Ontario

Ontario Ministry of Transportation (MTO)

Guideline for Geophysical Investigations for Foundations Engineering Applications

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NOTICE TO USER

This guideline is intended for the approved consultants (the Service Provider) in MTO's consultant acquisition system, "Registry, Appraisal and Qualification System (RAQS)" in low, medium and high complexity for Foundation Engineering.

The Service Provider undertaking a MTO Foundation Engineering assignment must refer to the project Terms of Reference (TOR) for project scope details and required services to successfully complete all the necessary tasks and to verify that all MTO Foundation Engineering requirements are met. The minimum requirements for Foundation Engineering specified in the project TOR shall govern where any conflict exist with this Guideline.

MTO Foundation Office is the custodian for this guideline. This guideline may be amended by the MTO Foundation Office in the future as required to maintain and ensure quality of Geophysical Investigation Services and related services for MTO projects.

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1 OVERVIEW

This guideline presents and discusses the use of common geophysical investigation methodologies for typical applications relating to Ontario Ministry of Transportation (MTO) Foundations Engineering Services. The general applications discussed herein include:

- Seismic site classification
- Stratigraphic profiling, especially for extensive and/or remote areas
    - Subsurface modelling
    - Groundwater modelling
    - Depth to bedrock
- Detection and delineation of voids, man-made utilities, and obstructions
- Re-use of existing foundations
- Offshore investigation

This guideline is intended to aid in the consistent design and implementation of geophysical investigations for the above-noted applications. It is intended that this guideline will also enhance the quality of geophysical investigations performed for MTO assignments by serving as a broad reference for designers and consultants needing to retain and communicate with experienced geophysical subconsultants.

The provided information is generic in nature and the applicability to project-specific site conditions and requirements should be evaluated on a case-by-case basis. The Service Provider undertaking the Foundation Engineering assignment must refer to the project Terms of Reference (TOR) to verify the project-specific requirements. Furthermore, the Service Provider must employ sound engineering judgement to successfully complete all the necessary tasks. Operation of geophysical equipment must be in accordance with the instructions provided by the manufacturer.

The minimum requirements described in the latest version of MTO's Guideline for Foundation Engineering Services should be referenced for other aspects of Foundation Engineering Services beyond the scope of this document.

1.1 Guideline Layout

This guideline is organized into three main parts.

Part I: An overview of commonly employed geophysical investigation methods is provided. Further details are presented in **Appendix A**, including high-level theory and discussion on various field techniques and analysis of data. Typical advantages and limitations associated with these methods are presented, with some additional commentary on relative costs where data was available.

Part II: The application and selection of geophysical investigation methods to specific challenges is discussed. For each application, several methods expected to be well-suited to overcoming the stated challenges are identified. The advantages and limitations of these methods are discussed in more detail with respect to the specified investigation objective(s) for different site conditions. Guidance on the investigation design and the selection of one or more appropriate methods is provided.

Part III: Reporting requirements for geophysical investigation reports prepared for MTO projects are discussed.

1.2 Selected Reference Materials

This guideline has been prepared with a focus on the application of geophysical investigation techniques to address some specific challenges faced by MTO. The theoretical background and general information on the methodologies presented herein is derived from a review of the available literature. Some comprehensive existing guidelines and studies which are suggested for further reading are listed below. A full list of references is provided at the end of this document.

Selected Guidelines, Textbooks, and Reports

- AGAP. (2024). *Les Fiches de Bonne Pratique*. https://www.agapqualite.org/les-fiches-de-bonne-pratique/
- J. A. Hunter, & H. L. Crow (Eds.) (2015). *Shear Wave Velocity Measurement Guidelines for Canadian Seismic Site Characterization in Soil and Rock*. Geological Survey of Canada.
- Everett, M. E. (2013). *Near-Surface Applied Geophysics*. New York: Cambridge University Press.
- Lowrie, W. (2007). *Fundamentals of Geophysics* (2nd ed.). Cambridge: Cambridge University Press.
- Hertlein, B., & Davis, A. (2006). *Nondestructive Testing of Deep Foundations*. West Sussex: John Wiley & Sons, Ltd.
- Wightman, W. E., Jalinoos, F., Sirles, P., & Hanna, K. (2004). *Application of Geophysical Methods to Highway Related Problems*. Washington: U.S. Department of Transportation, Federal Highway Administration.
- Milsom, J. (2003). *Field Geophysics* (3rd ed.). Chichester: John Wiley & Sons Ltd.
- Yilmaz, O. (2001). *Seismic Data Processing*. Tulsa: Society of Exploration Geophysicists.
- U.S. Army Corps of Engineers (1995). *Geophysical Exploration for Engineering and Environmental Investigations*. EM 1110-1-1802. Washington, DC.
- Eastern Research Group, Inc. (1993). *Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide*. Washington: US EPA.

ASTM Standards

- D6429, Standard Guide for Selecting Surface Geophysical Methods
- D5753, Standard Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging

- D5777, Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation
- D7128, Standard Guide for Using the Seismic Reflection Method for Shallow Subsurface Investigation
- D6431, Standard Guide for Using the Direct Current Resistivity Method for Subsurface Site Characterization
- G57, Standard Test Method for Measurement of Soil Resistivity Using the Wenner Four-Electrode Method
- D6639, Standard Guide for Using the Frequency-Domain Electromagnetic Method for Subsurface Site Characterizations
- D6820, Standard Guide for Use of the Time Domain Electromagnetic Method for Geophysical Subsurface Site Investigation
- D6432, Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation
- D6430, Standard Guide for Using the Gravity Method for Subsurface Site Characterization
- D5882, Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations
- D6760, Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing

MTO Publications

- Sadrekarimi, A., Molnar, S., & Darko, A. B. (2023). *Geophysical Methods for Subsurface Characterization*. Toronto: MTO.

PART I:

Overview of Geophysical Investigation Methods

2 INTRODUCTION TO GEOTECHNICAL GEOPHYSICS

2.1 What is Geotechnical Geophysics?

Geophysical investigation involves the use of geophysical techniques to collect data for the purpose of ascertaining subsurface conditions. These techniques are non-destructive and can be subcategorized as either active or passive methods depending on the input energy source. Active methods involve exerting a force, emitting energy, or creating a potential field to stimulate a response by the target material. Passive methods involve measuring the naturally occurring potential field generated by the target material.

2.2 Why use Geotechnical Geophysics?

Conventional investigations for foundations engineering applications typically involve drilled boreholes or probes, in-situ testing such as CPTU/PMT, monitoring wells, or test pits, supported by laboratory testing programs. It is noted that the scope of these conventional investigations could be reduced considerably by conducting a geophysical investigation, particularly when a site is large, or access is challenging. Furthermore, it may be impractical to drill a sufficient quantity of boreholes to characterize a site with variable subsurface conditions.

2.3 Supporting Investigations

While there can be tremendous value in geophysical investigations, it must be stressed that they should not be viewed as a *substitution* for conventional investigations. Rather, geophysical investigations are considered complementary to these conventional investigation techniques.

It is best practice to supplement a geophysical investigation with invasive investigation techniques. The invasive investigation may take the form of borehole drilling and sampling, monitoring well measurements, or test pits, or could involve the extraction or daylighting of buried structures or features. Physical observations derived from boreholes and samples should be collected to facilitate the development of a successful geophysical investigation strategy, to calibrate geophysical data and modelled properties, and to confirm conditions at key locations or depths (“ground truthing”).

Geophysical data requires skillful interpretation and reliance upon a single source of data may be subject to elevated risk due to the non-uniqueness of geophysical anomalies. This non-uniqueness highlights the importance of collecting physical observations to complement the geophysical data. The risk posed by non-uniqueness can be further mitigated by adopting multiple geophysical methods which exploit different (unrelated) physical phenomena.

2.4 Conveyance Modes

Geophysical investigation can be undertaken at, below, or above the ground surface. The relative advantages, challenges, and general considerations for each approach are discussed in the following sections.

2.4.1 Surface

Geophysical investigations are most commonly conducted from surface. Investigations from surface are non-intrusive and allow for data collection over vast areas. However, these surveys are often limited by physical site access (e.g., where difficult terrain, water bodies, or dense vegetation exists). Geophysical methods often deployed from the ground surface include ground penetrating radar (GPR), seismic, electromagnetic, and electrical resistivity imaging (ERI). Ground surveys are often the most economic option, as equipment and experienced service providers are readily accessible.

2.4.2 Subsurface

Geophysical investigations may also be conducted within the subsurface. Boreholes are a standard geotechnical investigation method included in most projects. Taking advantage of the subsurface access provided by boreholes allows for use of geophysical methods at greater depths of investigation than might be possible or practical from surface. Subsurface techniques are sometimes used to bypass near-surface materials which would otherwise attenuate signal energy, or to distance the source and/or sensor from sources of noise.

Geophysical methods which are adaptable to subsurface conveyance modes include but may not be limited to seismic, electrical/electromagnetic, nuclear, and magnetometry. Subsurface investigations require some special access considerations, primarily focused on drill rig logistics, utility locates, and ground disturbance permitting. Due to the use of a drill rig, subsurface investigation tends to be more expensive than surface investigation, unless boreholes are already present or included as adjacent scope.

2.4.3 Airborne and Submarine

There is an increasing utilization of drones and Remote Operated Vehicles (ROV) for geophysical surveys. These technologies offer significant advantages, particularly in regard to rapid coverage of large areas, improved safety, and access to difficult terrain. Aerial surveys are well-used in the mining sector for exploration and geological mapping purposes, as well as in the transportation sector for large-scale route planning.

The geophysical methods most commonly associated with the use of drones in civil engineering geophysics include magnetometry, electromagnetic surveys, and GPR for detecting unexploded ordnance, metallic waste, and utilities.

ROV and autonomous underwater vehicle (AUV) technologies are instrumental in conducting marine geophysics studies and underwater inspections. The shift towards utilizing drones, ROVs, and AUVs underscores the industry's commitment to enhancing safety protocols and expanding capabilities in accessing and analyzing geophysical data across various terrains and environments.

Airborne surveys face limitations, such as the inability to work in controlled air spaces or areas where air traffic may be a concern, where drone flight is illegal, or where drone flight requires a permit.

Geophysical surveys taken via satellite may also be classified as an airborne (above surface) method. Satellite-based techniques include gravimetry and interferometric synthetic aperture radar (InSAR). However, satellite techniques are beyond the scope of this guideline.

2.4.4 Selecting a Conveyance Mode

The decision to undertake geophysical investigation from the surface, below ground, or above ground will depend on several factors, including access, efficiency, and viability of the technique to obtain the required data quality and resolution.

The relative advantages, constraints, and costs are summarized for these conveyance modes in **Table 2-1** below. These factors are presented irrespective of the technical viability of specific geophysical methods. Selecting a conveyance mode should be on a case-by-case basis.

Table 2-1. Comparison of general considerations for different conveyance modes

Mode	Advantages	Constraints	Relative Cost
Surface	Inexpensive, non-intrusive, minimal permitting and logistical requirements	Exposure to noise, surface obstructions, difficult access	Low
Subsurface	Improved signal-to-noise ratio at target depth(s), minimizing influence of intervals above or below depth of interest	Requires borehole or other mode of access to subsurface, and access for drilling equipment, some specialized equipment (downhole sources and/or sensors), area of investigation limited to location of borehole(s)	High
Airborne	Rapid coverage of large areas, access to challenging terrain	Permitting requirements and air access restrictions, specialized airborne equipment and trained operators, limited to specific geophysical methods	Low-Moderate*

* Cost efficiency may improve considerably with increasing scale

2.5 Commonly Employed Geophysical Methods in Geotechnical Engineering

The geophysical techniques most commonly employed for foundations investigations are discussed herein and are organized into three main categories:

- Electrical and Electromagnetic Methods
- Seismic Methods, and
- Other Methods

Different methods within each of these categories are described at a high level in the following sections. The relevant physical properties and ideal site models for these methods are summarized in **Table 2-2** below.

Table 2-2. Physical property models and ideal site models for common geophysical methods

Method	Physical Properties	Ideal Site Model
Electrical Resistivity Imaging (ERI)	Resistivity, ρ Voltage, V Current, I	Moderately thick and horizontally stratified layers with unobstructed linear area at surface equal to twice the target depth of investigation, and absence of near-surface conductors and/or electrical noise sources
Time-domain Electromagnetics	Magnetic permeability, μ Electrical permittivity, ε Conductivity, σ Frequency, f	Similar to ERI but less affected by near-surface conductors and smaller surface footprint required
Frequency-domain Electromagnetics		Similar to ERI but smaller surface footprint required and particularly well-suited to determining orientation of conductors
Ground Penetrating Radar		Shallow, dry, non-cohesive soils free of buried conductors and electromagnetic noise sources
Seismic Reflection	Density, ρ Seismic velocity, v Shear modulus, G Bulk modulus, B Frequency, f	Flat-layered stratigraphy with increasing seismic velocity with depth and absence of seismic noise, with unobstructed linear area at surface equal to twice the target depth of investigation
Seismic Refraction		
SASW and MASW		Similar to seismic reflection and refraction but insensitive to seismic noise
Vertical Seismic Profiling		Similar to seismic refraction but a borehole is required and less sensitive to seismic noise
Crosshole Seismic		Similar to seismic refraction but multiple boreholes are required and insensitive to seismic noise
Microtremor Techniques		Sites with pervasive seismic noise, such as urban areas, and negligible space at surface required
TISAR		Similar to seismic reflection but less sensitive to seismic noise
NDT		Existing foundations ideally with surface exposure
Gravimetry	Density, ρ Distance, m Size, m	Flat topography with relatively near and massive target(s) at sites absent of ground vibrations
Nuclear Magnetic Resonance	Gyromagnetic ratio, γ Angular frequency, ω_0 Magnetic field strength, B_0	Borehole environments absent of magnetic interference such as metal casings or buried objects other than the targeted object(s)
Magnetometry	Magnetic field strength, B_0 Magnetic susceptibility, X	Proximity to magnetic targets such as existing foundations or utilities of interest in non-magnetic soils and/or bedrock
Radiometrics	Density, ρ	Borehole or access tube proximal to targeted materials, free of clay-based backfill

Further details are presented in **Appendix A**, including descriptions of the relevant theory, general arrangements, and equipment used for each method, as well as discussion of the relative strengths, limitations, and costs.

2.5.1 Electrical and Electromagnetic Methods

Electrical Resistivity Imaging (ERI) or Tomography (ERT): A geophysical technique involving the use of electrodes, designated the *current electrodes*, to inject an electrical current through the ground. The electrical potential difference is then measured between additional electrodes, designated the *potential electrodes* (Eastern Research Group, Inc., 1993). The apparent resistivity of the subsurface materials within the effective depth of the survey is calculated using Ohm's Law. Effective depth is controlled by the spacing of the electrodes and the relative resistivity of the subsurface layers. Actual resistivities and depths of boundaries must be calculated through inversion methods (Herman, 2001) and are subject to non-uniqueness. Other factors influencing resistivity survey results include moisture content, temperature, and salinity.

Electromagnetics: An electric current running through a loop of wire (i.e., a coil) will induce a magnetic dipole field. By varying this primary magnetic field to produce magnetic flux, eddy currents will be induced in nearby conductors. These, in turn, produce a secondary magnetic field which can be measured at a secondary, receiver coil. The apparent conductivity of a collection of subsurface materials, in siemens per metre (S/m), can hence be determined (Milsom, 2003). Electromagnetic (EM) surveying techniques apply this concept to infer subsurface conditions relating to variations in the measured conductivity. There are two broad categories of EM surveying techniques: time-domain electromagnetics (TDEM) and frequency-domain electromagnetics (FDEM). TDEM typically involves abruptly shutting off a modified symmetrical square wave current to produce magnetic flux, whereas FDEM involves the use of a continuous sinusoidal current at a fixed frequency.

Ground Penetrating Radar: Ground penetrating radar (GPR) uses reflected EM pulses, typically at high frequencies between 80 to 1,000 MHz, to generate a ground response for imaging purposes. The EM pulses will reflect off subsurface interfaces with contrasting dielectric properties, such as at the interface between soil, rock, and/or groundwater surfaces, as well as buried infrastructure (U.S. Army Corps of Engineers, 1995). Higher contrast interfaces will reflect more energy, resulting in a higher amplitude signal being detected (Hussain, et al., 2020). Like seismic reflection, the common offset and common midpoint reflection techniques are used in GPR (U.S. Army Corps of Engineers, 1995). The data processing techniques used in seismic and GPR are also highly similar (Lai, Chang, Völker, & Cheung, 2021).

2.5.2 Seismic Methods

Seismic Reflection and Refraction: Seismic reflection and refraction surveys measure the time it takes for induced body waves to return to the surface after reflecting or refracting at interfaces between materials with different acoustic properties. These methods apply Snell's Law to determine reflection and refraction angles, which in turn dictate the paths taken by the propagating wave energy. The resolution of these surveys depends on the frequency of the waves, with higher frequencies providing better resolution but shallower penetration. Seismic sources, such as sledgehammers or explosives, and geophone configurations influence the depth and resolution of the investigation.

Reflection surveys are effective for high-resolution mapping of stratigraphic sequences and anomalies, while refraction surveys are better for environments with steeply dipping layers and deeper deposits. Both methods are unaffected by electrical or magnetic properties but may be impractical in noisy environments or where acoustic energy attenuates rapidly. Challenges in interpreting seismic data include sloped surfaces, thin layers, and velocity inversions, which can skew results and mask layers (Milsom, 2003; Zohdy, Eaton, & Mabey, 1974).

SASW and MASW: Spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW) are seismic survey methods using Rayleigh waves at frequencies of 1-30 Hz for shear-wave velocity profiling, typically for depths less than a few tens of meters (Park, Miller, Xia, & Ivanov, 2007). These methods calculate phase velocities for fundamental-mode Rayleigh waves, producing dispersion curves that are analyzed to create 1D shear-wave velocity depth profiles (Miller, Xia, Park, & Ivanov, 1999). MASW, which uses multiple geophones, improves on SASW by eliminating the need for repeated reconfiguration of receivers (Park, Miller, & Xia, 1999).

Advantages of surface wave methods include strong energy generation, accurate shear-wave velocity determination, and effective noise isolation through multichannel recording (Park, Miller, & Xia, 1999). However, MASW is less suited for detecting subtle changes or small anomalies (Miller, Xia, Park, & Ivanov, 1999). Equipment for MASW includes a multichannel recording system, receiver array, and seismic source, with active methods using user-provided sources and passive methods utilizing ambient seismic energy (Park, Miller, Xia, & Ivanov, 2007). Optimal survey configurations involve specific offsets and receiver spacing to ensure accurate recording of planar Rayleigh waves (Xia, et al., 2004).

Borehole Techniques: Borehole techniques for seismic surveys include uphole, downhole, and crosshole methods, each involving different configurations of energy sources and geophones (Hunt, 2007). These techniques reduce the influence of layers above and below the layer of interest, especially for crosshole methods but with downhole methods providing similar results with good repeatability (Jung, Sim, Park, & Park, 2012). The cost of borehole techniques is primarily due to drilling rather than geophysical logging, with logging costs being a small fraction of drilling costs (Hughes, 2002).

Vertical Seismic Profiling (VSP) uses wave velocities to characterize layered media and is commonly used to determine the average shear-wave velocity to a depth of 30 m (v_{s30}), a parameter important in earthquake engineering (Moss, 2008; Arsenault, Hunter, & Crow, 2012). VSP involves using a vertical borehole with geophones and a source/triggering system, with downhole surveys typically using a sledgehammer and uphole surveys using various sources like airguns or small explosives (Crow, et al., 2015). The seismic cone penetration test (sCPT) is a cost-effective downhole survey method that eliminates the need for drilling and casing a borehole (Robertson, Campanella, Gillespie, & Rice, 1986). Parallel seismic testing is used for existing foundation elements, involving impacting the foundation and monitoring from an adjacent borehole (Hertlein & Davis, 2006). Crosshole seismic testing, as detailed in ASTM D4428/D 4428M, requires at least two boreholes spaced 3.0 to 4.5 m apart and involves measuring direct waves to avoid refracted waves that can mask low-velocity layers (ASTM, 2000). Accurate surveying of borehole verticality and horizontal distance is crucial for calculating wave velocity, especially as borehole depth increases.

<u>Microtremor Techniques</u>: Microtremor techniques utilize weak, low amplitude ambient vibrations, typically considered noise in conventional seismic surveys, as the primary input source for geophysical investigations (Okada, 2003). These techniques are effective in urban areas and can investigate depths of hundreds of meters (Jongmans, Ohrnberger, & Wathelet, 2005). The Microtremor Horizontal-to-Vertical Spectral Ratio (HVSR) method uses a single seismometer to record ambient noise and calculate the ratio of horizontal to vertical Fourier spectra, aiding in mapping site period and shear-wave velocity profiling (Molnar, et al., 2022; Perret, 2015). The Refraction Microtremor (ReMi) technique analyzes Rayleigh surface waves' dispersion properties to estimate shear-wave velocity profiles (Louie J. N., 2001; Stephenson, Louie, Pullammanappallil, Williams, & Odum, 2005).

<u>Testing and Imaging using Seismic Acoustic Resonance (TISAR)</u>: TISAR is a seismic technique developed for high-resolution imaging of geological strata, capable of investigating depths up to 70 m and resolving layers as thin as 10 cm (Situm, McClement, & Arsenault, 2011). TISAR relies on resonance signals from repeated seismic impulse reflections at interfaces between materials with different acoustic impedances, making it suitable for conductive subsurface environments where GPR is limited (Arsenault & Chouteau, 2002; Wang, et al., 2024).

<u>Non-destructive Testing (NDT) Techniques</u>: NDT methods are used to evaluate the integrity and capacity of existing foundations without causing damage. Stress-wave methods, such as impulse echo, involve generating and measuring stress-waves to estimate foundation length and identify deficiencies. These methods depend on factors like foundation length-to-diameter ratio and soil properties, with experienced operators able to detect defects of 10-15% of the shaft cross-sectional area (Hertlein & Davis, 2006). Downhole NDT methods, including parallel seismic testing, involve lowering sensors into boreholes to avoid soil damping effects and potentially provide more accurate results. Parallel seismic testing, which does not rely on assumed wave speeds, involves generating acoustic pulses and measuring their travel times to evaluate foundation length and condition (Rausche, 2004; Hertlein & Davis, 2006).

2.5.3 Other Methods

<u>Gravity Methods</u>: Gravimetry involves measuring the earth's gravitational field intensity to detect subsurface anomalies, which can indicate changes in mass or density. This field uses specialized instruments called gravimeters, which measure gravity differences in units called gals (Lowrie, 2007; Milsom, 2003). For shallow geotechnical applications, microgravimeters are used to detect small anomalies in the order of microgals (Eastern Research Group, Inc., 1993). These instruments require high precision and are sensitive to various errors such as movement, wind, and ground vibrations (U.S. Army Corps of Engineers, 1995). Surveys must account for several corrections, including drift, tidal, and terrain corrections (Lowrie, 2007). Gravimetric surveys can be costly due to the precision required and the high cost of equipment, and they are less effective in areas with variable topography or near-surface densities. Limitations include non-uniqueness of anomalies and the need for masses to be increasingly large to be detected at greater depths (U.S. Army Corps of Engineers, 1995).

<u>Magnetic Methods</u>: Two magnetic methods used in civil engineering include nuclear magnetic resonance (NMR) and traditional magnetometer surveys. NMR is a geophysical tool initially used in the 1960s for oilfield exploration and later adapted for hydrogeological investigation. It involves applying a strong magnetic field to induce precession of nuclei, which resonate at frequencies unique to each element when subjected to radio-frequency energy (Bushberg, Seibert, Leidholdt Jr., & Boone, 2020). NMR can be applied at the surface or more commonly in boreholes, allowing for the assessment of hydrogeologic characteristics of undisturbed soil or rock. It quantifies parameters such as total porosity, pore-size distribution, permeability, and saturation, and can differentiate between mobile and bound porosity fractions, as well as between water and certain petroleum hydrocarbons. NMR tools have a vertical resolution of 0.2 to 0.5 m and a radius of investigation between 0.15 to 0.50 m, with logging rates of up to 15 m per hour. Advantages include the ability to quantify key hydrogeologic parameters without radioactive sources and compatibility with existing PVC-cased monitoring wells. The practicality of NMR depends on borehole or well depth and diameter, with probes varying in size (Interstate Technology & Regulatory Council, 2019).

Magnetometry measures magnetic field strength in nanoTesla (nT) and compares it to the theoretical magnetic field strength predicted by the International Geomagnetic Reference Field (Lowrie, 2007). The difference, or magnetic anomaly, helps identify subsurface variations. The intensity of the magnetic field from a dipole is inversely proportional to the square of the distance from the dipole and proportional to the object's volume (Quesnel, Langlais, Sotin, & Galdeano, 2008). Unlike gravimeters, magnetometers require less sensitivity due to the significant differences in magnetic properties of earth materials. Magnetization, defined as the magnetic moment per unit volume, is proportional to the magnetic field and can be negative (diamagnetic) or positive (paramagnetic) (Milsom, 2003). Observable magnetization in rocks is generally due to minerals like magnetite, pyrrhotite, or maghemite, which can become permanently magnetized (remanent magnetization) (Lowrie, 2007). Magnetometer surveys are typically used to detect magnetic ores or rocks but can also be useful in areas like southern Ontario, where sediments may contain magnetic minerals from the Canadian Shield (Dietiker B. , Pugin, Crow, Brewer, & Russell, 2024). They can also help locate utility infrastructure, foundations, reinforced slabs, tunnels, or other structures with ferromagnetic materials (Hunt, 2007).

Radiometric Methods: Methods exploiting radioactivity have also been developed, such as. Gamma-Gamma Density Logging (GDL). This non-destructive testing technique is used in civil engineering to assess concrete integrity within boreholes, which can be cased with PVC or steel and filled with water or air (Wightman, Jalinoos, Sirles, & Hanna, 2004). It is also applied in the oil and gas industry for logging stratigraphic changes and estimating porosity (U.S. EPA, 2024). GDL detects changes in bulk density, indicating anomalies like voids or fractures, by measuring the intensity of gamma rays reflected back to a detector. The radioactive source, typically Cesium-137 or Cobalt-60, emits gamma rays that undergo Compton scattering, losing energy and being absorbed by denser materials, which reduces the gamma intensity reaching the detector (U.S. EPA, 2024). The gamma intensity is inversely proportional to the material's bulk density, but calibration with a block of a known density is required for quantification (Wightman, Jalinoos, Sirles, & Hanna, 2004). The effective radius of GDL is about half the distance between the source and detector, with depth of investigation also decreasing as bulk density increases (U.S. EPA, 2024).

