TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle

   Feasibility Study on Geophysical Methods to Estimate Geotechnical Properties in Louisiana

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5. Report No.

   FHWA/LA.22/667

6. Report Date

   October 2022

7. Performing Organization Code

   LTRC Project Number: 20-4GT
   SIO Number: DOTLT1000389

8. Type of Report and Period Covered Final Report

   12/2020 – 08/2022

9. No. of Pages

   75

10. Supplementary Notes

    Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

11. Distribution Statement

    Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

12. Key Words

    Geophysical; site investigation; electrical resistivity; refractometer; reflectometer; induced polarization (IP)

13. Abstract

Subsurface investigations currently rely on conventional soil borings with the aid of cone penetrometer test (CPT) soundings. However, these geotechnical explorations can be expensive and information is not provided between boreholes. Geophysical methods can aid in providing some information between the boreholes at a lower cost for the Louisiana Department of Transportation and Development (DOTD). These cost-effective geophysical surveys include other advantages, such as site accessibility, portability, operator safety, shorter project delivery times, and reduced construction delays.

This study evaluated a series of available geophysical methods. A survey determined the preferred applications that Louisiana is interested in incorporating. Researchers further refined this list to include test methods most suitable for implementation within the Department.

Analysis included applicability, advantages/disadvantages, and current test methods utilized in-house at other state DOTs. Researchers recommend more detailed field research directed toward implementing the following geophysical methods: electrical resistivity, seismic refraction, and cross-hole tomography.

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LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

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Feasibility Study on Geophysical Methods to Estimate Geotechnical Properties in Louisiana

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LTRC Project No. 20-4GT
SIO No. DOTLT1000389

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

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October 2022

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Subsurface investigations currently rely on conventional soil borings with the aid of cone penetrometer test (CPT) soundings. However, these geotechnical explorations can be expensive and information is not provided between boreholes. Geophysical methods can aid in providing some information between the boreholes at a lower cost for the Louisiana Department of Transportation and Development (DOTD). These cost-effective geophysical surveys include other advantages, such as site accessibility, portability, operator safety, shorter project delivery times, and reduced construction delays.

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Acknowledgments

The research was completed with the assistance of DOTD project engineers, LSU personnel, lab technicians, and others. The authors would like to thank all those who helped make this research possible.

DOTD and LTRC personnel: Murad Abu-Farsakh, Jesse Rauser, James Chatagnier, Brian Heath, Barry Moore, Matthew Jones, Phil Graves, Francisco Gudiel, and Max Soileau.

Other out-of-state personnel that were insightful and helpful with this project include: Derrick Dasenbrock (FHWA), Phil Sirles (Collier Geophysics), and Andrew Jalbrzikowski (ODOT).

Implementation Statement

The information, insight, and techniques included in this report will provide the Louisiana Department of Transportation (DOTD) methods and strategies to improve on geotechnical explorations for site investigations. Adding geophysical methods to current geotechnical exploration practices can improve DOTD's efforts and knowledge in subsoil investigations.

A supplement for these current practices is utilizing geophysical tools that measure specific parameters and provide physical properties of the Earth. This synthesis provides a better understanding of how geotechnical tools are used for site investigation. A series of surveys and meetings helped determine which best practices and tools are most suitable for the state of Louisiana and provide the department cost-effective and efficient testing methods.

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Introduction

Current geotechnical exploration practices in Louisiana rely on conventional soil borings with the aid of cone penetrometer test (CPT) soundings. The characteristics of these technologies are site specific by providing discrete profile information, missing any information between soil borings, CPTs, or any other discrete tests. Interpretations of conditions between borehole/cone locations are sometimes made by connecting similar soil layers with fence diagrams, but these approximations are an inexact science. Spatial variation exists and has been studied in relation to the proximity of adjacent boreholes. Subsurface investigations can be expensive, especially when samples are collected for laboratory testing. Increasing the number of subsurface boreholes improves and verifies the subsurface conditions, but doing so increases costs. Utilizing soil borings and CPTs do not provide information between each of holes tested. However, geophysical methods can aid in characterizing this missing information at a lower cost.

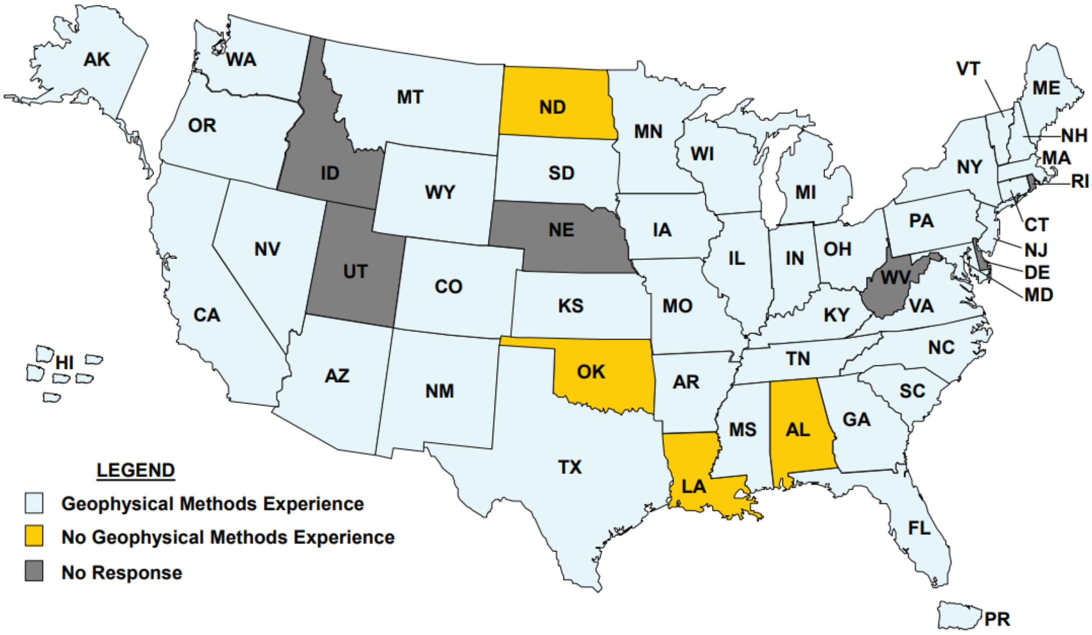
Geotechnical geophysical surveys are an effective and rapid means of obtaining subsurface information, and they can be used to select and reduce the amount of borehole locations [1]. Geophysical methods can provide cross-section information between typical bore/CPT holes and provide a broader area of continuous information for soil layers. Other advantages of geophysical technology include site accessibility, portability, nondestructive, operator safety, and others. This can allow geophysical surveys to be performed at locations, such as heavily urban areas, under bridges, extreme slopes, and marshy terrain [2].

The I-10 twin span project is an example of how the Department of Transportation and Development (DOTD) could save both time and construction costs by utilizing geophysical methods. The soil stratigraphy varied within the same pile group during construction, which caused significant cut-offs on many piles. This also added necessary, additional borings, which significantly increased the total cost of the project and increased construction times. These cost and time delays could have been avoided by utilizing geophysical testing, during preliminary geotechnical explorations. This construction project led to the initiation of this research project to help DOTD increase knowledge and understanding of advanced geophysical methods and learn more about geophysical testing applicable to Louisiana soils and conditions. Research is needed regarding the applicability of geophysical methods in Louisiana soils, costs of the equipment, and requirements regarding specialized knowledge to interpret the data.

Literature Review

Louisiana's concerns with geophysical methods included uncertainties with available methods and applicability on Louisiana soils. According to a National Cooperative Highway Research Program (NCHRP) (Synthesis 547), Louisiana agencies are one of the few states that responded to not having any geophysical method experience. Figure 1 shows agencies with or without these experiences (*not shown on the map*: Central Federal Lands Highway and Western Federal Lands Highway divisions indicated experience with geophysical methods, while District of Columbia indicated no experience) [3].

Figure 1. Map of agencies' responses dealing with geophysical experience [3]



The concerns to utilize these geophysical methods include site accessibility in heavily urban areas (New Orleans and Baton Rouge), soil investigation under current bridges or other superstructures, and marshy terrains/wetlands (such as the Atchafalaya Basin or Coastal Louisiana). There is also a need to provide pre-construction testing and analysis in hopes to avoid possible setbacks like the need for last-minute and time consuming soil borings (and other tests required) to complete project delivery. In some cases, these advanced geotechnical methods could save the department time and money.

Disadvantages of conventional site exploration techniques utilizing soil borings, CPTs, or other instrumentation include long field times for data collection, laboratory time needed to acquire sample information, and any further analysis required by the engineer [4]. Other disadvantages include site access with large equipment, permits required to use such equipment, cost of utilizing special equipment, and the discreteness of the testing performed. The Federal Highway Administration (FHWA) indicates that typical testing for geotechnical investigation covers less than 0.01% of the total soil volume for projects [4]. Utilizing geophysical methods can save time and money, expand insight into subsurface conditions, and provide assurance and safety to the design engineers and added public safety.

Geophysical Methods

1.) **Surface methods** are performed without the need for penetration into the subsurface through use of a borehole [5]. Surface geophysical methods are utilized for shallow evaluation of soil properties and quality control/quality assurance (QA/QC) of compacted embankment and pavement layers, with the help of receivers that are placed on the Earth's surface for measurement. Examples include multichannel analysis of surface waves (MASW), seismic reflection, seismic refraction, and ground penetrating radar (GPR). Seismic waves can directly relate the velocity of the waves to the small-strain modulus of the material and are generally used for analysis of earthquakes [3]. Whereas, GPR utilizes electrical waves that reflect through and back to the surface to detect distinct subsurface features, such as voids, bedrock depth, or the water table [3].

2.) **Borehole methods** investigate the subsurface through the means of a borehole or cone penetration test (CPT), and they are used for deep investigation to help define soil layering between soil borings. Examples include seismic analysis, seismic cone, cross-hole tomography, down-hole tomography, electrical resistivity methods, and magnet methods. Some surface methods, seismic and electrical waves, are also utilized borehole methods. The electrical resistivity method utilizes electrodes variably spaced in the borehole to determine lithology of the surrounding soil and/or rock [3]. This NCHRP list was a starting point for this research to investigate and synthesize available technologies for DOTD.

Table 1 summarizes geophysical surveying methods from an NCHRP synthesis report and includes the parameter measured for each test method, physical property models, and typical site models. These methods provide for a series of geotechnical engineering applications. According to the NCHRP synthesis 357, the three most commonly used geophysical applications are bedrock mapping, mapping soil deposits, and roadway subsidence [5]. Bedrock mapping is not applicable to DOTD; however, tools to help with soil mapping and subsidence would benefit Louisiana. This NCHRP list was a starting point for this research to investigate and synthesize available technologies for DOTD.

Table 1. Commonly used geophysical surveying methods for site investigations [5]

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model	Typical Site Model
Shallow seismic refraction	Travel times of refracted seismic energy	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	Density and acoustic velocity	Acoustic velocity	Geologic profile
Cross-hole seismic tomography	Travel times and amplitudes of seismic energy	Density and acoustic velocity	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 (sledge hammer)	Acoustic velocity	Acoustic velocity	Geologic profile
Refraction microtremor (ReMi)	Travel times of passive surface waves energy	Acoustic velocity	Acoustic velocity	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

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model	Typical Site Model
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 of spatial variations in clay content
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 remnant 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.)

Objective

This literature research investigated geophysical tools and test methods based on available research and advancements from other state DOTs, FHWA, and NCHRP. The objective of this study was to synthesize available geophysical methods and provide DOTD headquarters (HQ) geotechnical designers with a short list of appropriate technologies that can offer the department cost-effective alternatives. This includes a detailed description of each method's applicability to geotechnical engineering, pros and cons, cost of each method, and required equipment. The research also developed recommendations and provided an action plan for DOTD to consider using geophysical methods in various geotechnical applications in Louisiana.

Scope

This literature research evaluated the effectiveness of available geophysical methods and provided detailed descriptions of each method. A series of surveys and meetings with DOTD HQ led to a finalized, simplified list of geophysical tools to utilize for Louisiana applications. Device utilizations, cost-benefit scenarios, and training requirements (i.e., pros and cons) were also evaluated.

Methodology

The Louisiana Transportation Research Center (LTRC) geotechnical research team investigated previous and ongoing work and advancements consisting of geophysical methods and tools nationally. This list of methods would narrow to potential applications for Louisiana DOTD. Finally, the list would be further refined to include the most suitable geophysical methods that would be beneficial and easily utilized in the department.

Tasks

Task 1: Research existing state and federal efforts on geophysical testing methods

LTRC conducted a thorough literature review to investigate other previous and ongoing research regarding advancements in geophysical testing practices. Other neighboring state DOTs (such as Texas, Mississippi, Alabama, etc.) were examined for geophysical testing procedures. FHWA's *Advanced Geotechnical Methods in Exploration* (A-GaME) and the American Society of Civil Engineers (ASCE)'s *GeoTechTools* was also important in this literature review to provide a solid foundation for this research to build on. LTRC investigated NCHRP report 357 and FHWA's A-GaME for possible technologies that could be implemented within DOTD.

Task 2: List geophysical methods/technologies and describe their applications

The list briefly outlined each method, described the pros/cons of each method, and cited references. The research synthesized the list, and narrowed down the list to methods and technologies that would work with our predominantly alluvial soils (not rock) and high groundwater table. The list offered specifics on those technologies and how they could offer both performance improvement and improved cost-benefit ratios.

Task 3: Synthesize the applicability of the geophysical methods for Louisiana soils

This task focused on identifying the best geophysical methods for the different following applications: shallow investigation, deep investigation, evaluation of soil properties, pile or shaft structural integrity, unknown foundations. Analysis included the pros and cons of each method, equipment needed, testing procedure, technology/sensor/software needed, feasibility of using each method in Louisiana, potential benefit, and cost saving of each method, etc.

This analysis evaluated the methods regarding cost effectiveness in saving the department labor, time, and money. These methods will be evaluated based on other states' technologies and methods and what can provide benefits to Louisiana. Comparison with and without geophysical testing will be evaluated. The cost of previous construction projects needing additional soil borings and CPTs was considered. In contrast, the cost and ease of utilizations of specialized equipment for geotechnical exploration was analyzed. Training analysis, efforts, costs new technology was also evaluated.

Task 4: Discuss with Headquarters a potential list of geophysical methods for Louisiana

A survey was prepared for DOTD districts to determine current knowledge and interests of geophysical practices that can or have been utilized in Louisiana. The list from Task 3 was refined upon discussion with HQ to provide a more specific "short list" based on their experience and insight on benefits and implementation potential.

Geophysical methods apply to both shallow and deep foundations. Shallow foundations include spread footings and mats, and deep foundation applications include drilled shafts, driven piles, auger-cast piles, and micro-piles. These foundations often require costly boreholes and weeks of fieldwork, preliminary site investigation, and/or additional geophysical methods could help optimize efforts. One example of geophysical method is seismic refraction, and this test method consists of SH-waves which are used to study vibrations in subsurface layers for an earthquake resistant structural design [5]. Though Louisiana is not generally designed for seismic effects, these may provide some benefit to Louisiana.

Task 5: Recommendation of geophysical methods for Louisiana applications

The research team then developed a final draft list of preferred geophysical tools, where these options were evaluated for performance and cost-effectiveness. The research team made recommendations based on its analysis of research findings.

Based on aforementioned final list, the research team recommended specific geophysical methods per application (surface investigation, deep investigation, soil properties, QA/QC, structural integrity, etc.) for further consideration in Louisiana. A follow-up study with field and laboratory work would likely follow this research to validate benefits and provide the department efficient and economical implementation strategies.

Discussion of Results

Geophysical methods can assist in determining the uniformity of soil layers. Preliminary research indicates that the California, Kansas, and Missouri state DOTs currently utilize advanced geophysical methods for geotechnical evaluation, such as ground penetrating radar and seismic refraction. According to an NCHRP synthesis, California (Caltrans) would utilize seismic reflection technique to detect faulting; Kansas (KDOT) incorporates both resistivity and seismic refraction to determine bedrock depth; while Missouri (MoDOT) performed GPR across I-70 to determine layer thickness (primarily asphalt and concrete – not so much base course)[5][6]. In 2020, Alabama (ALDOT) and Auburn University had a case study that utilized electrical resistivity surveys near a repaired sinkhole to map the rock surface and identify possible karst features [7].

Even though Louisiana does not have to deal with karst, these states' geophysical test methods provide guidelines and a starting point for applicability on Louisiana's soils. An internal DOTD survey was conducted to look for insight into utilizing geophysical technologies for Louisiana.

