Resolution and Target Definition
Shallow Seismic Refraction	Intermediate. Spatial resolution and target definition are functions mostly of source frequency, propagation velocities, velocity contrasts, layer thickness and homogeneity, receiver spacing, background noise levels and site conditions. The shallow refraction tool is generally used to map horizons across which there is a significant velocity contrast (e.g., bedrock, water table, clastics overlying carbonates, etc.). The refraction tool cannot be used to map low-velocity layers or thin high-velocity layers. Low-frequency sources provide greater depth penetration but lower resolution.
Shallow Seismic Reflection	Intermediate. Spatial resolution and target definition are functions mostly of source frequency, propagation velocities, velocity and density contrasts, layer thickness and homogeneity, receiver spacing, background noise levels and site conditions. The shallow reflection tool can be used to map both low- and high-velocity layers. It is generally assumed that layers with thickness less than ¼ wavelength (function of seismic pulse frequency and layer velocity) cannot be accurately resolved. (For example, a relatively high-frequency 100 Hz acoustic pulse traveling through 2000 m/s velocity shale has a ¼ wavelength of 5m.) Subsurface discontinuities (such as an air-filled void) can generate identifiable, interpretable diffractions. Low-frequency sources provide for greater depth penetration but lower resolution.
Seismic Tomography	High. Spatial resolution and target definition are functions mostly of source frequency, propagation velocities, velocity and density contrasts, layer/unit homogeneity, source/receiver spacings, multiplicity of travel paths, background noise levels and site conditions. Seismic tomography employs very high-frequency acoustic source pulses (in KHz range) compared to seismic refraction and reflection and therefore provides superior resolution and target definition.
GPR	High - Very High. Spatial resolution and target definition are functions mostly of dominant EM source pulse frequency, propagation velocities, dielectric contrasts, layer thickness and homogeneity, lateral trace sampling density, background noise levels and site conditions. GPR employs high-frequency (in MHz range) pulsed EM radiation traveling at velocities approaching the speed of light. High-frequency (1500 MHz) antenna can effectively image layers with a thickness on the order of centimeters. Low-frequency sources provide for greater depth penetration but lower vertical and lateral resolution.
EM	Low - Very High. Spatial resolution and target definition are functions mostly of primary source frequency, target depth and conductivity, conductivity contrast, and sophistication of tool and inversion software. For example, a 5 cm diameter, 2m long, conductive metal pipe at shallow depth (< 0.5 m) in dry soil can be readily located using a suitable high-frequency EM tool. However the metal pipe, placed at a depth of 3 m, might be “invisible” to the same EM tool. Lower frequencies provide for greater depth penetration but poorer resolution and target definition. Technique works best in conductive environments and when imaging conductive targets. Data acquired over a range of frequencies can be inverted and used to generate a conductivity profile of the subsurface. Some tools provide data suitable for qualitative analyses only.
Electrical Resistivity	Low – Intermediate. Spatial resolution and target definition are functions mostly of primary current frequency, current and voltmeter electrode spacing, target depth and resistivity, resistivity contrast, and sophistication of tool and inversion software. Technique works best in resistive environments and when imaging resistive targets. Lower frequency current and increased electrode spacing provide for greater depth penetration but poorer resolution and target definition. Apparent resistivity data acquired over a range of electrode spacings can be inverted and used to generate a conductivity profile of the subsurface. Some tools/electrode configurations provide data suitable for qualitative analyses only.
IP	Low – Intermediate. Spatial resolution and target definition are functions mostly of electrode spacing, target depth and resistivity, susceptibility of target to induced polarization, resistivity contrast, and magnitude of background noise. Tool works best in resistive environments and when imaging targets susceptible to induced polarization. Increased electrode spacing and lower current frequencies provide for greater depth penetration but poorer resolution and target definition. Data are often acquired during course of resistivity surveying. Some tools/electrode configurations provide data suitable for qualitative analyses only.
SP	Low – Intermediate. Spatial resolution and target definition are functions mostly of voltmeter electrode spacing, target size and depth, magnitude of naturally occurring potential differences, and magnitude of background noise. Data generally suitable for qualitative analyses only.
Magnetics	Low – High. Spatial resolution and target definition are functions mostly of sophistication of tool and mode of deployment, spatial sampling intervals, magnitude of background noise, target depth and magnetic susceptibility, magnetic susceptibility contrasts, and external modeling constraints. Data can be inverted but are often interpreted qualitatively.
Gravity	Low –Intermediate. Spatial resolution and target definition are functions mostly of sophistication of tool and inversion software, spatial sampling interval, magnitude of background noise, target depth, density contrasts and external modeling constraints. Data are often interpreted quantitatively.