PART II:

Applications and Selection of Geotechnical Geophysical Methods

3 COMMON APPLICATIONS OF GEOTECHNICAL GEOPHYSICS

Common applications of geophysical methods to geotechnical challenges are discussed in the following sections. These applications are introduced below and summarized in **Table 3-1**.

- **Seismic Site Classification:** Understanding how earth materials respond to earthquakes is crucial for designing resilient structures. The Ontario and National Building Codes of Canada (OBC and NBCC) use the National Earthquake Hazards Reduction Program (NEHRP) guidelines to classify soils based on shear wave velocity (v_{s30}) in the upper 30 m. These classifications help determine the design ground motion for structures. Measuring v_{s30} using geophysical methods is preferred for critical infrastructure. This section discusses geophysical methods commonly used to measure v_{s30}.
- **Stratigraphic Profiling:** Site characterization involves identifying materials and their distribution. While boreholes and sample collection are standard practice, they provide limited, discrete data. Geophysical methods can enhance investigations by rapidly collecting continuous data, offering cost-effective coverage for large or inaccessible sites. This section discusses geophysical methods for determining material types, thicknesses, and groundwater and bedrock depth.
- **Detection and Delineation of Voids:** Conventional intrusive investigation techniques can miss voids or require costly reinstatement. Geophysical methods enhance void detection by covering large areas quickly and affordably, guiding confirmatory borings and rehabilitation. They also delineate void extents and can be conducted from the surface or within infrastructure. This section discusses these applications of geophysical methods, considering important variables such as site features, root cause, and potential noise sources.
- **Re-use of Existing Foundations:** Reusing existing foundations offers economic, environmental, and social benefits. However, assessing the reuse potential of existing foundations requires a detailed understanding of their size, condition, depth, and surrounding strata. This section discusses geophysical methods used for verification of these foundation details for several common foundation material types and sizes, as well as access constraints.
- **Offshore Investigation:** Geophysical methods enhance offshore investigations by collecting submarine and subsurface data more safely, quickly, and extensively than conventional techniques. Objectives discussed in this section include mapping sediment thickness and bedrock depth, characterizing material properties, and assessing scour.

Table 3-1. Common applications of geotechnical geophysics

Application		ERI	TDEM	FDEM	GPR	Seismic Reflection	Seismic Refraction	SASW and MASW	Vertical Seismic Profiling	Crosshole Seismic	Microtremor Techniques	TISAR	NDT	Gravimetry	Nuclear Magnetic Resonance	Magnetometry	Radiometrics
		Geophysical Method															
Seismic Site Classification						(x)	X	X	X	(x)	X						
Stratigraphic Profiling	*Subsurface Modelling*	X	X	X	X	X	X	(x)	(x)	X	X	X			(x)		X
	Groundwater Modelling	X	X	X	X	(x)	(x)	(x)	(x)	X		(x)		(x)	X		(x)
	Depth to Bedrock	X	X	(x)	(x)	X	X	(x)	(x)		X	X		(x)			
Detection / Delineation of Buried Features	*Voids*	(x)	(x)		X			(x)		X		(x)		X		X	
	Obstructions	(x)	(x)		X					X		(x)		X			
	Utilities	X		X	X							(x)		(x)		(x)	
Re-use of Existing Foundations				X									X			X	X
Offshore Investigation		X			(x)	(x)	X							(x)			

X Major application
(x) Minor application
* Freshwater applications only

3.1 Seismic Site Classification

Understanding the behaviour of earth materials in response to seismicity (i.e., earthquakes) is critically important to designing structures able to withstand the effects of these events. The Ontario Building Code (OBC) and the National Building Code of Canada (NBCC) (Canadian Commission on Building and Fire Codes, 2022) have adopted the National Earthquake Hazards Reduction Program (NEHRP), which categorizes soils into classes from A through F based on the average shear wave velocity in the upper 30 m (V_{s30}) (Building Seismic Safety Council, 2004). Amplification factors corresponding to the site classes are then applied to obtain the desired "design" ground motion, which is typically taken as the ground acceleration intensity corresponding to a 2% probability of exceedance in 50 years (Hunter & Crow, 2015).

The NEHRP guidelines allow for V_{s30} to be estimated or measured. Measurement is preferred, especially where site classes A or B are desired (to optimize design) or where sensitive infrastructure is present or planned. Measurement of travel-time weighted average shear wave velocity to a depth of 30 m using geophysical investigation techniques is discussed herein. Whereas mapping or delineation of subsurface features may benefit from applying a variety of geophysical methods, the most practical approach to seismic site classification is to use seismic methods since they directly measure the seismic velocity of the materials at a site.

The selection of a NEHRP site class based on the measured V_{s30} is not discussed. It is important to note the sensitivity of this approach to the thickness and shear wave interval velocity of the layers, particularly when the shear wave velocity contrast between layers is very high (Motazedian, Hunter, Pugin, & Crow, 2011). Professional judgement should be exercised to select an appropriate NEHRP site class when the value of V_{s30} is close to the threshold between classes. Ground truthing with intrusive investigation techniques remains an important aspect of site investigation which should be used to complement geophysical investigation.

3.1.1 Comparison of Methods

Where the primary objective is to measure the average shear wave velocity of the strata at a site, the methods most used for seismic site classification tend to be MASW, SCPT, and VSP.

The availability of different methods can lead to the question of which to use. Insights can be derived from studies utilizing these different methods at the same locations and comparing the data. Several such studies are summarized below:

- Motazedian, et al. (2011) presented results from using four seismic methods to evaluate V_{s30} and fundamental frequency, F_0, for development of an NEHRP map in Ottawa, Ontario. The data included downhole interval Vs measurements at 15 borehole sites, seismic refraction-reflection profile measurements from 686 sites, high-resolution shear wave reflection "landstreamer" profiling for 25 km, and HVSR of ambient seismic noise for 400 sites.

Motazedian, et al. (2011) concluded:

- Downhole seismic was one of the most direct measurement techniques, producing accurate results so long as the casing was well-bonded to the formation, but is relatively expensive due to drilling costs.
- Seismic refraction-reflection are fast, practical, reliable, and inexpensive. These methods can be highly effective where large impedance contrast exists and background noise is low.
- High-resolution seismic reflection profiling can also be cost-effective, rapid, and very accurate if the array lengths are greater than twice the depth of the subsurface targets.
- Spectral ratio methods (HVSR) are regarded as rapid and inexpensive for locating significant seismic impedance boundaries and approximately estimating the fundamental resonance and amplification at a soft-soil site.

- Moss (2008) investigated measurement uncertainty associated with estimates of V_{s30} by quantifying intramethod and intermethod variability. Intramethod variability was quantified using the coefficient of variation (COV) for data obtained from six comparative studies by others. For SASW and MASW, the COV was in the order of 5-6%. For downhole (invasive) methods, it was estimated at 1-3%.

  Intermethod variability was quantified using data from nine studies by others. Blind study results revealed a bias, with noninvasive methods providing higher estimates for softer sites (V_{s30} < 200 m/s) and lower estimates for stiffer sites (V_{s30} > 200 m/s) than the invasive methods. The author attributed this to soil disturbance associated with downhole methods, but noted more research was needed to confirm this hypothesis. A bias-corrected mean invasive shear-wave velocity was proposed as:

  $$\mu'_{v_{s30}} = \left(0.760962\mu_{v_{s30}} + 51.55451\right) \tag{14}$$

  Lastly, the author found the COV of V_{s30} based on correlated geologic units was in the order of 20-35% and increased with depth per the relationship described by Equation 15:

  $$COV = \left(0.000328\mu_{v_{s30}} + 0.165967\right) \tag{15}$$

- The Illinois State Geological Survey (ISGS), the University of Missouri-Rolla, and the U.S. Geological Survey (USGS) conducted MASW, downhole shear wave velocity measurements within cased holes, and seismic refraction and reflection at the same site to compare these methods. The site stratigraphy consisted of more than 30 m of sand with some gravel overlying limestone (Bauer, Su, Counts, & Karaffa, 2007). The team reported a 35% difference in the individual shear wave velocity values between the MASW and downhole methods, and a 15% difference in the V_{s30}.
- Williams, et al. (2003) compared seismic reflection/refraction to downhole techniques at six sites in Washington and California. The authors compared the V_{s30} and found a difference of less than 15% at four of the sites, and 21% and 48% at the remaining two.

- Hunter, et al. (2002) compared SASW and sCPT data from the same site and found they were similar, with differences attributed to possible shear wave anisotropy between the horizontal and vertical travel paths. They also compared MASW data to borehole data for six similar sites and found root-mean-square error ranging between 1 and 4 m/s. A seventh test with different near surface shear wave velocities also resulted in only a 9% difference between the MASW and borehole measurements.

Based on the findings from these comparative studies, the difference between the results derived from the different methods that were used appears to be less than 15% in most cases. Individual methods were also found to be highly repeatable, with intramethod COV of 6% or less. Hence, each of the evaluated methods may be considered for estimating V_{s30}.

The selection of a method to measure the average shear wave velocity at a site must also consider site conditions and cost. Anderson et al. (2006) evaluated sCPT, CH, MASW, and ReMi for their relative accuracy, functionality, cost, other considerations, and overall utility for determining shear wave velocity of soil. They concluded that the MASW method was the best option for soil classification up to 30 m depth. MASW was able to generate reliable data at relatively low cost and be implemented at sites not accessible to rigs needed for CH. The MASW method was also able to perform in strata impenetrable by an sCPT probe and did not rely on the presence of passive sources to provide an adequately high signal-to-noise ratio for quality ReMi data.

3.1.2 Survey Design Considerations

Survey design considerations influencing the selection of different seismic investigation techniques are discussed below. The considerations are based on a variety of common site conditions as well as the strengths and limitations of individual techniques.

Initial survey design parameters are also presented for consideration. It is critical to note that refinement of the field survey will be necessary based on actual site and subsurface conditions, noise analyses, and observed near- and far-offset effects after initial shot gathers.

3.1.2.1 MASW

For MASW surveys, the following initial survey design parameters could be considered based on Park, et al. (1999):

- Signal sources could include:
  - Vibratory sources, to generate swept surface-wave signals;
  - Sledgehammers, to generate impulsive data which will then need to be transformed to a swept-frequency record.
- Length of frequency-time plot or stretch function, T:
  - Set as long as feasible/possible. A longer T is needed when near-surface properties change rapidly with depth. T of 10 s or less is typically sufficient, with a sampling interval of 1 ms.

- First geophone offset distance, x_1:
  - Should be set greater than or equal to the target depth of the shear wave velocity profile. For V_{s30}, the offset should therefore be set to 30 m or more.
- Minimum definable thickness of the shallowest layer, H_1:
  - Will be equal to or greater than half of the minimum wavelength of the signal, λ_{min}.
  - Can also be reduced by reducing x_1 and/or the receiver spacing, d_x.
- Minimum receiver spacing, d_x, to avoid spatial aliasing should be greater than or equal to half of λ_{min}.

3.1.2.2 Seismic Reflection and Refraction Methods

These methods are typically inexpensive and can be utilized to collect complementary investigation data such as stratigraphic information (layer thicknesses and depths). Adequate space is required to accommodate the length of the array, however, which should be expected to be as long as two times the depth of interest.

Motazedian, et al. (2011) noted the following with respect to seismic reflection and refraction methods:

- Wide-angle seismic reflection techniques are preferred for sites with thick deposits of soft or loose overburden but are not effective for measuring the shear wave velocity of underlying very stiff overburden or bedrock if present.
- Refraction is preferred where measurement of the shear wave velocity of very stiff or dense soils or bedrock is needed.
- Refraction methods can potentially result in large error when hidden, lower-velocity materials underlie the upper strata.

Hunter, et al. (2022) presented a thorough review of shear wave reflection and refraction methods. They noted these techniques are well-suited to accomplishing shallow seismic site classification surveys but also listed limitations. Limitations listed for shallow refraction included:

- Difficulty identifying the signal in noisy environments;
- The importance of gathering forward and reverse shot positions to deal with dipping subsurface layers (up to 20°);
- Lack of reliability detecting velocity reversals/inversions; and,
- Minimum layer thicknesses required to be identified are controlled by array length.

Limitations listed for shallow reflection techniques included:

- Survey targets must be large relative to the signal wavelength to be resolved;
- Signal attenuation can be high, especially in dry, high-porosity unconsolidated sediments; and,

- A large range of source-receiver offsets is needed to accurately calculate velocity and must increase with depth to maintain the same accuracy.

3.1.2.3 HVSR and ReMi

Considerable effort may be needed to improve the signal-to-noise ratio when active seismic methods are used in environments with persistent environmental noise. Particularly in urban settings, active methods may sometimes also be constrained by limiting the source energy to reduce the likelihood of damaging property. An overreliance on data processing techniques is ill-advised, as these processes are applied based on varying judgement and skill levels.

Passive seismic methods such as HVSR and ReMi can be highly effective in these settings, as the noise is considered as the source rather than competing energy. Signal energy is also not affected by attenuation over larger distances or depths.

For the application of microtremor array techniques, the reader is referred to the findings and proposed general workflow presented by Jongmans et al. (2005) from Project SESAME for the determination of improved broadband dispersion curve characteristics. Their recommendations are summarized as follows:

1) Verify the one-dimensional structure of the site is compatible with the assumption of horizontal layering with depth-variable velocity;
2) Check the frequency content of the ambient vibrations and select a sensor with the appropriate frequency range;
3) Use large time windows, greater than 25 cycles, to improve the phase delay estimate;
4) Use a large number of windows to obtain good statistics;
5) The wave number limits, k_{min} and k_{max}, should be calculated using a theoretical array response, to define a validity range for the dispersion curve and ensure reliable dispersion curve estimations; and,
6) Combine the use of f-k and autocorrelation techniques to increase confidence in the results.

Application of the HVSR technique involves using only a single three-component seismometer and the survey setup is hence quite simple. The seismometer that is sourced must be capable of recording at frequencies lower than the frequency range of the environmental noise. As the resonator depth increases (i.e., thickness of unconsolidated overburden), the natural frequency of the selected seismometer should decrease. Furthermore, seismometers with high intrinsic noise levels should be avoided in general (Molnar, et al., 2022).

The seismometer should ideally be levelled, installed in firm contact with the ground, and protected from wind and rain. The seismometer should also be located away from structures and subsurface cavities or features, within a noise source-free buffer area of at least 5 m. A recording duration of at least $20(10/f_{0HV})$ in seconds is recommended by Molnar, et al. (2022).

The reader is cautioned that the HVSR technique requires a strong subsurface impedance contrast to succeed. The method can be used to estimate the fundamental mode resonance frequency, f_0, of the overlying soil layer. The fundamental mode resonance frequency is estimated from the lowest peak in the HVSR data, plotted as Fourier Amplitude vs. frequency.

Molnar, et al. (2022) state the resonance frequencies, f_n, of the vertically propagating, horizontally polarize shear-wave (SH) transfer function for a uniform viscoelastic medium of a thickness, h, and shear-wave velocity, v_s, will occur at:

$$f_n = (2n + 1)\frac{v_s}{4h} \tag{16}$$

Hence, if the thickness of the soil layer is known, a 1D shear-wave velocity profile can be developed. The composition of the microtremor wavefield however is ambiguous, however, and uncertainty concerning the HVSR curve and associated parameters must be considered by the user (Molnar, et al., 2022).

Regarding ReMi array data collection, best practices are discussed by Louie et al. (2017). The recommendations include:

1) Ensuring the total array length is at least twice the maximum target depth;
2) Utilizing a geophone spacing less than or equal to the minimum desired target depth; and,
3) Obtaining 10 records or more, each spanning a minimum of 30 seconds, for determinations of v_{s30}.

3.1.2.4 Borehole Methods

Borehole methods can include sCPT, suspension logging, and CH. These methods each require access for a drilling or CPT rig to access and setup at the desired survey locations. Where practical, these methods can present an opportunity to obtain data which is less impacted by environmental noise and the influence of soil layers above or below the interval of interest.

Some considerations specific to the application of borehole methods include:

- If utilizing a cased hole, a good quality bond between the casing and the formation is imperative and can be achieved by fully grouting the annular space.
- Best results can be obtained from an uncased, fluid-filled borehole if permitted based on the stability of the borehole.
- When the borehole is fluid-filled, hydrophones must be used.
- Seismometer contact with the borehole sidewalls can be achieved using air bladders, wedges, stiff springs, or mechanical expanders.
- For downhole surveys, the source should be located within 1-5 m of the borehole to reduce significant tube wave coupling to the casing but also minimize non-vertical (refractive) travel paths.
- The depth of investigation for sCPT may be limited by cone refusal.

3.2 Stratigraphic Profiling

An essential element of site characterization is determining what materials are present and how they are laterally and vertically distributed within a study area. Stratigraphic profiling almost always involves the advancement of boreholes or probes and collecting samples for index testing. This approach remains important, but a major shortfall is its a reliance upon semi-continuous observations at discrete locations which may only represent a fraction of a percentage of the site by volume. Additional borings can be expensive and time-consuming, particularly if access or work windows are limited. Geophysical investigation techniques can enhance site investigations by enabling the relatively rapid collection of continuous data between sampling locations, providing cost-effective site coverage especially for large and/or inaccessible sites.

This chapter discusses the application of several common geophysical methods for the purpose of stratigraphic profiling. Typical objectives are to determine the types, thicknesses, and distribution of layered overburden materials, and the depth to groundwater and bedrock. The selection of an investigation strategy should not be limited to the discussed methods, however, and should consider the experience of the geophysical contractor, the expected site conditions, both above and below ground, and the extensive literature available on this subject.

3.2.1 Investigation Design

The selection of one or more methods to characterize subsurface conditions at a site will depend on the investigation objectives and the expected conditions. The following discussion aims to guide the selection of possible geophysical methods which may yield favourable outcomes in achieving the identified investigation objectives for some typical site conditions. Three primary objectives are considered in this section:

1. **Lithological Characterization:** The investigation of material types, layer thicknesses, and material boundary depths.
2. **Bedrock Mapping:** Limited investigation focused on determining the depth to bedrock across a study area.
3. **Groundwater Mapping:** Limited investigation focused on determining the depth to the groundwater table across a study area.

Several common geophysical methods are discussed with respect to their application to stratigraphic profiling in the following sections.

3.2.1.1 Electrical Resistivity Imaging

Electrical Resistivity Imaging (ERI) relies on resistivity differences to resolve a model of the distribution of different earth materials below the ground surface. It typically involves the application of a direct current (DC) to a set of electrodes installed in the near-surface ground. A more in-depth discussion of the theory and components of this method is presented in **Section A.1.1**.

ERI is well-suited to conditions where resistivity contrast is expected to be high. Earth materials are generally highly resistive, and it is primarily the water contained within the pores or bound to the particles which is responsible for variations in the measured resistivity. Hence, ERI is expected to produce favourable results in settings which might include:

- Interlayered materials of differing grain size and porosity; or,
- Groundwater mapping.

In the above settings, the likelihood of a successful survey will be greatest where there is high electrical resistivity contrast. ERI will likely excel when delineating features such as buried peat or organic clays below sandy strata or determining the thickness of unconsolidated overburden materials above relatively tight igneous or metamorphic bedrock, for example.

Challenging conditions for the application of ERI would include settings with low resistivity contrast, excessive electrical noise, and/or a near-surface conductive layer. Examples of sites which might present these conditions could include:

- Swamps, where groundwater is high or above ground;
- Urban or built-up areas with a concentration of electrical utility infrastructure or nearby conductive buried objects; or,
- Thick clay deposits.

Hard surfaces such as asphalts and concretes can also present a challenge, as it may not be possible or practical to place electrodes where these surfaces exist. These conditions can be accommodated by adopting non-contacting methods where AC is used to induce a current, but this is less common and can be more expensive.

Where conditions are favourable for the application of ERI, the survey design must consider the objectives of the study. A comparison of relative strengths and weaknesses of the Wenner, Schlumberger, and Dipole-Dipole configurations is presented in **Table A-2**. Historically, the Wenner array has been popular for its simplicity, especially as automatic switching equipment is now commonplace. The Wenner array can be used to accomplish, both, depth soundings and lateral profiling and it performs well in horizontally layered stratigraphy or groundwater mapping.

Where space constraints exist, however, the Schlumberger array may be preferable for its improved depth of investigation (but lower signal strength) for the same array length. The Schlumberger array may also be favoured in settings where, both, vertical and lateral variations in resistivity are anticipated, such as undulating or dipping layers.

The Dipole-Dipole array can be an excellent choice where the primary objective is to delineate steeply dipping layers or features, such as dikes, trenches, or infrastructure.

Automatic switching equipment can facilitate the application of multiple configurations and is strongly encouraged to enhance survey design flexibility at the time of data acquisition.

3.2.1.2 Seismic Methods

Stratigraphic profiling has been accomplished for many decades using seismic reflection and seismic refraction. Other techniques, including MASW and borehole techniques, can also be used under certain circumstances. The relative advantages and disadvantages of these different techniques for stratigraphic profiling purposes are presented in **Table 3-2**.

Table 3-2. Comparison of different seismic techniques for stratigraphic profiling

Technique	Advantages/Strengths	Disadvantages/Limitations
Seismic Refraction	• Relatively inexpensive technique • Low computational requirements • Non-invasive surface method	• Array length should be at least 3-4x the desired depth of investigation, which may be prohibitive • Seismic velocity must increase with depth
Seismic Reflection	• High resolution imaging capability • Non-invasive surface method	• High computational requirements • Steeply dipping layers can be masked or go “unseen”
MASW	• Less affected by cultural noise than refraction/reflection • Non-invasive surface method	• Resolution decreases with depth, as increasing depth corresponds to lower frequencies and longer wavelengths • A horizontally layered system is assumed
CH Seismic	• Least influence from layers above or below a layer of interest • Depth of investigation can be increased without increasing surface footprint • Acquisition of other geotechnical data in tandem	• Expensive due to required sets of borings (minimum two, ideally three)
VSP & sCPT	• Single borehole required, with limited footprint • Reduced influence from layers above or below a layer of interest • Acquisition of other geotechnical data in tandem • sCPT is relatively rapid • sCPT does not require a cased borehole	• Access and space for a drilling rig is required • Hard, bouldery, or bedrock conditions may impede advancement, especially for sCPT

Additional Considerations

Trapped gases in swamps can attenuate the energy of compressive (P-) waves since gases are compressible. These conditions may, therefore, present challenges for seismic refraction surveys with long spreads and/or deep targets. If the target cannot be resolved due to these conditions, it may be necessary to utilize a higher energy source or consider alternate methods.

Concerning resolution, looser or softer soils with lower seismic velocities can be excellent target media to which seismic imaging techniques could be applied. The lower velocities in these materials will generally result in higher resolution since wavelength is proportional to velocity (see Equation 6 in **Section A.2.1**).

Where environmental noise from sources such as wind or traffic is present, the use of a vibratory seismic source can facilitate data collection by producing a highly repeatable signal with long recording times. This can enhance the signal-to-noise ratio in these noisy environments (Pugin, Pullan, & Hunter, 2013).

3.2.1.3 Electromagnetics & GPR

Electromagnetic (EM) methods including frequency-domain (FD), time-domain (TD), and ground penetrating radar (GPR) can be effective tools for stratigraphic profiling where the ground profile is expected to contain materials with contrasting electromagnetic properties. Such contrasts may exist as a result of varying clay or organic content, moisture and/or groundwater, salinity, or fractures. These contrasts can be exploited to detect lateral and vertical changes in soil or rock types, as well as depth to groundwater.

EM methods can achieve the same depth of investigation as array-based methods such as ERI or seismic while occupying a much smaller footprint. The depth of investigation for EM methods will be in the order of the loop diameter (U.S. Army Corps of Engineers, 1995).

Similar to electrical methods, the main sources of noise which affect EM methods are power lines and metallic structures, but radio, radar, and lightning can also affect results. With FDEM and TDEM methods, the size of the transmitter loop and required current to ensure a sufficient signal-to-noise ratio will need to be determined using forward layered-earth modelling software during design of the investigation.

Relative advantages and disadvantages specific to TDEM, FDEM, and GPR are discussed below.

TDEM

The use of TDEM systems is favoured over electrical and FDEM methods at sites underlain by highly conductive overburden materials. Since TDEM methods involve shutting off the primary field when measuring the secondary field, very high power can be used for the primary field without interfering with the measurement. This use of very high power allows the user to compensate for the limited skin depth in these highly conductive conditions. Furthermore, the use of the same coil as, both, the transmitter and receiver, reduces the coil spacing to zero. This reduced coil spacing allows TDEM to produce higher resolution data than FDEM, which can be advantageous especially when locating relatively small targets (Milsom, 2003).

When comparing with ERI, some additional advantages associated with the use of TDEM methods include the relative rapidity of surveying, improved lateral resolution and resolution of conductive electrical equivalence, and no problems with injecting current past a resistive surface layer. However, TDEM does not work well if no conductive layers are present within the depth of influence of the primary field since it is these conductive layers which will produce the induced secondary field (U.S. Army Corps of Engineers, 1995).

FDEM

FDEM systems involve the use of a separate transmitter and receiver loop. The transmitter loop produces the primary field while measurements of the induced secondary field are taken using the receiver loop. Since the primary and secondary fields are present concurrently, the orientation of the loops will influence the degree to which they interact with one another as well as the fields induced in the target conductors. This influence is called coupling. Coupling can be exploited to determine the orientation of these target conductors. The measured response will be greatest and most defined when surveying orthogonal to the orientation of the conductor. The ratio of the vertical to horizontal field can also be measured and used to infer the angle at which the conductor is dipping (Milsom, 2003).

GPR

GPR offers, arguably, a more direct method of profiling the ground compared to other EM methods. Whereas TDEM and FDEM methods involve measuring an induced field and producing a ground model using inversion techniques, GPR involves measuring the return times of reflected EM pulses. Hence, a notable advantage of GPR over other EM methods is the ability to achieve real-time imaging in the field before data processing is performed.

The frequencies used for GPR are also much greater and the vertical resolution that can achieved is correspondingly improved. As a consequence of the high frequencies, the depth of investigation using GPR is generally much less than that of FDEM and TDEM methods. In particular, it will be severely limited where conductive materials are present near or at surface.

GPR is typically undertaken using the common offset configuration, deployed in the form of a rover pushed by an operator or towed by a vehicle. This format offers greater mobility and speed for surveying at the cost of the flexibility of being able to modify antenna spacing or orientation.