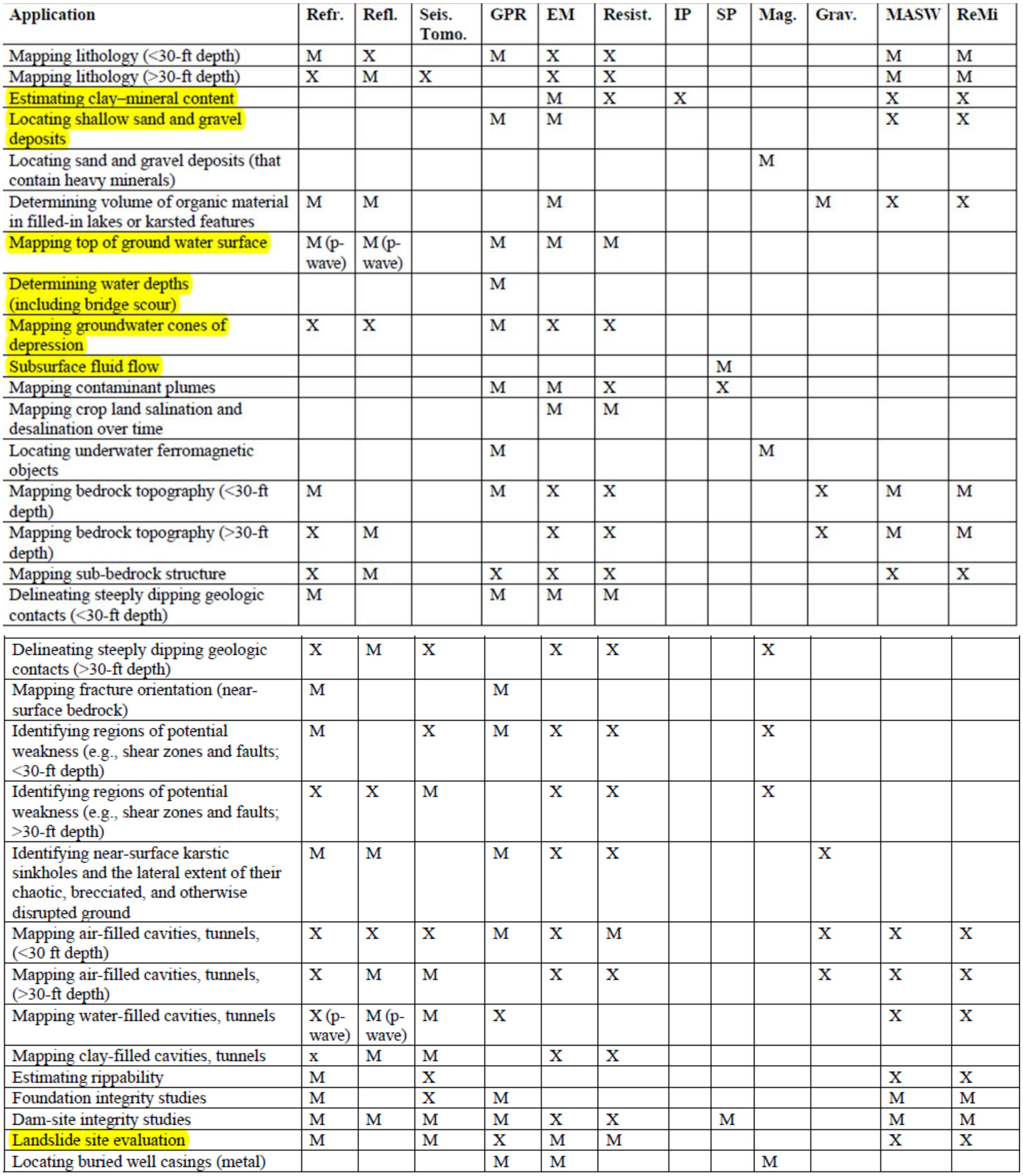
DOTD Survey

Researchers created a survey for DOTD HQ Geotechnical and the Project Review Committee (PRC) members to gauge their insight and awareness regarding geophysical knowledge and need in Louisiana. The PRC meeting was held on August 24, 2021, and attendees were asked to rate applications based on importance for Louisiana as well as interests in certain geophysical tools. Table 2 presents the different geophysical applications that are applicable to use to investigate subsurface provided by Anderson in 2006 [4]. The top row has abbreviated names for the geophysical tools and the list follows as:

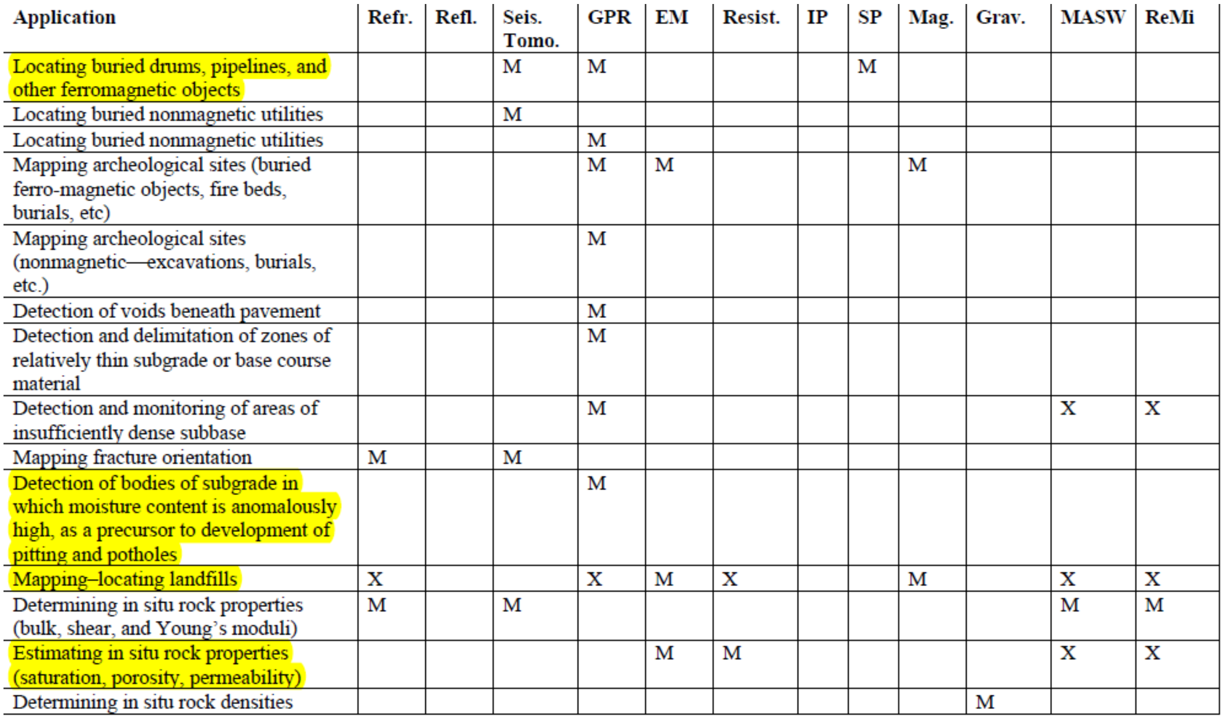
- Refr. (seismic refraction)
- Refl. (seismic reflection)
- Seis. Tomo. (cross-hole seismic tomography)
- GPR (ground penetrating radar)
- EM (electro-magnetics)
- Resist. (electrical resistivity)
- IP (induced polarization)
- SP (self/spontaneous potential)
- Mag. (magnetics)
- Grav. (gravity)
- MASW (multichannel seismic waves)
- ReMi (refraction microtremor)

The “M” and “X” values indicate major and minor application utilizing that certain geophysical tool, respectively. Some of the applications are highlighted indicating initial popular recommendations for Louisiana.

Table 2. Potential geotechnical applications of commonly employed geophysical methods (Anderson, 2006) [4]



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						
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			



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		

The survey determined the preferred applications that Louisiana is interested in incorporating into site investigations. Utilizing Anderson's table (Table 2), the DOTD geotechnical personnel can pick out which geophysical methods or tools (indicated by "M" rather than an "X" or left blank) are most important in accomplishing these certain applications. Further studies will commence to improve the department's knowledge on these selected geophysical methods.

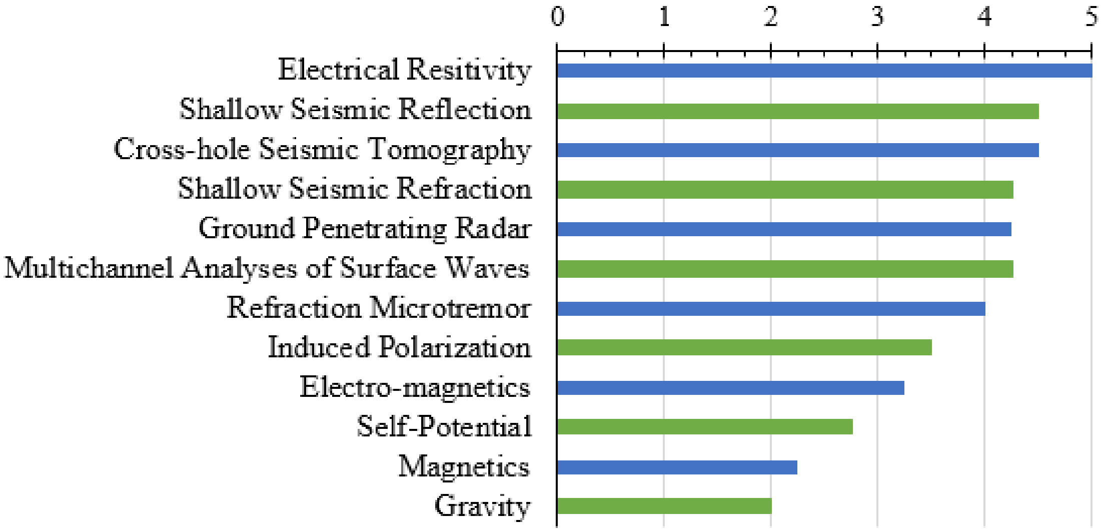
Table 3 shows the results from the primary meeting/survey with DOTD geotechnical personnel. The 12 applications listed below from Anderson's NCHRP report scored the best from a scale of 1-5 (5 being the highest score). Most of applications omitted from this table dealt with bedrock, tunnels, or faults, which are scarce to non-existent in Louisiana. The geophysical tools that can contribute the most to each application are listed in the rightmost column. The selected geophysical tools are GPR, shallow seismic refraction, EM, MASW, ReMi, electrical resistivity, shallow seismic reflection, and cross-hole seismic tomography.

Table 3. DOTD survey results for geophysical applications

Potential Geotechnical Applications	**Average score** (out of 5)	**Geophysical Methods (Major Contribution)**
Mapping lithology (< 30-ft depth)	4.5	Refr., GPR, MASW, ReMi
Mapping lithology (> 30-ft depth)	4.5	Refl., MASW, ReMi
Foundation integrity studies	4.5	Refr., GPR, MASW, ReMi
Landslide site evaluation	4.5	Refr., Seis. Tomo., EM, Resist.
Detection of voids beneath pavement	4.5	GPR
Mapping top of ground water surface	4.25	Refr., Refl., GPR, EM, Resist.
Subsurface fluid flow	4.25	SP
Detection and delimitation of zones of relatively thin subgrade or base course material	4.25	GPR
Detection of bodies of subgrade in which moisture content is unusually high, (development of pitting and potholes)	4.25	GPR
Locating shallow sand and gravel deposits	4	GPR, EM
Determining water depths (bridge scour)	4	GPR
Detection and monitoring of areas of insufficiently dense subbase	4	GPR

The DOTD geotechnical group were also asked to score each individual geophysical method or tool in ranking of importance or interest. Figure 2 indicates the results in descending order. The top seven geophysical methods follow suit with the more important applications for Louisiana that scored the highest in Table 3. The survey results from DOTD geotechnical group can be found in the Appendix

Figure 2. Ranking of geophysical methods from DOTD survey



Upon completion of the DOTD survey, the results indicated the DOTD/PRC preference of geophysical methods to be electrical resistivity, seismic reflection, cross-hole seismic tomography, seismic refraction, GPR, MASW, and ReMi.

Geophysical Method Analysis and Comparisons

Electrical Resistivity

This geophysical method is perhaps the most commonly used, and it measures the resistivity of a volume of soil and rock. This is done by producing an electric current through a pair of electrodes [3]. The electrical resistivity method involves the measurement of electrical resistivity of soils as it passes between two surface points. Results are plotted as a function of elevation (depth) and horizontal position. The different colors indicate the electrical resistivity profile as a relative heat map with red as the highest value and blue as the lowest value [2]. The colors help differentiate between cohesive and granular soils based on their resistivities. Figure 3 shows the device in use, while Figure 4 shows an example from Minnesota (MnDOT) indicating the electrical resistivity profile of a construction site [4][8]. This particular geophysical technology can aid designers by providing information between the borings, reducing the unknowns, and estimating potential construction costs.

Figure 3. Electrical resistivity device [8]

Figure 4. MnDOT geotechnical site characterization example [4]

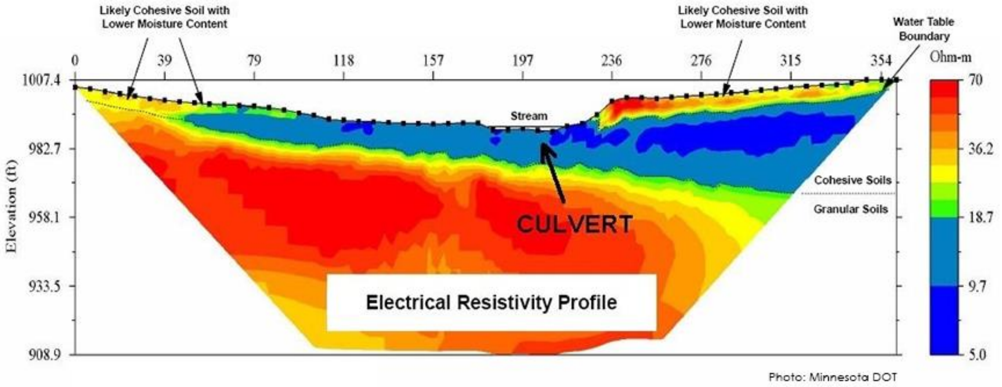


Photo: Minnesota DOT

- Advantages:
    - Very detailed in determining the wide range of soils types and water table
    - Simple to use and follow procedures
    - Fast results when testing less than 165 ft. in depth. (50 m)

    - Easy to utilize in saturated areas

- Disadvantages:
    - Difficult to place electrode devices in the asphalt or concrete
    - Grounded metal objects near the electrodes may influence the data
    - May need to saturate electrodes with water to enhance electrical contact with the ground

A technology that offers potential to Louisiana is the electrical resistivity profile method, which utilizes the electrical resistivity for knowledge in the spaces, which soil borings and CPTs will have missed. Determination of types of soil and water can be classified utilizing a list provide by ASCE in Table 4. However, it should be noted that there are some factors not included in these attributes, such as moisture contents, soil fabric, and salinity of pore water in south Louisiana [9].

Table 4. Typical values of electrical resistivity

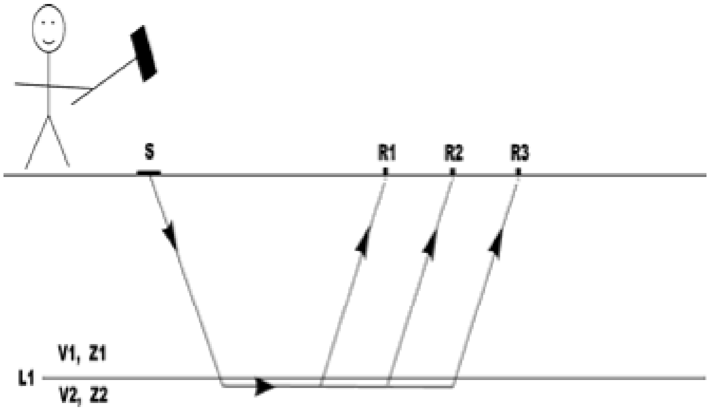
Soil Type	**Electrical Resistivity (ohm-m)**
Well Graded Gravel	600 – 1,000
Poorly Graded Gravel	1,000 – 2,500
Clay Gravel	200 – 400
Silty Sand	100 – 800
Clayey Sand	50 – 200
Low Plasticity Silty/Clayey Sand	30 – 80
Fine Sandy Soils	80 – 300
High Plasticity Inorganic Clays	10 – 55
Surficial Soils	1 – 50
Clay	2 – 100
Sandy Clay	100 – 150
Pore Water	**Electrical Resistivity (ohm-m)**
Pure Water	18,200
Sea Water	0.2

Shallow Seismic Refraction

Seismic refraction (SR) is a surface geophysical method that utilizes the refraction of seismic waves on geology layers and rock/soil units to characterize subsurface geologic conditions [10]. A dropped weight (typically a hammer) or a mechanical vibrator generates the seismic waves. Shallow seismic refraction is primarily utilized in mapping bedrock at depths of less than 100 ft.; however, other applications include determining the soil stiffness, the mapping of the groundwater table, and the mapping of sands, clays, and gravels [3]. Figure 5 is an image the seismic refraction test method with the hammer plate (on the left most end), the strip of geophone receivers, and the seismograph on the 4-wheeler. Figure 6 is an illustration provided by Circular E-C130, and it indicates the source location of acoustic pulses (S), the predetermined receiver locations (R1, R2, and R3), and the "horizon of interest" (L1) [4]. L1 is the critical wave path between two different soil layers.

Figure 5. Seismic refraction device [10]

Figure 6. Seismic refraction illustrated diagram [4]



- Advantages:
    - Field recording is fast and easy
    - Data can be viewed on the recorder screen as the survey progresses
    - Antenna frequency can be altered to either enhance resolution or penetration

- Disadvantages:
    - Traffic vibrations may show as “noise” and obscure the refractions
    - Not applicable where seismic velocities of layers decrease with depth (i.e., higher velocity layers of stiff clays overlie a lower velocity of sand or gravel)
    - When dealing with bedrock, a water table in close proximity may obscure the bedrock and cause false interpretation of the bedrock depth

Shallow Seismic Reflection

Seismic reflection is a surface geophysical method that records seismic waves reflected from geologic strata, giving an estimate of their depth and thickness [4]. In contrast to seismic refraction, the seismic reflection method is generally utilized to determine stratigraphy at depths greater than 80-100 ft. The device setup and seismic wave diagram are similar to Figure 5 and Figure 6 for seismic refraction; however, the reflected seismic waves reflect back to the surface rather than following along the “horizons of interest” between the different soil layers.