Table 2: The spatial resolution and target definition provided by a geophysical technique is a function mostly of the characteristics of the specific tool employed, site conditions, and the physical properties of the target.

Method	Site Conditions (Strengths)	Site Conditions (Weaknesses)
Shallow Seismic Refraction	Technique can provide reliable velocity/depth profile of subsurface (major acoustic interfaces only). Ideal for mapping the top of the saturated zone (p-wave only) and bedrock, estimating soil/rock velocities, and determining rippability. Relatively inexpensive compared to seismic reflection and resistivity techniques.	Velocity/depth models are usually restricted to five layers or less. Low-velocity and thin, high-velocity layers cannot be imaged. Resolution is diminished in structurally complex and highly fractured areas. Voids cannot be directly imaged, but may be characterized by anomalous travel times. Presence of fluids is not detected by s-wave tool. Tool doesn't work well if site is covered by loose, dry, soils/sediment because of poor source and receiver coupling.
Shallow Seismic Reflection	Technique is ideal for imaging bedrock and sub-bedrock layers. Can provide relatively detailed velocity/depth control in structurally complex areas. Larger voids are characterized by prominent diffractions and can be imaged effectively.	Technique is labor and processing intensive, and therefore relatively expensive compared to seismic refraction, resistivity and EM techniques. Tool doesn't work well if site is covered by loose, dry soil because of poor source and receiver coupling.
Seismic Tomography	Technique is ideal for imaging lateral/vertical heterogeneities (including cavities), and for determining elastic moduli in-situ. Provides for much greater resolution and target definition than reflection or refraction techniques.	Technique is very expensive, due to the cost of drilling and casing boreholes. Tool doesn't work well if subsurface is comprised of thin (relative to borehole spacing) layers characterized by significant velocity variations.
GPR	Technique is relatively rapid and inexpensive (compared to reflection seismic). Can provide detailed structural control in complex areas. Suitable for analyzing concrete, pavement, quarry rock, locating voids, etc.	Tool doesn't work well in conductive (clayey) environment. Depth penetration is limited (typically <10 m) compared to reflection seismic and resistivity techniques. Determination of velocities (for inversion purposes) may require invasive ground-truthing.
EM	Technique works well in conductive environment and when imaging a conductive target. Acquisition is rapid and relatively inexpensive. Equipment doesn't need to be coupled to surface. Can be used to generate moderately detailed conductivity/depth model. Lithologies, salinities, clay content, etc. can often be inferred.	Technique doesn't work well in highly resistive environments. Resolution and target definition (re: generation of cross-sectional lithology/structural model) is usually less than that provided by seismic methods. Output models usually are restricted to five layers or less.
Electrical Resistivity	Technique works well in resistive environments. Can be used to generate moderately detailed resistivity/depth model in areas where seismic and EM techniques are not effective. Lithologies, salinities, etc., can be inferred. Suitable for mapping larger subsurface voids.	Tool doesn't work well in highly conductive environments. Resolution and target definition is usually less than that provided by seismic methods. Acquisition is expensive relative to EM technique. Electrodes need to be coupled to surface. Output models are usually restricted to five layers or less.
IP	Good indicator of clay content (or metallic mineralization). Complements resistivity data.	Low spatial resolution and target definition. Not suitable for detecting air-filled voids.
SP	Good indicator of fluid flow in subsurface (or metallic mineralization). Rapid and relatively inexpensive.	Provides low spatial resolution and target definition. Not suitable for detecting air-filled voids in this situation.
Magnetics	Good indicator of ferrimagnetic and ferromagnetic materials in the subsurface. Acquisition, processing and interpretation are relatively rapid and inexpensive. Equipment doesn't need to be coupled to surface.	Interpretation is usually qualitative rather than quantitative. Generally provides low spatial resolution and target definition. Not suitable for detecting air-filled voids.
Gravity	Good indicator of large air-filled voids in subsurface. Equipment doesn't need to be coupled to surface.	Acquisition and processing are relatively slow and expensive. Generally provides low to intermediate spatial resolution and target definition. Effects of irregular surface and subsurface topography, and subsurface heterogeneities can mask signature of target.