3.3 Detection and Delineation of Voids

Conventional intrusive investigation techniques will either involve relatively small footprints that risk not intersecting voids, or large footprints which may involve costly reinstatement. The use of geophysical investigation techniques can enhance the detection of voids by covering a large footprint relatively rapidly and at low cost. The results of a geophysical survey can then be used to guide the placement of confirmatory borings and/or rehabilitation. Additional benefits can include the ability to delineate the extents of areas containing voids, and the flexibility to undertake the survey from surface or from within borings or underground infrastructure, such as from within a tunnel.

Prior to selection of one or more geophysical investigation techniques, the root cause and setting suspected to have led to the formation of the voids must be considered. The formation of voids below the ground surface can occur in response to a variety of processes including ground loss from tunnelling or adjacent excavation, settlement induced by vibration or dewatering, or flowing water in the form of leaking utility infrastructure, infiltration, seepage, piping, and/or dewatering operations. These processes can occur during or after construction of buried infrastructure such as culverts, utilities, or foundations. The formation of voids is more likely where these conditions persist in a continuous or intermittent manner, and materials susceptible to those conditions exist. Materials with increased susceptibility to the formation of voids may include non-cohesive materials in a very loose to loose state of compaction with appreciable content of silt- to sand-sized particles. Material boundaries can be especially prone to the formation of voids due to a change in material properties disrupting the flow of water.

Voids will generally present an issue for existing or newly completed infrastructure, though voids can also be problematic when working with greenfield sites where karstic features are expected. At sites where existing infrastructure is present, the subsurface soils can generally be expected to include a pavement structure consisting of asphalt underlain by engineered granular fill materials, in turn underlain by embankment fill materials and native subgrade soils and/or bedrock. Other materials which may be present could include reinforced concrete associated with composite or rigid pavements, bridge approach slabs, abutments, or foundations, buried utility infrastructure, culverts, or tunnels.

While the processes and conditions leading to the formation of voids are well-understood, it can be challenging to detect and delineate voids at their onset and before potentially damaging or dangerous conditions present at surface. Voids posing a risk to infrastructure are most likely to form at the base of or within embankment fills, immediately below or adjacent to foundations, or above tunnels and culverts. Hence, the required depth of investigation will vary depending on the site features but will typically be less than 10 m. However, the selected method or methods must be capable of being deployed between and around these infrastructure features. As with any geophysical investigation application, consideration will need to be given to possible sources of signal noise, which could impede a survey depending on the type of energy being measured.

3.3.1 Investigation Design

Based on the available literature and past studies commissioned by the MTO, geophysical investigation methods that are expected to be well-suited to the detection of voids include ground penetrating radar (GPR), gravimetry, seismic reflection, and electrical resistivity imaging. The general application of these methods to void detection is discussed below, along with possible survey configurations and some potential limitations. It is noted that the identified methods are by no means an exclusive nor exhaustive list of methods for accomplishing the stated objective and are presented herein solely as a starting point in identifying potentially viable options.

3.3.1.1 GPR

GPR has been used successfully to detect and delineate voids within existing highway embankments involving culverts and drains, and below reinforced approach slabs at bridge abutments.

The popularity of this method is owed to the relatively high resolutions that can be rendered by GPR along with expected large contrasts in dielectric permittivity if voids are present. The ideal conditions for GPR include dry, granular soils especially during the late summer months when road salting operations are inactive and groundwater levels are typically lower.

It is important to note the depth of investigation and/or resolution of GPR surveys can be adversely affected in the presence of the following factors:

- Clayey soils
- Salt or salt-containing media
- Wet soil or high groundwater table
- Metallic objects
- Sources of EM interference/noise
- Boulders or other dispersive reflectors

Where the above-noted factors may be present, especially in tandem, it may be preferable to consider an alternative method of investigation depending on the anticipated extent or impact of these factors on detecting voids.

Equipment

Equipment utilizing a broad frequency bandwidth should be used to enhance resolution and investigation depth. The center frequency or frequencies used for the GPR survey should be selected based on the desired depth of investigation, considering the expected subsurface conditions. An approximate guide for estimating an appropriate GPR center frequency is shown in **Table 3-3** below assuming a vertical resolution of approximately 10 cm. The reader is cautioned that the indicated depths of investigation are for ideal conditions and could be severely reduced due to the presence of conductive materials and/or diffractive reflectors.

Table 3-3. Estimated GPR frequency for different depths and 0.1 m resolution in ideal conditions

Depth of Investigation (m)	Estimated GPR Center Frequency (MHz)			
	Dry Sand	**Wet Sand**	**Silts, Shales**	**Clays**
0.5	1130	450	530	410
1.0	950	380	450	340
2.0	800	320	370	Not recommended for depths beyond 2 m
3.0	720	290	340	
4.5	650	260	310	
6.0	610	240	Not recommended	
10.0	530	210		

Alternatively, an initial estimate of a suitable center frequency, f, in MHz, can be obtained using Equation 12 (Milsom, 2003) for a desired spatial resolution, d, in metres, with reference to the relative permittivity, ε, of the anticipated subsurface materials. Approximate relative permittivities of common earth materials are summarized in **Table A-3**. A spatial resolution equal to half the diameter of the smallest feature of interest is suggested.

$$f = \frac{150}{d\sqrt{\varepsilon}} \tag{12}$$

Field Setup Considerations

The survey limits should ideally overlap with at least one location where a void has been physically confirmed. This overlap will facilitate identification of additional voids, especially if they are interconnected. Where no such confirmation is available prior to the GPR survey, the survey area should be centered about the feature suspected to be associated with the formation of voids. The survey limits should then extend beyond the edge of this feature by a distance no less than the depth to the bottom of the feature. The rationale for this survey limit is to encompass the approximate zone of influence of the feature, where related voids are most likely.

The survey should be undertaken in a grid configuration and the spacing of survey lines should be no greater than one quarter of the wavelength, which can be approximated with Equation 13 (Milsom, 2003):

$$\frac{75}{f\sqrt{\varepsilon}} \tag{13}$$

The survey lines should ideally be completed in a consistent direction, to facilitate stitching of adjacent survey areas if necessary. The orientation of the survey lines will depend on the objective of the study. For example, if the objective is to delineate a utility trench or culvert crossing a highway, it may be desirable to orient the survey lines perpendicular to the suspected orientation of these features. Alternatively, orienting the survey lines parallel with a feature could be beneficial for evaluating the continuity of the feature or variations in the elevation of the feature along its axis. Often, including a set of survey lines in both directions (i.e., parallel and perpendicular) can be valuable due to the complementary nature of the information obtained in each direction.

3.3.1.2 Seismic Methods

Seismic methods may be suitable for the detection and delineation of voids, especially where greater depth of investigation is required in the presence of near-surface clayey deposits, high groundwater levels, or other conductive settings. As discussed previously, these conditions are expected to limit the depth of investigation of EM and electrical methods.

The acquisition of seismic data also faces several challenges. Surface obstructions which limit the length of the seismic array may negatively impact data quality, by limiting resolution, accuracy, and depth of investigation. These space constraints are typical when the survey crosses a roadway, especially for divided highways. Aligning the survey parallel to the roadway may alleviate this constraint but this may not always be prudent. Where possible, preference should be given to aligning the survey in the same direction as the source of potential voids to collect more complete/continuous coverage rather than many discrete “slices” aligned with lanes.

Sources of seismic noise, such as vehicular traffic and construction activities, could also negatively affect the quality of the seismic survey data. The impacts of noise can potentially be mitigated by adopting larger seismic energy sources, utilizing shear waves (which are less influenced by traffic noise), and/or the application of post-processing techniques such as stacking (Wightman, Jalinoos, Sirles, & Hanna, 2004).

Despite these general limitations, seismic methods can still serve as a valuable tool for void detection and delineation. Seismic methods which may be well-suited to a highway setting are discussed below.

3.3.1.2.1 Shear Wave Reflection

Seismic reflection can be used to directly detect voids. The use of a shear wave source can further improve results since shear waves will not be transmitted through fluid or air. Hence, ray paths encountering voids filled with these materials can reflect off the feature but will not propagate through it (Wightman, Jalinoos, Sirles, & Hanna, 2004). Furthermore, it has been shown that using shear waves in soil can more than double the survey resolution, as compared to using compressive waves (Johnson & Clark, 1992). This superior resolution is theoretically supported by the fact that the resolution is proportional to wavelength, which, for an equivalent wave frequency, will be shorter for the relatively slower shear waves. Pugin et al. (2019) note that S-wave seismic wavelengths are typically four to ten times shorter than P-wave wavelengths in the near surface environment.

As with other methods, the shear wave reflection technique has limitations. The most obvious limitation is that the survey must be designed such that a sufficiently small wavelength can be produced (and recorded) to detect the survey target(s). Hunter et al. (2022) note the following additional factors which can hinder the success of a shear wave reflection survey by limiting depth of investigation, resolution, and general survey quality:

- Dry, high-porosity unconsolidated sediments at or near surface can severely attenuate high-frequency shear wave energy;
- Sources of seismic noise can reduce the signal-to-noise ratio; and,
- The accuracy of calculated shear wave velocities will decrease with depth for a set array length.

Equipment

Selection of seismograph sampling rates will depend on the expected dynamic properties of the materials at the site. For shear-wave velocity measurements in unconsolidated materials, a sampling rate of 50 μs is recommended. The equivalent sampling frequency is 20 kHz.

Seismographs should have a minimum of three (3) recording channels (Arsenault, Hunter, & Crow, 2012). Three-component geophones, consisting of two orthogonal horizontal sensors and one vertical sensor, should be used. Geophone resonant frequency of 8-15 Hz with 60-70% damping is recommended to capture low frequency horizontally polarized shear waves. Geophone range should extend up to 100 Hz (Arsenault, Hunter, & Crow, 2012).

The seismic source is a critical component of the survey. It must be firmly coupled with the ground to ensure the seismic energy is transferred to the subsurface. Some seismic shear wave sources and the corresponding frequency bandwidths are listed in **Table 3-4**. It is important to note the frequency at which the maximum spectral amplitude will be achieved depends on the material through which the wave energy is propagated.

Table 3-4. Examples of seismic shear wave sources and corresponding frequency bandwidths

Seismic Source	Bandwidth (Hz)	Reference
Horizontal Sledgehammer Impact	20 – 120	Pugin et al. (2019)
Horizontal Sledgehammer Impact with 3-inch Steel Cylinder	40 – 200 (S-wave) 60 – 350 (P-wave)	Johnson & Clark (1992)
Industrial Vehicles International “Minivib” 3.5-ton Version	20 – 80	Pugin et al. (2019)
INOVA “UV2”	1 – 400	INOVA Geophysical (2024)

Geological Survey of Canada "Microvibe"	20 – 350 (SH-wave) 100 – 500 (P-wave)	Pugin et al. (2019)
OYO Corporation P-S Logging System (Downhole Source)	500 – 5000	Wightman et al. (2004)
Crosshole Seismic Waves	25 – 300	Wightman et al. (2004)

Field Setup Considerations

Wightman et al. (2004) note that a major difference when comparing to compressional wave surveys is that shear wave surveys will use smaller geophone spacing for an equivalent depth of investigation. Other factors influencing the geophone spacing and spread are the expected diameter and depth of the voids; smaller, shallower voids will require shorter spacing and spread. Resolving smaller voids will also require higher frequency waves. Wightman et al. (2004) note the typical depth resolution that can be expected is about half the wavelength, though they suggest a wavelength of no more than 0.25 times the size of the void. As an example, for soils corresponding to Site Class E, as presented in Table 4.1 of the CHBDC (CSA Group, 2019), Vs_{30} velocities up to 180 m/s would apply. Hence, a wavelength of 1.8 m can be achieved for a wave with a predominant frequency of 100 Hz. The smallest void that could potentially be detected in this example would therefore be approximately 0.9 m in diameter.

Based on the frequency bandwidths presented in **Table 3-4** and shear-wave velocity ranges corresponding to the seismic site classes as per Table 4.1 of the CHBDC (CSA Group, 2019), theoretical estimates for the corresponding wavelengths are provided in **Table 3-5**. The reader is cautioned that these values are provided as a rough approximation to assist with investigation planning, but results (i.e., achievable resolution) may differ substantially due to the heterogeneity and complexity of the actual subsurface conditions that are present.

Table 3-5. Estimated wavelengths for different site class S-wave velocities and source frequencies

Site Class and Ground Profile Name	S-Wave Velocity (m/s)	Frequency (Hz)				
		25	50	100	200	350
		Estimated Wavelength (m)				
A – Hard Rock	> 1,500	60.0+	30.0+	15.0+	7.5+	4.3+
B – Rock	760 to 1,500	30.4 – 60.0	15.2 – 30.0	7.6 – 15.0	3.8 – 7.5	2.2 – 4.3
C – Very Dense Soil and Soft Rock	360 to 760	14.4 – 30.4	7.2 – 15.2	3.6 – 7.6	1.8 – 3.8	1.0 – 2.2
D – Stiff Soil	180 to 360	7.2 – 14.4	3.6 – 7.2	1.8 – 3.6	0.9 – 1.8	0.5 – 1.0
E – Soft Soil	< 180	< 7.2	< 3.6	< 1.8	< 0.9	< 0.5

The source is often oriented in line with one of the horizontal sensors but can also be oriented at 45° to the axes to produce equal energy in both horizontal sensors.

Geophones must be firmly seated against the ground surface to achieve good quality data. For a highway setting, pavement surfaces may present a challenge in achieving this due to gravel and other road debris, or imperfections and unevenness in the road surface.

Provided the surface is relatively clear of debris and smooth, one potential option is to deploy geophones via a landstreamer. This equipment is designed to allow geophones to be towed in a line along the ground surface, stopping at each station where a record is to be collected. This equipment typically features clips at specified spacings and base plates to allow the geophones to slide along the ground. Some landstreamer equipment will also include anti-rotation wings.

Studies have shown data quality is comparable between landstreamer and conventional spiked geophone deployment (Park Seismic LLC, 2024). In some conditions, however, the coupling between the geophones and the ground surface may be poorer when using a landstreamer, reducing the signal-to-noise ratio (SNR). The SNR can sometimes be enhanced by increasing the weight of the receiver plates and reducing the source-receiver offset. The poorer coupling may also be acceptable when conducting surveys with higher energy sources or wave types (such as surface waves) and shallower depth of investigation (Hanafy, 2022). The use of landstreamers may also be favoured where the length of site closures must be limited, since this approach can increase the speed of deploying a line of geophones by up to an order of magnitude compared to conventional geophone deployment (Park Seismic LLC, 2024). For example, Hanafy (2022) found installation time for a 96-channel landstreamer system took 20 minutes, whereas conventional installation of the same geophone array took 120 minutes. Collecting the landstreamer after data acquisition then took less than 15 minutes, while collecting the conventional array took 60 minutes or more.

Application Examples

Pugin et al. (2019) present three case studies wherein shear wave reflection methods were utilized to detect buried glacial boulders, a sewage tunnel, and abandoned coal mine tunnels. These case studies involved the use of transverse horizontal (H2) impulsive and vibrator sources and H2 geophones deployed via a multichannel landstreamer.

It was demonstrated that the horizontally polarized shear (SH) wave imagery produced by this technique had a 1-2 m wavelength, which is comparable to GPR imagery while also reaching greater depths. Details from the three case studies are summarized below. All three case studies involved the use of geophones deployed via landstreamer.

- **Case Study 1:** The site was located in southeast Manitoba and underlain by a 150-m thick sequence of glacial deposits. The survey utilized a 3.5-ton minivib source producing a 20 Hz to 100 Hz sweep. A geophone spacing of 0.75 m and a near offset of 3 m were used. The survey managed to reveal a layer of boulders within the top of the glacial diamicton at a depth of about 60 m.
- **Case Study 2:** The site was located in Ottawa, Ontario and was underlain by postglacial marine clays and limestone. A two-component microvib source was deployed, using a 9 s linear sweep and 1 s listening time. The source frequency ranged from 20 Hz to 350 Hz in the H2 mode and 20 Hz to 500 Hz in the V mode. Geophones were spaced 0.75 m

apart, with a near offset of 1.5 m. The survey managed to locate a 3-m diameter concrete-lined tunnel at a depth 17 m.

- **Case Study 3:** The site was located in northwest Kentucky and underlain by up to 40 m of unconsolidated fluvial sediments followed by bedrock. The survey utilized a 0.5-kg sledgehammer impacted against the axle of a pressurized cylinder rolled on the ground surface. A source frequency range of 5 Hz to 130 Hz was reported. The geophones were spaced 1.5 m apart, with a near offset of 1.5 m. Unmapped abandoned coal mine tunnels at about 27 m below ground, as well as the overlying top of bedrock, were identified using the survey data.

3.3.1.2.2 Uphole and Crosshole Seismic Tomography

Voids may present an elevated risk to highly sensitive or critical infrastructure with high-volume traffic. In these circumstances, solutions which do not impact traffic operations are required. The need for high-resolution monitoring and early warning also remains. Seismic tomography utilizing boreholes may be able to satisfy these requirements. Uphole and crosshole techniques can be used to produce high-resolution 2D or 3D imagery of a study area by using a network of borehole-deployed geophone strings and/or sources.

To minimize impacts to traffic, boreholes could be installed at strategic locations beyond the road embankment or with flushmount casings within the road shoulder. An example uphole configuration is depicted in **Figure 3-1** but could be modified for downhole or crosshole alternatives. An experienced geophysicist should be consulted to ensure the offset distances are appropriate, since the number of traffic lanes may present a technical limitation to this approach.

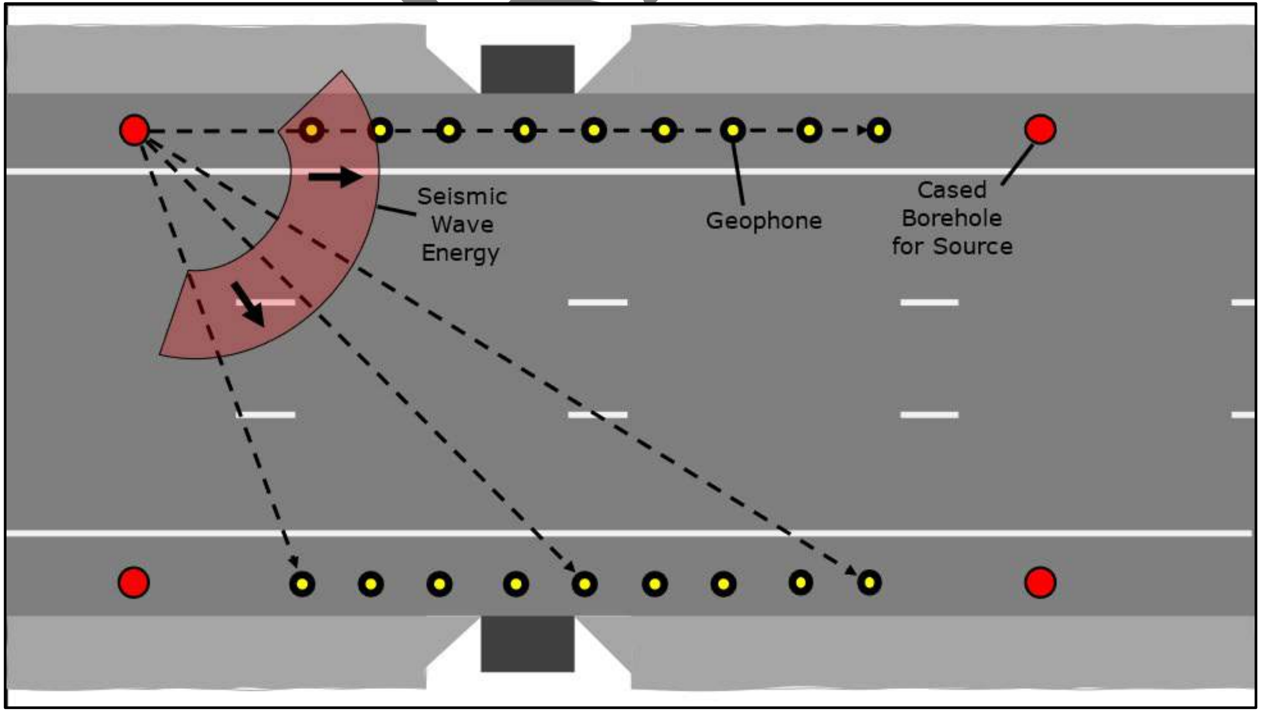

Figure 3-1. Example configuration depicting possible uphole seismic survey in a highway setting

Surface impacts could be further minimized if radio-enabled geophones are installed, to eliminate the need for landlines. If the boreholes are left in place, the survey could be repeated regularly, presenting options for baselining and monitoring throughout construction at the desired intervals.

Two considerable drawbacks to the above-described strategy are cost and data intensity. The primary source of the elevated cost associated with these approaches is that of drilling and casing boreholes. However, as foundations investigations are almost always a required component in the planning stages for proposed crossings, a proactive approach of leaving the boreholes in place could significantly mitigate this drawback. Such a strategy could be worthy of consideration for highly sensitive or critical infrastructure sites.

3.3.1.3 Electrical Resistivity Imaging

Resistivity methods can be effective for detecting and delineating voids due to the contrast that may exist between the surrounding ground and a high-resistivity air-filled void or a low-resistivity water-filled void. These techniques may be especially effective when the formation of voids is related to leaking utility infrastructure or culverts, or gaps behind / between structures where water or other fluids could preferentially flow. Such fluids would be expected to be conductive and strongly contrast with the surrounding resistive materials.

For surveys at the ground surface, the depth of investigation will be constrained by the array spacing and the resistivity of the near-surface layers, though depths of investigation beyond 30 m are unlikely to be warranted except with new alignments passing through known karstic terrain.

Traverses utilizing the dipole-dipole array or variations thereof are suggested for an initial pass to locate possible voids, followed by soundings utilizing the Wenner or Schlumberger array to refine the depth of the identified voids (Wightman, Jalinoos, Sirles, & Hanna, 2004).

Ideally, resistivity surveys should be scheduled during the summer and fall, when subsurface conditions are likely to be drier and more consistent. Frozen ground can present a challenge for planting electrodes and will increase the resistivity of the near-surface soils. Conversely, the presence of dissolved salt from de-icing operations can decrease resistivity considerably. Elevated moisture from spring melt will also reduce resistivity. The presence of these near-surface complicating factors can negatively affect the results of a resistivity survey by making processing and interpretation more challenging.

When the objective is to identify voids, however, it may be desirable to conduct a survey several days after a heavy rainfall. The presence of voids might be expected to provide preferential pathways for infiltration, presenting areas of high contrast due to the concentration of moisture and/or the absence of material (airspace).

Field Setup Considerations

As discussed in **Section A.1.1**, the depth of investigation for a resistivity survey will be influenced by the total array length, AB, and the resolving depth will be influenced by the array configuration and the available current from the survey equipment. Both will be influenced by the ground conditions and sources of noise. Survey design must account for the expected site conditions. Modeling is strongly recommended prior to mobilizing to the field, to refine the survey parameters before attempting the work. In general, a larger electrode spacing will yield greater depth of investigation at the cost of lower resolution. The smallest spacing to achieve the desired depth of investigation, as indicated by modeling, should therefore be adopted.

The depth of investigation will also vary depending on the thicknesses, geometry, and relative resistivity of the subsurface layers, sources of noise, and the available power source. However, a few rules of thumb are shown in **Table 3-6** for informational purposes and potentially a "first guess" during preliminary planning and modelling.

Table 3-6. Approximate depth of investigation as a fraction of array length by configuration

Depth of Investigation	Array Configurations	Source
0.2 x Total Array Length	Schlumberger, Wenner, Dipole-Dipole	Bernard (2003)
0.9 x Total Array Length	Pole-Pole	Bernard (2003)
0.5 x Total Array Length	Wenner	Herman (2001)
<0.3 x Total Array Length	All configurations	Wightman et al. (2004)

The presence of conductive layers or media such as clays, groundwater table, or buried utility infrastructure may impede the success of a resistivity survey. Where the signal-to-noise ratio is expected to pose a challenge, configurations which promote greater signal strength should be considered. The Wenner array is expected to provide the greatest signal strength due to its low geometric factor (Loke, 2000).

The use of downhole electrodes can also enhance electrical resistivity tomography results by increasing the depth of investigation beyond that which is possible from surface, whether due to space constraints or due to near-surface conductive layers (Vilar, Ustra, & Mendonça, 2015). Crosshole electrical resistivity tomography (ERT) is one approach which uses downhole electrodes. This technique typically utilizes the pole-pole array, which has a high signal-to-noise ratio but low resolving power, so combining the survey with pole-dipole data may be warranted (Huang & Mayne, 2008).

Post-processing techniques may also need to be undertaken to enhance the signal-to-noise ratio where persistent and/or strong sources of noise are present, such as nearby electrical utility infrastructure, whether above or below ground. Where numerous factors are identified that could negatively affect the outcome of the resistivity survey, other geophysical methods should be considered.

3.3.1.4 Gravimetry

Gravimetry may be a feasible option for investigating the presence of voids depending on the site conditions, and the size and depth of the possible voids. The ideal conditions for gravimetric surveying would be:

- Flat site and surroundings;
- Minimal noise, which includes vibrations, rain, and wind;
- Small area.

For gravimetry to be feasible, the suspected voids should be sufficiently large and close to surface to be detected. The detection limits applicable to microgravimetry will be determined by the instrument sensitivity, accuracy, and operator skill. A practical limit given by the U.S. Army Corps of Engineers (1995) is approximately 2 m depth per 1 m of diameter for a 1.0 g/cm^3 density contrast. In unconsolidated overburden materials, the density of these materials may be in the order of 1.2 g/cm^3 for clays to 1.5 g/cm^3 for sands. The density of shales and limestones, in which voids (and caves) can also often be present, can range from 2.0 g/cm^3 to 2.7 g/cm^3.

Several drawbacks to gravimetric surveying must be considered. The equipment is expected to be relatively expensive, due to the necessary sensitivity to detect voids at the early stages. The survey itself can be time intensive as well, as detailed elevation and location surveying is needed for elevation, terrain, and latitude corrections. Detailed time keeping is necessary, as well as "closing the loop", to allow for tidal and drift corrections. These corrections, among the others discussed in **Section A.3.1**, are applied during post-processing.

Where the source or cause of the suspected voids is itself an excavation, such as a tunnel, culvert, drain, or other void space, the presence of this principal feature may obscure the presence of smaller voids above or around it.

Equipment

For highway settings, the size of the potential voids with which one might be concerned could range from centimeters (the size of a pothole) to several meters (significant sinkholes). As the size of the potential void increases, so too does the likelihood that evidence of its presence will be visible at surface. It is more likely that void detection studies would be focused on smaller voids which are not yet evident at surface. Hence, microgravimeters used for these purposes should be sensitive and repeatable to 10 µGal or better.

