

EVALUATING THE UTILITY OF GEOPHYSICAL SURVEYING METHODS

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ABSTRACT

Engineering geophysical techniques measure specific physical parameters and are routinely applied to highway-related problems. The engineer responsible for site investigation should ensure that geophysical technique(s) employed provide cost-effective information about physical properties of interest at the required levels of spatial resolution and target definition.

As an aid to the highway engineer, we present tabularized information about some commonly employed geophysical methods, and a generalized approach for evaluating their utility. Our discussions are intended to be informative - not exhaustive. For more rigorous treatments of the geophysical techniques the reader is referred to the selected bibliography. The engineer engaged in 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), self potential (SP), magnetics, and gravity.]

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 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 resolution?

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 data are required to constrain the interpretation of the acquired geophysical control?

Is the overall program cost-effective?

Herein we present tabularized information about some commonly employed geophysical methods, and a generalized approach for evaluating their utility. To illustrate the ideas discussed, we consider a hypothetical site characterization situation, and address the "questions" [posed above] sequentially.

In our hypothetical situation, a transportation engineer is wanting to detect air-filled voids (radial cavities with extended near-horizontal, linear axis) in otherwise uniform limestone at a bridge site (100 m x 30 m). There are no physical constraints with respect to site accessibility. The limestone is overlain by a thin (<1 m thick) veneer of silty sand, and underlain by lower-velocity shale (at a depth of 50 m). The geophysical technique(s) employed need to be capable of detecting small cavities (0.3 m diameter) at shallow depths less than 3 m, intermediate-sized cavities (2 m diameter) at depths on the order of 7.5 m, and larger cavities (7.5 m diameter) at depths on the order of 20 m. Cavities at depths greater than 20 m do not constitute a risk.

**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 shallow, air-filled cavities in limestone would be characterized by spatial variations in density, acoustic velocity, EM velocity, dielectric constant, and electrical conductivity and resistivity. 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 only), our engineer would rank the various geophysical techniques in a manner consistent with Table 3. 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 20 m.

**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 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 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 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 judgement.

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 data are required to constrain the interpretation of the acquired geophysical control?

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 5 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 methodology information above and beyond that presented in this paper. References to well logging techniques are also included in Table 6.

REFERENCES

- Blakely, R. J., 1996, Potential theory in gravity and magnetic applications, Cambridge University Press, 441 p.
- Clay, C., S., 1990, Elementary exploration seismology: Prentice Hall, 346 p.
- Corwin, R. F., 1990, the self-potential method for environmental and engineering applications, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Daniels, D., 1996, Surface-penetrating radar: IEEE, 320 p.
- Daniels, J. J., and Keys, W. S., 1990, Geophysical well logging for hazardous waste sites, *in* Ward, S.H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Evans, B. J. 1997, A handbook for seismic data acquisition in exploration: Society of Exploration Geophysicists, 305 p.
- Fink, J. B., Sternberg, B. K., McAlister, E. O., Wieduwilt, W. G., and Ward, S. H., editors, 1990, Induced polarization, applications and case histories: Society of Exploration Geophysicists, 414 p.
- Griffiths, D.H., and King, R.F., 1981, Applied Geophysics for geologist and engineers: Pergamon Press, 230p.
- Hinds, R. C., Anderson, N. L., and Kuzmiski, R., 1996, VSP interpretative processing: Theory and practice: Society of Exploration Geophysicists, 205p.
- Hinze, W. J., 1990, The role of gravity and magnetic methods in engineering and environmental studies, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Howard, K. W. F., 1990, Geophysical well logging for detection and characterization of fractures in hard rocks, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Keary, P. and Brooks, M., 1991, An introduction to geophysical exploration: Blackwell scientific Publications, 254 p.
- Lankston, R. W., 1990, High-resolution refraction seismic data acquisition and interpretation, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- McNeill, J. D., 1990, Use of electromagnetic methods for groundwater studies, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- McCann, D. M., Eddleston, M., Fenning, P. J., and Reeves, G. M., editors, 1997, Modern geophysics in engineering geology: The Geological Society of London, 441 p.
- Nabighian, M. N., editor, 1988, Electromagnetic methods in applied geophysics, volume 1, theory: Society of Exploration Geophysicists, 513 p.
- Sheriff, R. E., 1991, Encyclopedic dictionary of exploration geophysics, third edition: Society of Exploration Geophysicists, 376 p.
- Sheriff, R. E., and Geldart, L. P., 1995, Exploration Seismology, second edition: Cambridge University Press, 592 p.
- Steeple D. W., and Miller, R. D., 1990, Seismic reflection methods applied to engineering, environmental and groundwater problems, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, vol. 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Telford, W. M., Geldart, L. P., and Sheriff, R. E., 1990, Applied geophysics, second edition: Cambridge University Press, 770 p.
- Tychsen J., and Nielson, T., 1990, Seismic reflection used in the sea environment, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Ward, S. H., 1990, Resistivity and induced polarization methods, *in* Ward, S. H., editor, Geotechnical and environmental geophysics, volume 1: review and tutorial: Society of Exploration Geophysicists, 389 p.
- Yilmaz, O., 1988, Seismic data processing: Society of Exploration Geophysicists, 526 p.