- Advantages:
    - Good for marine applications, such as lakes and rivers, because the water's inability to transmit shear waves makes a collection of higher quality reflection data [11]
    - Data recorded quickly
    - Displayed on screen during field testing

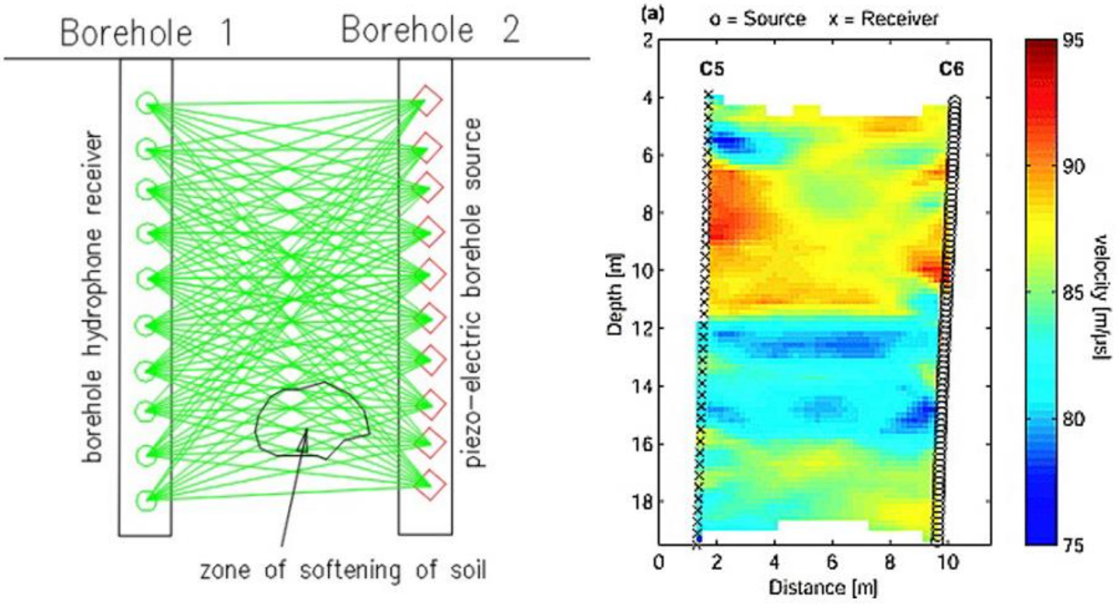
- Disadvantages:
    - Unable to have images of layers underlying a clay layer
    - Expensive
    - Depths less than 80 ft., reflections tend arrive at the geophones at the same time no matter the amplitude of the surface waves

Cross-hole Seismic Tomography

Cross-hole tomography measures the velocities of seismic waves between two or more boreholes. The tests consist of placing seismic source down one hole and receivers (or geophones) down another. The source is then "fired" at the predetermined depth of the geophone in the adjacent boreholes, where the travel time is converted into a seismic velocity [12]. Figure 7 shows the two devices that are placed in adjacent boreholes for cross-hole tomography testing. Figure 8 depicts a visualization of the two boreholes with piezo-electric sources and hydrophone receivers, as well as an example showing the velocity of sounds at seismic frequencies.

Figure 7. P-wave source probe (left) and hydrophone receivers (right) [13]

Figure 8. Diagram of cross-hole seismic tomography [12]



- Advantages:
  - Applies to both shallow and deep subsurface investigations
  - Provides a 2D or 3D (if three boreholes were constructed) volumetric image of the soil layer in between.
  - Can image the entire length of a borehole — deeper than geophysical surface techniques
  - Can provided one of the biggest array of targets between each borehole

- Disadvantages:
  - Hard to interpret data — the solution quality depends on the distance between the boreholes
  - Difficult to have two vertical and straight boreholes to conduct the test
  - Seismic surveys near urban environments can disrupt the test

Ground Penetrating Radar

This geophysical method is also more commonly used, and it utilizes electromagnetic energy to be transmitted down below the surface and reflected/refracted back up. The travel times and amplitudes of reflected electromagnetic energy are usually recorded, and a GPR profile (2-D time–amplitude image) is generated from these variables. The data can be transformed into a 2-D velocity–depth model [5]. GPR can be beneficial for subsurface stratigraphic changes, finding cavities and voids in karst terrain, and finding unground storage tanks. More importantly, GPR can determine the water table, which is beneficial for Louisiana.

Figure 9 shows a simplistic image of the GPR devices transmitting waves for data collection. Figure 10 shows an example of a 2-D GPR profile of a streambed and various water depths. This GPR profile example contains only prominent reflection indicating two different layers: (1) water and (2) relatively uniform sand [4].

Figure 9. GPR device diagram [14]

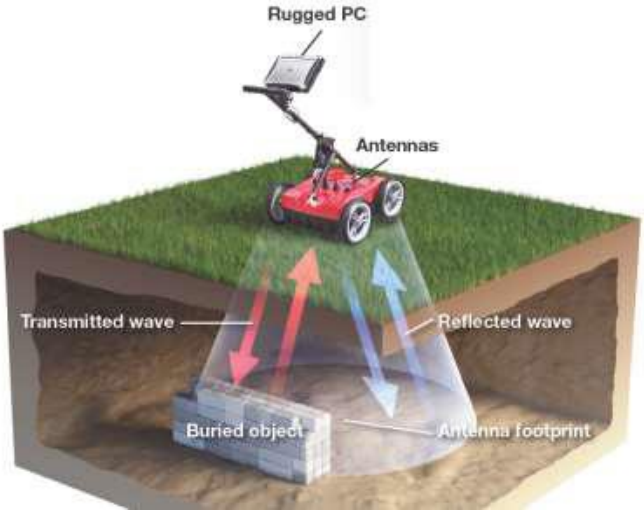
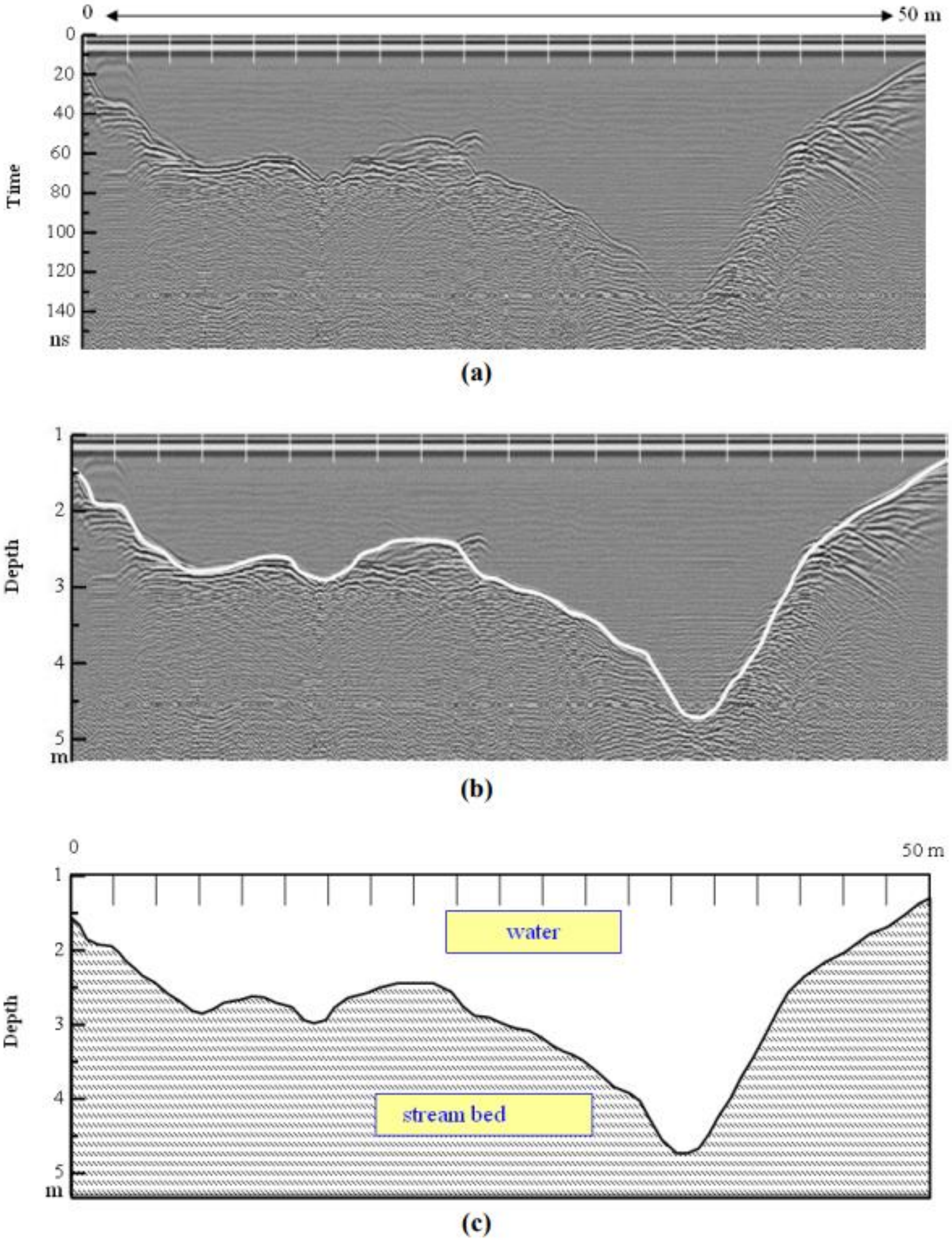


Figure 10. (a) GPR profile of a stream bed; (b) GPR physical property model (interpreted layer boundaries); and (c) geologic–hydrologic site model [4]



(a)

(b)

(c)

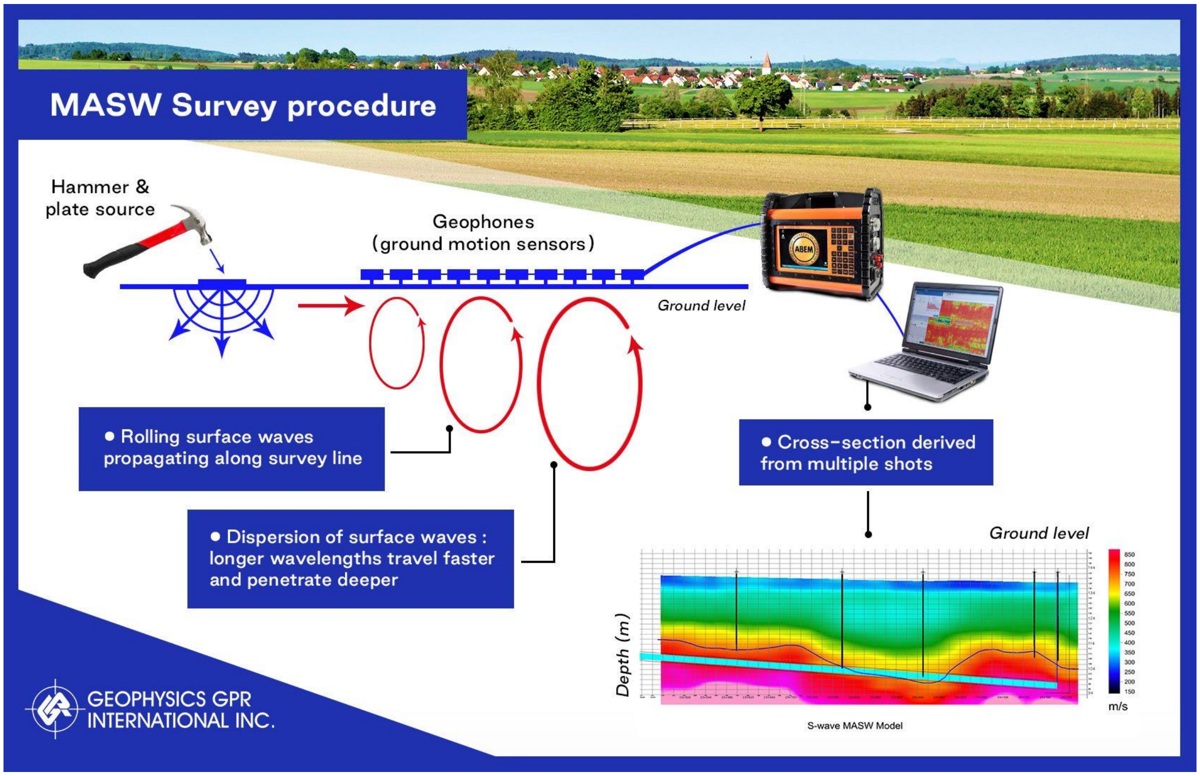
- Advantages:
    - Data recorded quicker than other methods due to device setup (no geophones, etc.)
    - Displayed on screen during field testing
    - Antenna frequency can be altered to either enhance resolution or penetration
    - Suitable for pavements and dryer materials such as sandy soils and limestone

- Disadvantages:
    - Cannot image layers beneath a clay layer
    - More pavement related studies, rather than geotechnical
    - Reflections from surface or metal features such as buildings and power lines can cause affect to the survey

Multichannel Analyses of Surface Waves

The multichannel analyses of surface waves (MASW) test method analyzes the dispersion of surface waves and inverts them into terms of shear wave velocity [5]. These surface wave (Rayleigh wave) energies are generated by a nearby acoustic source. Data can produce a dispersion curve (phase velocity versus frequency) to generate a 1-D shear wave velocity profile [4]. The non-invasive and non-destructive MASW method has the potential of sampling a larger volume of the subsurface than borehole methods. Figure 11 shows the MASW survey procedure and analysis provided by Geophysics GPR International, Inc. [15].

Figure 11. MASW survey procedure [15]



- Advantages:
  - Data recording is fully automated and user friendly
  - Displayed on screen during field testing
  - Antenna frequency can be altered to either enhance resolution or penetration

- Disadvantages:
  - Outside factors (traffic) may limit the signal noise ratio at low frequencies.
  - Resolution is dependent on the size of the surface waves — an empirical rule says that the minimum size the anomaly that can be resolved is about a tenth of the depth [16]

Refraction Microtremor

Similar to the seismic refraction method, the refraction microtremor (ReMi) is a passive surface wave geophysical method that utilizes linear ambient surface waves, and the abundance of this ambient low frequency energy makes this method useful for deep applications [5]. According to synthesis 547, the Ohio Department of Transportation has compared ReMi and electrical resistivity (ER) geophysical methods and found that ReMi was more beneficial alternative to ER in urban environments. This is because the utilities interfere with the more widespread ER method. Figure 12 shows a ReMi setup to evaluate fill conditions underneath a concrete slab [17].

Figure 12. Small-scale setup of the ReMi [17]

- Advantages:
    - Data is recorded with small (lighter) and more modern exploration devices
    - Can be effective in more urbanized or noisier sites compared to other seismic techniques
    - Can be utilized in deep applications in urban environments

- Disadvantages:
    - This method is one-dimensional and can require more tests to compete with widespread geophysical test method, such as ER
    - More geophysical exploration methods may be required to characterize subsurface conditions effectively

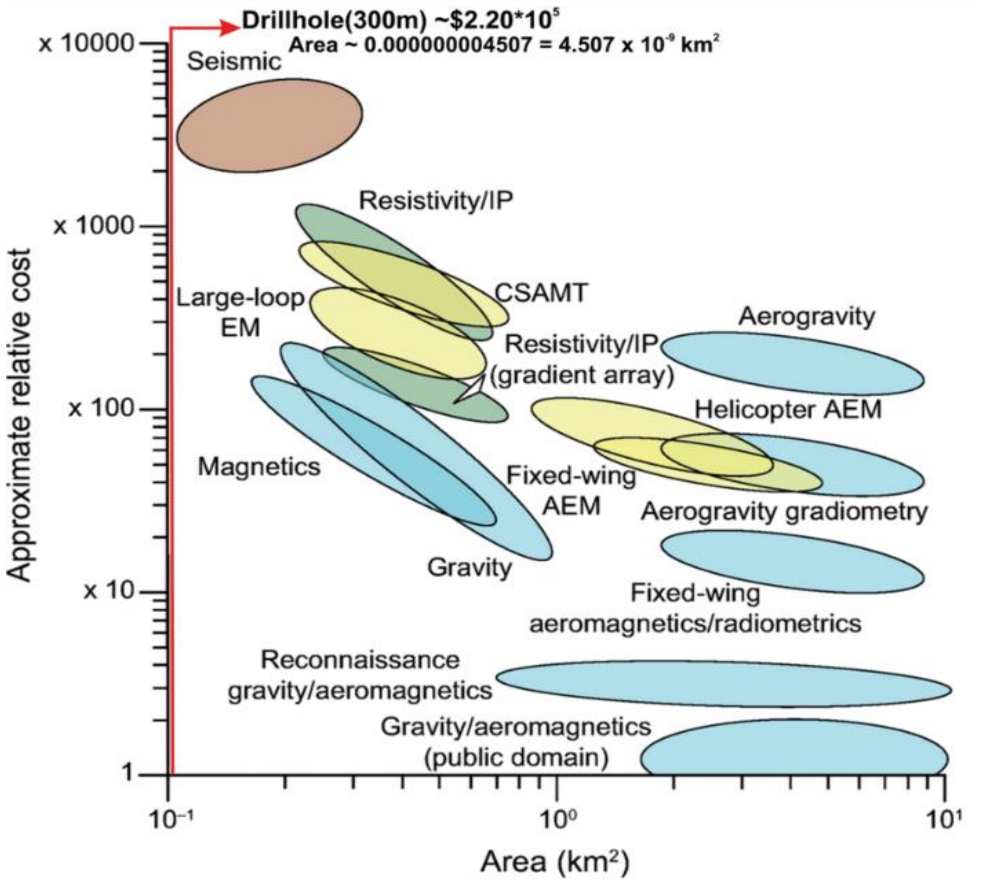
Cost Analysis

DOTD is in search of geophysical methods that help with aiding the transportation infrastructure in the most beneficial and economical way. Through discussions with this report's project committee, a typical 120-ft. boring could cost the department around $15,000 each, so no matter what geophysical methods, it is worth a look to save money for DOTD's future.