To ensure the applicable corrections are also of high quality, survey equipment capable of measuring elevations to 0.01 m accuracy should be used. This will likely necessitate the use of local differential systems.

Field Setup Considerations

A microgravimetry survey will typically be carried out in a grid pattern, with measurement points or *stations* at the intersection points of the grid. The size of the grid should be determined based on the expected size and depth of the potential voids being sought. For geotechnical applications, the relatively small size of the survey target(s) will require a high density of stations (Seigel, 1995).

For a comprehensive guide to designing and undertaking microgravimetry surveys, the reader is referred to *A Guide to High Precision Land Gravimeter Surveys* (Seigel, 1995). A summary of the main steps in the standard field procedure suggested by Seigel include:

1. Allow time for the gravimeter to stabilize after powering on and setting up.
2. Establish and mark the survey grid and select some stations for use as base stations.
3. Start the survey at the selected base stations and close out the survey loops at these locations, to correct for drift.

4. Take barometric readings at the same time and place as gravity readings to correct for severe weather front movements.
5. Average the corrected readings at the base stations and use this average as a “correct” value for these locations.
6. Complete the survey systematically and tie-in to at least one of the base stations at the beginning and end of the day, if not more.
7. Survey the elevation and location of the stations.
8. Tie-in with the national gravity grid, especially if absolute levels or if use of other existing gravity survey data are desired.

3.4 Re-use of Existing Foundations

The re-use of existing foundations can offer considerable economic, environmental, and social benefits. Survey responses from 62 transportation agencies presented in NCHRP Synthesis 505 (Boeckmann & Loehr, 2017) identified economic considerations, accelerated construction, and constructability as the top three motivations for foundation reuse. The motivations can be grouped into six drivers: costs, sustainability, site constraints, mobility, historic/aesthetic preservation, and environmental impacts and permitting (Agrawal, Jalinoos, Davis, Hoomaan, & Sanayei, 2018).

Without a complete understanding of the size, depth, founding strata, and condition of existing foundations, however, the reuse of foundations can introduce considerable risk. This section describes several geophysical approaches to investigating these parameters to aid in assessing the integrity, durability, and capacity of the existing foundations. The specific case of construction quality assurance involving the use of access tubes placed within the foundations during installation is excluded.

Past serviceability is not an adequate indication of the condition of existing foundations. Existing foundations must be investigated to re-evaluate the remaining life and capacity of these elements. Hertlein and Davis (2006) and Agrawal, et al. (2018) both describe several case studies involving structures that had previously been in service for over a decade where NDT revealed considerable defects with the remaining foundation elements when they were inspected for potential reuse. Some of the case studies involved foundation defects that likely stemmed from construction, while others involved foundation elements which had experienced varying degrees of degradation from environmental factors such as scour, corrosivity, or seismicity. Damage is also possible from previous loading and settlement, demolition of the superstructure they previously supported, vibration, or traffic impacts over its existence to date.

Beyond defects, the reliability of an existing foundation may be doubted if little is known about the supporting strata. An excellent subsurface model is of great importance, but equally important to assessing the capacity of a foundation is knowing its position within that subsurface model. This uncertainty is particularly relevant to driven foundations, which may not be founded in the target stratum if not successfully (and verifiably) driven straight. Uncertainty may also exist when considering the reuse of foundations for which the construction records are illegible or no longer available. The reasons for loss or inadequacy of documentation could stem from the digitization of records in the 90s, changes to reporting requirements, or change of ownership over the life of the foundations. Regardless of the reason, verification of documented foundation details or filling information gaps is another valuable application of geophysical methods when considering foundations for re-use.

3.4.1 Investigation Design

Geophysical investigation techniques can be particularly valuable for investigating existing foundations due to their inherently non-destructive nature. Without non-destructive alternatives, it becomes necessary to extract a greater number of foundation members to perform a reliable evaluation of the remaining service life and capacity of the leftover foundations. Those members which are removed cannot be used and the extraction process could disturb those nearby. Geophysical investigation can be used to complement this intrusive investigation approach by reducing the number of members needing to be extracted or perhaps even enabling a limited daylighting approach instead.

Foundations will typically consist of steel and/or concrete but some may also consist of wood. In general, resistivity, magnetometry, or electromagnetic techniques may be well-suited to detecting steel foundations or those containing steel in the form of reinforcement or a casing. Seismic or acoustic methods may also be effective since foundations are generally stiffer than the surrounding ground. The relative advantages and limitations of these methods, as well as additional survey design considerations, are discussed in the following sections.

It is important to note that solely the use of geophysical methods is discussed herein. The re-use of existing foundations will likely require some or all of the following additional investigation tasks to be considered: pile extraction, visual examination, tensile testing, and ultrasonic thickness readings of extracted piles, corrosivity testing of soil and groundwater, and borehole logging to verify soil, groundwater, and bedrock conditions.

3.4.1.1 Borehole Magnetometry

Magnetometry involves measuring the magnetic field using a device called a magnetometer. A magnetic anomaly can be caused by induced and/or remanent magnetization. Induced magnetization is the result of a magnetically susceptible material interacting with the earth’s magnetic field (e.g., the ambient field). The intensity of the former is equal to the product of the two latter. Remanent magnetization is independent of the ambient field and depends on the material properties as well as its thermal, mechanical, and magnetic history. Remanent magnetization is caused by the magnetic domains of the material becoming oriented parallel with the ambient field at the time of intense heating, then becoming fixed in that orientation upon cooling. When pertaining to metals, remanent magnetization is often referred to as permanent magnetization (Breiner, 1999). Induced magnetism and remanent magnetization are both of interest in the case of detecting existing foundations, as magnetically susceptible foundation elements can be expected to exert an influence on the ambient field. A magnetic anomaly is defined as the deviation between the measured field intensity and that of the expected ambient field. Ambient field data for a specific location can be obtained from sources such as the US

National Oceanic and Atmospheric Administration Magnetic Field Calculator (NOAA, 2024) (see: NCEI Geomagnetic Calculators).

Borehole magnetometry, also sometimes referred to as parallel inductive field testing (Rausche, 2004), is carried out from within a borehole installed alongside an existing foundation element of an unknown length. The foundation element would need to contain ferromagnetic material, whether in the form of reinforcement, casing, or the pile material itself. Borehole magnetometry is expected to be most useful for steel piles and sheet piles of any length. The required borehole for conveyance of the magnetometer should be no more than 0.75 m away from the pile of interest (Rausche, 2004).

Provided the borehole extends beyond the depth of the foundation element, the depth to which the foundation extends could be determined based on the point at which the magnetic anomaly begins to rapidly diminish (Wightman, Jalinoos, Sirles, & Hanna, 2004). It should be noted that separate anomalies can be expected at joints if multiple segments were adjoined, due to the independent thermal and mechanical histories affecting each (Breiner, 1999). The borehole used to convey the magnetometer should be logged in detail to characterize the materials adjacent to and below the foundation.

The volume of the magnetic material can be estimated based on the measured dipole magnetic moment, the susceptibility of the material, and the ambient field (Breiner, 1999). However, it is expected that minor variance in the distance between the borehole and the foundation element would render this estimate unreliable unless the precise distance between the magnetometer and the foundation is known. It is therefore advised that interpretation be limited to estimating the depth of the foundation element only.

It may be effective in some circumstances to measure the gradient of the magnetic field, which is the difference in the field intensity detected at different sensors and/or measurement locations divided by the distance between measurements. This can be achieved using a conventional portable magnetometer or with a differential magnetometer (i.e., a gradiometer). Advantages of gradiometry include the automatic removal of the regional magnetic gradient and temporal variations, in addition to enabling the use of the vector properties of the gradient to determine depths, moments, shapes, and locations of anomalies (Breiner, 1999). However, gradiometry is more sensitive to magnetic noise sources, and it can require more readings be taken with greater care than conventional magnetometry.

A few case studies demonstrating the use of borehole magnetometry are summarized below:

MTO's Greenock Creek Bridge

- Borehole magnetometry was used to aid in identifying the depth extent of existing steel pile foundations as part of an evaluation for potential pile re-use at a creek crossing.
- The subsurface conditions at the borehole magnetometer test locations are summarized in **Table 3-7**:

Table 3-7. Summary of subsurface conditions at Greenock Creek Bridge test locations

Material Description	**Soil Depths (m)**			
	Borehole 22-03	**Borehole 22-04**	**Borehole 22-05**	**Borehole 22-06**
Granular Fill	0.2 - 2.2	0.3 - 2.2	0.1 - 3.0	0.1 - 3.0
Silty Clay to Clayey Silt	2.2 - 3.0	2.2 - 3.0	3.0 - 3.7 4.5 - 6.0	3.0 - 3.7 4.5 - 6.0
Peat	-	-	3.7 - 4.5	3.7 - 4.5
Sand and Gravel	3.0 - 6.9	3.0 - 6.9	6.0 - 8.7	6.0 - 8.7
Silty Sand Till	6.9 - 10.4	6.9 - 12.5	8.7 - 15.5	8.7 - 15.5
Groundwater	Not recorded	Not recorded	3.7	3.7

- A Sensys FM3D three-axis Fluxgate magnetometer was used to take magnetic field readings at 0.5-m intervals along the borehole, at a 10 Hz sampling frequency referenced to cable timed cable markers.
- A LIM BHTV42 acoustic televiewer equipped with a magnetometer was also used to measure and record the magnetic field at 0.02 m intervals.
- A low pass filter was applied to the data to remove high-frequency noise, followed by analysis of the vertical and horizontal components of the magnetic field.
- The base of the steel piles was identified based on the midpoint of the slope in the magnetic field data and the peak of the first derivative of the vertical magnetic field.
- Pile depths estimated using the magnetometer data ranged from 6.8 m to 7.6 m for the four test holes, which were consistent with estimates produced using the parallel seismic, electromagnetic, and natural gamma methods.

MTO's Highway 401 Underpass at Hallecks Road

- Borehole magnetometry was used to investigate the depth of abandoned steel piles at a bridge replacement site, using a borehole installed 2 m away from an existing pile.
    - The borehole was cased with 51-mm outside diameter Sched. 40 PVC, which was grouted in place along its full depth.
- A LIM Instruments acquisition system with motorized winch and tripod were used to deploy an Electromind logging probe and BHTV42 acoustic televiewer into a test hole, to record the total magnetic field.
- The BHTV42 acoustic televiewer was equipped with three magnetometers and an accelerometer. The accelerometer was used to differentiate magnetic anomalies due to changes in soil type, as inferred from bulk density changes, from those induced by the presence or absence of the metal pile.
- A log was recorded during, both, the upward and downward passes to increase accuracy.

- At approximately 5.9 m depth, disruptions in the magnetometer and accelerometer signals were observed, likely due to a geological transition between silty sand and glacial till.
- At approximately 7.5 m depth, a strong magnetic anomaly was detected by the magnetometers but not by the accelerometers, indicating the presence of a metallic object which was interpreted to be the bottom of the pile.
- The borehole magnetometer results corresponded well with the results from parallel seismic testing and bedrock depth.
- The subsurface conditions at the test hole are summarized in **Table 3-8**:

Table 3-8. Summary of subsurface conditions at Hallecks Road test location

Material Description	**Soil Depths (m) (Borehole 23-01)**
Granular Fill	0.0 - 2.9
Silty Sand to Silt	2.9 - 5.9
Silty Sand with Gravel, Cobbles, and Boulders (Glacial Till)	5.9 - 7.4
Dolostone Bedrock	7.4 - 13.0
Groundwater	Not recorded

Forensic Diagnosis of a Deep Collapsed Excavation in Singapore (Ishihara & Lee, 2008)

Ishihara and Lee (2008) documented a forensic investigation following the collapse of a deep excavation during construction of a subway station in Singapore. Borehole magnetometry was used to detect ferrous metal obstructions, such as broken pieces of walers, structs, or construction equipment, within the collapse debris.

The magnetometry was conducted from within 67 boreholes drilled at 2-m intervals, located approximately 3-5 m behind diaphragm walls along the north and south sides of the collapsed excavation. The collapsed excavation was approximately 31 m deep and spanned an area of about 100 m by 20 m. The soil profile at the site generally consisted of 3-5 m of fill overlying soft to very soft marine clays extending to about 35 m below surface. The marine clay was underlain by an older alluvium layer comprising stiff silty sand.

The use of a borehole magnetometer aided the investigators in identifying the exact locations of the exposed tops of the diaphragm wall panels. This information was critical in developing an understanding of the failure mechanism. It was concluded that the toe of the diaphragm walls had kicked in, with the retained soil flowing into the excavation from underneath. This application successfully demonstrated the use of borehole magnetometry to detect and delineate ferrous objects of varying sizes, shapes, orientations, and distances from the boreholes.

3.4.1.2 Electromagnetic Induction

Electromagnetic induction involves generating an electromagnetic field to induce currents in nearby conductive materials. By measuring the secondary magnetic field produced by these induced currents, the presence of different materials can then be inferred. This method can be categorized into two main types:

1. **Time-Domain Electromagnetics (TDEM)**: Uses a square wave current that is abruptly shut off, resulting in magnetic flux which induces secondary currents in the ground. The decay of these currents in turn produces magnetic flux, inducing currents which are measured to determine resistivity at various depths.
2. **Frequency-Domain Electromagnetics (FDEM)**: Uses a continuous sinusoidal current to generate a primary field. The secondary field induced in the ground is measured at different frequencies to infer subsurface conductivity.

This method is particularly effective for detecting metallic foundation elements, which will be relatively conductive compared to the surrounding subsurface soils and/or bedrock. The conductivity and magnetic susceptibility of the surrounding materials can also be measured, which can be valuable for assessing corrosion potential especially when paired with the self-potential method.

However, electromagnetic induction methods can be affected by external electromagnetic noise from power lines, electronic devices, and other sources, which can complicate data interpretation. Furthermore, while effective at detecting large metallic objects, the resolution may be insufficient for identifying small defects or fine details within the foundation.

Electromagnetic Induction at MTO's Greenock Creek Bridge

Electromagnetic induction was applied at MTO's Greenock Creek Bridge site to evaluate the length of existing foundations. Clear anomalies were identified in the electromagnetic data that corresponded to the depth of the steel piles, based on significant changes in electrical conductivity. The pile tips were correlated to peaks in the electrical conductivity data and were found to be consistent with the results from other geophysical methods (borehole magnetometry and parallel seismic). Natural gamma logging was carried out in conjunction with the electromagnetic logging to help differentiate elevated conductivity measurements caused by clay layers and bentonite clay backfill material from those caused by metallic objects (i.e., the piles).

A Geonics EM39 tool was used at the Greenock Creek Bridge investigation. The tool contained two coaxial coils with an intercoil spacing of 50 cm, yielding an effective radius of exploration of approximately 1 m into the surrounding soil. The tool was deployed using a mini-winch and data collection was handled by an ALT Matrix Logger. Measurements were taken at 0.05 m intervals in the uphole and downhole travel directions, at a rate of approximately 1.5-2.0 m/min. Prior to logging, a zero-reading was taken to calibrate the tool. The zero-reading was taken by suspending the tool 3 m in the air and ensuring it was at least 10 m away from any large metallic objects.

3.4.1.3 Acoustic Methods

The parallel seismic and impulse echo methods are expected to be effective tools to aid in the evaluation of existing foundations. Both methods require a portion of the foundation element to be exposed at surface, to varying degrees. Parallel seismic is further limited to those foundations with sufficient space for adjacent drilling.

These techniques are expected to primarily aid in the determination of the size and integrity of these foundation elements. Pulse velocity can be correlated to different material properties, including strength and elastic properties. Caution is advised, however, as these relationships can be complex and depend on many independent factors relating to the material composition as well as its age (International Atomic Energy Agency, 2002).

Though potentially expensive due to the need for a borehole, the parallel seismic method is expected to be the most accurate of the acoustic methods for determination of an unknown foundation depth. A 95% accuracy or better is typical (Wightman, Jalinoos, Sirles, & Hanna, 2004).

Practical depth limits for these techniques are presented in **Table 3-9**. Practitioners should ensure they are familiar with the limitations of the specific equipment they are using, as well as their own professional experience. Actual depth limits will be dictated by site-specific conditions including the subsurface soils and rock, the pile type, the presence of splices, pile cross-section, pile material or cross-section variability, quality of analyzer electronics, surrounding or adjoining structures, and more (Pile Dynamics, Inc., 2024).

Table 3-9. Suggested practical depth limits for acoustic methods

Method	Related Parameter	Practical Depth Limit
Impulse Echo	Length-to-Diameter Ratio	60 diameters or less (Rausche, 2004) 30 to 60 diameters (Pile Dynamics, Inc., 2024)
	Embedded Pile Length	15 m for timber piles (Pile Dynamics, Inc., 2024) 50 m for large diameter piles (Pile Dynamics, Inc., 2024)
Parallel Seismic	Embedded Pile Length	10 m or less, especially for steel piles (Rausche, 2004)

Key equipment and survey best practices are discussed below for the impulse echo and parallel seismic methods.

Impulse Echo

Key equipment required for the impulse echo method include:

- Impulsive source to generate stress waves;
    - Typically, a light (1 kg) plastic- or rubber-tipped hammer equipped with a trigger mechanism is used. The trigger mechanism activates the data acquisition system upon impact.
    - Heavier hammers may be prudent for larger diameter (1 m or more) and/or longer piles, or where a thick pile cap or other overlying element is present;
- Receivers, in the form of geophones or accelerometers, to detect the reflected waves from the bottom of the foundation element and/or changes in impedance due to cracks, voids, material changes, etc.;
- Data acquisition system to record and process the signals from the receivers;

- Cables and connectors to connect the receivers to the data acquisition system; and,
- Software for data analysis and interpretation, often including signal processing and visualization tools.

Best practices for impulse echo surveys include but are not limited to the following:

- The pile should be struck at or near the pile axis;
- Record multiple strikes to allow for stacking. A minimum of four strikes should be recorded but more may be desired and/or necessary to enhance the signal-to-noise ratio. Background noise can be reduced roughly by a factor of √n, where n is the number of strikes, as shown in **Table 3-10**.

Table 3-10. Approximate noise reduction factors from stacking an increasing number of records

Number of Test Strikes (Records)	Approximate Noise Reduction Factor	Approximate Reduction in Noise
1	1.00	0%
2	1.41	29%
3	1.73	42%
4	2.00	50%
5	2.24	55%
6	2.45	59%
7	2.65	62%
8	2.83	65%
9	3.00	67%

- It is recommended to use four or more receivers to aid in the interpretation of wave response. Using multiple receivers can:
  - Help isolate the signal response from noise sources such as surface waves;
  - Provide redundancy to mitigate the effects of debonding or cracking near any individual receiver; and,
  - Facilitate filtering of wave frequencies.
- Receivers should be coupled to the pile using grease- or gel-based couplant.
- The recording equipment must be able to deconvolute and amplify the response, especially for deep reflectors and dampening soil conditions.
- Analysis methods:
  - The frequency-domain approach is best suited to detecting defects in the top few metres and is well-suited to cast-in-place piles which are expected to have variable cross-sections.
  - The time-domain approach is typically adequate for piles with constant cross-sections, such as pre-cast driven piles.

Parallel Seismic

The key equipment required for the parallel seismic method is similar to that which is required for the impulse echo method. The primary differences include:

- The conveyance of geophones or hydrophones within a borehole;
  - Good coupling between the sensor and the borehole walls is critical. This can be accomplished by using hydrophones in a water-filled borehole or using air bladders, wedges, stiff springs, or mechanical expanders to press geophones against the borehole wall.
  - If the borehole is cased, the annular space between the casing and the ground must be backfilled with grout to ensure good coupling.
  - The borehole should extend 3 to 5 m below the expected bottom of the foundation element of interest and should ideally be no further than 1.5 m away. Distances of up to 6.0 m may be possible in very uniform soils, but data interpretation difficulty will also increase (Wightman, Jalinoos, Sirles, & Hanna, 2004).

Some case studies demonstrating the application of the parallel seismic method are summarized below.

MTO's Highway 401 Underpass at Hallecks Road

The parallel seismic method was applied at a Highway 401 underpass at Hallecks Road, to aid in determining the depth of abandoned steel H-piles as part of a pile re-use evaluation. A fully-grouted cased borehole was installed to enable the testing.

The parallel seismic testing was conducted using a probe with a built-in 3-orthogonal components geophone. The probe was lowered to the bottom of the borehole and subsequently raised in 1-m increments to take measurements. Coupling was achieved using an electro-mechanical bow-spring to press the geophone against the PVC casing.

The seismic source was a 9-kg sledgehammer, impacted at three distinct source-points: a strike plate offset 1.5 m from the borehole center, and a horizontal beam anchored at distances of 2.12 m and 1.75 m from the borehole. The strike plate was used for vertical strikes, whereas the horizontal beam was used to generated strongly polarized shear waves. Site equipment was driven onto the beam to anchor it to the ground.

Data acquisition was accomplished using an ABEM Instruments Terraloc Pro2 seismograph. Data was sampled at 50 μs time increments with a pre-trigger delay of 10 ms, resulting in the recording of 4,096 samples per trace.

The parallel seismic results indicated a pile depth of 7.5 m below ground, which corresponded well to the depth of bedrock and was consistent with results from borehole magnetometer testing at the same location.

MTO's Greenock Creek Bridge

At MTO's Greenock Creek Bridge rehabilitation project, the parallel seismic method was one of several geophysical methods used to determine the depth of existing piles. Four boreholes were drilled and cased for the geophysical testing program, at the inside corners of the abutments.

A triaxial geophone was used to detect the seismic wave arrival times from within the boreholes. The geophone was coupled to the borehole casing using a motorized wall-lock. The seismic source was a 9-kg sledgehammer, impacted against a steel bar placed adjacent to the bridge for three of the borehole locations and directly against the concrete of the bridge at one location due to increased fill material being present. Two impacts were recorded per measurement depth and location; a vertical impact (downward) and a horizontal impact in the direction of the abutment.

An ABEM Instruments Terraloc Mark 6 seismograph was used for data acquisition at this project. Traces were recorded over 200 ms on a 25 μs sampling interval, including a pre-trigger delay of 10 ms, resulting in 8,192 samples per trace.

The results of the parallel seismic testing indicated the piles extended to approximately 7.0 m to 7.6 m below ground. Good agreement was found when comparing to the results from borehole magnetometry, electromagnetic, and natural gamma ray logging, which were conducted at the same locations.

Evaluations of the Depth of a Root-Pile and a Caisson Foundation (de Jesus Souza, Hemsi, Gandolfo, & Aoki, 2017)

De Jesus Souza et al. (2017) describe two case studies in which the parallel seismic method was used to evaluate the depth of two different pile types supporting telecommunication towers in Brazil.

At the first site, the structure was founded on a 3.1-m x 3.1-m x 1.1-m block supported by eight 25-cm diameter root piles. The stratigraphic profile at this site consisted of 2 m of soft clay underlain by a hard sandy clay. Groundwater was found at 2 m below ground.

At the second site, a 230-cm diameter caisson was investigated. The described stratigraphy predominantly consisted of residual micaceous clayey sandy silt. The soil was identified as soft in the upper 1 m, and hard below 10 m. The water table was found at about 20 m below ground.

At both test sites, the authors used a 1.8 kg sledgehammer as the seismic source for the testing, impacted directly against the central portion of the concrete pile cap. The sledgehammer was equipped with a coupled transducer to initiate the recordings. Measurements were taken at 0.5 m vertical intervals and recorded using a 12-channel Geometrics SmartSeis seismograph.

Test measurements were obtained using a triaxial downhole geophone with a resonant frequency of 8 Hz. Coupling between the geophone and the borehole casing was achieved using a pneumatic clamping mechanism.

For the root-pile foundations, a 19-m deep borehole was advanced 0.4 m away from the foundation block to conduct the parallel seismic testing. The depth of the root-piles was estimated to be 11 m. For the caisson foundation, a borehole was advanced 1.2 m away and to a depth of 15 m. The parallel seismic results indicated the depth of the caisson was 8 m.

The parallel seismic results from both sites were compared to as-built records after all interpretation was completed. It was found that the depths estimated from the testing matched the depths indicated in the as-built records, validating the reliability of the tests.

3.5 Offshore Investigation

Geophysical investigation methods can enhance investigations in offshore settings by enabling the collection of submarine and subsurface data in a way that may be safer, faster, and provide greater coverage than conventional investigation techniques. Ground truthing remains an important aspect of investigation, however, and geophysical data should be tied in at strategic locations to calibrate data and validate interpretations.

Objectives of offshore investigation may include:

- Mapping sediment thickness and/or bedrock depth along waterways and crossings;
- Characterization of underwater overburden and bedrock properties, such as dredgeability, anchoring capacity, or bearing capacity; and/or,
- Assessing the presence and extent of scour.

Offshore investigation for MTO will typically involve a shallow (<100 m) freshwater system in the form of rivers, tributaries, lakes, or submerged wetlands.

Though guidance on safe work practices is beyond the scope of this document, it is an apt time to stress that working on or around water (or ice) demands special consideration. Additional measures may be necessary, such as ensuring an emergency rescue plan is in place and providing high-visibility clothing and Personal Flotation Devices (PFDs).

3.5.1 Investigation Design

The application of seismic reflection, seismic refraction, electrical resistivity, and ground penetrating radar are discussed in the following sections. The relative advantages and limitations of these methods are presented along with practical surveying considerations with respect to a submarine setting.

For additional information and guidance concerning offshore investigation design, the reader is referred to the following comprehensive resources:

- ISSMGE TC1. (2005). *Geotechnical & Geophysical Investigation for Offshore and Nearshore Developments*. International Society for Soil Mechanics and Geotechnical Engineering.
- Plets, R., Dix, J., & Bates, R. (2013). *Marine Geophysics Data Acquisition, Processing and Interpretation*. English Heritage.

3.5.1.1 Underwater Seismic Reflection & Refraction

Techniques have been developed for applying seismic reflection and seismic refraction to offshore settings. Underwater seismic method is highly similar to land seismic surveying. Key differences are that a transducer located either just below the surface of the water or along the seabed itself is used to generate seismic energy at regular intervals as it is towed by a boat or line. Monitoring is performed by hydrophones, often towed separately (Davis, 1996), which record the return of the seismic energy. As few as one hydrophone could be used, though streamers deployed for marine surveys can be in the order of a kilometer long (Geometrics, 2021). Lines can be run for multiple 2D profiles and stitched to provide a 3D dataset, but some newer technologies allow for multiple streamers to be used side-by-side in close spacing to more efficiently generate 3D data (Ebuna, Mitchell, Hogan, Nishenko, & Greene, 2013). Coupling between the water and hydrophones (and source) is excellent (Geometrics, 2021).