Geophysical Method	Measured Parameter	Physical Property	Physical Property Model (Highway Application)	Typical Site Model
Shallow Seismic Refraction	Travel times of refracted seismic energy (p-wave or s-wave)	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Acoustic velocity/depth model	Geologic profile, with ground water surface
Shallow Seismic Reflection	Travel times/amplitudes of reflected seismic energy (p-wave/s-wave)	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Acoustic velocity/depth model	Geologic profile, with ground water surface
Seismic Tomography	Travel times/amplitudes of seismic energy (p-wave or s-wave)	Density and acoustic velocity (acoustic velocity is a function of bulk elastic moduli and density)	Model depicting spatial variations in acoustic velocity	Geologic profile
GPR (ground-penetrating radar)	Travel times and amplitudes of reflected electromagnetic energy	Dielectric constant, magnetic permeability, conductivity and EM velocity	EM velocity/depth model	Geologic profile Internal material profile
Electromagnetics (EM)	Response to electromagnetic energy	Electrical conductivity and inductance	Conductivity/depth model	Geologic/hydrologic profile
Electrical Resistivity	Earth resistance	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 mineralization
Self Potential (SP)	Electrical potentials	Electrical conductivity	Model depicting spatial variations in natural electric potential of the subsurface	Hydrologic model (seepage beneath dam, through fractured bedrock, etc.)
Magnetics	Spatial variation 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: Ten geophysical surveying methods commonly employed for highway site investigations. Each of these techniques measures different physical properties of the site being investigated. The typical physical property model is developed from single method data alone. The site model is generated fusing multiple geophysical data sets and available non-geophysical control.