Table 3: The overall usefulness of a specific geophysical tool is partly a function of site conditions.

Ranking: Small Voids (scale 1-3)	Rationale (target: small voids at shallow depths, < 3m)	Ranking: Intermediate Voids (scale 1-3)	Rationale (target: intermediate sized voids at depths on the order of 5m)	Ranking: Large Voids (scale 1-3)	Rationale (target: large voids at depths on the order of 15m)
1 GPR	Technique provides high spatial resolution and target definition in resistive terrain. Voids should be identified on data acquired using intermediate frequency (about 400 MHz) antenna.	1 GPR	Technique provides relatively high spatial resolution and target definition at depth in resistive terrain. Voids should be identified on data acquired using low frequency (about 100 MHz) antenna.	1 Seismic Tomography	Technique provides relatively high spatial resolution and target definition. Target should be imaged, providing cased boreholes are appropriately spaced and of sufficient depth.
2 Resistivity	Target is probably too small and too shallow to be effectively imaged using conventional resistivity tool.	1 Resistivity	Resistivity tool should provide reasonable definition of intermediate-sized voids at intermediate depth in resistive terrain.	1 Resistivity	Resistivity tool should provide reasonable definition of large-sized voids at greater depth in resistive terrain.
3 EM	EM tool does not work well in resistive terrain and when imaging resistive target. Target is probably too small.	1 Seismic Tomography	Technique provides relatively high spatial resolution and target definition. Target should be imaged - providing cased boreholes are appropriately spaced and of sufficient depth.	1 Gravity	Anomalies should be large enough to delineate using gravity technique. Site conditions are very suitable for acquisition of gravity data.
3 Gravity	Anomalies generated by target are probably too small to be confidently identified and differentiated from background noise and the superposed signatures of larger voids. Would require very close spatial sampling.	2 Gravity	Anomalies generated by target are probably too small to be confidently identified and differentiated from background noise and the superposed signatures of larger voids. Would require very close spatial sampling.	2 Seismic Reflection	Prominent diffractions originating from larger voids should be prominently displayed and identified on processed seismic profiles – providing quality data can be acquired. Loose surficial material will create coupling problems.
3 Seismic Tomography	Anomalies generated by target are probably too small to be confidently identified. Would require very close spatial sampling.	3 EM	EM tool does not work well in resistive terrain and when imaging resistive target	2 GPR	It is unlikely that quality reflected GPR data could be acquired from depths on the order of 15m.
3 Seismic Reflection	Target is too small and too shallow. Events originating from the voids would be masked by first breaks.	3 Seismic Reflection	Target is probably too small and too shallow. Events originating from the voids would be masked by first breaks.	3 EM	EM tool does not work well in resistive terrain and when imaging resistive target.
3 Seismic Refraction	Lack of prominent sub-bedrock refractors. A refraction would not be generated from the limestone/shale interface.	3 Seismic Refraction	Lack of prominent sub-bedrock refractors. A refraction would not be generated from the limestone/shale interface.	3 Seismic Refraction	Lack of prominent sub-bedrock refractors. A refraction would not be generated from the limestone/shale interface.

Table 4: Generalized ranking of seven geophysical techniques considered for hypothetical void detection case study. Situations considered include: A) small voids at shallow depths; < 3m; B) intermediate sized voids at depths on the order of 5m; and C) large voids at depths on the order of 15m.