Sources and Surveying

Sources can vary from a handheld hammer struck against a submerged metal plate to more technologically sophisticated equipment such as Compressed High-Intensity Radiated Pulse (CHIRP) sub-bottom profilers (Pugin, Brewer, & Brooks, 2019). Other sources include pingers, boomers, airguns, and sparkers, though sparkers are no longer in common use (ISSMGE TC1, 2005). The selection of a seismic source will be based on the survey type (reflection vs. refraction), the desired penetration, and the desired frequency bandwidth, but allowable options may be controlled by the applicable environmental permits (Ebuna, Mitchell, Hogan, Nishenko, & Greene, 2013).

Fixed frequency or swept frequency signals can be generated depending on the source type. Fixed frequency “pingers” usually generate signals centered at 3.5, 7.0, or 14 kHz (Wightman, Jalinoos, Sirles, & Hanna, 2004), though processing in frequency bands as low as 0.5 kHz to 1.5 kHz can also be carried out. Boomers tend to have broader frequency bandwidths, from 500 Hz to 5 kHz. CHIRP systems are used to generate swept-frequency signals, from 3 kHz to 40 kHz (ISSMGE TC1, 2005). Boomers and CHIRP systems are most common for shallow water environments, with boomer systems being recommended in coarse sands or larger, or CHIRP systems for finer soils (Plets, Dix, & Bates, 2013).

Higher frequencies will provide higher resolution imaging at the cost of investigation depth. For example, a 14 kHz signal can image up to 6 m below the top of sediment, whereas a 3.5 kHz signal can image up to 50 m or more (ISSMGE TC1, 2005), depending on the material. The vertical resolution of the 14 kHz and 3.5 kHz signals is in the order of 30 cm and 75 cm, respectively (Wightman, Jalinoos, Sirles, & Hanna, 2004).

Regarding surveying, Plets, et al. (2013) note that towing speed should be kept between 3 to 4 knots and the system should be towed beyond the vessel’s wake. The towing direction should be aligned with or against the current when it is strong, as it can affect data quality due to turbulence and positioning challenges.

Challenges

Challenges with underwater seismic reflection can include sources of noise or interference, such as reflections from nearby structures or the shore, or echoes from subbottom reflectors, which are referred to as "multiples" (Davis, 1996). Where such sources of noise are identified, it may be desirable to select a transducer with a narrower beam angle if possible (Wightman, Jalinoos, Sirles, & Hanna, 2004).

In shallow water systems, a minimum water depth is needed to ensure the influence of multiples from the water bottom is suppressed (Davis, 1996). These reverberations typically have a high amplitude owing to the fact that the impedance contrast between the water and the underlying earth material is relatively high. Minimum water depths of 1.2 m for 14 kHz to 2.0 m for 3.5 kHz are suggested by Wightman, et al. (2004).

If the water bottom reflector is very strong, it can also mask deeper reflectors by limiting the amount of energy which passes to those subsequent materials. Coarse-grained water bottom materials are noted to generally have a greater reflection coefficient than fine-grained sediment and, thus, may limit the depth of penetration (Wightman, Jalinoos, Sirles, & Hanna, 2004). Bedrock water bottoms may also be expected to function as strong reflectors.

Another challenge is that the source and hydrophones are often towed by a marine vessel, which is not static. The positions and orientations of the source and receivers must be carefully tracked throughout the survey using GPS (Ebuna, Mitchell, Hogan, Nishenko, & Greene, 2013). For refraction surveys, which utilize sleds towed along the seabed, the sleds must be stationary during measurements. Tow systems have been developed which allow the tow cables to be let out while measurements are being taken and retracted when moving to the next station (ISSMGE TC1, 2005).

Air bubbles created by organic off-gassing and/or turbulence will scatter seismic signals (Wightman, Jalinoos, Sirles, & Hanna, 2004). Therefore, this method should not be used in settings where this condition might be expected, such as some swamps or in rapids.

A challenge with the use of seismic refraction for offshore applications is that there is typically very small P-wave velocity contrast between the water and the unconsolidated, saturated sediment layers along the seabed (Davis, 1996). This small contrast makes it difficult to identify the seabed and differentiate the underlying layers. This may be of small consequence, however, if the objective is to delineate the bedrock surface.

Alternatively, shear-waves can be utilized and may result in greater contrasts between sublayers. Another valuable use for shear wave velocity data is as a predictor of liquefaction potential. However, the use of shear wave methods requires that the source and receivers be in contact with the seabed since shear waves will not propagate through the water column (Davis, 1996).

3.5.1.2 Underwater Geo-electric

The underwater geo-electric method is similar to seismic surveys utilizing shear waves in that the survey involves a sled being towed along the seabed. In the case underwater geo-electric surveying, the sled is trailed by a streamer which hosts the electrodes from which current is injected and measured. Telemetry and power for the streamer is provided via the tow cable. For a depth of investigation of approximately 3-5 m, a streamer length of 20 m is typical. As with terrestrial surveying practices, a longer streamer with greater electrode spacing can be used to increase the depth of investigation, at the cost of resolution and accuracy.

The electrode configuration described by the ISSMGE TC1 (2005) is depicted in **Figure 3-2**.

Current is injected as an alternating square wave at 1 Hz to compensate for self-potential effects. In addition to the seabed measurement array, a quadripole antenna is deployed via the tow sled to measure the resistivity of the seawater. The ratio between the resistivity of the seabed and seawater is called the *formation factor* and empirical correlations have been established between this parameter and saturated marine sediment porosity, soil type, and states of consolidation (ISSMGE TC1, 2005).

As with terrestrial resistivity surveys, inversion of the survey data is necessary to generate an interpretation of the stratigraphy using the apparent resistivity results.

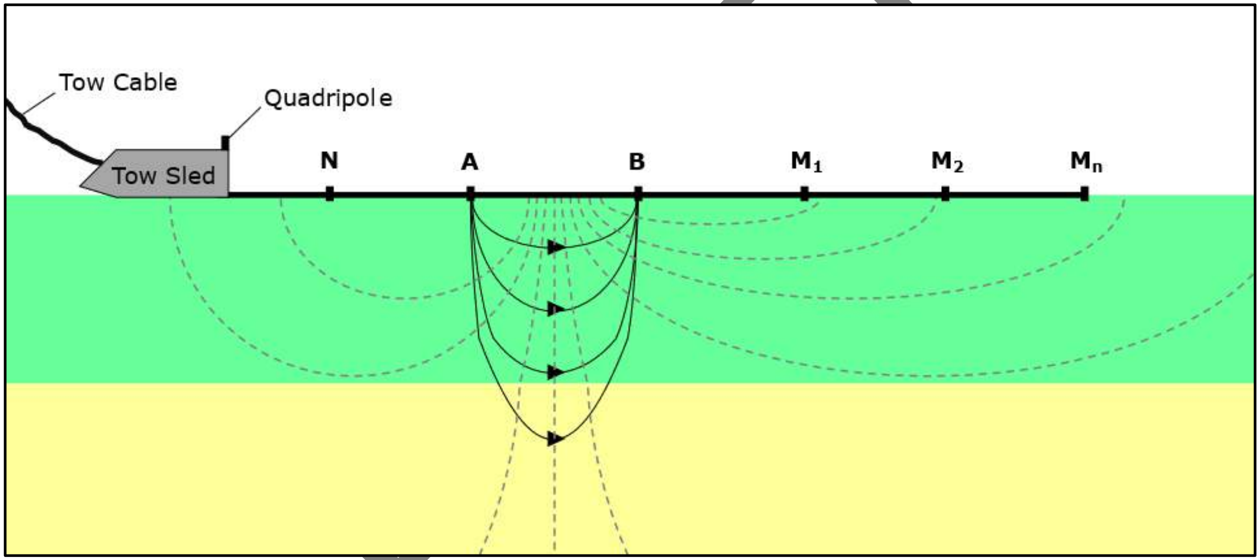

Figure 3-2. Schematic depiction of underwater geo-electric array, after ISSMGE TC1 *(2005)*

3.5.1.3 Underwater Geo-radar

Underwater geo-radar is the application of Ground Penetrating Radar (GPR) to a submarine setting. This method should only be used in freshwater systems, as the conductivity of saltwater would rapidly attenuate the EM energy emitted for this type of survey, rendering it ineffective.

Advantages of using GPR are that continuous and rapid imaging is possible in a non-invasive manner. This method is capable of imaging the top of sediment and often several meters into the sediment. Field data can be viewed and interpreted at the time of acquisition, though it can benefit from post-acquisition processing to enhance interpretability. The imaging capabilities of GPR are considered excellent, with vertical resolution in the order of 0.1 m using a 200 MHz system (Wightman, Jalinoos, Sirles, & Hanna, 2004).

The primary challenge of using this method in submarine settings is deployment of the GPR system. Wightman, et al. (2004) note the typical approach to deploying GPR over the water surface is to use a small rubber boat to carry the GPR antennae and a GPS for tracking its location. The rubber boat is towed by a motorized boat carrying the data recording equipment. Another option could involve the use of tow lines to deploy the GPR across planned transects and to host the recording equipment onshore, provided lines of an adequate length are sourced.

Other limitations include the depth of investigation, which is normally 9 m or less in water, and the potential for noise due to multiple reflections or echoes off the existing structure (Wightman, Jalinoos, Sirles, & Hanna, 2004).

4 SELECTION OF APPROPRIATE GEOPHYSICAL METHODS

4.1 Method Selection for Seismic Site Classification

Geophysical methods which can be used for the purpose of seismic site classification were discussed in **Section 3.1**. Some methods involve the use of arrays of geophones, whereas others may only need a single station. Measurement and analysis may occur in the time-domain or the frequency-domain, with different benefits to each. Survey logistics may require the drilling and casing of boreholes, mobilizing specialized rigs, or running cables through challenging terrain. Evidently, there is a multitude of geophysical techniques from which to pick and choose to fit the unique circumstances at each site. The selection of one or more methods will require careful consideration on a case-by-case basis.

Some general factors in selecting one or more methods for seismic site classification are listed below:

- **Surface Conditions:** Are conditions at the ground surface accessible and conducive to deployment of the equipment required for the proposed survey?
    - The presence of sloped, soft, and/or wet ground may impede rig access, which is necessary for borehole-based methods.
    - Vegetation and other spongy ground cover may affect coupling. Where necessary, geophones should be outfitted with spikes, buried, and/or covered.
    - Array-based methods will require unobstructed space to accommodate the array length necessary to achieve the desired depth of investigation, accuracy, and resolution.
- **Environmental Noise:** Have sources of environmental noise been identified and can the contemplated methods achieve an acceptable SNR in those conditions?
    - Where noise is pervasive, frequency-domain methods such as MASW can be more robust than time-domain methods. Passive (microtremor) methods which use environmental noise, such as ReMi and HVSR, may also be practical.
    - Selecting a swept source, reversing source polarity, or increasing source energy may all improve the SNR by increasing the signal amplitude or making the signal more distinguishable.
    - Processing techniques such as filtering and stacking can reduce the influence of noise but may require planned redundancy in the survey design, such as common midpoints and/or repeated shots.
- **Investigation Criteria:** What are the requirements for the data to be collected?
    - What is the target depth of investigation? Greater depths will require longer arrays and/or stronger signals.

  - If an average across the upper strata is acceptable, surface methods may be practical. If a specific buried layer is of interest, borehole methods may be necessary.
  - What are the dimensions of the study area and what degree of data coverage is needed? Array-based methods can provide efficient 2D coverage of large areas, whereas single-station or borehole methods may be more practical for 1D coverage of a limited quantity of individual points of interest.
  - What are the lateral and vertical resolution requirements? Surface methods will suffer from reduced resolution and accuracy with increasing depth, shorter arrays, or increased geophone spacing.
  - Is the stratigraphy expected to be horizontal or is it complex? Dipping layers, velocity inversions, and small velocity contrast can affect data quality. Mitigating these factors may require additional survey and processing steps.
- **Other Investigation Activities:** Ideally, the selected geophysical methods should complement other planned investigation activities.
  - Are there other investigation objectives being pursued in tandem, such as stratigraphic profiling, that could be accomplished with the same method(s)?
  - Will the selected method(s) produce redundancy (overlap) in an independent manner that reduces uncertainty and non-uniqueness?
  - Will the selected method(s) enhance coverage between and beyond that of other investigation locations?
  - Are borings planned that could be repurposed for downhole geophysical investigation for limited additional cost?

A summary of these considerations and the relative costs associated with the discussed methods in this Chapter is presented in **Table 4-1**.

Table 4-1. Comparison of geophysical methods for seismic site classification

Method	Relative Cost	Access / Space	Background Noise	Complementary Investigation	Depth Limits
sCPT	Moderate	CPT rig access required	Relatively unaffected	Can be paired with other CPT probes	Cone refusal
Suspension Logging	High	Drill rig access required	Relatively unaffected	Borehole logging	Depth of borehole
Seismic Reflection-Refraction	Low	Space for array (>60 m)	Low noise accommodated	Stratigraphic profiling can be undertaken	< 0.5 x the array length
MASW	Low	Space for array (>60 m)	Moderate noise accommodated	Limited stratigraphic profiling	< 0.5 x the array length

ReMi	Low	Space for array (>60 m)	Uses noise as passive source	Limited stratigraphic profiling	< 0.5 x the array length
HVSR	Low	Minimal footprint, flexible access	Uses noise as passive source	Limited	30 m or more

4.2 Method Selection for Stratigraphic Profiling

Non-uniqueness remains an inherent challenge in geophysical data interpretation, so it is best practice to consider the application of two or more unique (and complementary) geophysical methods. An intrusive investigation must be completed in conjunction with the geophysical investigation to facilitate geophysical model calibration and ground-truthing.

Method selection must consider the anticipated stratigraphic conditions and the investigation objectives. Consideration of the following additional factors is expected to enhance the value and success of a geophysical investigation:

1. **Complementary Investigation:** How might geophysical investigation fit within a proposed investigation framework to complement other investigation methods?

   Consider which method(s) would be most efficient and successful for uses such as:

   a. Identifying favourable locations within a study area to target during the detailed investigation stage and plan future investigation strategies;

   b. Producing a continuous bedrock profile between borings, to reduce intrusive investigation effort; or,

   c. Providing insight with respect to the spatial variability of the material properties to supplement and corroborate laboratory testing data with in-situ data.

2. **Data Quality:** Are certain geophysical investigation methods likely to suffer from poor data quality? Consider the following impediments:

   a. Sources, pervasiveness, and magnitude of signal noise;

   b. Subsurface material types, groundwater, and surface water, and their effect on source energy attenuation;

   c. Thickness of sublayers and the corresponding resolution requirements; or,

   d. Distribution and dip angle of sublayers, and the possibility for lost signal.

3. **Space Constraints:** Does the investigation strategy need to accommodate site surface conditions to promote surveying efficiency and maintain data quality? Consider:

   a. If the site is very small, how much space does the considered method require? If the site is very large, can the considered method cover large areas efficiently?

   b. Do site conditions warrant the consideration of different deployment techniques (surface, air, or borehole) based on accessibility and/or coverage requirements?

c. Are surface obstructions (e.g., concrete barriers, slopes, etc.) present which would add complexity to the survey configuration, affect data quality, or limit the depth of investigation?

Electrical resistivity imaging (ERI), seismic methods including refraction, reflection, MASW, TISAR, microtremor, and HVSR, and electromagnetic methods including TDEM, FDEM, and GPR were discussed in this chapter. The use of these methods for achieving common investigation objectives is briefly described below for four generalized site conditions:

Flat Layered

A flat layered system can lend itself well to almost any geophysical method and selecting a method will depend on what the layers consist of, the required resolution, the presence of groundwater, and sources of noise. The success of any geophysical method hinges on there being relative contrast between the layers being delineated.

Electrical and EM methods may be suitable where resistivity contrast is anticipated, perhaps due to differing grain sizes and/or porosity associated with different soil or bedrock layers or at a groundwater interface. Electrical and EM methods will be ill-suited where that contrast is muted by high groundwater or strong noise sources. Conductive materials near surface may limit the depth of investigation of ERI, FDEM, and GPR, and hard surfaces can impede installation of electrodes needed for ERI.

Seismic methods will be effective where density contrasts are expected, which may be especially apparent at an overburden-bedrock interface. The presence of velocity inversions or steeply dipping layers, however, can potentially mask the presence of those layers. Loose, dry soils may attenuate seismic energy rapidly and limit the depth of investigation.

Dipping Layers

Where dipping layers or features are present, one must be more selective of the methods being used. Reflective methods such as seismic reflection or GPR may be poorly suited to this condition due to heavy offsets or loss of signal returns.

Instead, ERI or seismic refraction could be better options as they can both accommodate dipping features if a suitable strategy is adopted. With ERI, the use of array configurations sensitive to lateral variations in resistivity such as Schlumberger or Dipole-Dipole can enhance the user's ability to detect and delineate steeply dipping or even vertical features such as dykes. Seismic refraction can be an effective option for subsurface layers dipping up to 20° provided that forward and reverse shots are taken to complete velocity corrections.

Swamp

Wetlands and swamps can present significant challenges to conventional investigation. The use of mats or amphibious equipment to access strategic investigation locations can be costly and may be undesirable from an environmental perspective. Geophysical methods with light footprints and which are highly mobile can be effective options in these settings.

These environments are expected to feature elevated groundwater tables and high organic content. The use of EM methods, particularly TDEM, could be considered when delineating the thickness or lateral extent of organic deposits. GPR can also be effective provided a surface from which to deploy the rover is present, such as when dealing with buried peat deposits, and if the target depth is limited. Where a depth to bedrock is desired, seismic refraction could be an effective option especially where the organic deposits are expected to be extremely thick.

Urban

With increasing degrees of urbanization comes two primary complications to geophysical investigation: space and noise. Methods which are less susceptible or, better yet, utilize environmental noise should be sought in these environments. Passive seismic (microtremor) options could include HVSR where space is severely constrained, or ReMi if space for an array is available. The success of active source methods may be improved if a swept source can be used, to enhance the operator's ability to distinguish the seismic signal from environmental noise. Frequency-domain methods such as TISAR or MASW can also be quite robust in noisy settings.

Each of these methods is likely to be suitable for characterizing a stratigraphic sequence, though TISAR and ReMi may offer the best vertical resolution.

Summary

A summary of the discussed methods and their suitability for achieving different investigation objectives when presented with these site conditions is shown in **Table 4-2**.

Table 4-2. Possible investigation methods for different objectives and site conditions

	Site Conditions			
Objectives	**Flat Layered**	**Dipping Layers**	**Swamp**	**Urban**
Lithological characterization	ERI, Seismic refraction and/or reflection, GPR, TISAR, MASW	ERI, Seismic refraction	EM, GPR*	Microtremor (ReMi or HVSR), TISAR, MASW
Bedrock mapping		Seismic refraction, HVSR	EM, Seismic refraction, GPR*	
Groundwater mapping	EM, ERI	EM, ERI	EM	EM, ERI

* Provided a trafficable surface is available, such as a weathered crust or working pad

4.3 Method Selection for Detection of Voids

The selection of geophysical methods for void detection will depend on the site conditions and the size and depth of the potential voids being targeted. As with all geophysical studies, the use of more than one unique method is recommended where practical and justified depending on the importance of the study. The purpose of the following section is to aid in the selection of one or more methods which may be best suited to common conditions. A qualitative comparison of several methods is presented in **Table 4-3** for void detection under different survey conditions. The discussion below includes mention of some methods not featured in **Section 3.3**; the reader is referred to the corresponding sections in **Appendix A** for more details pertaining to other methods.

Table 4-3. Qualitative comparison of methods for void detection under different survey conditions

Method	**Survey Conditions** **Ideal**	**Manageable**	**Avoid**
GPR	Shallow; sandy; dry; small/short and flat area	Silty; damp; long and flat areas	Clayey; wet; salinity; very large area; sharp topographic change
Seismic Reflection	Deep, large voids; dense or hard soils free of cobbles and boulders; far from vibration sources; long and unobstructed space for survey line	Compact or stiff soils; some boulders; light traffic, or random vibration	Loose or soft soils; very bouldery; shallow, small voids; heavy traffic, and other vibratory noise; short survey lines
CH Seismic	Minimal vibratory noise; thick and horizontal stratigraphy; short distance between boreholes	Some random noise; lightly dipping or undulating stratigraphy	Heavy noise; very thin layers; steeply dipping or severely undulating stratigraphy; very large borehole spread
ERI	Dry; soft surface material for planting electrodes; large, open sites for survey grid	Damp; hard surfaces requiring pre-drilling holes for electrodes; long, narrow sites	Near-surface clay or other conductive material; electrical noise from utilities
Gravimetry	Very large, shallow targets, air filled targets (high density contrast)	Moderately sized, deeper, water filled targets	Small, deep, soil filled targets (reduced density contrast); heavy traffic, and other vibratory noise; sharp topographic change

Consideration #1: Site Access

Given the relatively small scale (typically < 1 m) and moderate depth (3-10 m) of the potential voids being targeted for highway settings, terrestrial techniques with broad coverage are the preferred approach to void detection and delineation at existing highway sites. Any of the discussed geophysical methods may be considered further if terrestrial access is expected.

Where space is limited (< 20 m), GPR may be preferred depending on other factors (see *Step 2: Expected Subsurface Conditions*). Though not ideal, seismic methods such as MASW and TISAR are also possible; however, the depth of investigation will be limited to approximately 0.5 x array length and accuracy will be negatively impacted by shorter arrays. It may be preferable to select an alternative approach unless the accuracy of the survey can be carefully validated through the use of alternate data types.

The use of borehole techniques should be reserved for circumstances where the study area is relatively small / constrained and 3D mapping is deemed necessary based on the importance of the study. Alternatively, borehole techniques could be considered after a preliminary screening to guide the strategic location of the borings. Studies aiming to identify and delineate suspected voids relating to scour or other processes in a marine environment, the reader is referred to **Section 3.4**.

Airborne techniques are not anticipated to be able to reliably detect and delineate small voids at the permissible altitudes from which these techniques could be deployed within the highway right-of-way. However, if permitted by the applicable regulatory bodies, airborne techniques can be effective if the suspected voids are large and/or shallow. These conditions may exist when the study area is located in a karstic environment, around mining sites, or when targeting large, buried infrastructure such as tunnels. Airborne techniques will likely be limited to gravity, resistivity, and electromagnetic methods. The use of these methods must consider additional factors in determining whether the survey is likely to be successful or if alternate approaches should be selected.

Consideration #2: Expected Subsurface Conditions

The selection of a geophysical survey method should next be based on the expected subsurface conditions. Consider the following challenging subsurface conditions:

Wet at Surface / Shallow Groundwater: Geophysical methods which may be adversely affected by wet conditions should be avoided where standing water or shallow groundwater conditions are identified / anticipated. These methods include GPR and electrical resistivity. The relatively conductive environment corresponding to high groundwater may limit the investigation depth for these methods, impeding the detection of voids below the water interface.

Clays: Similar to wet conditions, clays are relatively conductive and will limit the depth of investigation for GPR and electrical methods. In particular, the high frequencies used for GPR lead to rapid signal attenuation in clays.

Buried Objects: The presence of buried cobbles, boulders, or other objects with convex surfaces can disperse reflective signals such as those associated with GPR and seismic reflection. These dispersive objects can make it more difficult to identify potential voids by adding complexity to the data and also reducing signal strength and limiting investigation depth beyond the reflectors.

Consideration #3: Size and Depth of Suspected Voids

As their size decreases and as depth increases, the difficulty of detecting suspected voids will increase rapidly. Higher resolution becomes necessary to detect voids as they become smaller, but typically comes at the cost of shallower depths of investigation. The relative suitability of a selection of methods for detecting voids of different depths and sizes is depicted qualitatively in **Figure 4-1**.

If voids are less than 7.5 m below ground, GPR can be an excellent choice provided the subsurface conditions are conducive to its success (i.e., no conductive or saline conditions). Gravity methods may also be appropriate, if relatively large (>2 m) voids are expected.

Seismic reflection methods can offer high resolution where sufficient space exists to host an array at least twice as long as the targeted depth. Shear wave methods are preferred to achieve the highest resolution. Impulsive sources may be considered where the depth of investigation is no greater than 30 m, but vibrator sources should be used if greater depths are needed. A vibrator source may offer more flexibility in terms of frequency, enhancing the signal-to-noise ratio and enhancing an operator’s ability to differentiate the signal from potential noise sources.

Electrical methods may also be a suitable choice up to 30 m, subject to the same array length requirements as seismic reflection methods. Electrical methods would be a better choice than seismic in the presence of very soft or loose subgrade conditions, or if frequent cobbles, boulders, or other dispersive reflectors might be anticipated.

The use of borehole techniques should be considered where the depth of suspected voids is greater than 7.5 m and space is constrained, especially if vertical delineation is required.

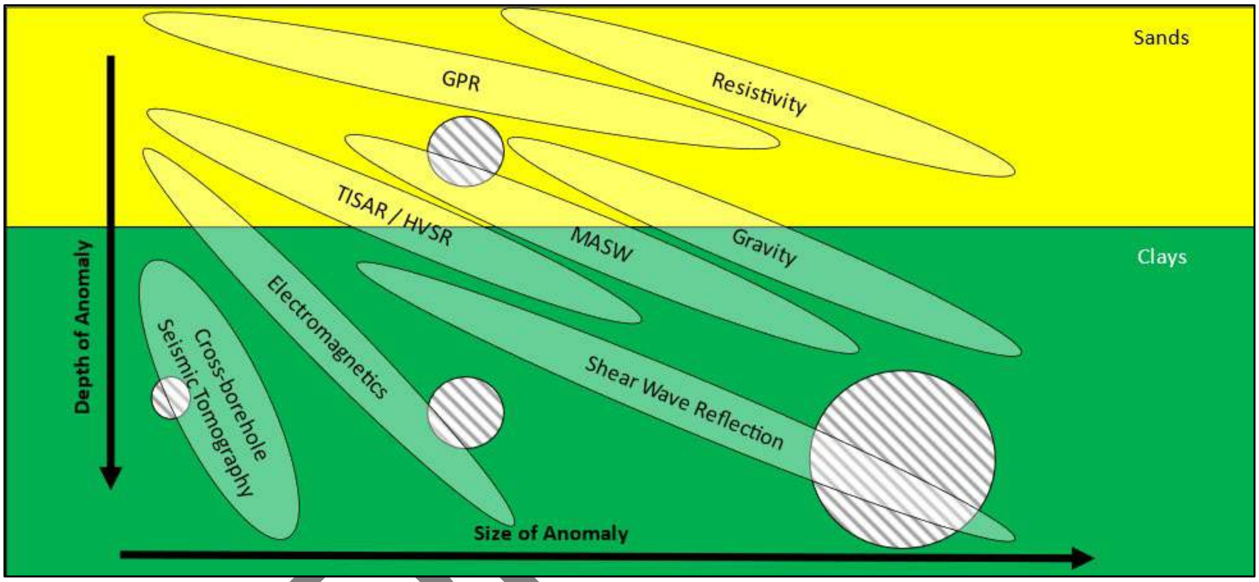

Figure 4-1. Relative suitability of methods for detection of differing sizes and depths of voids

4.4 Method Selection for Re-use of Existing Foundations

A critical aspect in evaluating the re-use potential of existing foundations is determining the founding depth. Borehole magnetometry, electromagnetic induction, and acoustic methods have been demonstrated to be reliable techniques for obtaining that information. The relative advantages and limitations of each of these methods is summarized below and in **Table 4-4**.