Method	Spatial Resolution and Target Definition	Site Conditions (Strengths)	Site Conditions (Weaknesses)
Shallow Seismic Refraction	<i>Spatial resolution:</i> intermediate (function of frequency, velocity, receiver spacing). <i>Target definition:</i> intermediate (depth/velocity estimates generally accurate to within $\pm 10\%$).	Can provide reliable shallow velocity/depth control. Often ideal for mapping top saturated zone (p-wave only) and top bedrock, and determining rippability. Relatively inexpensive compared to seismic reflection and resistivity.	Velocity/depth models usually restricted to five layers or less. Low velocity and thin, high velocity layers cannot be imaged. Resolution diminished in structurally complex and highly fractured areas. Voids cannot be directly imaged - may be characterized by anomalous travel times. Water not detected by S-waves
Shallow Seismic Reflection	<i>Spatial resolution:</i> intermediate (function of frequency, velocity and receiver spacing). <i>Target definition:</i> intermediate (depth/velocity estimates generally accurate to within $\pm 10\%$).	Often ideal for imaging bedrock and sub-bedrock layers. Can provide relatively detailed velocity/depth control in structurally complex areas. Larger voids can be characterized by prominent diffractions, and effectively imaged.	Relatively expensive compared to seismic refraction, resistivity and EM. Doesn't work well if site is covered by loose, dry soils/sediment (results in poor receiver coupling).
Seismic Tomography	Intermediate to high (function of frequency, velocity, borehole spacing, and source/ receiver intervals).	Often ideal for imaging lateral/vertical heterogeneities, including cavities. Useful for determining elastic moduli in-situ.	Expensive, due to the cost of drilling boreholes. Technique doesn't work well if subsurface is comprised of thin (relative to borehole spacing) layers with significant velocity variations.
GPR (ground-penetrating radar)	Very high. Resolution/target definition is function of frequency and velocity. Lower frequency sources provide for greater depth penetration but lower resolution.	Rapid and relatively inexpensive. Can provide detailed structural control in complex areas. Suitable for analyzing concrete, pavement, quarry rock, locating voids, etc.	Doesn't work well in conductive (clayey) environment. Limited depth penetration, compared to reflection seismic and resistivity techniques.
Electromagnetics (EM)	Low to intermediate. Lower frequencies provide for greater depth penetration but poorer resolution and definition.	Works well in conductive environment. Rapid and relatively inexpensive. Equipment doesn't need to be coupled to surface. Provides moderately detailed conductivity/depth model. Lithologies, salinities can be inferred.	Doesn't work well in highly resistive environment. Resolution/definition is usually less than that provided by seismic methods. Output models usually restricted to five layers or less.
Resistivity	Low to intermediate. Lower frequencies and increased electrode spacing provide for greater depth penetration but poorer resolution and target definition.	Works well in resistive environment. Can provide moderately detailed resistivity/depth model in areas where seismic and EM techniques are not effective. Lithologies, salinities can be inferred. Suitable for mapping larger voids.	Doesn't work well in highly conductive environment. Resolution/definition is usually less than that provided by seismic methods. More expensive than EM. Electrodes need to be coupled to surface. Output models usually restricted to five layers or less.
Induced Polarization (IP)	Low. Lower frequencies and increased electrode spacing provide for greater depth penetration, but poorer resolution and target definition.	Good indicator of clay content (or metallic mineralization). Complements resistivity data.	Low spatial resolution and target definition. Not suitable for detecting air-filled voids.
Self Polarization (SP)	Low spatial resolution and target definition.	Good indicator of fluid flow in subsurface (or mineralization). Rapid and relatively inexpensive.	Low spatial resolution and target definition.
Magnetics	Low spatial resolution and target definition.	Good indicator of ferromagnetic materials in the subsurface. Rapid and inexpensive.	Interpretation is qualitative rather than quantitative. Generally low resolution/target definition.
Gravity	Low to intermediate spatial resolution and target definition.	Good indicator of substantive voids in subsurface. Equipment doesn't need to be coupled to surface.	Relatively expensive. Generally low resolution/definition. Background noise may mask data.

Table 2: Each geophysical tool provides for different spatial resolution and target definition. The overall utility of a particular technique is a function of site conditions.

Ranking: Small voids (scale 1-3)	A. Rational (focus on delineating small voids at shallow depths; < 3 m)	Ranking: Interm. voids (scale 1-3)	B. Rational (focus on delineating intermediate sized voids at depths on the order of 7.5 m)	Ranking: Large voids (scale 1-3)	C. Rational (focus on delineating large voids at depths on the order of 20 m)
1 GPR	High spatial resolution, high target definition in resistive material.	1 GPR	High resolution, reasonable definition at depth in resistive material.	1 Seismic tomography	Target should be imaged.
2 Resistivity	Target is probably too small and too shallow.	1 Resistivity	Reasonable definition at depth in resistive material.	1 Resistivity	Reasonable definition at depth in resistive material.
3 EM	Highly resistive terrain. Target is too small.	1 Seismic tomography	Target should be imaged.	1 Seismic reflection	Prominent diffractions could be imaged.
3 Gravity	Target is too small.	2 Gravity	Target may be too small to resolve.	1 Gravity	Anomalies may be large enough to delineate.
3 Seismic tomography	Target is probably too small and too shallow.	3 EM	Highly resistive terrain.	2 GPR	Problems with limited depth penetration.
3 Seismic reflection	Target is too small and too shallow.	3 Seismic reflection	Target is probably too small and too shallow.	3 EM	Highly resistive terrain.
3 Seismic refraction	Lack of prominent sub-bedrock refractors.	3 Seismic refraction	Lack of prominent sub- bedrock refractors.	3 Seismic refraction	Lack of prominent sub-bedrock refractors.

Table 3: Ranking of seven techniques considered for hypothetical void detection case study. Situations considered include: A) small voids at shallow depths; < 3 m; B) intermediate sized voids at depths on the order of 7.5 m; and C) large voids at depths on the order of 20 m. Cavities are assumed to have lengths that greatly exceed their diameters.