Cost for geophysical methods tended to be hard to quantify precisely. There is a wide range of factors including cost of certain contractors or geophysical experts, the size of the geophysical crew required to conduct survey, and the size of the test area in width and depth. Northern California (NORCAL) Geophysical Consultant based out of San Francisco Bay area states, "Geophysical surveys can range in costs from less than $1,000 to over $100,000." The latter number is a result of utilizing helicopter aerial surveys. However, typically NORCAL conducts geophysical tests that take one to three days and cost from about $2,500 to $7,500 [18].

Another geophysical report out of the University of Saskatchewan compared various costs of geophysical methods to the cost of a 300-m drill hole and logging. Figure 13 indicates that the various ranges of geophysical test costs are still cheaper than a $220,000 drill-hole operation [19].

Figure 13. Cost comparison of methods from a University of Saskatchewan report [19]



The Interstate Technology & Regulatory Council (ITRC) Implementing Advanced Site Characterization Tools Team has published a report on borehole and surface geophysical characterization tools, including an in-depth analysis on tool utilization, quality control, and estimated costs [20]. The report compared the following geophysical methods: electrical resistivity, GPR, seismic refraction, seismic reflection, MASW, and electromagnetics. In Table 5, ITRC researchers found the amount of personnel required for tests, typical cost for a day, and data processing time. MASW is the only method where an exact range of cost or data processing time were not included. All methods range from $1,000 to $4,000 in cost and require one to three personnel to operate the tests, all while providing the customer a cheaper way to conduct subsurface investigations.

Table 5. ITRC's cost and utilization comparison of select geophysical methods [20]

	Minimum Personnel Required	**Cost*** (typically a day-rate basis)	**Data Processing Time** (for every day of field acquisition)
Electrical Resistivity	2	\$2,000 - \$4,000	0.5 days
GPR	1	\$3,000 [for 1 - 1.5 acres]	NA
Seismic Refraction	2	\$2,000 - \$4,000	1 day
Seismic Reflection	3	\$1,000 - \$2,000	1 day
MASW	NA	"Relatively cost-effective"	"Relatively rapid"
Electromagnetics	1	\$2,000 - \$3,000 [for 2-3 acres]	0.5 days

* Ignoring the complexity of the survey and site conditions

Geophysical Method Applications across Various DOTs

DOT In-house Utilization

Another way to figure out which geophysical method to use is to see what others states have already implemented in-house or through the aid of specialized consultants. According to the 2020 NCHRP synthesis 547 [3]: *Advancements in Use of Geophysical Methods for Transportation Projects*, the survey results about how frequent agencies have utilized geophysical methods were consistent with that of 2006 survey. Perhaps this is caused by the lack of funding or inexperience with geophysics across the nation. However, there is a promising note that seven of the 43 surveyed have indicated that they utilize geophysical methods more than 10 times a year: Caltrans, Florida (FDOT), KDOT, MnDOT, South Carolina (SCDOT), Virginia (VDOT), and Wisconsin (WisDOT) [3]. In addition,

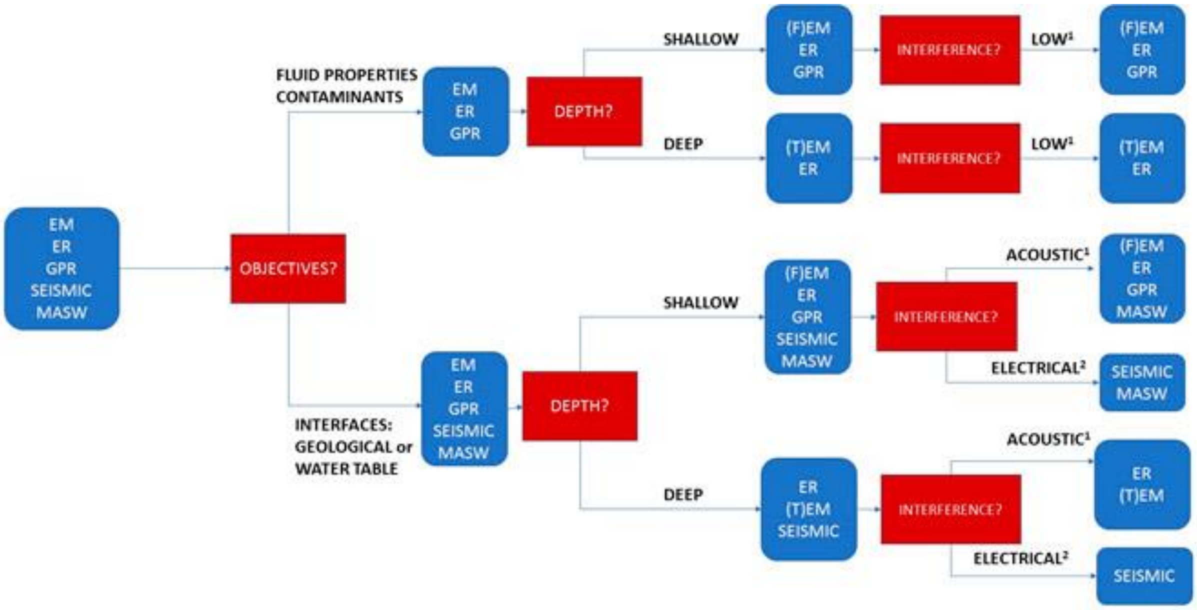
Table 6 shows all of the respondents that have indicated which geophysical methods are performed regularly. The two most common geophysical methods utilized in-house are the seismic refraction and GPR methods. The closest neighbors to Louisiana in the table, Missouri and Florida, utilize the electrical resistivity geophysical method in-house.

Table 6. Geophysical methods performed in-house [3]

State	Geophysical Method
Arizona	Seismic Refraction
California	Seismic Refraction Tomography Ground Penetrating Radar (GPR) Induced Polarization (IP) Refraction Microtremor (ReMi) Borehole geophysical logging Magnetometry
Central Federal Lands	Seismic Refraction Multichannel Seismic Waves (MASW)
Colorado	Seismic Surface Wave Seismic Refraction
Florida	GPR Electrical Resistivity (ER) Seismic Surface Wave
Michigan	GPR Falling Weight Deflectometer (FWD)
Minnesota	GPR ER Self-Potential (SP) IP Seismic Refraction MASW Cross-hole Tomography
Missouri	ER
Nevada	ReMi MASW Seismic Refraction Down-hole Tomography
New Mexico	Seismic Refraction GPR
Ohio	ER Seismic Refraction ReMi Shear Wave Velocity with the Cone Penetrometer (CPT)
South Dakota	Seismic Refraction
Virginia	FWD GPR
Vermont	GPR
Washington	Seismic Refraction ReMi
Western Federal Lands	Seismic Refraction
Wisconsin	FWD GPR Seismic Refraction Vibration Monitoring

The Interstate Technology & Regulatory Council (ITRC) devised a flow chart for selecting surface geophysical tools, as seen in Figure 14. No such flowchart was developed for borehole investigation.

Figure 14. ITRC selection of surface geophysical tools flow chart [20]



Notes:

-This flowchart provides a high-level overview regarding tool applicability. Specific tool details (e.g. resolution, applicable depth, appropriate geologic setting, study objectives, considerations) is included on Table 5-1.

-For this flowchart, "seismic" refers to both seismic reflection and seismic refraction.

-For this flowchart, "shallow" is generally within 120 feet of the ground surface. "Deep" is generally greater than 120 feet from the ground surface.

[1] Electrical methods can be effective if the degree of electrical interference/noise (e.g., power lines, generators, etc.) is limited. Electrical methods are less affected by acoustic interference/noise. MASW may overcome acoustic interference with vertical stacking of data acquisition to increase signal to noise ratio.

[2] Seismic methods may still be effective in conditions with high degree of electrical interference/noise.

In Figure 14, the tools compared for surface geophysics were electromagnetics, electrical resistivity, GPR, seismic (refraction and reflection) and MASW. The flow chart follows a path of whether this is for fluid properties or geological and whether the geotechnical application is shallow or deep (greater than 120 ft.). The resulting outcomes (rightmost bubbles) for each application included at least two for the following: electrical resistivity and seismic test methods.

Case Studies

MnDOT. The Minnesota Department of Transportation (MnDOT) has reported using geophysical methods more than 10 times per year in the NCHRP Synthesis 547 [3]. Geophysical methods became necessary for MnDOT after the agency experienced issues related to karst throughout Minnesota in the late 1990s. The department primarily uses in-house capabilities (listed in Table 6) to perform geophysical measurements unless the project is designated design-build in which an external contractor would be required. MnDOT has found it cost-effective to perform most of it geophysical work in house with on-the-job training supplied primarily by equipment manufacturers.

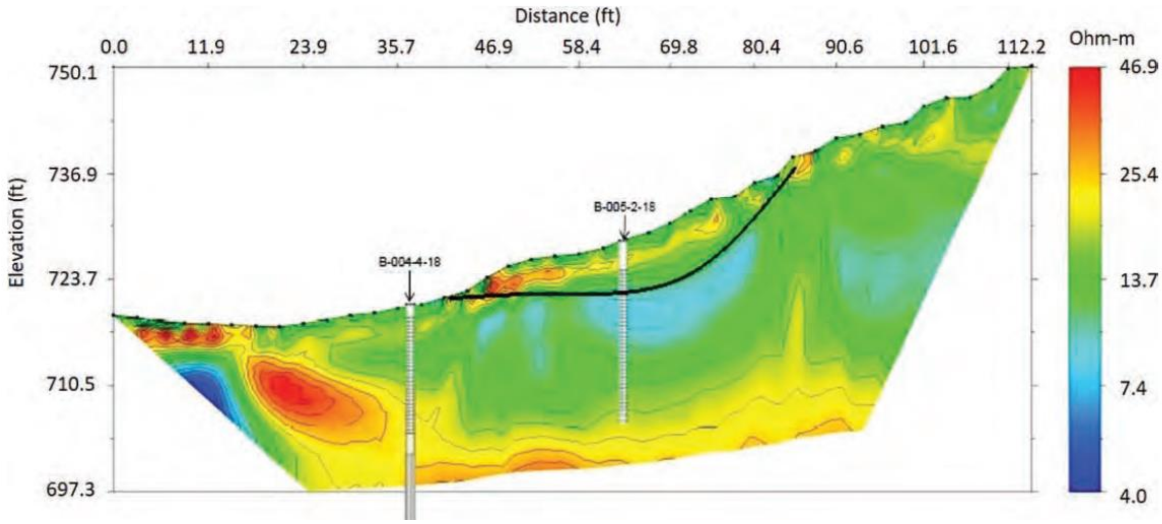
One case study (*Bridge over Miller Creek in Duluth, Minnesota* [3]) had the decision to use a shallow or a deep foundation for a new bridge that required information about the depth of bedrock. There were access issues to the site, such as amount of space required for drill rig, concerns of property damage, and the adjacent Miller Creek is a designated trout stream. These restrictions led MnDOT to disregard utilizing traditional soil/rock borings and CPTs. The department instead relied on electrical resistivity imagery for subsurface investigation. The geophysical survey indicated bedrock at a depth of about 10 ft. and provided enough confidence for the decision to utilize a shallow foundation. This decision led to a cost savings of between \$50,000 to \$100,000, according to MnDOT when factoring in cost of mobilization, pile materials, and labor [3][21].

This case study provided successful use of ER to design a bridge foundation with restrictions of typical boring methods. The case study can be found in Appendix II.

ODOT. The Ohio Department of Transportation (ODOT) has stated utilizing geophysical methods on projects more frequently at approximately 6-10 times per year, according to the NCHRP Synthesis 547 [3]. Geophysical methods were initially contracted out for ODOT; however, in the past 10 years, the department has incorporated in-house geophysical test procedures to perform ER and seismic work. ODOT primarily uses in-house capabilities (listed in Table 6) to detect voids in abandoned mines and karst features [3]. In a brief survey with ODOT, the department also utilizes ER for delineating peat deposit and locating pipelines prior to construction. ODOT uses the seismic refraction geophysical method and ReMi for top of bedrock and mine void detections, in conjunction with ER equipment. ODOT also utilizes the GPR in contract with a consultant to detect void beneath pavements [22].

One case study (*Imaging a Shallow Embankment failure in Northwest, Ohio* [3]) had a project site where the high plasticity clay embankment was unstable at all four corners of an overpass. The transportation department utilize traditional borings, dynamic cone penetrometer (DCP), inclinometers, and ER geophysical surveys. In Figure 15, the ER survey indicates soil with higher resistivity above a shallow layer of low-resistivity (light blow) material near the boring #005-2-18 [3]. The case study states that the ER survey agreed with slope inclinometer data from the site.

Figure 15. Profile of ER survey (courtesy of ODOT) [3]



Utilizing multiple subsurface methods provided confidence for ODOT, where the department expects to use ER surveys in the future to image shallow embankment failures. The ER geophysical method will reduce the disturbance and effort needed for traditional drilling exploration at slope site locations [3]. Upon further investigation, the LTRC researchers asked ODOT about possible cost savings on this project. It was concluded that cost savings were not exactly calculated. However, due to confidence in the ER survey after drilling on one side of the slope, ODOT did not have to perform difficult access drilling on the opposite slope. The department has “since used this technique successfully on other shallow embankment failures” ODOT [22].

Another case study (*Full Waveform Inversion to Characterize Abandoned Mines* [3]) utilized the seismic method full wave inversion (FWI) to develop a subsurface model of an abandoned underground coal mine in Athens County, Ohio. Results indicated an anomaly at a depth of about 15 m, and this was later confirmed with borings that showed the depth of the anomaly within 1 m above the seismic method. This case exampled showed the consistency of utilizing the FWI seismic method and boring logs [3]. Both case studies provided successful use of ER and a seismic geophysical method, and they can be found in Appendix II.

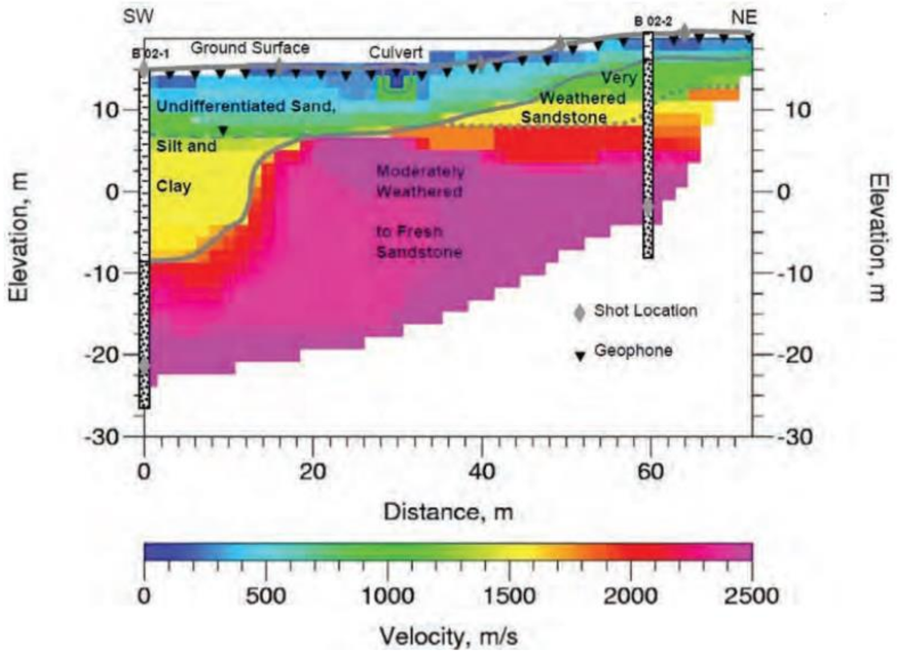
Caltrans. The California Department of Transportation (Caltrans) has utilized geophysical methods on projects the most according to a survey from the NCHRP Synthesis 547 [3]. Before 1990, Caltrans primarily used seismic refraction for determining rock *rippability* (the ease of soil and/or rock for excavation) and depth of bedrock. Caltrans' Geophysics and Geology Branch performs in-house geophysical tests, as listed in Table 6. Beneficial for Louisiana, Caltrans has reported using ER for mapping sand and clay deposits. Caltrans has indicated that surface wave measurements and seismic reflection are typically contracted out.

Favorable results from geophysical test methods have shown Caltrans effectiveness on geotechnical investigations and produce cost savings "significantly." It is hard to exactly quantify cost savings; however, the agency states it benefits utilizing routine geophysical methods in-house thanks to the training resources from specialized consultants to help educate engineers [3].