Table 4-4. Comparison of selected geophysical methods for investigating existing foundations

Method	Advantages	Limitations
Borehole Magnetometry	Unaffected by splices Unaffected by pile slenderness	Not suitable for timber, concrete, or masonry May be affected by nearby magnetic anomalies (hematite-containing soil/rock, buried metal objects)

Electromagnetic Induction	Unaffected by splices Unaffected by pile slenderness Can obtain conductivity and magnetic susceptibility data for surrounding soils	Not suitable for timber, concrete, or masonry Should be paired with natural gamma ray logging to differentiate elevated conductivity readings from clay vs. pile Affected by EM noise
Impulse Echo	Suitable for any material type Does not require a borehole Relatively quick and inexpensive	Requires surface of foundation to be exposed Pile slenderness of 30:1 or less, ideally Splices or discontinuities may attenuate signal Very stiff soils may attenuate signal
Parallel Seismic	Suitable for any material type Less affected by weak source or strong attenuation compared to impulse echo	Requires surface of foundation to be exposed

Borehole Magnetometry

Borehole magnetometry is suitable for the detection of steel foundations or those containing significant amounts of steel. This technique can be especially favourable when investigating steel H-piles, due to their high length-to-diameter ratio and high surface area to volume ratio, which can cause rapid dampening of signals in other methods. Borehole magnetometry is also well-suited for spliced foundation elements. Magnetometry will be ineffective, however, for detecting timber piles and foundation elements primarily consisting of other non-magnetic materials.

This technique is less affected by very stiff surrounding soil, which can obscure signals in other methods like PIT and parallel seismic. Another advantage is that access to the surface of the foundation elements is not required. However, a borehole is required, and it should be advanced as close as possible to the foundation elements to promote detection.

Electromagnetic Induction

Similar to borehole magnetometry, electromagnetic induction is well-suited to the detection of steel and steel-containing foundation elements but ineffective for detecting timber piles.

One noteworthy advantage is that conductivity of the surrounding materials can also be measured, which can be valuable for assessing corrosion potential especially when paired with the self-potential method.

Electromagnetic induction should be paired with natural gamma ray logging to differentiate elevated conductivity readings due to clay from that of the targeted foundation element. Electromagnetic induction methods can also be affected by external electromagnetic noise from power lines, electronic devices, and other sources.

Acoustic Methods

Acoustic methods discussed herein included the impulse echo method (PIT) and the parallel seismic method. Acoustic methods can be used to determine the dynamic stiffness of foundations and can be used for various materials (concrete, timber, steel).

The impulse echo method is relatively inexpensive and rapid to implement, as it does not require the installation of a borehole. Applications include detecting defects, soil inclusions, pile necking, bulbing, and approximating pile lengths. Ideal candidates for this technique include free-standing, columnar-shaped foundation elements without a structure on top, especially if the length-to-diameter ratio is 30:1 or less. This technique is effective in soft soils where the toe reflection is discernible, but very stiff surrounding soil will attenuate signals more rapidly.

The impulse echo method is less suitable for steel H-piles due to high length-to-diameter ratio and high surface area to volume ratio, resulting in rapid dampening of the signal by surrounding soils. The presence of splices may also act as intermediate reflectors, resulting in attenuation of deeper signals. Other pile types which can be challenging for the impulse echo method include micropiles due to their small size and high length-to-diameter ratio, and hollow piles due to the inability to achieve a plane wave. The tapered shape of timber piles can negatively affect toe reflection (Pile Dynamics, Inc., 2024), as can very rigid soil or rock which may result in compression reflection instead of tension reflection of bar waves.

The parallel seismic method can be a favourable alternative acoustic method if there are concerns regarding attenuation of surface signals due to intermediate reflectors or significant cover material. Some (attached) part of the structure must be exposed, however. As with the impulse echo method, parallel seismic is suitable for various foundation materials, including concrete, steel, masonry, and wood.

Additional Considerations

A borehole is required for each of these methods except for the impulse echo method and is typically the most expensive component of the survey. Consideration should thus be given to using multiple methods to take advantage of the borehole and enhance the reliability of the results.

The discussion also focused on the most common pile materials: steel, concrete, and timber. Rockfill or stone columns are sometimes encountered in ground-improvement applications and may require characterization as well. However, these materials disperse stress waves and are non-magnetic and non-conductive. For these types of columns, borehole radar may be a better option. The high variability of deep soil mixed columns also makes them challenging for acoustic methods, so CH radar and electrical resistivity may be more viable alternatives (Hertlein & Davis, 2006).

PART III:

MTO Reporting Requirements for Geophysical Investigations

4.5 Method Selection for Offshore Investigation

Offshore investigation will generally involve more rigorous preparations to ensure the safety and technical success of the investigation. The use of geophysical investigation techniques may be particularly beneficial for offshore investigation by eliminating or reducing the use of drilling equipment on barges or at the edge of a water body and by enabling the efficient acquisition of continuous or semi-continuous data over large areas. Offshore settings may encompass a variety of unique conditions and the development of an investigation strategy will require careful consideration of those conditions on a case-by-case basis. A general commentary on favourable uses of seismic, electric, and electromagnetic methods is provided below and summarized in **Table 4-5**. Some investigation considerations are also discussed.

Table 4-5. Summary of offshore geophysical investigation methods selection considerations

Method	Strengths	Limitations
Seismic Reflection	Water bottom profiling in water body of almost any depth; Thin sediment and/or scour delineation	Often limited depth of investigation beyond water bottom; Interference from nearby structures and multiples can negatively impact SNR

Seismic Refraction	Characterization of subbottom material elastic properties	Compressive wave velocity contrast between water, water bottom, and individual sediment layers may be small; Shear wave systems require use of towed sled along water bottom; Attenuation of signal if gases are present
Geo-electric	Water bottom profiling; Unaffected by gases; Can be used in saline water	Requires towed sled along water bottom; Inversion is required to interpret stratigraphy from apparent resistivity results
Geo-radar	High resolution, real-time imaging; Small equipment does not require vessel equipped with A-frame or crane to be deployed	Restricted to fresh water only; Limited to water depths of about 9 m or less; Interference from nearby structures or boulders can diffract signal, causing attenuation

Methods Summary

Seismic methods can be deployed in an offshore / submarine setting using streamers towed within the water column or along the water bottom. Towing could be by a marine vessel, in settings with deeper water and wider spans, or using a cable system anchored onshore if practical.

Seismic reflection is likely to be most useful when the primary objective is to obtain a subbottom profile or delineating scour, with potentially limited depths of investigation beyond the water bottom. Depths of investigation can be expected to decrease when the water bottom is lined with coarser grained sediments or in the presence of gassy organics. The signal-to-noise ratio may also suffer in very shallow water bodies, in turbid conditions, and/or proximal to existing structures due to interference from multiples and echoes.

It may be desirable to apply seismic refraction if the primary objective is to characterize engineering properties of the subbottom materials. Applications could include evaluating dredgeability, strength for anchoring or bearing, and liquefaction potential (Davis, 1996). Depth of investigation as well as impedance contrast may be limited for systems suspended within the water column, restricted to utilizing compressive waves. The use of a sled system towed along the water bottom should be considered where viable, to bypass the water column and to allow the measurement of shear waves. The use of a towed sled system is more intrusive and must consider the potential for obstructions (e.g., vegetation, rip rap, debris) in addition to permitting requirements from the applicable regulatory bodies.

The parallel seismic method, as discussed in **Section A.2.5.2**, may be an effective seismic investigation technique for identifying and delineating scour affecting bridge piers. This method requires the installation of a cased borehole within 1.5 m laterally and extending a few meters below the target pier. A mud-filled scour zone would be expected to strongly attenuate the signal, making these zones distinguishable on a seismic log. An experimental example of this application is described by Wightman, et al. (2004).

The geo-electric method will require similar considerations to that of seismic surveys utilizing towed sled systems. Electric methods are not expected to be adversely affected by gas-charged sediments, however, and could be a suitable alternative to seismic methods when such conditions exist. It is necessary to calibrate these systems to the water depth, salinity, and temperature of the study area to obtain meaningful quantitative data (ISSMGE TC1, 2005).

Geo-radar can be useful for detailed imaging of scour or sediment layers as thin as 0.1 m and to depths up to 9 m (Wightman, Jalinoos, Sirles, & Hanna, 2004) along the water bottom. An advantage over other methods is the relative rapidity with which data can be obtained using geo-radar, since real-time imaging is possible. This method will be subject to the same limitations which affect terrestrial GPR; of particular relevance for offshore investigation is that the use of geo-radar will only work well in freshwater systems.

Investigation Considerations

Some considerations for offshore geophysical investigation are briefly described below:

- Reconstruction or rehabilitation of existing infrastructure in offshore settings could include ferry docks, wharfs, sea walls, bridges and piers, or culverts. Existing structures may be a source of potential echoes or interference for seismic reflection and GPR. Geoelectric and/or borehole methods may be more robust in settings where strong reflective interference is anticipated.
- The presence of riprap can potentially interfere with all methods discussed in this chapter, but especially if towing a sled. Where riprap is anticipated or identified, methods which are suspended in or above the water column may be preferable. Furthermore, riprap may have a diffractive effect on seismic reflection or GPR signals, which will cause attenuation and reduce resolution. The investigator may wish to exploit this diffractive behaviour, however, if one of the investigation objectives is to delineate the extent of riprap. The parallel seismic method may be most effective when evaluation of the materials covered by riprap is required, but installation of the required borehole may be particularly challenging.
- An opportune time to carryout seismic or GPR surveys across water bodies may be during the winter, when the water surface is frozen. Working on ice may require additional safety precautions, such as verifying ice thickness, the use of crampons, and tying off to a safety line.
- The span of the water body must be considered in the investigation plans, as it may be possible to conduct the survey using land-anchored cables rather than chartering a marine vessel. This approach, where viable, may be considerably less expensive, faster, and safer depending on the water conditions (current, obstructions, depth, etc.) and the size of the study area.
- Swamps with gassy organics may negatively affect seismic survey data quality. It is advisable to incorporate an electrical or GPR survey with seismic in case such a condition is encountered, whether expected or not.

- The relative rapidity with which GPR can be deployed and imaging obtained lends itself well to using this method for preliminary screening followed by the use of other methods once investigation targets are better identified / located.
- If a marine vessel is chartered for offshore geophysical investigation, it may be desirable and cost effective to add microgravimetry to the survey suite to maximize the use of the vessel.

5 REPORTING REQUIREMENTS

This section describes reporting requirements for geophysical investigations carried out directly for MTO or for a service provider on behalf of MTO. These minimum requirements are to be met to ensure consistency amongst deliverables for the purpose of quality control, communicating investigation parameters and results, and satisfying MTO investigation objectives.

5.1 General

The following requirements are applicable to geophysical investigation reports in general, irrespective of the methods and objectives. The listed subsection titles are not strictly required but may be adopted to aid in organizing report contents.

- Introduction:
    - State the investigation objectives (e.g., stratigraphy mapping across a swamp, to resolve the geology from surface down to and including the bedrock contact);
    - Site description;
    - Date(s) of investigation activities;
- Data Acquisition Methodology:
    - Methods and equipment used (e.g., resistivity data were collected using…) including technical specifications;
    - Description, tables, and figures depicting survey location(s), coordinates of geophones and spreads, sources, direction of survey with chainages and elevations, orientation of geophones / sensors, as applicable;
    - Applicable survey parameters, such as frequencies, grid spacing, configuration, etc., including units of measure and justification, if applicable;
    - Survey limitations, such as equipment / array length due to obstructions, topography, etc.
- Data Processing and Interpretation:
    - Post-processing parameters, such as analytical method, noise reduction techniques, etc., including software used;
    - Commentary on noise levels, signal-to-noise ratio, quality of the raw (seismic or electrical records) and processed (dispersion, inversion) data, including site-specific factors which may have affected the data;
    - Interpretations and error analyses should be available for review, if applicable;
- Results:
    - Figures: plans, profiles, annotated with interpreted features of interest;
    - Plotted data should include contours, if applicable, using consistent and legible legends to facilitate comparison between figures if needed;

    - Depth slices should be presented if warranted, including depth, annotations of features, and limits of survey/spreads;

5.2 Project-specific

Some or all of the following requirements may apply depending on the specific objectives of the geophysical investigation. This list is not exhaustive, and the geophysical contractor should include any relevant sections, comments, data, or observations based on their experienced judgement.

- As suggested by Hunter, et al. (2022), shear-wave velocity calculations should be presented in tabular format. The table should include the interpreted layer thicknesses, velocities, and the calculated traveltime within each layer.
- Where shear-wave velocity is being investigated, the velocity range and average should be presented, and any trends should be described. For example, if shear wave velocity is found to differ at each end of a west-east oriented spread, it could be presented as X m/s (at west end of spread) and Y m/s (at east end of spread). If different velocities are calculated over multiple shot records, as is typically done, the minimum, maximum, and average should be presented.
- For NDT investigations, anomalies should be classified based on severity as described in Hertlein and Davis (2006), adapted from Dr. Joram Amir (2002):
    - Anomalies, defined as observations in the test data caused by equipment, test configuration aspects, or noise;
    - Flaws, defined as imperfections or irregularities in the inspected element with limited to no impact to its capacity or durability; or,
    - Defects, defined as critical imperfections or irregularities in the inspected element which affect its capacity or durability and must be evaluated further.

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Appendix A:
Geotechnical Geophysical Methods Theory and Background

A.1 Electrical and Electromagnetic Methods

Earth materials (i.e., soil and rock) consist of collections of minerals which resist the flow of an electric current to different degrees depending on the type of material that is present. Electrical and electromagnetic methods exploit this phenomenon to generate an inferred model of subsurface conditions and stratigraphy. To differentiate between materials, these methods depend upon a contrast existing between the resistivity or electromagnetic properties of the materials. Representative resistivity values for some typical earth materials are presented below in **Table A-1**, after Peck et al. (1974).

An electric current can be directly applied to the subsurface using electrodes, or it can be induced by generating electromagnetic flux. Methods utilizing electrical currents are generally termed, *resistivity methods*, since these methods aim to provide a measurement of apparent resistivity across a medium. Methods utilizing electrical and magnetic fields to induce one another are termed, *electromagnetic methods*, and they aim to estimate the conductivity of a medium based on the strength of the induced field.

Table A-1. Representative resistivity values for typical earth materials, after Peck et al. *(1974)*

Material	**Resistivity (ohm-m)**
Clay and saturated silt	0 to 100
Sandy clay and wet silty sand	100 to 250
Clayey sand and saturated sand	250 to 500
Sand	500 to 1,500
Gravel	1,500 to 5,000
Weathered rock	1,000 to 2,000
Sound rock	1,500 to 40,000

Common electrical and electromagnetic methods are presented in the following sections.

A.1.1 Electrical Resistivity Imaging

Electrical resistivity imaging (ERI) is a geophysical technique involving the use of electrodes to inject an electrical current through the ground. This technique is also known as electrical resistivity tomography (ERT). In this technique, a current is usually applied directly to the ground via electrodes, designated the *current electrodes*, which form the above-ground part of a circuit while the ground itself forms the remainder of the circuit. The electrical potential difference is then measured between additional electrodes, designated the *potential electrodes* (Eastern Research Group, Inc., 1993).

While it is typical to apply a direct current (DC), commutated DC or low frequency alternating currents (AC) can also be used (U.S. Army Corps of Engineers, 1995). The placement of electrodes may not be practical or possible where a site is surfaced with concrete, asphalt, or other hard materials. Under these circumstances, AC can be used to induce a current in the ground without direct contact. These so-called non-contacting methods could also be used if airborne surveying is necessary (Milsom, 2003).

The resistivity of the subsurface materials between the current electrodes can be calculated based on the geometry and spacing of the electrodes, the current that was applied, and the voltage difference that was measured (Eastern Research Group, Inc., 1993). The resistivity of the different subsurface materials is calculated using Ohm's Law, which describes the resistance, R, across a resistor as the quotient of the voltage (or potential), V, and the electric current, I, as expressed in Equation 1:

$$R = \frac{V}{I} \tag{1}$$

The resistivity, ρ, of the material can be found by factoring the resistance by the cross-sectional area, A, over the length, ℓ, of the resistor, as per Equation 2:

$$\rho = R\frac{A}{\ell} \tag{2}$$

Equation 1 can be substituted into Equation 2 to express resistivity in terms of the voltage and current in a system of a defined cross-sectional area and length:

$$\rho = \frac{V}{I} * \frac{A}{\ell} \tag{3}$$

In practice, the cross-sectional area over length is accounted for using a geometric factor, K, which is determined based on the relative positions of the electrodes used for the measurement. The signal strength of an array will be inversely proportional to the geometric factor; hence, smaller geometric factors will be more desirable in general, and especially where background noise is high (Loke, 2000).

Furthermore, the earth is heterogeneous and so the resistivity indicated in Equation 3 is not the resistivity of any one resistor, but rather an apparent resistivity, ρ_a, representing the weighted influence of all materials in a heterogeneous and often layered system. Equation 3 can thus be rewritten as:

$$\rho_a = \frac{V}{I} * K \tag{4}$$

Geometric factors can be determined for any configuration of electrodes. However, the use of linear and well-defined configurations can greatly simplify the calculation of geometric factors and lends itself to more efficient data processing (Pierce, Liechty, Rittgers, & Markiewicz, 2012). Common electrode configurations discussed below include the Schlumberger array, the Wenner array, and the dipole-dipole array. Each of these configurations have their respective strengths and weakness which must be considered when selecting a configuration that will satisfy the objectives of a study.

Wenner Array

The Wenner array is regarded as the simplest configuration. It consists of four, equally spaced electrodes. The current electrodes, A and B, are placed at the two opposite ends of the configuration, while the potential electrodes, M and N, are placed between them.

This configuration can be used for depth soundings by increasing the spacing, *a*, between the electrodes and maintaining a constant center point at the location of interest. Lateral profiling can be performed by shifting the array along a survey alignment while maintaining the same electrode spacing (Herman, 2001). Lateral profiling is depicted in **Figure A-1**.

This configuration is relatively well suited to characterizing vertical changes in resistivity but poorly suited to detecting changes horizontally (Loke, 2000). Thus, recommended applications of the Wenner array might include supplemental characterization of a horizontally layered stratigraphic profile or estimating a depth to groundwater.

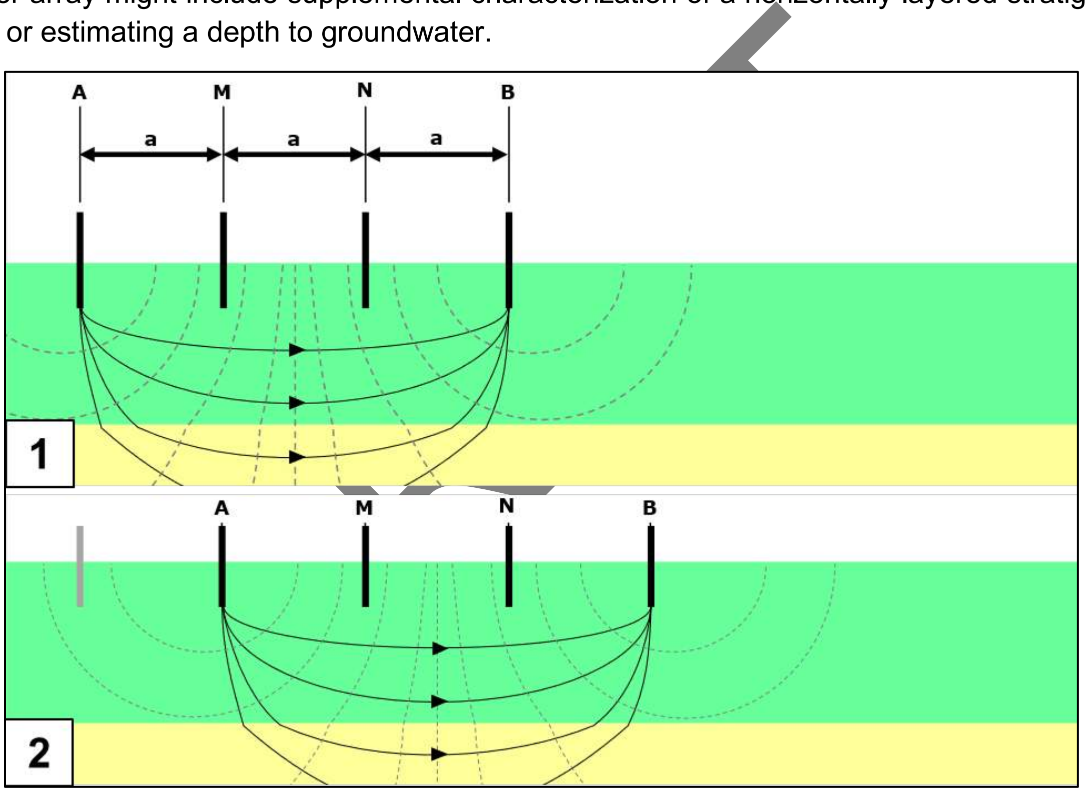

Figure A-1. Wenner array advancing laterally from [1] to [2]

Schlumberger Array

The Schlumberger array is one of the most common configurations used to carryout resistivity sounding surveys (Loke, 2000). It is named after the Schlumberger brothers, who were pioneers of the electrical resistivity survey method.

This configuration is similar to the Wenner array except that the spacing between the two potential electrodes, *a*, is kept relatively small compared to the distance between the outer current electrodes, *s*. Depth soundings are achieved by progressively moving the outer current electrodes further away (i.e., increasing *s*) while keeping the inner potential electrodes stationary (Hunt, 2007). Lateral profiling is accomplished by stepping the potential electrodes along the survey line, moving from A to B or vice versa, while keeping the current electrodes stationary.

Loke (2000) notes this array is moderately sensitive to both horizontal and vertical changes in resistivity. The depth of investigation is also slightly greater than that of the Wenner array for the same distance between the two outer current electrodes, but signal strength is lower.

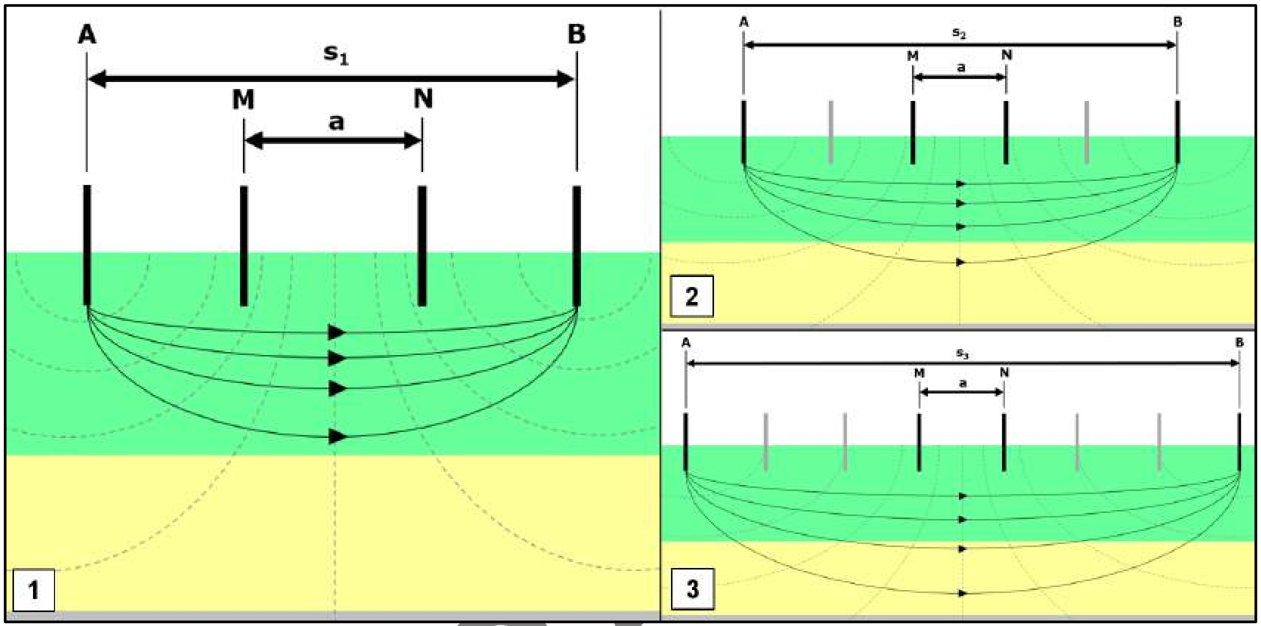

Figure A-2. Schlumberger array used for a depth sounding by increasing spacing, s, from [1] to [3]

Dipole-dipole Array

The dipole-dipole array is less labour intensive than the Wenner and Schlumberger arrays. This array is particularly well-suited to lateral profiling applications (U.S. Army Corps of Engineers, 1995). It is also popular for combined resistivity/IP surveys because there is low electromagnetic coupling produced between the current and potential electrodes (Loke, 2000).

For this configuration, the current electrode pair, AB, is placed a distance, "*a*", apart. The potential electrode pair, MN, are placed with the same separation. The distance between B and M is a multiple of that spacing, denoted as, "*na*". This "*n*" multiple is typically incremented sequentially up to about 6 to increase the depth of investigation (Loke, 2000).

This array is highly sensitive to horizontal changes in resistivity but relatively insensitive to vertical changes. Horizontal data coverage is also better than that achieved with the Wenner array (Loke, 2000).

This configuration yields a lower vertical resolution than the Wenner and Schlumberger arrays for an equivalent signal strength (Herman, 2001). The depth of investigation is also shallower for the dipole-dipole array than the Wenner array for an equal array length with "*n*" values below about 3. An important limitation of this configuration is that signal strength decreases by the cube of "*n*" (Loke, 2000). Therefore, a sufficiently sensitive resistivity meter and good ground contact are critical at large values of "*n*", and a practical limit will exist depending on the available voltage and the background noise levels that exist at the site.