Ranking: Cost- Effectiveness	Cost	Effectiveness	Complementary nature of data
1 GPR	About 20 parallel GPR profiles (100 m length; spaced at 2 m intervals) would be required to fully investigate the shallow subsurface. Investigation of intermediate depths would require a second grid of profiles (10 lines; 100 m length; 3 m intervals; lower frequency antenna). Data acquisition is relatively rapid.	GPR is probably the best tool for investigating shallow to intermediate depths. Will provide required spatial resolution and target definition.	GPR profiles will provide detailed information about depth to bedrock and internal character (fracturing, bedding, lithology variations, etc.).
2 Resistivity	Resistivity profiles are expensive to acquire. The tool is probably not cost-effective with respect to the investigation at shallow depths. The deeper subsurface would probably be adequately imaged by a grid of profiles (perhaps 6 lines; 100 m length (subsurface coverage); spaced at 5 m intervals).	Resistivity is probably the best tool available as far as the investigation of large cavities at intermediate to greater depths 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; 100 m in length; spaced at 5 m intervals).	Large cavities can be characterized by prominent diffractions on quality reflection seismic data. Data quality might be compromised by cavities at shallow depths.	Reflection seismic data can provide info about subsurface structure below zone of primary interest (ground water surface, and depths to layers at depths in excess of a couple hundred meters or more).
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 smaller voids is concerned. Larger voids could be effectively imaged by a grid of boreholes (perhaps 8; depths on the order of 40 m). Costs would be very high compared to resistivity and reflection seismic profiling.	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 used for injecting grout.	Seismic tomography data (p-wave and s-wave) will provide information about the elastic moduli of bedrock at various depths. This information could be useful if excavations are planned, or if the site is in a seismically-active area.
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 of is concerned.	Gravity data are the most ambiguous of the five techniques (re: spatial resolution and target definition).	The gravity tool probably would provide relatively little additional information about the character of the study site.

Table 4: Ranking of five techniques considered for hypothetical void detection case study. Cost and overall effectiveness are considered.

Application	Seismic refract.	Seismic reflect.	Seismic tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
Mapping lithology (<10 m depth)	M	x		M	x	x				
Mapping lithology (>10 m 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 (<10 m depth)	M			M	x	x				x
Mapping bedrock topography (>10 m depth)	x	M			x	x				x
Mapping sub-bedrock structure	x	M		x	x	x				
Delineating steeply dipping geologic contacts (<10 m depth)	M			M	M	M				
Delineating steeply dipping geologic contacts (>10 m 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 and faults; <10 m depth)	M		x	M	x	x			x	
Identifying regions of potential weakness (e.g., shear zones and faults; >10 m 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 (<10 m depth)	x	x	x	M	x	M				x
Mapping air-filled cavities, tunnels (>10 m 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				

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

Application	Seismic refract.	Seismic reflect.	Seismic tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
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	
Locating buried drums, pipelines and other ferromagnetic objects				M	M				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 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						

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

Application	Seismic refract.	Seismic reflect.	Seismic tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.
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, infilled 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; x-minor)

Geophysical Technique	Suggested References
Seismic refraction	Clay (1990), Evans (1997), Griffiths and King (1981), Keary and Brooks (1991), Lankston (1990), McCann et al. (1997), Sheriff (1991), Sheriff and Geldart (1995), Telford et al. (1990), Griffiths, D.H., and King, R.F., 1981,
Seismic reflection	Clay (1990), Evans (1997), Hinds et al. (1996), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Griffiths and King (1981), Sheriff and Geldart (1995), Telford et al. (1990), Tychsen and Nielson (1990), Yilmaz (1988)
Seismic tomography	Clay (1990), Hinds et al. (1996), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Sheriff and Geldart (1995), Telford et al. (1990)
GPR	Daniels (1996), McCann et al. (1997), Sheriff (1991)
EM	Griffiths and King (1981), Keary and Brooks (1991), McNeill (1990), McCann et al. (1997), Nabighian (1988), Sheriff (1991), Telford et al. (1990)
Resistivity	Griffiths and King (1981), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Telford et al. (1990) Ward (1990)
IP	Griffiths and King (1981), Fink et al. (1990), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Telford et al. (1990), Ward (1990)
SP	Corwin (1990), Keary and Brooks (1991), Griffiths and King (1981), McCann et al. (1997), Sheriff (1991), Telford et al. (1990)
Magnetics	Blakely (1996), Hinze (1990), Griffiths and King (1981), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Telford et al. (1990)
Gravity	Blakely (1996), Hinze (1990), Griffiths and King (1981), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Telford et al. (1990)
Well logging	Daniels and Keys (1990), Howard (1990), Keary and Brooks (1991), McCann et al. (1997), Sheriff (1991), Telford et al. (1990)

Table 6: Selected Bibliography