One case study (*Freeway Improvement Project at Interstate 80 and Willow Avenue in contra Costa County* [3]) utilized refraction tomography, which stated to be the most common geophysical method performed by Caltrans. Refraction tomography was necessary in determining the information between two boreholes spaced 60 m from each other, and the results can be seen in Figure 16. The seismic velocities can delineate the various soils types seen: sand, silt, clay, and weathered/fresh sandstone. The case study states more borehole shots provided a better subsurface image.

This case study provided successful use of refraction tomography utilizing the cross-hole method for subsurface investigation. The full case study can be found in Appendix II.

Figure 16. Profile of refraction tomography (courtesy of Caltrans) [3]



Conclusions

This research focused on evaluating geophysical application methods that are serviceable for Louisiana and DOTD. The main motivation for this study was to help aid in current geotechnical exploration practices in which the department can provide a more detailed pre-construction characterization of the geotechnical conditions. Other potential benefits include shorter project delivery times, reducing possible setbacks, improved QA/QC, and reducing risks within the areas between investigated subsurface site conditions.

Survey results showed that the following geotechnical applications are of interest to DOTD:

- Mapping lithology (< 30-ft. depth)
- Mapping lithology (> 30-ft. depth)
- Foundation integrity studies
- Landslide site evaluation
- Detection of voids beneath pavement

Geophysical methods/tools that met DOTD interest were further investigated and are listed below:

- Seismic refraction
- Seismic reflection
- Cross-hole seismic tomography
- Ground penetrating radar
- Electrical resistivity
- Multichannel seismic waves
- Refraction microtremor

Researchers further refined the geophysical method list based on the following analysis: HQ survey, comparison of geophysical methods, current in-house practices across state DOTs, previous works with contractors utilizing geophysical methods for the department, and case studies across the state DOTs. Ultimately, the geophysical methods of most benefit to the department with relative ease of implementation are:

- Electrical resistivity
- Seismic refraction
- Cross-hole tomography

Recommendations

Based on the research work and conclusions, the following items are recommended for implementation.

- Researchers recommend a more detailed research study directed toward implementing the following geophysical methods in Louisiana:
    - Electrical resistivity
    - Seismic refraction
    - Cross-hole tomography
- The recommended follow-up study should include field and laboratory work to validate the benefits and provide the department efficient and economical implementation strategies.
- Device-specific training is recommended for any implemented devices.

Acronyms, Abbreviations, and Symbols

Term	Description
A-GaME	Advanced Geotechnical Methods in Exploration
AASHTO	American Association of State Highway and Transportation Officials
ALDOT	Alabama Department of Transportation
ArDOT	Arkansas Department of Transportation
ASCE	American Society of Civil Engineers
Caltrans	California Department of Transportation
CPT	Cone Penetrometer Test
DCP	Dynamic Cone Penetrometer
DOTD	Louisiana Department of Transportation and Development
DOTs	State Department of Transportation(s)
EM	Electro-magnetics
ER	Electrical resistivity
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
ft.	foot (feet)
FWI	Full Wave Inversion
GPR	Ground-penetrating Radar
Grav.	Gravity or Gravimeters
HQ	Headquarters for DOTD
IP	Induced Polarization
ITRC	Interstate Technology & Regulatory Council
LTRC	Louisiana Transportation Research Center
KDOT	Kansas Department of Transportation
m	meter(s)
Mag.	Magnetics or Magnetometers
MASW	Multichannel Analyses of Surface Waves

Term	**Description**
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
NORCAL	Northern California
NCHRP	National Cooperative Highway Research Program
ODOT	Ohio Department of Transportation
PRC	project review committee
QA/QC	quality assurance/quality control
Refl.	Shallow Seismic Reflection
Refr.	Shallow Seismic Refraction
ReMi	Refraction Microtremor
Resist.	Electrical Resistivity
Seis. Tomo.	Cross-hole Seismic Tomography
SCDOT	South Carolina Department of Transportation
SP	Self-Potential or Spontaneous Potential
SR	Seismic Refraction
VDOT	Virginia Department of Transportation
WisDOT	Wisconsin Department of Transportation

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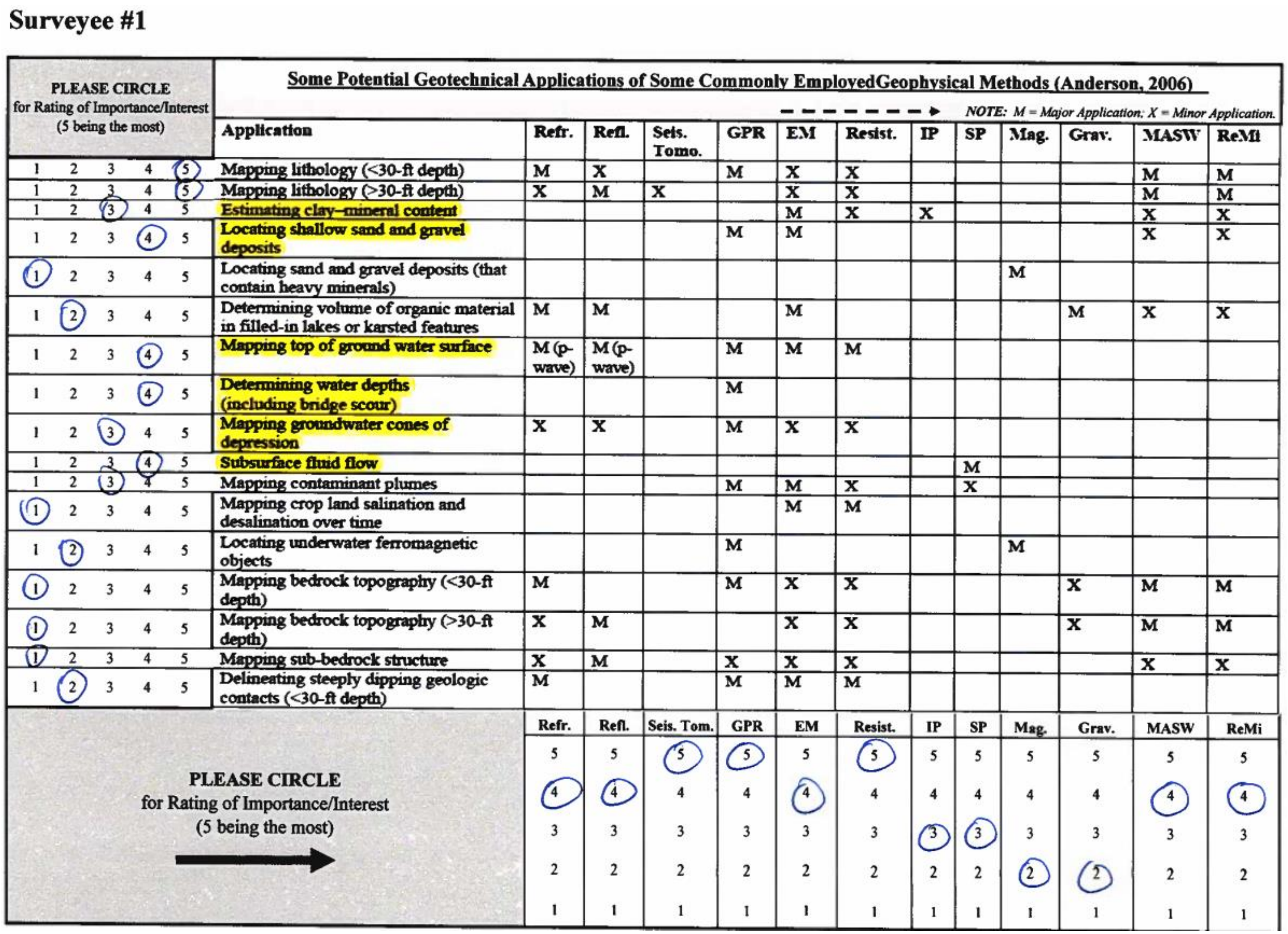
Appendix

Figure 17. Surveys from the DOTD geotechnical section



Surveyee #1

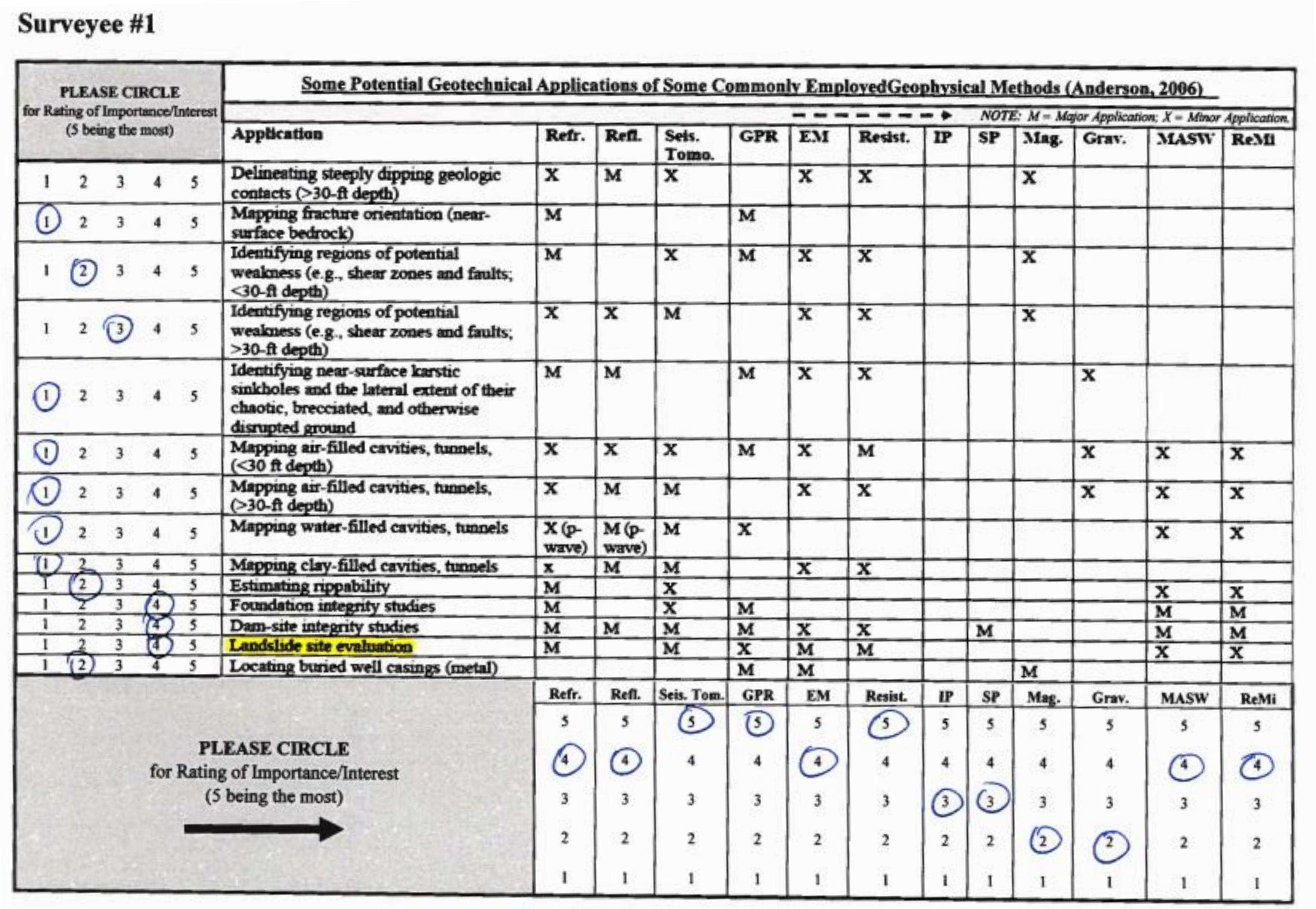
Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 2 3 4 [✓ 5]	Mapping lithology (<30-ft depth)	M	X		M	X	X					M	M
1 2 3 4 [✓ 5]	Mapping lithology (>30-ft depth)	X	M	X		X	X					M	M
1 2 [✓ 3] 4 5	Estimating clay–mineral content					M	X	X				X	X
1 2 3 [✓ 4] 5	Locating shallow sand and gravel deposits				M	M						X	X
[✓ 1] 2 3 4 5	Locating sand and gravel deposits (that contain heavy minerals)									M			
1 [✓ 2] 3 4 5	Determining volume of organic material in filled-in lakes or karsted features	M	M			M					M	X	X
1 2 3 [✓ 4] 5	Mapping top of ground water surface	M (p-wave)	M (p-wave)		M	M	M						
1 2 3 [✓ 4] 5	Determining water depths (including bridge scour)				M								
1 2 [✓ 3] 4 5	Mapping groundwater cones of depression	X	X		M	X	X						
1 2 3 [✓ 4] 5	Subsurface fluid flow								M				
1 2 [✓ 3] 4 5	Mapping contaminant plumes				M	M	X		X				
[✓ 1] 2 3 4 5	Mapping crop land salination and desalination over time					M	M						
1 [✓ 2] 3 4 5	Locating underwater ferromagnetic objects				M					M			
[✓ 1] 2 3 4 5	Mapping bedrock topography (<30-ft depth)	M			M	X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping bedrock topography (>30-ft depth)	X	M			X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping sub-bedrock structure	X	M		X	X	X					X	X
1 [✓ 2] 3 4 5	Delineating steeply dipping geologic contacts (<30-ft depth)	M			M	M	M						

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most) →	Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
	5	5	[✓ 5]	[✓ 5]	5	[✓ 5]	5	5	5	5	5	5
	[✓ 4]	[✓ 4]	4	4	[✓ 4]	4	4	4	4	4	[✓ 4]	[✓ 4]
	3	3	3	3	3	3	[✓ 3]	[✓ 3]	3	3	3	3
	2	2	2	2	2	2	2	2	[✓ 2]	[✓ 2]	2	2
	1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #1



Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 2 3 4 5	Delineating steeply dipping geologic contacts (>30-ft depth)	X	M	X		X	X			X			
[✓ 1] 2 3 4 5	Mapping fracture orientation (near-surface bedrock)	M			M								
1 [✓ 2] 3 4 5	Identifying regions of potential weakness (e.g., shear zones and faults; <30-ft depth)	M		X	M	X	X			X			
1 2 [✓ 3] 4 5	Identifying regions of potential weakness (e.g., shear zones and faults; >30-ft depth)	X	X	M		X	X			X			
[✓ 1] 2 3 4 5	Identifying near-surface karstic sinkholes and the lateral extent of their chaotic, brecciated, and otherwise disrupted ground	M	M		M	X	X				X		
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (<30 ft depth)	X	X	X	M	X	M				X	X	X
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (>30-ft depth)	X	M	M		X	X				X	X	X
[✓ 1] 2 3 4 5	Mapping water-filled cavities, tunnels	X (p-wave)	M (p-wave)	M	X							X	X
[✓ 1] 2 3 4 5	Mapping clay-filled cavities, tunnels	x	M	M		X	X						
1 [✓ 2] 3 4 5	Estimating rippability	M		X								X	X
1 2 3 [✓ 4] 5	Foundation integrity studies	M		X	M							M	M
1 2 3 [✓ 4] 5	Dam-site integrity studies	M	M	M	M	X	X		M			M	M
1 2 3 [✓ 4] 5	Landslide site evaluation	M		M	X	M	M					X	X
1 [✓ 2] 3 4 5	Locating buried well casings (metal)				M	M				M			

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)

→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	5	[✓ 5]	[✓ 5]	5	[✓ 5]	5	5	5	5	5	5
[✓ 4]	[✓ 4]	4	4	[✓ 4]	4	4	4	4	4	[✓ 4]	[✓ 4]
3	3	3	3	3	3	[✓ 3]	[✓ 3]	3	3	3	3
2	2	2	2	2	2	2	2	[✓ 2]	[✓ 2]	2	2
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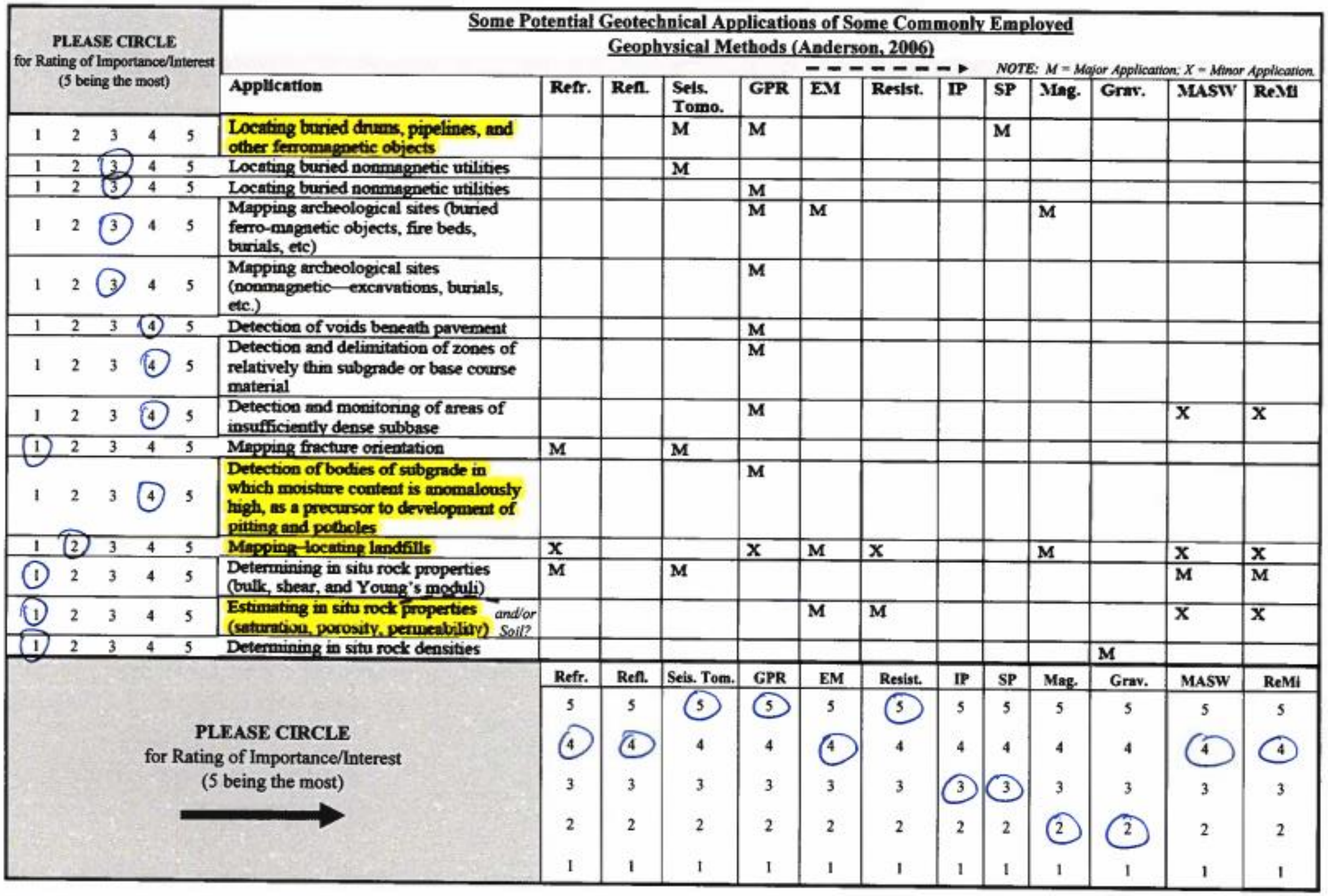
Surveyee #1