Recommended applications for the dipole-dipole array include mapping vertical features such as trenches, cavities, or dykes (Loke, 2000).

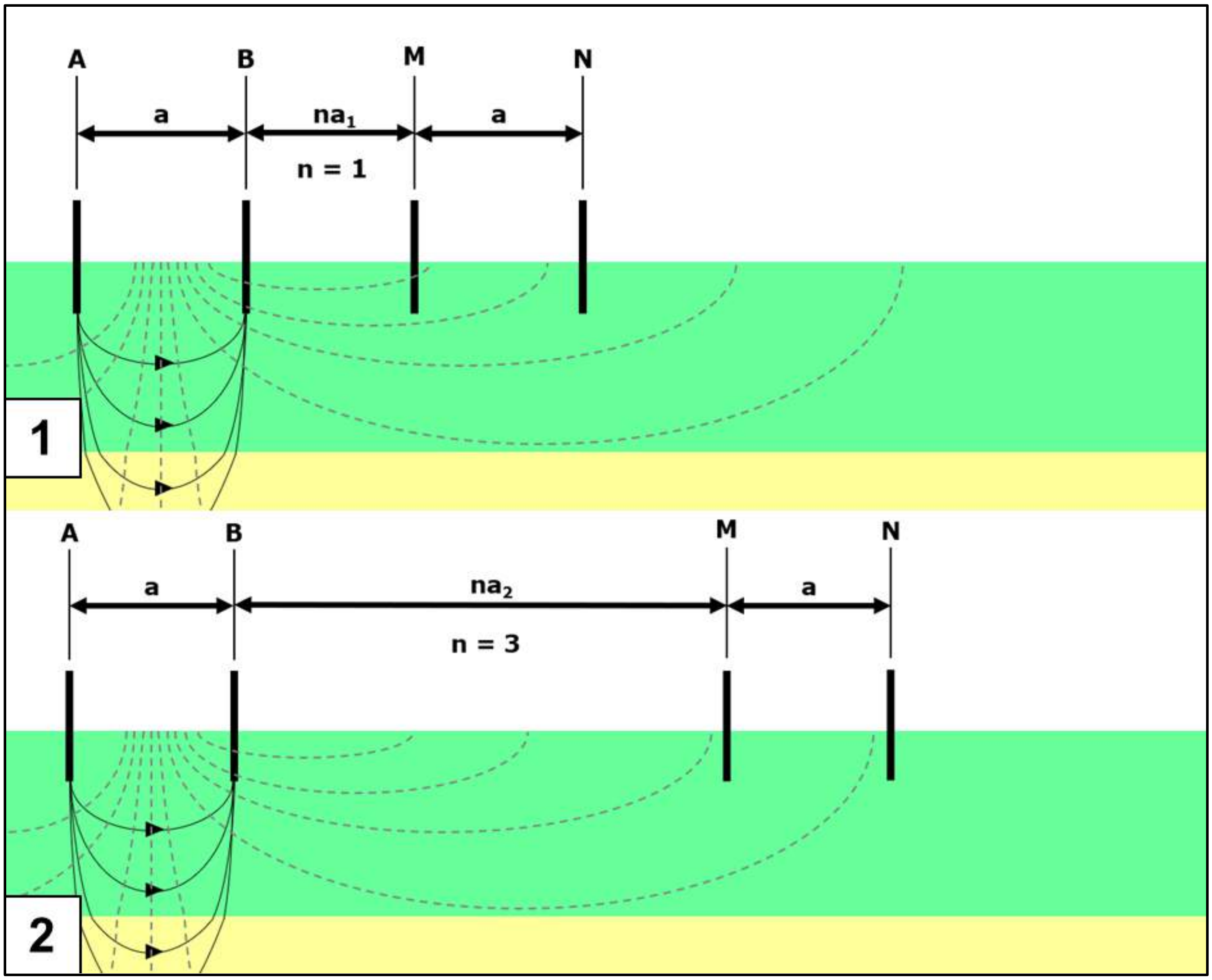

Figure A-3. Dipole-dipole array with increasing spacing, na, from [1] to [2]

The relative strengths and weakness of these configurations are summarized in **Table A-2**.

Table A-2. Relative strengths and weakness of common resistivity arrays

Configuration	Strengths	Weaknesses
Wenner	• Simplicity of ρ_a formula • Moderately sensitive to vertical variations in resistivity • Relatively small current required • Availability of large album of theoretical master curves for two- to	• Insensitive to lateral variations in resistivity • More susceptible to drifting or unstable potential differences than Schlumberger array

	four-layer earth models per Mooney and Wetzel (1956)	• Labour intensive but mitigated by use of automatic switching equipment (Herman, 2001)
Schlumberger	• Readily smoothed sounding curve • Moderately sensitive to lateral and vertical variations in resistivity • Less susceptible to stray currents due to smaller spacing than Wenner array • Less labor and setup time than Wenner array • Greater depth of investigation and resolution than Wenner for equal AB spacing	• Longer data processing than Wenner array if asymmetric geometry is used (Pierce, Liechty, Rittgers, & Markiewicz, 2012)
Dipole-Dipole	• Highly sensitive to lateral variations in resistivity • Reduced field measurement times • Fewer issues with current leakage and inductive coupling	• Insensitive to vertical variations in resistivity • Lower vertical resolution • Large generator required especially for deep soundings • Interpretation of data is more complicated than Wenner and Schlumberger

Apparent Resistivity, Effective Depth, and Other Factors

As discussed previously, the measured apparent resistivity will be a representation of the weighted influences of all materials through which the current passes. The relative influence of deeper layers will increase as the effective depth of a survey increases. The effective depth represents the depth at which most of the current travels. Actual resistivities and depths of boundaries must be calculated through inversion methods (Herman, 2001) and are subject to non-uniqueness.

Two principal factors control the effective depth of an electrical resistivity survey: the spacing of the electrodes and the relative resistivity of the subsurface layers. The apparent resistivity will be closer to surface at small electrode spacings and will approach the resistivity of deeper layers as the electrode spacings increase (U.S. Army Corps of Engineers, 1995).

The effective depth of investigation, z, can be approximated for simple array configurations. As an example, given a Wenner array with an electrode spacing, MN = a, the total array length, AB, will be $3a$. The effective depth of investigation is taken as the depth where half the current, I, passes through the ground above z and half passes through the ground below z. For the Wenner array, z is approximated as AB/2.

The relative resistivity of the subsurface layers will also control the effective depth of investigation because electric currents will always follow the path of least resistance. The presence of a near-surface conductive layer would therefore act as a preferential pathway for an applied current and the relative influence of deeper resistive layers would be obscured (Pierce, Liechty, Rittgers, & Markiewicz, 2012).

Other factors which will affect electrical resistivity survey results include moisture content, temperature, and salinity. Most soil and rock-forming minerals are poor conductors (i.e., highly resistive) and it is the water that is present within the pore space that primarily conduct an applied ground current. Clay minerals can also carry electrical currents due to the water that is bound to these extremely small particles (Milsom, 2003). An increase in moisture content due to increasing saturation or an increase in porosity due to looser particle arrangements can therefore decrease resistivity because of the relative increase in the volume and influence of the pore fluids.

The relative effect of moisture content on resistivity is greatest at low water contents and in coarser soils. Merritt et al. (2016) found the resistivity of a fine sand sample increased by four orders of magnitude with moisture content decreasing from 5% to 1%. Silt and clay samples were both observed to follow the same inverse relationship between moisture content and resistivity, though the magnitude of change was much less for equivalent changes in moisture content. The resistivity of silt and siltstone changed by two to three orders of magnitude over a 10% change in moisture content. The resistivity of clay changed by about one order of magnitude over a 20% change in moisture content. Through a review of other studies in addition to their own testing, Kazmi et al. (2016) found that increases to moisture content beyond about 20% in silty sand to sand did not significantly reduce resistivity.

Increasing the temperature of a material also reduces resistivity due to increased ion agitation (Kazmi, Qasum, Siddiqui, & Azhar, 2016). For example, increasing the temperature of water from 0°C to 20°C can decrease its resistivity by a factor of 2. In soil extracts, conductivity has been found to increase by about 2% per additional degree centigrade (Campbell, Bower, & Richards, 1949). Conversely, electrical resistivity will increase by several orders of magnitude if the pore water freezes (U.S. Army Corps of Engineers, 1995).

Lastly, increasing the concentration of dissolved NaCl from 50 mg/L to 10,000 mg/L can reduce the resistivity of water by 200 times (Milsom, 2003).

A.1.2 Electromagnetics

An electric current running through a wire which is shaped into a loop will induce a magnetic dipole field. If this primary magnetic field is varied, to produce magnetic flux, eddy currents will be induced in nearby conductors. The eddy currents induced in these nearby conductors will, in turn, produce a secondary magnetic field proportional to its mutual inductances with the transmitter coil and a second wire loop or coil, designated as the receiver coil. The apparent conductivity of a collection of subsurface materials, in siemens per metre (S/m), can hence be determined (Milsom, 2003). Electromagnetic (EM) surveying techniques apply this concept to infer subsurface conditions relating to variations in the measured conductivity. Conditions which may influence the apparent electrical conductivity include soil salinity, soil types, water content, organics, and more (Doolittle & Brevik, 2014).

Electromagnetic Attenuation

The energy associated with seismic (elastic) waves, electromagnetic waves, currents induced by electrical fields, or radioactive particle fluxes, will experience exponential decay as it propagates. This decay is a result of absorption and geometrical attenuation, and it can be described in a homogeneous medium as a function of the distance travelled (or time lapsed) and an attenuation (or decay) constant (Milsom, 2003).

The attenuation constant, α, for electromagnetic wave propagation is given by Equation 5:

$$\alpha = \omega \left[\frac{\mu_a \varepsilon_a \left\{ \sqrt{\left(1 + \frac{\sigma^2}{\omega^2 \varepsilon_a^2}\right)} - 1 \right\}}{2} \right]^{\frac{1}{2}} \qquad (5)$$

where,

μ_a is the absolute value of magnetic permeability,

ε_a is the absolute value of electrical permittivity,

ω is the angular frequency, equal to $2\pi f$, and

σ is the conductivity.

The frequency of the signals used by EM techniques is in the order of 10 Hz to 100 kHz (Eastern Research Group, Inc., 1993). At these frequencies, the magnitude of $\omega\varepsilon_a$ is small compared to σ for most earth materials (Milsom, 2003) and Equation 5 is often approximated as:

$$\alpha = \sqrt{\mu_a \sigma \omega} \qquad (6)$$

A useful concept is that of the *skin depth*, which is taken as the reciprocal of the attenuation constant (i.e., $1/\alpha$), and which describes the depth or distance over which the wave energy has dropped to $1/e$ (or approximately 36.8%) of its original value at the source. Skin depth can be approximated as $500/\sqrt{\sigma f}$ (Milsom, 2003).

<u>EM Methods</u>

There are two broad categories of electromagnetic surveying techniques discussed below: time-domain electromagnetics (TDEM) and frequency-domain electromagnetics (FDEM).

A.1.2.1 Time-Domain Electromagnetics

TDEM techniques typically use a modified symmetrical square wave current, which is abruptly reduced to zero for a quarter period after every second quarter-period and then reversed. This abrupt shut-off of the transmitter current produces magnetic flux, which induces a secondary current in the ground. The amplitude of the induced current will begin to decay as it travels through the resistive subsurface materials, in turn producing magnetic flux and inducing other currents. This cycle will continue to propagate deeper and further from the transmitter. By measuring the amplitude of the decaying magnetic fields associated with the induced currents, the resistivity can be measured for progressively deeper subsurface materials over time (U.S. Army Corps of

Engineers, 1995). TDEM is also known as transient electromagnetics (TEM) (Eastern Research Group, Inc., 1993; Milsom, 2003).

TDEM systems are popular where overburden conductivity is high and skin-depth is limited, since the absence of the primary field when measuring the secondary field allows for very high power to be used. TDEM is superior to FDEM for precisely locating very small targets due to the ability to use the same coil as the transmitter and the receiver, thereby reducing the coil spacing to zero (Milsom, 2003). It is also noteworthy that by measuring the ground response immediately after shutting off the transmitter current, small errors in the location of the receiver coil do not affect the accuracy of the measurement since there will be no coupling between the transmitter and receiver coils. This insensitivity offers a considerable advantage over FDEM, which is very sensitive to variations in the spacing between the transmitter and receiver coils (U.S. Army Corps of Engineers, 1995).

A variant of the TDEM method is the University of Toronto Electromagnetic (UTEM) system. UTEM was invented by Drs. Yves Lamontagne and Gordon West in the 1970s at the University of Toronto. The UTEM system is a wide-band variant of the TDEM method which measures the step function of a subsurface section during the waveform “on-time”. This is to say, it is the opposite of traditional TDEM methods which measure the subsurface response upon shutting off the transmitter (i.e., during the “off-time”).

With UTEM, the depth of investigation is up to approximately 1.5 to 2.0 times the dimensions of the loop that is used. For mineral exploration purposes, loop sizes can range from 300 m to 4 km in diameter for highly resistive terrain. Smaller loops are used for conductive terrain or shallow soundings. The UTEM system is reportedly capable of detecting anomalies as low as 0.01 pT at 5 Hz and above and can be deployed from boreholes as well as from above ground.

A.1.2.2 Frequency-Domain Electromagnetics

FDEM techniques involve the use of a sinusoidal transmitter current at a fixed frequency. The frequency used for these surveys will be selected based on the required depth of investigation, with higher frequencies yielding shallower surveys (U.S. Army Corps of Engineers, 1995). FDEM techniques are also referred to as continuous wave electromagnetics (CWEM) (Milsom, 2003).

Survey configuration has important effects on FDEM surveys. Increasing coil separation will increase the depth of penetration but reduce resolving power. Coil orientation is also important, as it will affect the degree to which the primary induced field is in-phase with the receiver coil. Coupling is maximized with co-planar and co-axial coils and minimized with orthogonal coils. As coupling increases, sensitivity to coil separation increases and sensitivity to coil alignment decreases.

Coupling can be exploited, however, since varying the orientation of survey lines will change the coupling between the coils and the target conductors. Hence, the orientation of a target conductor can be determined. The detected anomalies will be greatest (and most defined) when survey lines are run orthogonal to the orientation of the target conductor. Ratios of vertical to horizontal fields can also be measured and used to indicate dip angles (Milsom, 2003).

A.1.2.3 Ground Penetrating Radar

Ground penetrating radar (GPR) uses reflected electromagnetic (EM) pulses to generate a ground response for imaging purposes. The EM pulses used for GPR surveys are considered high frequency, typically ranging between 80 to 1,000 MHz (U.S. Army Corps of Engineers, 1995).

The EM pulses will reflect off subsurface interfaces where a contrast exists between the dielectric properties of the materials which are present. Such contrasts may exist at the interface between soil, rock, and/or groundwater surfaces, as well as buried infrastructure (U.S. Army Corps of Engineers, 1995). Higher contrast interfaces will reflect more energy, resulting in a higher amplitude signal being detected (Hussain, et al., 2020). Like seismic reflection, the common offset and common midpoint reflection techniques are used in GPR (U.S. Army Corps of Engineers, 1995). The data processing techniques used in seismic and GPR are also highly similar (Lai, Chang, Völker, & Cheung, 2021).

<u>Conductivity and Dielectric Properties</u>

The attenuation equation, given by Equation 5 in Section A.1.2, also applies to GPR. However, the frequencies used for GPR are several orders of magnitude greater than those used for other EM techniques. At these high frequencies, low frequency approximations are no longer permissible and the conductivity, σ, and permittivity, ε, of the media are important properties which control the propagation of the EM waves (U.S. Army Corps of Engineers, 1995).

The conductivity of a material is the reciprocal of its electrical resistivity, and it is commonly reported in milliSiemens per meter (mS/m). Permittivity, previously known as the dielectric constant (Milsom, 2003), is a dimensionless parameter which describes the polarizability of a material subjected to a steady-state electric field (U.S. Army Corps of Engineers, 1995). Relative permittivity, ε_r, is defined as the ratio of the permittivity of a material to that of a vacuum, ε_o (Milsom, 2003).

There are three components of polarization: atomic, molecular, and interfacial. Within the GPR frequency range, the EM wave velocity is primarily impacted by molecular polarization. Atomic polarization can be come important at frequencies above 10 GHz, well above those used for GPR, and interfacial polarization can be come important at frequencies below 100 MHz. The velocity in turn impacts the degree of reflection, diffraction, and scattering of the EM waves (Everett, 2013). Water molecules are highly polarizable and hence have a relatively large relative permittivity of approximately 81. For comparison, the relative permittivity of most earth materials is between 3 to 8.

In earth systems, water and water-rich materials such as clay are therefore critically important when considering the application of GPR. An EM field will lose much of its energy to interactions with polarizable materials, such as water. Water, whether in pore spaces or bound to clay minerals, will also have a controlling effect on conductivity in most earth materials, which are otherwise highly resistive. Clay minerals will have an important influence on GPR signals not only due to adsorbed water, but also due to their polarizability because of trapped cations along their surfaces. Furthermore, clay minerals are also relatively conductive.

These aspects of water and clay result in these materials dominating the displacement current flow at the frequencies used for GPR. Correspondingly, for high water and/or clay content, relative permittivity will be high and EM wave velocity will be lower (U.S. Army Corps of Engineers, 1995). Variations in the water and clay content will, hence, also have an essential role in determining the amplitude of the reflected waves in most (resistive) earth materials. Other factors which reduce the amplitude of reflections are a smaller and rougher reflective surface (Milsom, 2003).

It can be seen from Equation 5 that the attenuation of radar waves is primarily due to electrical conductivity. However, the GPR signal strength along a given travel path will also attenuate because of EM absorption from polarization, scattering from rough reflecting surfaces, and diffraction from small or sharply angled reflectors (Everett, 2013; Milsom, 2003). These processes result in a smaller portion of the original signal travelling along the ray path reaching the receiver antenna. Milsom (2003) notes for GPR surveys to be successful, at least 1% of the incident wave energy must be reflected.

The dielectric constant and rate of attenuation for some common earth materials are presented in **Table A-3**, as seen in Everett (2013), after Davis and Annan (1989). The attenuation rates are based on a center frequency of 100 MHz. It is evident from these values that GPR signals will attenuate rapidly in the presence of conductive materials like clays and saline water.

Table A-3. Dielectric constants and rates of attenuation for GPR signals at 100 MHz

Material	Dielectric Constant	Attenuation (dB/m)
Air	1	0
Freshwater	80	0.1
Seawater	80	1000
Sand (Dry)	3-5	0.01
Sand (Saturated)	20-30	0.03-0.3
Clay	5-40	1-300
Limestone	4-8	0.4-1.0
Granite	4-6	0.01-1.0

Resolution and Attenuation

While an understanding of the factors which will affect the propagation of EM waves is of great importance in selecting and designing a GPR survey, only the frequency and pulse width of the emitted EM wave can be readily controlled.

Based on wave theory, wavelength is a function of wave velocity and frequency. Higher frequencies correspond to shorter wavelengths. It is typically accepted that the smallest feature that may be resolved by a wave is equal to approximately half the wavelength in size.

For a feature to be distinguished by a GPR system, the detected EM pulses which are returning to the receiver antenna at surface must also arrive at distinct times. The resolution of a GPR system is hence limited by the width of the transmitted pulses, Δt. Pulse arrivals which overlap will be indistinguishable, masking the presence of thinner features which do not sufficiently spread the respective arrivals of the pulses reflecting off the top and bottom of the feature. The transmitted pulse width is also inversely proportional to the frequency bandwidth, Δf, so a shorter pulse width will broaden the frequency bandwidth (Everett, 2013).

It can be seen from Equation 5 that increasing frequency will increase attenuation, thereby limiting the depth of investigation. The depth of investigation can be increased by broadening the pulse width and hence lowering the frequency bandwidth, but resolution will suffer.

GPR systems will typically have a center frequency identified, but they will emit a frequency bandwidth ranging from about 50% below to 50% above that central frequency (Milsom, 2003). The center frequency of this band should be selected to yield the highest resolution while still reaching the desired depth of investigation.

Equipment

The basic components of a GPR system are a control and recorder unit (CRU), a pair of receiver and transmitter units, and receiver and transmitter antennae which may be separate or integrated. Connections between each component are provided via fibre optic cables to eliminate a source of electrical interference (Milsom, 2003).

The survey settings are inputted in the CRU, including the frequency, recording time, and stacking. Milsom (2003) reports typical recording windows are between 32 to 2,048 ns and up to 2,048 traces are stacked. A sampling rate of at least four but ideally eight times the center frequency is advised.

The EM pulses are emitted by the transmitter antenna, positioned close to the ground surface. Detection of the reflected EM pulse can be achieved by that same antenna or by a dedicated receiver antenna. Common-offset profiling, in which the spacing between the antennae is held constant, is most common for GPR surveys. The common midpoint configuration, in which the antennae spacing is increased about a fixed location, is very rarely used for GPR surveys (Milsom, 2003) and is not discussed further. The common-offset configuration lends itself well to mobility, since the antennae can be housed in a single sled which is then pushed or towed for rapid survey traverses.

GPR Data Processing

GPR survey data is processed similarly to seismic reflection data. Some of the most common processing techniques applied to GPR data are described below. A valuable advantage of using GPR is that the data can be viewed and much of the processing done in the field, which allows adjustments to the survey parameters to be made right away.

Stacking: A technique whereby multiple signals recorded at the same station can be added together. Each recorded signal should comprise a portion of the EM pulse emitted by the transmitter antenna and subsequently reflected to the receiver antenna, and a random component consisting of environmental noise. Since the emitted signal is consistent and repeatable and the noise should be random, at least in part, the addition of these traces has the effect of amplifying the signal and cancelling or at least reducing the effect of random noise. Stacking is especially convenient for GPR surveys due to the high sampling rates that are used (Milsom, 2003).

Low-cut and high-cut filters**:** The recorded traces are curves which depict the amplitude of the reflected waves recorded by the receiver antenna. The application of low-cut and high-cut filters eliminates parts of the trace that are outside of a specified amplitude range. The very low or very high amplitude responses eliminated by these filters generally correspond to noise.

Automatic gain control (AGC)**:** As the EM waves travel through the ground, the signal strength will decay. This decay can be modelled and therefore corrected by applying an amplification function to the trace. At the field level, AGC is used to accomplish this.

Advantages and Limitations

The clear advantage of using GPR is the relatively sharp resolution that can be achieved, which is of great value in applications such as void detection, delineating buried infrastructure, or detailed stratigraphic model. Furthermore, the ability to generate preliminary imagery directly in the field is beneficial to ensuring the investigation objectives are met, by allowing for modification of the survey limits or input parameters in response to initial findings.

There are, however, several important factors that can severely limit the success of a GPR survey. These factors include:

- Sources of interference, such as radio frequency transmitters, extensive metal structures including cars, power poles (U.S. Army Corps of Engineers, 1995), and cell phones (Milsom, 2003).
- Water, clay soils, and other strong conductors, which limit the depth of investigation by increasing the attenuation of GPR waves (U.S. Army Corps of Engineers, 1995)
- *Sideswipe*, which is a term used to describe reflected or radiated EM energy from nearby reflectors, especially in conductive environments or in the presence of metallic objects (Milsom, 2003).

A.2 Seismic Methods

Seismic methods exploit the propagation of acoustic energy as an elastic wave to measure the dynamic properties of subsurface materials. The propagation of seismic energy is controlled by the acoustic impedance of the media, which is the product of the bulk density, ρ, and the seismic velocity. To distinguish different materials in the subsurface, seismic methods depend on acoustic impedance contrasts between those materials. The seismic velocity is, in turn, also controlled by density as well as by the elastic moduli of the materials (Interstate Technology & Regulatory Council, 2019).

Different energy sources can be used to generate the elastic waves measured by seismic methods. Seismic energy sources can be as simple as a sledgehammer and strike plate, to as sophisticated as large mobile harmonic oscillators. Higher frequency sources are generally preferred as they will produce shorter wavelengths, which aid in precisely identifying arrival times in the data (U.S. Army Corps of Engineers, 1995). Explosive sources are sometimes used for investigations with deep targets and/or offshore studies.

A multitude of seismic methods have been developed around the variety of wave types that exist. There are two general categories of seismic waves: body waves and surface waves. Body waves can be further classified as compressional (longitudinal) waves and shear waves. Compressional waves are the fastest seismic waves and are characterized by particle oscillation in the same direction of wave propagation (Duke, 1969). These are typically designated as the primary wave, or P-wave. Shear waves, also referred to as the secondary wave or S-wave, are characterized by particle oscillation perpendicular to the direction of wave propagation (Duke, 1969). They travel at approximately half (Hunt, 2007) to 0.6 (Wightman, Jalinoos, Sirles, & Hanna, 2004) times the velocity of the P-wave. S-waves will generally have horizontal (SH) and vertical (SV) components (Duke, 1969).

Surface waves are sometimes referred to collectively as the ground roll (Milsom, 2003). Surface waves include different wave types as well, such as Rayleigh waves (R), Love waves (L) (Lowrie, 2007), and Stoneley waves. Only R-waves and L-waves are commonly used for site characterization (Addo & Robertson, 1992). Rayleigh waves are characterized by particle oscillation in a vertically oriented retrograde elliptical pattern parallel to the direction of wave propagation. Most of the R-wave amplitude dissipates by the time it reaches a depth of about 1/3 of its wavelength. R-waves propagate at a velocity of approximately 5% less than S-wave velocity (Duke, 1969) up to 90% of the P-wave velocity of the near-surface material (Hunt, 2007). Love waves are characterized by horizontally oriented particle oscillation, transverse to the direction of wave propagation. L-wave velocity is roughly the same as S-wave velocity for the surface layers (Duke, 1969).

The acoustic energy measured in a seismic study is recorded by a sensor known as a seismometer. On land, seismometers are also known as geophones, and in water they are known as hydrophones. The geophones detect acoustic energy at discrete points along the wavefront reaching them, converting an acceleration into a voltage (Interstate Technology & Regulatory Council, 2019) using solenoids. Geophones will typically be around the size of a large puck and will often be triaxial (i.e., containing three sensors oriented orthogonal to one another; two horizontal and one vertical). Some geophones also feature a hole through the middle to allow them to be bolted to a structure or to the ground.

Two of the most important parameters for seismic surveys are the seismometer *spacing*, which is the distance between the individual seismometers, and the *spread*, which refers to the distance and geometry of a group of seismometers relative to the seismic source. The most commonly used seismic spreads are: split-spread, where the seismic source is located centrally along a line of seismometers; and single-ended (or end-on) spread, where the seismic source is located at some distance beyond the end of the seismometer line (Kearey, Brooks, & Hill, 2013). The seismic source can be aligned with the seismometer line, or it can be offset. The spread length is the distance between the seismic source and the nearest seismometer(s). The path taken by the wave energy as it travels to the geophones is often approximated as a ray-path (Milsom, 2003).