Ranking: Cost-Effectiveness	Summary of Cost Considerations	Effectiveness of Tool	Complementary Nature of Acquired Data
1 GPR	About 20 parallel GPR profiles (100m length; spaced at 2m intervals; intermediate frequency antenna) would be required to fully investigate the shallow subsurface (depth ≤ 3 m). Investigation of intermediate depths (≤ 5 m) would require a second grid of profiles (10 lines; 100m length; 4m intervals; low frequency antenna). Acquisition, processing and interpretation is relatively rapid.	GPR is probably the best tool for investigating shallow to intermediate depths. Tool is capable of providing required spatial resolution and target definition.	GPR profiles will also provide detailed information about depth to bedrock and internal character (fracturing, bedding, lithology variations, etc.).
2 Electrical Resistivity	Resistivity profiles are expensive to acquire. The tool is probably not cost-effective with respect to investigation of small- to intermediate-sized linear voids at shallow to intermediate depths. Larger linear voids centered at depths of about 15m would probably be adequately imaged by a grid of parallel profiles (perhaps 6 lines; 100m length (subsurface coverage); spaced at 8m intervals).	Resistivity is probably the best tool available as far as the investigation of large cavities (≥ 10 m diameter) at depths on the order of 15m is concerned.	Resistivity and simultaneously acquired IP data provide info about the subsurface (e.g., depth to ground water surface, conductivity of clay/soil, metallic mineralization, etc.).
3 Seismic Reflection	Reflection seismic profiles are expensive to acquire and process, and the tool is probably not cost-effective as far as the investigation of shallow to intermediate depths are concerned. The deeper subsurface would probably be adequately imaged by a grid of profiles (perhaps 6 full fold lines; 100m in length; spaced at 8m intervals).	Large cavities can be characterized by prominent diffractions on reflection seismic data. Data quality might be compromised by cavities at shallow depths. Loose, surficial soil will make acquisition of quality data difficult.	Reflection seismic data can provide info about subsurface structure below zone of primary interest (e.g., ground water surface, and interfaces at depths in excess of hundred meters).
4 Seismic Tomography	Seismic tomography data are expensive to acquire and process. The tool functions much better below the water table than above. The technique is probably not cost-effective as far as the mapping of small- to intermediate-sized voids is concerned. Larger voids could be imaged effectively by a grid of boreholes (perhaps 8, with depths on the order of 25m). Costs would be very high compared to resistivity and reflection seismic profiling, and refractions from the water table could present interpretational problems.	If a grid of closely spaced boreholes was employed, excellent results could be expected. However, this approach could be prohibitively expensive, unless the boreholes were also to be used for injecting grout.	Seismic tomography data (p-wave and s-wave) will provide information about the elastic moduli of bedrock at various depths.
5 Gravity	The shallow and intermediate targets are probably too small to resolve/define. The larger cavities may be too small as well. Gravity data are expensive to acquire and process, and the tool is probably not cost-effective as far as the investigation site is concerned.	Gravity data are the most ambiguous with respect to resolution and target definition.	The gravity tool will probably provide little additional information about the nature of the study site.

Table 5: Generalized ranking of five geophysical techniques considered potentially suitable for hypothetical void detection case study. Cost-effectiveness and overall usefulness of interpreted data are considered.