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

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 2 3 4 5	Locating buried drums, pipelines, and other ferromagnetic objects			M	M				M				
1 2 [✓ 3] 4 5	Locating buried nonmagnetic utilities			M									
1 2 [✓ 3] 4 5	Locating buried nonmagnetic utilities				M								
1 2 [✓ 3] 4 5	Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M			
1 2 [✓ 3] 4 5	Mapping archeological sites (nonmagnetic—excavations, burials, etc.)				M								
1 2 3 [✓ 4] 5	Detection of voids beneath pavement				M								
1 2 3 [✓ 4] 5	Detection and delimitation of zones of relatively thin subgrade or base course material				M								
1 2 3 [✓ 4] 5	Detection and monitoring of areas of insufficiently dense subbase				M							X	X
[✓ 1] 2 3 4 5	Mapping fracture orientation	M		M									
1 2 3 [✓ 4] 5	Detection of bodies of subgrade in which moisture content is anomalously high, as a precursor to development of pitting and potholes				M								
1 [✓ 2] 3 4 5	Mapping–locating landfills	X			X	M	X			M		X	X
[✓ 1] 2 3 4 5	Determining in situ rock properties (bulk, shear, and Young's moduli)	M		M								M	M
[✓ 1] 2 3 4 5	Estimating in situ rock properties (saturation, porosity, permeability) and/or Soil?					M	M					X	X
[✓ 1] 2 3 4 5	Determining in situ rock densities										M		

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	5	[✓ 5]	[✓ 5]	5	[✓ 5]	5	5	5	5	5	5
[✓ 4]	[✓ 4]	4	4	[✓ 4]	4	4	4	4	4	[✓ 4]	[✓ 4]
3	3	3	3	3	3	[✓ 3]	[✓ 3]	3	3	3	3
2	2	2	2	2	2	2	2	[✓ 2]	[✓ 2]	2	2
1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #2

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

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 2 3 [✓ 4] 5	Mapping lithology (<30-ft depth)	M	X		M	X	X					M	M
1 2 3 [✓ 4] 5	Mapping lithology (>30-ft depth)	X	M	X		X	X					M	M
1 2 3 [✓ 4] 5	Estimating clay-mineral content					M	X	X				X	X
1 2 3 [✓ 4] 5	Locating shallow sand and gravel deposits				M	M						X	X
1 [✓ 2] 3 4 5	Locating sand and gravel deposits (that contain heavy minerals)									M			
[✓ 1] 2 3 4 5	Determining volume of organic material in filled-in lakes or karsted features	M	M			M					M	X	X
1 2 [✓ 3] 4 5	Mapping top of ground water surface	M (p-wave)	M (p-wave)		M	M	M						
1 2 [✓ 3] 4 5	Determining water depths (including bridge scour)				M								
[✓ 1] 2 3 ~~4~~ 5	Mapping groundwater cones of depression	X	X		M	X	X						
1 2 3 [✓ 4] 5	Subsurface fluid flow								M				
1 2 3 [✓ 4] 5	Mapping contaminant plumes				M	M	X		X				
1 2 [✓ 3] 4 5	Mapping crop land salination and desalination over time					M	M						
[✓ 1] 2 3 4 5	Locating underwater ferromagnetic objects				M					M			
[✓ 1] 2 3 4 5	Mapping bedrock topography (<30-ft depth)	M			M	X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping bedrock topography (>30-ft depth)	X	M			X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping sub-bedrock structure	X	M		X	X	X					X	X
[✓ 1] 2 3 4 5	Delineating steeply dipping geologic contacts (<30-ft depth)	M			M	M	M						

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)
→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
[✓ 5]	[✓ 5]	5	5	5	[✓ 5]	[✓ 5]	5	5	5	5	5
4	4	[✓ 4]	4	4	4	4	4	4	4	[✓ 4]	[✓ 4]
3	3	3	[✓ 3]	[✓ 3]	3	3	3	3	3	3	3
2	2	2	2	2	2	2	[✓ 2]	[✓ 2]	[✓ 2]	2	2
1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #2

Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 [✓ 2] 3 4 5	Delineating steeply dipping geologic contacts (>30-ft depth)	X	M	X		X	X			X			
[✓ 1] 2 3 4 5	Mapping fracture orientation (near-surface bedrock)	M			M								
1 2 [✓ 3] 4 5	Identifying regions of potential weakness (e.g., shear zones and faults; <30-ft depth)	M		X	M	X	X			X			
1 2 [✓ 3] 4 5	Identifying regions of potential weakness (e.g., shear zones and faults; >30-ft depth)	X	X	M		X	X			X			
[✓ 1] 2 3 4 5	Identifying near-surface karstic sinkholes and the lateral extent of their chaotic, brecciated, and otherwise disrupted ground	M	M		M	X	X				X		
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (<30 ft depth)	X	X	X	M	X	M				X	X	X
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (>30-ft depth)	X	M	M		X	X				X	X	X
[✓ 1] 2 3 4 5	Mapping water-filled cavities, tunnels	X (p-wave)	M (p-wave)	M	X							X	X
[✓ 1] 2 3 4 5	Mapping clay-filled cavities, tunnels	x	M	M		X	X						
1 2 [✓ 3] 4 5	Estimating rippability	M		X								X	X
1 2 3 [✓ 4] 5	Foundation integrity studies	M		X	M							M	M
1 2 3 [✓ 4] 5	Dam-site integrity studies	M	M	M	M	X	X		M			M	M
1 2 3 [✓ 4] 5	Landslide site evaluation	M		M	X	M	M					X	X
[✓ 1] 2 3 4 5	Locating buried well casings (metal)				M	M				M			

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)
→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
[✓ 5]	[✓ 5]	5	5	5	[✓ 5]	[✓ 5]	5	5	5	5	5
4	4	[✓ 4]	4	4	4	4	4	4	4	[✓ 4]	[✓ 4]
3	3	3	[✓ 3]	[✓ 3]	3	3	3	3	3	3	3
2	2	2	2	2	2	2	[✓ 2]	[✓ 2]	[✓ 2]	2	2
1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #2

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

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
[✓ 1] 2 3 4 5	Locating buried drums, pipelines, and other ferromagnetic objects			M	M				M				
[✓ 1] 2 3 4 5	Locating buried nonmagnetic utilities			M									
[✓ 1] 2 3 4 5	Locating buried nonmagnetic utilities				M								
[✓ 1] 2 3 4 5	Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M			
[✓ 1] 2 3 4 5	Mapping archeological sites (nonmagnetic—excavations, burials, etc.)				M								
1 2 3 [✓ 4] 5	Detection of voids beneath pavement				M								
1 2 3 [✓ 4] 5	Detection and delimitation of zones of relatively thin subgrade or base course material				M								
1 2 3 [✓ 4] 5	Detection and monitoring of areas of insufficiently dense subbase				M							X	X
1 2 3 [✓ 4] 5	Mapping fracture orientation	M		M									
1 2 3 [✓ 4] 5	Detection of bodies of subgrade in which moisture content is anomalously high, as a precursor to development of pitting and potholes				M								
1 [✓ 2] 3 4 5	Mapping—locating landfills	X			X	M	X			M		X	X
[✓ 1] 2 3 4 5	Determining in situ rock properties (bulk, shear, and Young's moduli)	M		M								M	M
[✓ 1] 2 3 4 5	Estimating in situ rock properties (saturation, porosity, permeability) and/or Soil?					M	M					X	X
[✓ 1] 2 3 4 5	Determining in situ rock densities										M		

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most) →	Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
	[✓ 5]	[✓ 5]	5	5	5	[✓ 5]	[✓ 5]	5	5	5	5	5
	4	4	[✓ 4]	4	4	4	4	4	4	4	[✓ 4]	[✓ 4]
	3	3	3	[✓ 3]	[✓ 3]	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	[✓ 2]	[✓ 2]	[✓ 2]	2	2
	1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #3

Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

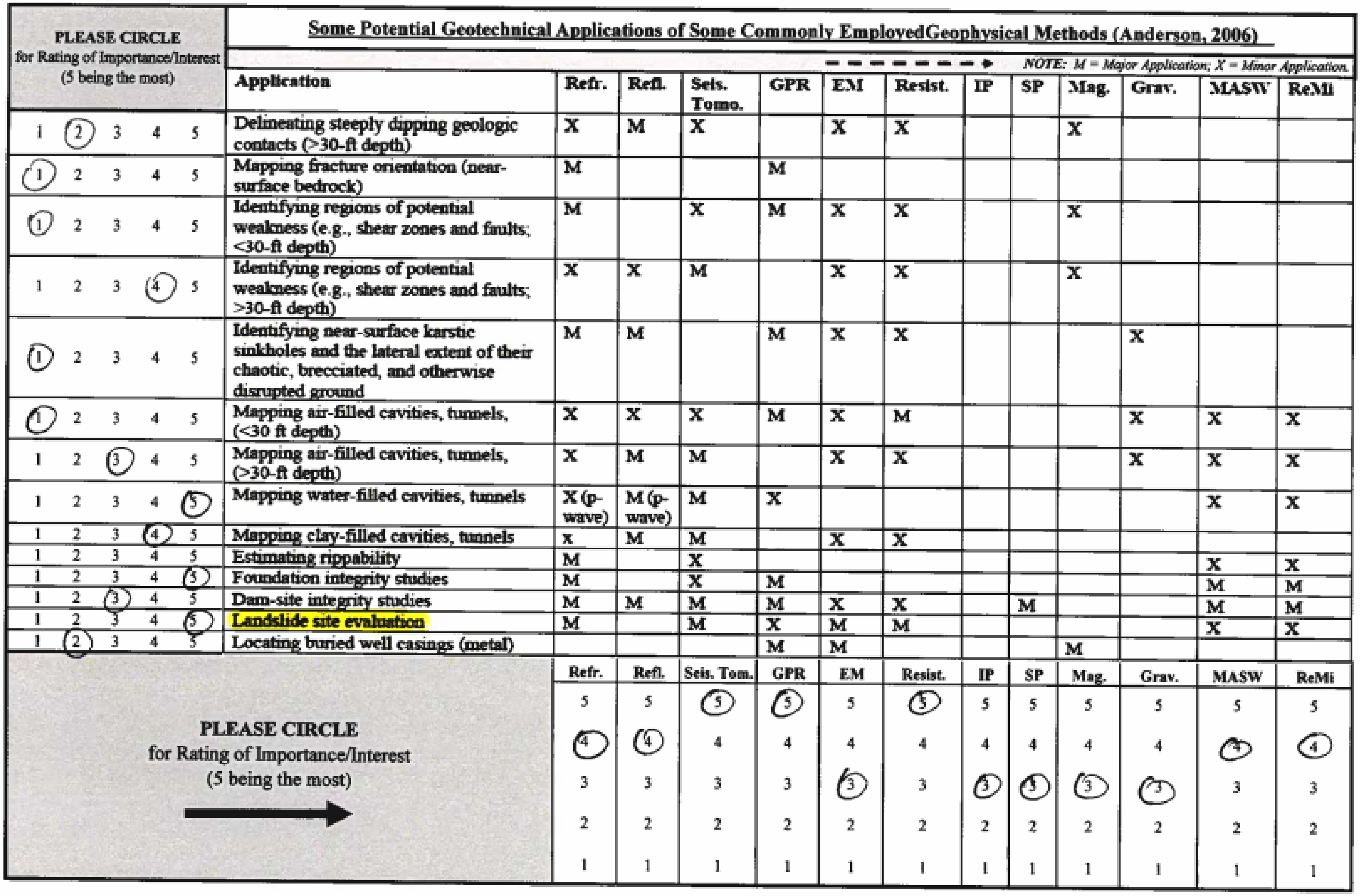
NOTE: M = Major Application; X = Minor Application.

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	**Application**	**Refr.**	**Refl.**	**Seis. Tomo.**	**GPR**	**EM**	**Resist.**	**IP**	**SP**	**Mag.**	**Grav.**	**MASW**	**ReMi**
1 2 3 4 [✓ 5]	Mapping lithology (<30-ft depth)	M	X		M	X	X					M	M
1 2 3 4 [✓ 5]	Mapping lithology (>30-ft depth)	X	M	X		X	X					M	M
1 2 3 4 [✓ 5]	Estimating clay–mineral content					M	X	X				X	X
1 2 3 [✓ 4] 5	Locating shallow sand and gravel deposits				M	M						X	X
1 2 [✓ 3] 4 5	Locating sand and gravel deposits (that contain heavy minerals)									M			
1 [✓ 2] 3 4 5	Determining volume of organic material in filled-in lakes or karsted features	M	M			M					M	X	X
1 2 3 4 [✓ 5]	Mapping top of ground water surface	M (p-wave)	M (p-wave)		M	M	M						
1 2 3 4 [✓ 5]	Determining water depths (including bridge scour)				M								
1 2 3 4 [✓ 5]	Mapping groundwater cones of depression	X	X		M	X	X						
1 2 3 4 [✓ 5]	Subsurface fluid flow								M				
1 2 3 [✓ 4] 5	Mapping contaminant plumes				M	M	X		X				
1 [✓ 2] 3 4 5	Mapping crop land salination and desalination over time					M	M						
1 2 [✓ 3] 4 5	Locating underwater ferromagnetic objects				M					M			
[✓ 1] 2 3 4 5	Mapping bedrock topography (<30-ft depth)	M			M	X	X				X	M	M
1 2 [✓ 3] 4 5	Mapping bedrock topography (>30-ft depth)	X	M			X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping sub-bedrock structure	X	M		X	X	X					X	X
[✓ 1] 2 3 4 5	Delineating steeply dipping geologic contacts (<30-ft depth)	M			M	M	M						

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)
→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	5	[✓ 5]	[✓ 5]	5	[✓ 5]	5	5	5	5	5	5
[✓ 4]	[✓ 4]	4	4	4	4	4	4	4	4	[✓ 4]	[✓ 4]
3	3	3	3	[✓ 3]	3	[✓ 3]	[✓ 3]	[✓ 3]	[✓ 3]	3	3
2	2	2	2	2	2	2	2	2	2	2	2
1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #3



Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

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

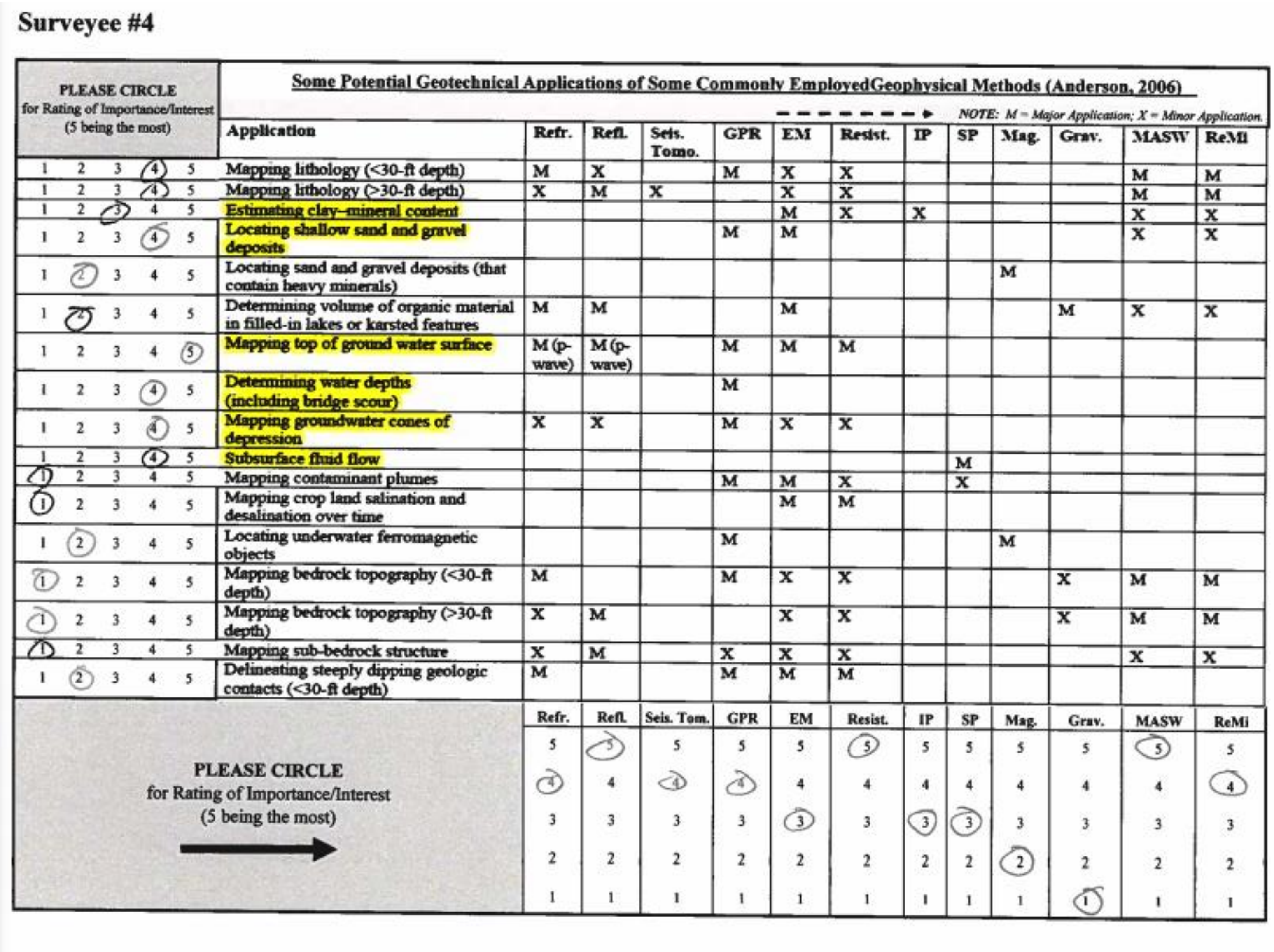
PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 [✓ 2] 3 4 5	Delineating steeply dipping geologic contacts (>30-ft depth)	X	M	X		X	X			X			
[✓ 1] 2 3 4 5	Mapping fracture orientation (near-surface bedrock)	M			M								
[✓ 1] 2 3 4 5	Identifying regions of potential weakness (e.g., shear zones and faults; <30-ft depth)	M		X	M	X	X			X			
1 2 3 [✓ 4] 5	Identifying regions of potential weakness (e.g., shear zones and faults; >30-ft depth)	X	X	M		X	X			X			
[✓ 1] 2 3 4 5	Identifying near-surface karstic sinkholes and the lateral extent of their chaotic, brecciated, and otherwise disrupted ground	M	M		M	X	X				X		
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (<30 ft depth)	X	X	X	M	X	M				X	X	X
1 2 [✓ 3] 4 5	Mapping air-filled cavities, tunnels, (>30-ft depth)	X	M	M		X	X				X	X	X
1 2 3 4 [✓ 5]	Mapping water-filled cavities, tunnels	X (p-wave)	M (p-wave)	M	X							X	X
1 2 3 [✓ 4] 5	Mapping clay-filled cavities, tunnels	x	M	M		X	X						
1 2 3 4 5	Estimating rippability	M		X								X	X
1 2 3 4 [✓ 5]	Foundation integrity studies	M		X	M							M	M
1 2 [✓ 3] 4 5	Dam-site integrity studies	M	M	M	M	X	X		M			M	M
1 2 3 4 [✓ 5]	Landslide site evaluation	M		M	X	M	M					X	X
1 [✓ 2] 3 4 5	Locating buried well casings (metal)				M	M				M			

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	5	[✓ 5]	[✓ 5]	5	[✓ 5]	5	5	5	5	5	5
[✓ 4]	[✓ 4]	4	4	4	4	4	4	4	4	[✓ 4]	[✓ 4]
3	3	3	3	[✓ 3]	3	[✓ 3]	[✓ 3]	[✓ 3]	[✓ 3]	3	3
2	2	2	2	2	2	2	2	2	2	2	2
1	1	1	1	1	1	1	1	1	1	1	1

Surveyee #3

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Some Potential Geotechnical Applications of Some Commonly Employed Geophysical Methods (Anderson, 2006) - - - - - - - ► NOTE: *M = Major Application; X = Minor Application.*												
	Application	**Refr.**	**Refl.**	**Seis. Tomo.**	**GPR**	**EM**	**Resist.**	**IP**	**SP**	**Mag.**	**Grav.**	**MASW**	**ReMi**
1 2 3 4 [✓ 5]	Locating buried drums, pipelines, and other ferromagnetic objects			M	M				M				
1 2 3 [✓ 4] 5	Locating buried nonmagnetic utilities			M									
1 2 3 4 5	Locating buried nonmagnetic utilities				M								
1 [✓ 2] 3 4 5	Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M			
1 [✓ 2] 3 4 5	Mapping archeological sites (nonmagnetic—excavations, burials, etc.)				M								
1 2 3 4 [✓ 5]	Detection of voids beneath pavement				M								
1 2 3 4 [✓ 5]	Detection and delimitation of zones of relatively thin subgrade or base course material				M								
1 2 3 [✓ 4] 5	Detection and monitoring of areas of insufficiently dense subbase				M							X	X
1 [✓ 2] 3 4 5	Mapping fracture orientation	M		M									
1 2 3 4 [✓ 5]	Detection of bodies of subgrade in which moisture content is anomalously high, as a precursor to development of pitting and potholes				M								
1 2 3 [✓ 4] 5	Mapping–locating landfills	X			X	M	X			M		X	X
1 [✓ 2] 3 4 5	Determining in situ rock properties (bulk, shear, and Young's moduli)	M		M								M	M
1 2 3 4 [✓ 5]	Estimating in situ rock properties and/or Soil? (saturation, porosity, permeability)					M	M					X	X
1 [✓ 2] 3 4 5	Determining in situ rock densities										M		
		Refr.	**Refl.**	**Seis. Tom.**	**GPR**	**EM**	**Resist.**	**IP**	**SP**	**Mag.**	**Grav.**	**MASW**	**ReMi**
PLEASE CIRCLE for Rating of Importance/Interest (5 being the most) →		5	5	[✓ 5]	[✓ 5]	5	[✓ 5]	5	5	5	5	5	5
		[✓ 4]	[✓ 4]	4	4	4	4	4	4	4	4	[✓ 4]	[✓ 4]
		3	3	3	3	[✓ 3]	3	[✓ 3]	[✓ 3]	[✓ 3]	[✓ 3]	3	3
		2	2	2	2	2	2	2	2	2	2	2	2
		1	1	1	1	1	1	1	1	1	1	1	1



Surveyee #4

Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

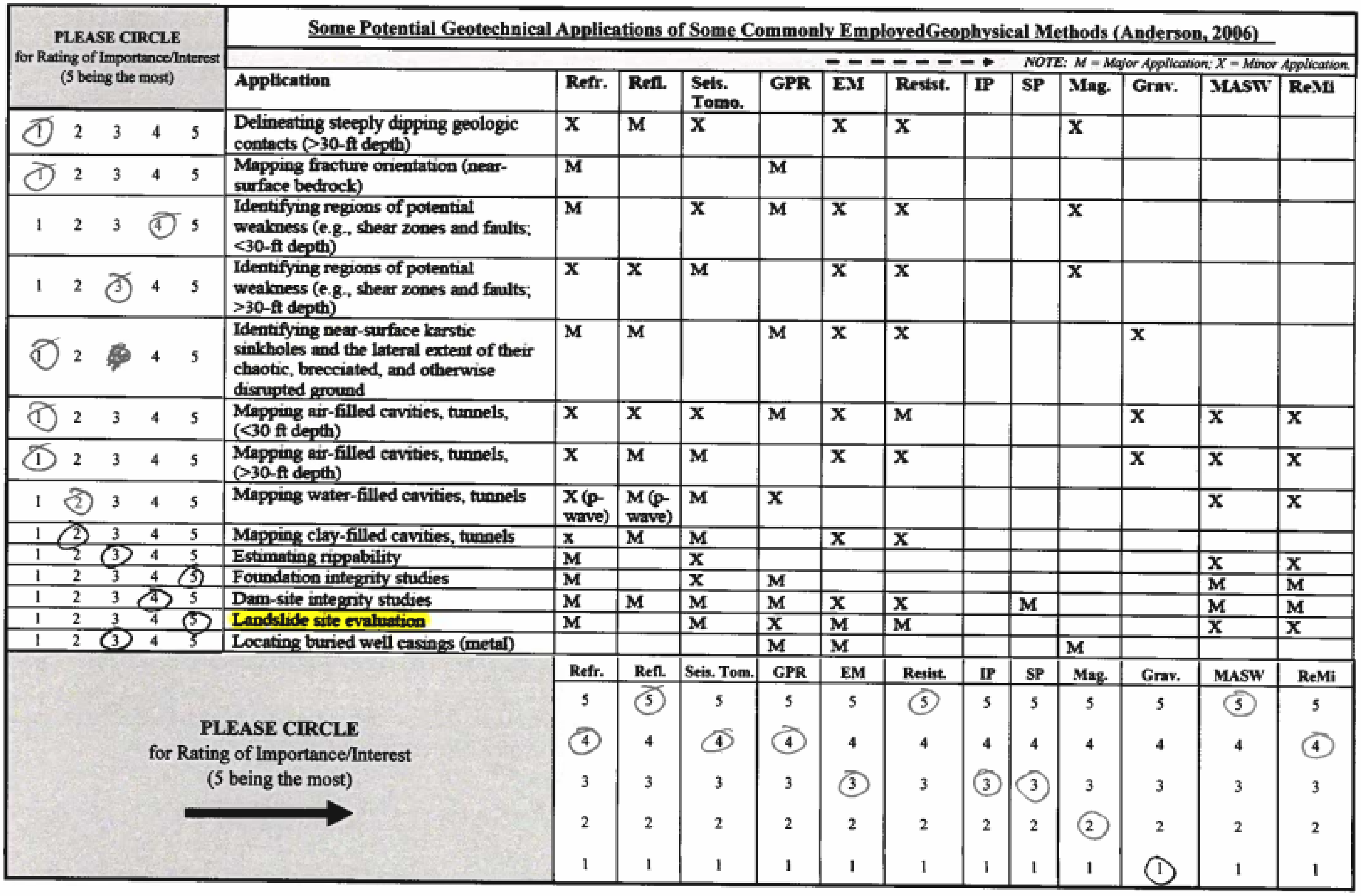
NOTE: M = Major Application; X = Minor Application.

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 2 3 [✓ 4] 5	Mapping lithology (<30-ft depth)	M	X		M	X	X					M	M
1 2 3 [✓ 4] 5	Mapping lithology (>30-ft depth)	X	M	X		X	X					M	M
1 2 [✓ 3] 4 5	Estimating clay–mineral content					M	X	X				X	X
1 2 3 [✓ 4] 5	Locating shallow sand and gravel deposits				M	M						X	X
1 [✓ 2] 3 4 5	Locating sand and gravel deposits (that contain heavy minerals)									M			
1 [✓ 2] 3 4 5	Determining volume of organic material in filled-in lakes or karsted features	M	M			M					M	X	X
1 2 3 4 [✓ 5]	Mapping top of ground water surface	M (p-wave)	M (p-wave)		M	M	M						
1 2 3 [✓ 4] 5	Determining water depths (including bridge scour)				M								
1 2 3 [✓ 4] 5	Mapping groundwater cones of depression	X	X		M	X	X						
1 2 3 [✓ 4] 5	Subsurface fluid flow								M				
[✓ 1] 2 3 4 5	Mapping contaminant plumes				M	M	X		X				
[✓ 1] 2 3 4 5	Mapping crop land salination and desalination over time					M	M						
1 [✓ 2] 3 4 5	Locating underwater ferromagnetic objects				M					M			
[✓ 1] 2 3 4 5	Mapping bedrock topography (<30-ft depth)	M			M	X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping bedrock topography (>30-ft depth)	X	M			X	X				X	M	M
[✓ 1] 2 3 4 5	Mapping sub-bedrock structure	X	M		X	X	X					X	X
1 [✓ 2] 3 4 5	Delineating steeply dipping geologic contacts (<30-ft depth)	M			M	M	M						

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)
→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	[✓ 5]	5	5	5	[✓ 5]	5	5	5	5	[✓ 5]	5
[✓ 4]	4	[✓ 4]	[✓ 4]	4	4	4	4	4	4	4	[✓ 4]
3	3	3	3	[✓ 3]	3	[✓ 3]	[✓ 3]	3	3	3	3
2	2	2	2	2	2	2	2	[✓ 2]	2	2	2
1	1	1	1	1	1	1	1	1	[✓ 1]	1	1

Surveyee #4



Some Potential Geotechnical Applications of Some Commonly EmployedGeophysical Methods (Anderson, 2006)

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

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
[✓ 1] 2 3 4 5	Delineating steeply dipping geologic contacts (>30-ft depth)	X	M	X		X	X			X			
[✓ 1] 2 3 4 5	Mapping fracture orientation (near-surface bedrock)	M			M								
1 2 3 [✓ 4] 5	Identifying regions of potential weakness (e.g., shear zones and faults; <30-ft depth)	M		X	M	X	X			X			
1 2 [✓ 3] 4 5	Identifying regions of potential weakness (e.g., shear zones and faults; >30-ft depth)	X	X	M		X	X			X			
[✓ 1] 2 [illegible] 4 5	Identifying near-surface karstic sinkholes and the lateral extent of their chaotic, brecciated, and otherwise disrupted ground	M	M		M	X	X				X		
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (<30 ft depth)	X	X	X	M	X	M				X	X	X
[✓ 1] 2 3 4 5	Mapping air-filled cavities, tunnels, (>30-ft depth)	X	M	M		X	X				X	X	X
1 [✓ 2] 3 4 5	Mapping water-filled cavities, tunnels	X (p-wave)	M (p-wave)	M	X							X	X
1 [✓ 2] 3 4 5	Mapping clay-filled cavities, tunnels	x	M	M		X	X						
1 2 [✓ 3] 4 5	Estimating rippability	M		X								X	X
1 2 3 4 [✓ 5]	Foundation integrity studies	M		X	M							M	M
1 2 3 [✓ 4] 5	Dam-site integrity studies	M	M	M	M	X	X		M			M	M
1 2 3 4 [✓ 5]	Landslide site evaluation	M		M	X	M	M					X	X
1 2 [✓ 3] 4 5	Locating buried well casings (metal)				M	M				M			

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)
→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	[✓ 5]	5	5	5	[✓ 5]	5	5	5	5	[✓ 5]	5
[✓ 4]	4	[✓ 4]	[✓ 4]	4	4	4	4	4	4	4	[✓ 4]
3	3	3	3	[✓ 3]	3	[✓ 3]	[✓ 3]	3	3	3	3
2	2	2	2	2	2	2	2	[✓ 2]	2	2	2
1	1	1	1	1	1	1	1	1	[✓ 1]	1	1

Surveyee #4

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

- - - - - - - - ▸ *NOTE: M = Major Application; X = Minor Application.*

PLEASE CIRCLE for Rating of Importance/Interest (5 being the most)	Application	Refr.	Refl.	Seis. Tomo.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
1 2 3 4 [✓ 5]	Locating buried drums, pipelines, and other ferromagnetic objects			M	M				M				
1 2 3 [✓ 4] 5	Locating buried nonmagnetic utilities			M									
1 2 [✓ 3] 4 5	Locating buried nonmagnetic utilities				M								
1 [✓ 2] 3 4 5	Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)				M	M				M			
1 2 [✓ 3] 4 5	Mapping archeological sites (nonmagnetic—excavations, burials, etc.)				M								
1 2 3 4 [✓ 5]	Detection of voids beneath pavement				M								
1 2 3 [✓ 4] 5	Detection and delimitation of zones of relatively thin subgrade or base course material				M								
1 2 3 [✓ 4] 5	Detection and monitoring of areas of insufficiently dense subbase				M							X	X
1 [✓ 2] 3 4 5	Mapping fracture orientation	M		M									
1 2 3 [✓ 4] 5	Detection of bodies of subgrade in which moisture content is anomalously high, as a precursor to development of pitting and potholes				M								
1 2 [✓ 3] 4 5	Mapping–locating landfills	X			X	M	X			M		X	X
[✓ 1] 2 3 4 5	Determining in situ rock properties (bulk, shear, and Young's moduli)	M		M								M	M
1 [✓ 2] 3 4 5	Estimating in situ rock properties (saturation, porosity, permeability) and/or Soil?					M	M					X	X
[✓ 1] 2 3 4 5	Determining in situ rock densities										M		

PLEASE CIRCLE
for Rating of Importance/Interest
(5 being the most)
→

Refr.	Refl.	Seis. Tom.	GPR	EM	Resist.	IP	SP	Mag.	Grav.	MASW	ReMi
5	[✓ 5]	5	5	5	[✓ 5]	5	5	5	5	[✓ 5]	5
[✓ 4]	4	[✓ 4]	[✓ 4]	4	4	4	4	4	4	4	[✓ 4]
3	3	3	3	[✓ 3]	3	[✓ 3]	[✓ 3]	3	3	3	3
2	2	2	2	2	2	2	2	[✓ 2]	2	2	2
1	1	1	1	1	1	1	1	1	[✓ 1]	1	1

Appendix II

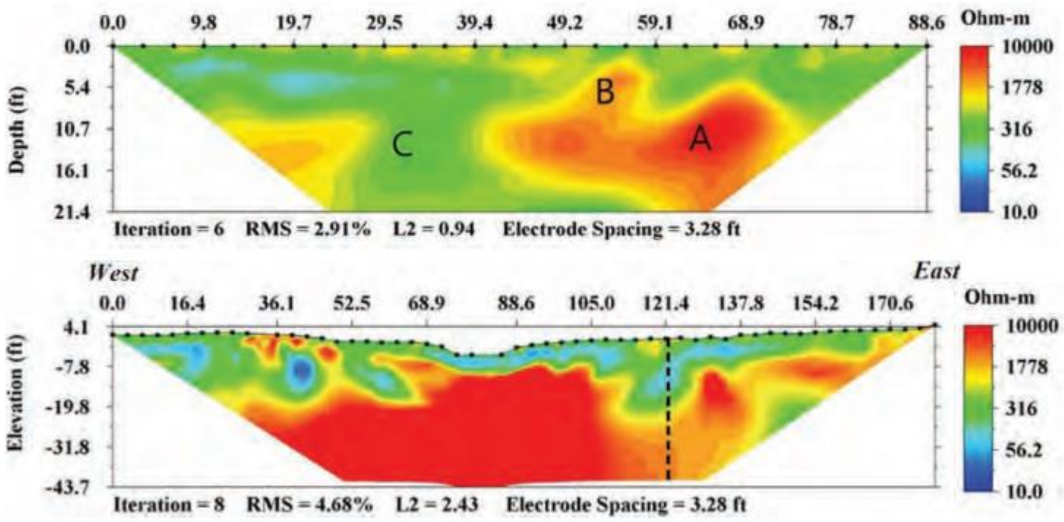
MnDOT Case Study: Bridge over Miller Creek in Duluth, Minnesota [3]

An early application of ER by MnDOT took place in 2006 in Duluth, Minnesota, at the site of a new bridge, roadway, and retaining walls. The decision to use a shallow or a deep foundation for the new bridge at this site required information about the depth to bedrock. Although bedrock is typically around 20 ft. deep in this area, nearby borings showed bedrock at 40 ft. The description that follows is taken from the Richter (2010) paper and the phone interview with MnDOT personnel.