Application	Seismic Refraction	Seismic Reflection	Seismic Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
Mapping lithology (<10m depth)	M	X		M	x	x				
Mapping lithology (>10m depth)	x	M	X		x	x				
Estimating clay/mineral content					M	x	x			
Locating shallow sand and gravel deposits				M	M					
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
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 (<10m depth)	M			M	x	x				x
Mapping bedrock topography (>10m depth)	x	M			x	x				x
Mapping sub-bedrock structure	x	M		x	x	x				
Delineating steeply dipping geologic contacts (<10m depth)	M			M	M	M				
Delineating steeply dipping geologic contacts (>10m depth)	x	M	x		x	x			x	
Mapping fracture orientation (near-surface bedrock)	M			M						
Mapping fracture orientation	M		M							
Identifying regions of potential weakness (e.g., shear zones & faults; <10m depth)	M		x	M	x	x			x	
Identifying regions of potential weakness (e.g., shear zones & faults; >10m 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, (<10m depth)	x	x	x	M	x	M				x
Mapping air-filled cavities, tunnels, (>10m depth)	x	M	M		x	x				x
Mapping water-filled cavities, tunnels	X (P-wave)	M (P-wave)	M	x						
Mapping clay-filled cavities, tunnels	x	M	M		x	x				
Estimating rippability	M		x							
Foundation integrity studies	M		x	M						
Dam-site integrity studies	M	M	M	M	x	x		M		
Landslide site evaluation	M		M	x	M	M				
Locating buried well casings (metal)				M	M				M	

Table 5: Potential applications of various geophysical methods in engineering and environmental studies (M-major application; x-minor application)

Application	Seismic Refraction	Seismic Reflection	Seismic Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
Locating buried drums, pipelines and other ferromagnetic objects			M	M				M		
Locating buried non-magnetic utilities			M							
Locating buried non-magnetic utilities				M						
Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M	
Mapping archeological sites (non magnetic - excavations, burials, etc)				M						
Concrete integrity studies and inspection				M						
Detection of delamination and incipient concrete spallage on bridge decks				M						
Locating rebar in concrete				M	M				M	
Detection of corrosion of rebar embedded in concrete				M						
Evaluation of presence, pattern and density of rebar embedded in concrete destined for demolition				M	x				x	
Pavement integrity studies				M						
Detection of voids beneath pavement				M						
Detection and delimitation of zones of relatively thin sub-grade or base course material				M						
Detection and monitoring of areas of insufficiently dense sub-base				M						
Large-area differentiation and monitoring of insufficient thickness of pavement as a quality assurance measure during construction				M						
Large-area differentiation and monitoring of insufficient pavement thickness as post-construction monitoring technique				M						
Detection of bodies of sub-grade 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	
Determining in-situ rock properties (bulk, shear and Young's moduli)	M		M							
Estimating in situ rock properties (saturation, porosity, permeability)					M	M				
Determining in situ rock densities										M
Determining in situ rock properties (dielectric constant)				x						
Mapping abandoned, in-filled open-pit mines and quarries	M	M		x	x	x			x	x
Mapping abandoned underground mines		M	x			x				
Detecting abandoned Mine shafts		x	x	M	M	x			x	

Table 5 (continued): Potential applications of various geophysical methods in engineering and environmental studies (M-major application; x-minor application).

Geophysical Technique	Suggested Bibliography
Seismic Refraction	Evans (1997), Griffiths and King (1981), Keary and Brooks (1994), Lankston (1990), McCann <i>et al.</i> (1997), Sheriff (1991), Sheriff and Geldart (1995), Telford <i>et al.</i> (1990)
Seismic Reflection	Clay (1990), Evans (1997), Hinds <i>et al.</i> (1996), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Griffiths and King (1981), Sheriff and Geldart (1995), Telford <i>et al.</i> (1990), Tychsen and Nielson (1990)
Seismic Tomography	Clay (1990), Hinds <i>et al.</i> (1996), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Sheriff and Geldart (1995), Telford <i>et al.</i> (1990)
GPR	Daniels (1996), McCann <i>et al.</i> (1997), Sheriff (1991)
EM	Keary and Brooks (1994), McNeill (1990), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990)
Resistivity	Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990) Ward (1990)
IP	Fink <i>et al.</i> (1990), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990), Ward (1990)
SP	Corwin (1990), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990)
Magnetics	Blakely (1996), Hinze (1990), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990)
Gravity	Blakely (1996), Hinze (1990), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990)
Well Logging	Daniels and Keys (1990), Howard (1990), Keary and Brooks (1994), McCann <i>et al.</i> (1997), Sheriff (1991), Telford <i>et al.</i> (1990)

Table 6: Suggested bibliography. This reference list is by no means exhaustive. The engineer is encouraged to work with a knowledgeable geophysicist.