Access to the proposed bridge location for site investigation was difficult. Property owners denied access because of concerns about property damage and because Miller Creek, which runs through the area, is a designated trout stream. Because of these restrictions, MnDOT determined that traditional soil and rock borings and cone penetration test soundings could not be used. Instead, MnDOT used its newly acquired ER system to obtain subsurface information. Soil conditions within the bridge area were complex, with variably saturated silty, sandy, and gravelly organic soil and many boulders present (Richter 2010). Two ER surveys were performed, the first using 28 electrodes with 1-m spacing and the second performed orthogonally to the first using 56 electrodes with 1-m spacing.

In this case, the resistivity results were interpreted without the benefit of boreholes for corroboration. The results generally showed a large contrast in resistivity at about 10 ft., which was attributable to the change between the more conductive near-surface soils and the underlying bedrock (Figure 18). Noisy data in the western portion of the survey produced artifacts that complicated the interpretation (Figure 18, bottom). Region C in Figure 18 (top) indicates a low-resistivity region in the interpreted bedrock, which was thought to be either a glacial pothole or a zone of highly weathered or fractured bedrock. The high-resistivity regions A and B in Figure 18 (top) were thought to be knobs of the gabbro bedrock.

Figure 18. Resistivity results along north-south line (top) and east-west line (bottom) showing shallow bedrock starting at about 10 ft. (courtesy of MnDOT) [3]



The survey results were communicated to personnel from the bridge office and the Duluth district. Before the survey, the default foundation option had been to use drilled piles because no information was available to support other options. The results from the resistivity survey, however, provided support for using shallow foundations on the east side of the creek for the retaining walls and bridge abutment and possibly on the west side. Shallow foundations were designed for the east end of the abutment, and deep foundation elements were designed for the west end with the option to switch to shallow foundations. When excavations were performed for the foundation, bedrock was encountered within 10 ft. of the surface on both the east and the west side of the creek, which precluded the need for the deep foundation elements originally designed for the west side. The excavation also offered an opportunity to ground-truth the resistivity results. The exposed excavation showed two bedrock knobs (A and B) and a pocket of weathered and highly fractured bedrock (C), as shown in Figure 19.

Figure 19. Photo of excavated site associating features with two high resistivity regions (A and B) and low resistivity region (C) in resistivity results (courtesy of MnDOT) [3]

Primarily because of differences in material and equipment costs, MnDOT saw a modest cost savings of between $50,000 to $100,000 by constructing shallow foundations [Richter 2010]. This project was the first time that MnDOT had based a bridge design solely on geophysical data. Because of its novel approach, the project was given an award for bridge construction by the General Contractors of America. More importantly, the project instilled in MnDOT personnel confidence in their use of geophysical methods.

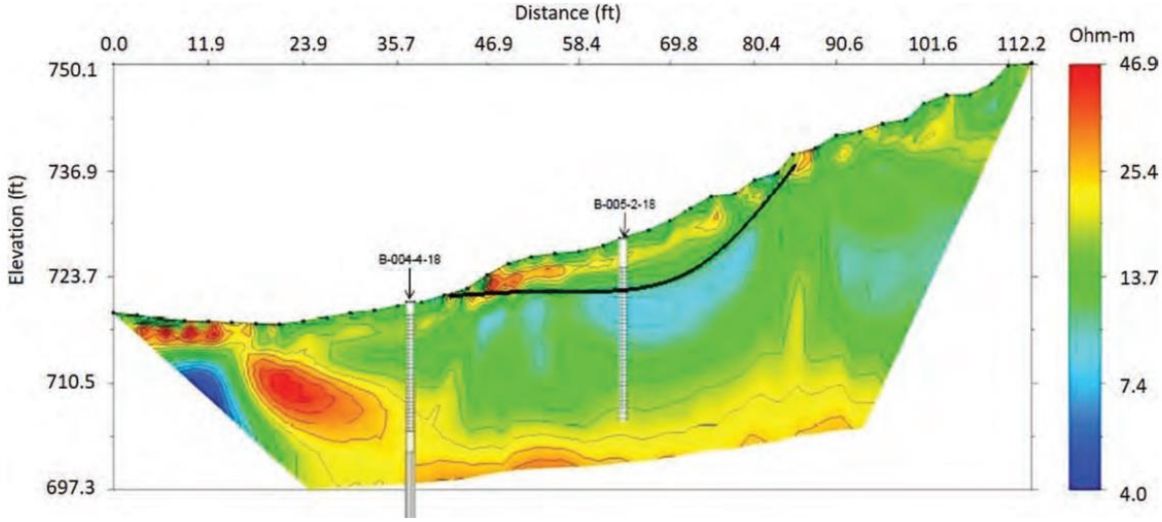
ODOT Case Study 1: Imaging a Shallow Embankment Failure in Northwest Ohio [3]

Paulding County in northwestern Ohio lies within the Paulding Clay Basin physiographic region, an area characterized as a nearly flat lacustrine plain. Soils are typically high-plastic clays, which tend to have poor long-term strength when used for embankment construction. The project area is where US-24 passes over a county road and a railroad spur. The embankments were experiencing instability at all four quadrants of the overpass, with the northeastern quadrant exhibiting the greatest distress. The surface features indicated a shallow surficial sloughing of the outer embankment soils.

A subsurface exploration was planned to determine the failure mode of the embankment using traditional borings, dynamic cone penetration (DCP) soundings, and geophysical surveys. Borings were completed at the top, mid-slope, and base of the embankment. Inclinometers were installed mid-slope and at the toe to determine a failure surface. The DCP soundings were completed in sections with the borings to confirm the potential sliding surface. In addition to the traditional exploration techniques, an ER imaging survey was completed perpendicular to the roadway down the embankment slope.

The traditional exploration and monitoring techniques indicated that the shallow embankment failure was a result of saturated and low-strength soils along the outer embankment slope. The ER survey indicated a shallow layer of higher-resistivity material underlain by low-resistivity material (Figure 20). This contrast in resistivity was probably attributable to higher moisture contents along the failure surface. The results from the ER survey showed strong agreement with slope inclinometer data from the site, which showed the slide surface at a depth of 4-6 ft.

Figure 20. Profile of ER measurements performed over shallow landslide with approximate slide surface shown with solid black line separating high-resistivity material from lower-resistivity material below (courtesy of ODOT) [3]

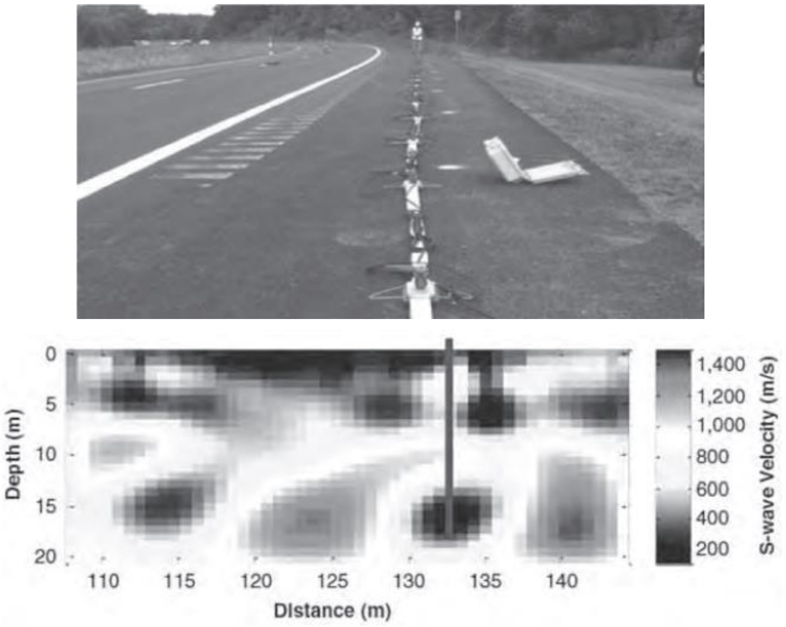


Informed by the results of this project, ODOT expects to use ER surveys in the future to image shallow embankment failures and to minimize the disturbance and effort needed for traditional drilling exploration at mid-slope locations.

ODOT Case Study 2: Full Waveform Inversion to Characterize Abandoned Mines [3]

While many other seismic methods are based on matching first arrival times of recorded waveforms, full waveform inversion (FWI) works by developing a subsurface model that provides a match to the full-recorded waveform at each location. The 2D FWI technique was applied by researchers from Clarkson University to image abandoned underground coal mines under US 33 in Athens County, Ohio. The description that follows is summarized from Sullivan et al. (2016). The test area selected was thought to be a likely location of abandoned mines. Previous borings performed by ODOT showed a 1.5-2.5-m thick coal seam located about 12-18 m below the surface, with the overburden consisting of clay shales and sandstones. A total length of 576 m was investigated using test segments of 36 m consisting of 24 4.5-Hz geophone receivers spaced at intervals of 1.5 m (Figure 21). A sledgehammer source was used to excite energy at 25 locations spaced 1.5 m apart along the geophone spread, and a land streamer was used to collect the data, which allowed for rapid data collection along the roadway.

Figure 21. (top) Land streamer of geophone used to collect data; (bottom) Inverted image of shear wave velocities showing low-velocity region at depth of about 15 m (Sullivan et al. 2016) [3]



The results indicated the presence of two anomalies along the profile. The results from one of the segments that contained an anomaly are shown in Figure 21. A low shear wave velocity anomaly is observed at a depth of about 15 m in the image. Borings performed at this location about three weeks after the measurement showed the presence of a void over the depth range of 13.8-14.6 m. The other suspected void was also confirmed with drilling.

This case example shows the capabilities of one of the more advanced seismic methods, full waveform inversion. The method successfully detected small voids at depths of about 15 m, although the size of the void appeared to be overestimated by the FWI results.

Caltrans Case Study: Freeway Improvement Project at Interstate 80 and Willow Avenue in Contra Costa County [3]

Refraction tomography is the most common surface method used by Caltrans and has largely replaced conventional refraction processing. An example of the use of borehole-to-surface refraction tomography for a freeway improvement project at Interstate 80 and Willow Avenue in Contra Costa County is presented here.

The site is located near a heavily traveled urban freeway, whose traffic produced significant broad-band seismic noise. Refraction tomography measurements were performed to fill in information between two boreholes spaced approximately 60 m apart at the site, as shown in Figure 22. The depth to rock at these two boreholes varied from about 3 m to the north to 20 m to the south. Because a limited footprint was available for performing surface refraction measurements, two source shots were performed at depth in the borehole in addition to the surface shots, in an effort to adequately image the deep end of the profile. The ray coverage produced by this shot arrangement is shown in Figure 23, where the hit count indicates the number of rays passing through a pixel. The refraction tomography results provided an excellent image of the variable subsurface conditions between the boreholes, as shown in Figure 24. For comparison, the pseudo ray path model without the borehole shots is shown in Figure 25. When the borehole shots are not included, the depth of resolution is greatly limited and the measurement is unable to image the deeper rock. These results illustrate the dramatic effect of adding just a few borehole shots on the depth resolution of refraction tomography measurements.

Figure 22. Plan view of location of refraction tomography measurements used to fill in between two boreholes at project site (courtesy of Caltrans) [3]

Figure 23. Pseudo ray path model for velocity section shown in Figure 24 (courtesy of Caltrans) [3]

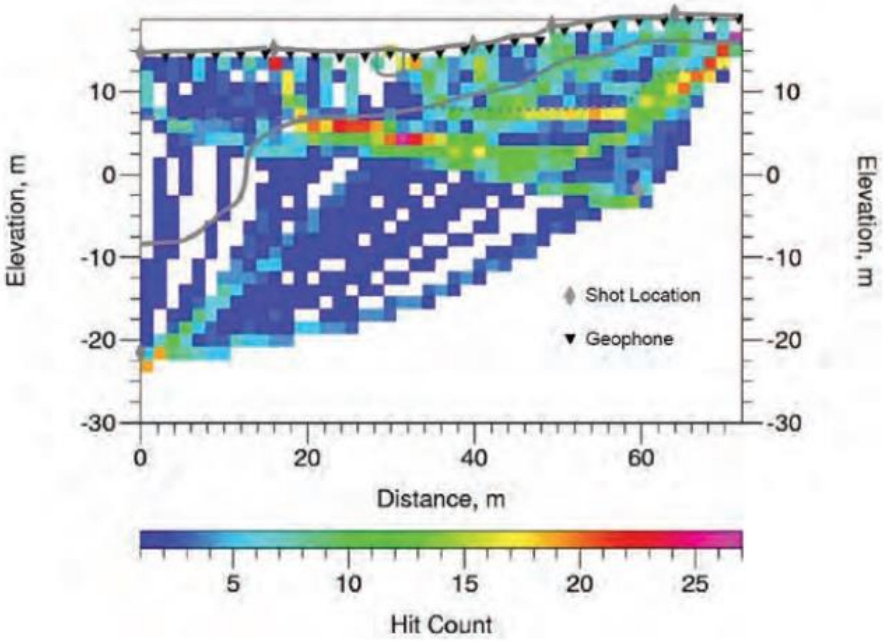


Figure 24. Velocity model and lithology interpretation between boreholes using borehole logs and borehole-to-surface tomography at I-80 and Willow site (courtesy of Caltrans) [3]

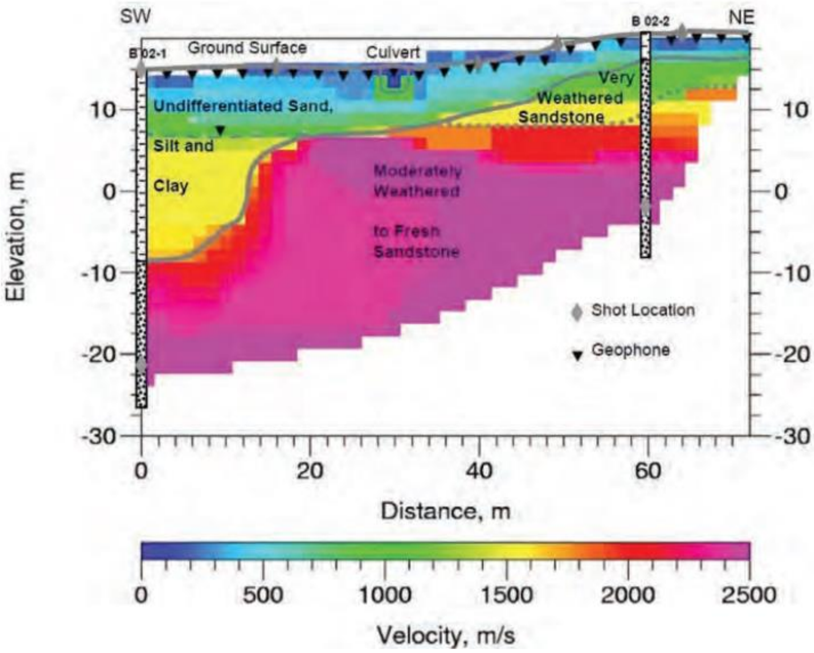


Figure 25. Pseudo ray path model using only surface sources, showing change in depth of investigation (courtesy of Caltrans) [3]