Seismic methods can be categorized by the analytical approach that is taken. Methods where the analysis is primarily focused on the time-domain include seismic reflection and seismic refraction. Examples of methods where the analysis focuses on the frequency-domain include multi-channel analysis of surface waves (MASW), horizontal-to-vertical spectral ratio (HVSR), and testing and imaging using seismic acoustic resonance (TISAR). This large number of variations to seismic surveying and data analysis introduces an element of flexibility in designing the survey around the specific objectives of the study. Furthermore, the source and/or the geophones may be deployed at ground surface, below ground (such as within a borehole), or underwater.

A noteworthy benefit of seismic surveys includes the ability to obtain a direct measurement of the wave velocity of a material or collection of materials. The velocity at which P-waves and S-waves propagate through a medium is of great interest for engineering applications, as these velocities relate to the shear modulus, G, the bulk modulus, B, and the density, ρ (Davis, 1996). The relation between the P-wave velocity, v_p, the S-wave velocity, v_s, and these dynamic elastic properties is as follows:

$$v_p^2 = (B + \frac{4}{3}\, eG)/\rho \tag{7}$$

$$v_s^2 = G/\rho \tag{8}$$

The wave velocity can consequently be used to infer the likely material type as well as other characteristics of the material through empirical relationships. For example, the P-wave velocity has been related to the material type and its rippability for excavation purposes (Milsom, 2003; Caterpillar, 2000). The shear wave velocity can be used to select a site classification using Table 4.1 of the Canadian Highway Bridge Design Code (CHBDC) and allows for the adoption of Site Classes A or B (CSA Group, 2019). Approximate primary wave velocities are presented below for common earth and construction materials in **Table A-4**.

Table A-4. Approximate primary wave velocities for common earth and construction materials

Material	**P-wave Velocity (m/s)**
Air	330 [2]
Water (Fresh)	1,450 [2]
Ice	3,000 – 4,000 [2]
Sand (Dry)	200 – 800 [2]
Sand (Saturated)	800 – 1,900 [2]
Clay	1,100 – 2,500 [2]
Sandstone	1,500 – 4,500 [2]
Limestone	2,500 – 6,500 [2]
Granite	3,600 – 7,000 [2]
Basalt	5,000 – 8,400 [2]
Concrete	3,700 – 4,300 [1]

[1] (Hertlein & Davis, 2006)

[2] (Everett, 2013)

[3] (U.S. Army Corps of Engineers, 1995)

Seismic methods are not without challenges, as they rely on a contrast between seismic velocities between materials. Where this contrast is gradual or confounded by suspended boulders or irregular bedrock surfaces, well-defined interfaces may not be identifiable. Thin or steeply dipping layers may also be difficult to identify. Lastly, the presence of lower-velocity materials will be obscured by overlying higher-velocity materials, which are typically denser earth materials but could also include frozen ground (Hunt, 2007).

A.2.1 Seismic Reflection and Refraction

The elastic wave produced by a seismic energy source will propagate in all directions. When a body wave reaches an interface between materials with different acoustic properties, a portion of the wave energy will reflect, and the remainder will refract. This is depicted schematically in **Figure A-4**. Seismic reflection and seismic refraction surveys exploit this phenomenon by measuring the time it takes for an induced body wave to return to the surface at a known distance. This approach of measuring the time of returns is also known as working in the *time domain*.

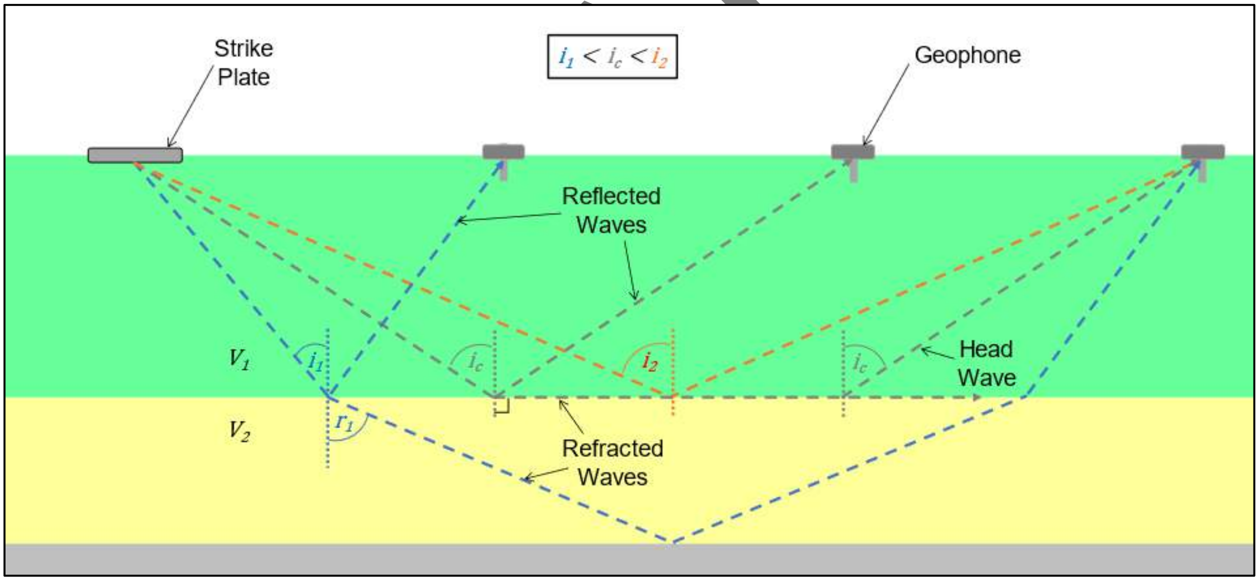

Figure A-4. Reflected and refracted wave ray paths for different incident angles, i

<u>Snell's Law</u>

The angle at which the wave energy will reflect is equal to the angle of incidence. The angle at which the remaining wave energy will refract is governed by Snell's law:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2} \tag{9}$$

where,

i is the angle of incidence, as measured from vertical,
r is the angle of refraction, as measured from vertical,
V_1 is the wave velocity in the first (upper) medium, and
V_2 is the wave velocity in the second (lower) medium.

Seismic wave velocity is a function of bulk density and will typically increase with depth. The wave will refract *toward* the interface if the seismic wave velocity increases across the interface (i.e., $i < r$). At a critical angle of incidence where $\sin i$ is equal to V_1 / V_2, then $\sin r$ will equal unity and thus, the angle of refraction will be parallel to the interface (i.e., r = 90°). Under this circumstance, the refracted wave energy will follow the interface and produce head waves until the energy has fully attenuated. The head waves will leave the interface at the critical angle of incidence. At angles greater than this critical angle of incidence, the wave energy is fully reflected (i.e., there is no refracted wave) (Milsom, 2003).

In some instances, looser or softer material exists below denser or stiffer material. Such circumstances might result in the seismic wave velocity decreasing with depth, and seismic waves would refract *away* from the interface between these media (i.e., $r < i$). In a layered system where seismic velocity decreases with depth, refracted waves would hence not return to surface and the wave energy will not be detected. Where lower velocity strata are interlayered within higher velocity strata, this will result in these lower velocity strata being masked and potentially skewing inversion results.

Resolution

The resolution of a seismic survey is often described as the minimum thickness of a layer that can be detected. That minimum detectable thickness is generally determined by the length of the waves that are being monitored (i.e., the wavelength). An approximate rule of thumb for this minimum thickness is between 1/4 and 1/8 of the wavelength. The wavelength, λ, can be calculated by taking the seismic velocity of the propagating medium, v, divided by the wave frequency, f (Johnson & Clark, 1992), as shown in Equation 10:

$$\lambda = \frac{v}{f} \qquad (10)$$

The propagating medium dictates the velocity of the acoustic wave energy. Thus, the operator's influence over the resolution is limited to selecting a seismic source which will generate wave energy at a range of frequencies yielding the desired resolution. Selecting a seismic source is discussed in more detail below.

Seismic Sources & Survey Configurations

For seismic reflection and refraction surveys, the selection of a seismic source and the configuration of the geophones are the two primary means by which to influence the depth of investigation and the resolution.

The seismic source will control the frequency of the initial wave energy. Like with electromagnetic wave theory, higher frequency acoustic waves will attenuate or decay more rapidly. However, higher frequency waves will correspond to shorter wavelengths and hence better resolution. Therefore, a trade-off between depth of investigation and resolution exists and must be considered in the context of the investigation objectives.

The selection of a seismic source should also consider the energy output, which will impact the signal to noise ratio that can be achieved. In noisy environments, a source which can produce larger energy output may be necessary. Note that it can sometimes be more practical to utilize a source with lower energy output but that which is highly repeatable, and to increase the number of shots recorded for stacking purposes at the subsequent processing stage.

Some examples of common sources and approximate investigation depths include:

- For shallow (< 10 m) depths, 5.5-8.0 kg sledgehammer impacted against:
    - Loaded and/or partially embedded I-beam, wooden beam / railroad tie;
    - Steel plate; or,
    - Steel pipe.
- For intermediate (< 20 m) depths, downhole shotgun (buffalo gun) device or .22 caliber rifle; or,
- For deep (> 20 m) investigation, vibratory devices, oscillators, or explosives.

When selecting sources, the coupling with the ground or media to which the acoustic energy is being transferred is of critical importance. Different subgrade conditions may allow different approaches to coupling. For example, for rigid to semi-rigid surface materials (compacted gravel, pavement, concrete), a wooden beam loaded by the wheels of a heavy vehicle may be appropriate. On soft ground, a small (0.3 m to 0.5 m) steel I-beam with one flange partially sunk into the ground may yield better energy transfer (Arsenault, Hunter, & Crow, 2012).

The second primary means by which to influence the depth of investigation and resolution of the survey is the survey configuration. Seismic reflection and refraction surveys are most often configured in multi-channel geometries, which involve a single source and a spread of geophones all monitoring for that single source. Split spread and single-ended spreads are common and are often both included in a single study. By varying the shot locations and overlapping the multi-channel geometry as it is advanced along a survey alignment, common midpoint (CMP) data can be obtained and used for stacking (Interstate Technology & Regulatory Council, 2019). For example, typical seismic refraction surveys involve the collection of seven records per spread (Situm, McClement, & Arsenault, 2011). Each record is associated with a different shot location. This overlapping data can enhance the clarity of the subsurface imagery that is generated. Forward and reverse shot locations (i.e., shots at mirrored locations) should also be made to identify the potential presence of dipping layers and to reconcile potentially erroneous velocity values when such conditions exist (Haeni, 1988).

The spread length affects depth of influence by controlling the distance that seismic energy can travel between the source and the receiver. Provided that the signal strength at the receiver is of a sufficient magnitude to be distinguished from noise, longer distances correspond to longer travel paths, which can include those which go deeper. An approximate rule of thumb is the maximum depth of investigation will be about 20% of the total spread length, including offset distances (Interstate Technology & Regulatory Council, 2019).

The total spread length can be increased by increasing the spacing between geophones and by increasing the offset between the source and the nearest geophone. Though this would result in increased depth of investigation, lateral resolution and data quality may suffer. First, increasing geophone spacing will increase the subsurface sampling interval (Eastern Research Group, Inc., 1993), which is the lateral distance between points of incidence. Increasing the sampling interval reduces lateral resolution. This can potentially influence the interpretation of a subsurface topography, as depicted in **Figure A-5**.

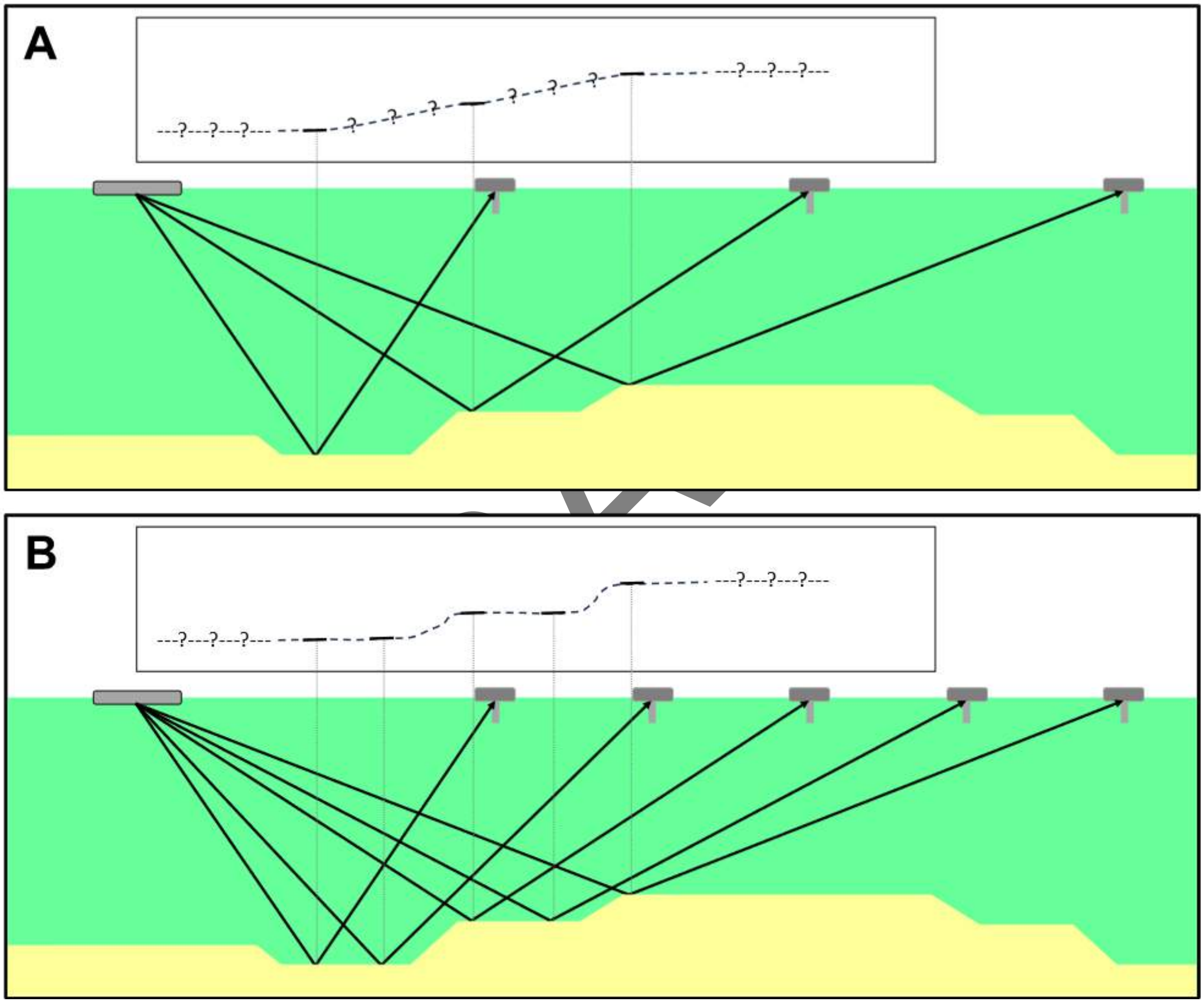

Figure A-5. Possible interpretations of a subsurface reflector based on different sampling intervals

Lastly, the offset distance between the source and the receivers will influence the arrival times for different components of the wave energy. Since surface waves are considered noise in reflection and refraction surveys, a minimum offset is desired to ensure the arrival of the body waves can be distinguished. Too large of an offset, however, will reduce the energy reaching the geophones and negatively affect the signal-to-noise ratio.

Advantages and Limitations

Seismic reflection and refraction surveys are focused on the arrival of elastic body waves. The propagation of this wave energy is controlled by spatial variations in the bulk density and elasticity of the subsurface materials. These methods are therefore unaffected by the electrical or magnetic properties of earth materials and may be well-suited to conditions where electrical or magnetic interference is anticipated to be high. These methods may, however, be impractical at sites with sustained or heavy acoustic noise, such as high volumes of traffic, shorelines (wave action), or industrial activities. Techniques for improving the signal-to-noise ratio such as stacking and/or selecting a source with greater energy output or less frequency overlap with the anticipated sources of noise can help. However, it may be more practical to consider alternative methods when very noisy conditions are identified.

The choice between seismic reflection and seismic refraction depends on the investigation objectives and expected site conditions. Seismic reflection can be an effective choice for high resolution mapping of stratigraphic sequences and discrete structures or anomalies, such as tunnels, voids, or boulders. The use of common midpoint configurations can also be exploited to determine seismic velocities. Seismic reflection also requires less input energy and shorter spreads than seismic refraction (Zohdy, Eaton, & Mabey, 1974).

Seismic refraction is better suited in environments with steeply dipping layers. It is also better suited to deeper or thicker deposits which would necessitate very long spreads or borehole techniques if reflection were to be used. Seismic refraction requires increasing velocity with depth though and typically involves longer arrays than those used for seismic reflection (Zohdy, Eaton, & Mabey, 1974).

Both seismic reflection and seismic refraction may be ineffective in environments where acoustic energy is rapidly attenuated, such as in loose, dry soils. These methods may also be impractical at sites with limited space or obstructions at surface, which can limit the depth of investigation, coupling between the source and/or geophones and the ground, or necessitate radio-enabled equipment if routing cables is impractical.

Interpreting seismic data can be especially challenging where specific conditions exist. Some examples of conditions which can make seismic data interpretation more challenging include:

- **Sloped ground surfaces and/or dipping layers:** These features can skew apparent velocities when a horizontal earth model is assumed. Corrections can be applied when the slope of the ground is known, but this adds processing complexity.
- **Unrecognized layers:** Two examples of cases which may result in unrecognized layers are the existence of thin layers and velocity inversions. Thin layers can go unrecognized due to the first arrivals of underlying, higher velocity layers overtaking those from the thin layer(s). Where a velocity inversion exists, whereby there is a material of a lower velocity than the overlying and underlying materials, no head wave will be generated (and detected) by refraction. The existence of velocity inversions will not only mask the presence of the associated layer, but they will also result in overestimation of the depth to the underlying layer (Zohdy, Eaton, & Mabey, 1974).

A.2.2 SASW and MASW

Spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW) are two seismic survey methods which use surface (Rayleigh, or R) waves, generally at frequencies of 1-30 Hz, for depths of investigation less than a few tens of meters (Park, Miller, Xia, & Ivanov, 2007). These methods are most often used for shear-wave velocity profiling. It is common to use the data to calculate V_{s30} based on the harmonic mean of the interval velocities, by dividing 30 m (or another depth of interest) by the sum of the travel times in each interval up to that depth. Error for MASW is estimated to be +/- 10-15% for overburden, and higher for bedrock.

The velocity of the Rayleigh waves will depend on the signal frequency and the density, geometry, and elastic properties of the medium. This dependence of wave velocity on frequency is referred to as *dispersion*. Dispersive surface waves will be produced in a system which is bounded and inhomogeneous (Addo & Robertson, 1992). In other words, surface waves will only exhibit dispersion in a layered medium with increased velocity with depth (ClearView Geophysics Inc., 2019). An important consideration is that R-waves will only penetrate up to 1 to 2 wavelengths in depth. Longer wavelengths will have a greater depth of penetration, so the velocity of those waves will be influenced by deeper materials (GEOVision, "SASW Method"). These longer wavelengths will, however, be subject to greater uncertainty (ClearView Geophysics Inc., 2019).

The SASW and MASW methods take advantage of these dispersive characteristics and involve calculating the phase velocities for a fundamental-mode Rayleigh wave. This is achieved by setting up a pair of receivers at different intervals which are determined based on the calculated ground roll wavelengths. Accurate measurement of phase velocities is critical to MASW. Sources of noise that must be filtered out include nonplanar, nonfundamental-mode Rayleigh waves, body waves, scattered and nonsource-generated surface waves, and higher-mode surface waves (Park, Miller, & Xia, 1999).

Dispersion curves, or plots of wave velocity against frequency or wavelength, are produced from MASW and SASW surveys by first gathering field data by recording shot gathers. Next, a dispersion curve is extracted for each record. The dispersion curves are then analyzed using a technique called inversion to produce 1D shear-wave velocity depth profiles (Miller, Xia, Park, & Ivanov, 1999). These profiles represent the average of the bulk area within the middle third of the geophone spread (Geophysics GPR International Inc., 2019). Inversion is subject to non-uniqueness, so background information on the stratigraphy, values for Poisson's ratio, and density are critical to calibrating the model. Nevertheless, dispersion curves have been found to be reliable for estimating average shear wave velocity and overburden thickness for depths less than 30 m. Where sufficient velocity contrast exists, MASW can also be used to detect the groundwater table since shear wave velocity will be higher for saturated soil compared to dry soil (Park, Miller, & Xia, 1999).

SASW was first introduced in the early 1980s (Heisey, Stokoe, Hudson, & Meyer, 1982) and involved the repeated use of a single pair of geophones in different configurations to sample a desired frequency range. The reconfigurations are determined based on wavelength calculations made throughout the survey. The MASW method improved on this concept by introducing more geophones, thereby eliminating the labour involved in repeatedly reconfiguring the receiver array (Park, Miller, & Xia, 1999). Another difference between MASW and SASW is in how the dispersion curves are analyzed. For the SASW method, the dispersion curve analysis is based on the phase shift between two receivers as a function of frequency. For the MASW method, the dispersion curve analysis is based on the relation between phase angles and source-to-receiver offset, or 2D wavefield transformation of surface wave (Miller, Xia, Park, & Ivanov, 1999).

Advantages and Limitations of Surface Wave Methods

Advantages of using surface waves are that surface waves are always generated and have the strongest energy (amplitude). Their velocity is primarily determined by the shear-wave velocity of the materials. Sampling depth is directly proportional to wavelength, and hence frequency (Park, Miller, Xia, & Ivanov, 2007). The use of dispersion curves to determine shear-wave velocity has been shown to be accurate based on comparison with downhole profile methods (Park, Miller, & Xia, 1999). For example, blind comparisons conducted by Stephenson et al. (2005) generally matched borehole results to within 15% for average shear-wave velocity estimates to depths of 30, 50, and 100 m, and spectral amplifications to within 15% from 1 to 10 Hz. Long and Donohue (2007) also noted consistent and repeatable results after a series of tests at eight different sites and comparing with shear wave velocity profiles generated using other techniques.

Park et al. (1999) note that multichannel recording can permit effective identification and isolation of noise thanks to distinct trace-to-trace coherency in arrival time and amplitude. The multichannel measurement process utilized for MASW surveys is also relatively fast, as it allows for a broad range of depths to be surveyed using a single measurement. It also provides high levels of redundancy without the need to reconfigure the survey. The signal-to-noise (SN) ratio can be maximized in real-time due to the ability to separate frequency components during acquisition and processing.

The presence of horizontal discontinuities at surface can also introduce noise in the form of backscattered surface waves. These discontinuities can be present in the form of foundation elements, berms, retaining walls, or utility trenches. Techniques such as decomposition of the recorded wavefields can be applied to reduce noise in the data (Park, Miller, & Xia, 1999).

While MASW is insensitive to seismic noise, it is not well-suited to delineating subtle changes and/or small anomalies (Miller, Xia, Park, & Ivanov, 1999). Miller et al. (1999) note, however, that voids or collapse features as small as a few feet have been detected by this method.

Equipment and Configurations for Surface Wave Methods

The equipment used for MASW includes a multichannel (as few as 12 but typically 24 or more) recording system, a receiver array, and a source. The MASW method can be active or passive. The active method involves the use of a seismic source provided by the user. Active sources can be impulsive, such as a sledgehammer and strike plate, or swept, such as a vibrator. Park et al. (1999) note that swept sources may be preferred when optimized for frequency and amplitude for the desired target. The disadvantage of impulsive source data is that decomposition is required to transform the data into a swept-frequency format. However, no appreciable difference was identified in the overall effectiveness when they compared swept source and impulsive source data. The passive method utilizes existing seismic energy occurring in the surrounding environment, such as that produced by nearby vehicular traffic. It is interesting to note that the depth of investigation with the active method is typically up to 30 m, whereas that of the passive method can be several hundred meters depending on the available seismic source (Park, Miller, Xia, & Ivanov, 2007).

Ideally, the survey should utilize high-output, low-frequency geophones without recording filters (Park, Miller, & Xia, 1999). The geophones are typically arranged as close as 2 m to up to 200 m away from the source (Park, Miller, Xia, & Ivanov, 2007). The offset to the nearest receiver should theoretically be set to at least half the maximum desired wavelength, to avoid near-field effects and allow the Rayleigh waves to be treated as horizontally travelling plane waves. This distance is also suggested as the maximum depth to which shear-wave velocity can be calculated with reasonable accuracy (Park, Miller, & Xia, 1999). It is likely that further refinement to the survey configuration will be necessary after initial shot gathers, to optimize the configuration based on noise analyses and observed near- and far-offset effects.

As reported by Xia et al. (2004), optimal recording for surface wave techniques requires field configurations and acquisition parameters which favour the recording of planar Rayleigh waves. They note the following guidance for configuring an MASW survey:

- Near-offset should be greater than half the maximum desired wavelength, to permit plane-wave propagation to occur;
- Near-offset should be approximately equal to the principal investigation depth;
- Far-offset should be approximately two times the principal investigation depth, to balance being close enough to record high frequencies (which attenuate rapidly with distance) but also long enough of a spread to obtain a higher resolution dispersion image;
- Receiver spacing should be less than half the shortest measured wavelength, to avoid spatial aliasing.

Inside, end, and offset shots are typical, ideally at multiples of the geophone receiver spacings. Off-end shots are necessary to allow accurate measurement of surface waves since the offset distance allows the other, faster waves to pass first and allows the low frequency surface waves to fully develop.

A.2.3 Borehole Techniques

Several configurations for seismic surveys involving boreholes are possible. As described by Hunt (2007), these can include:

- *Uphole*, where the energy source is located within a borehole and the geophones are arranged at surface;
- *Downhole*, where the energy source is located at surface and the geophones are arranged within one or more boreholes; or,
- *Crosshole*, where the energy source is located within a borehole and the geophones are arranged within one or more surrounding boreholes.

For this guideline, the discussion presented herein considers both the uphole and downhole techniques under *vertical seismic profiling* (VSP).

In a layered system that is mostly horizontal, the advantage of borehole techniques is a reduced influence from layers above and below a layer of interest (Hunt, 2007). While the crosshole method in particular is regarded as being highly accurate, Jung et al. (2012) found the downhole method was able to produce very similar results and that both methods had good repeatability.

The cost of applying borehole techniques is generally greater than that of surface methods. However, it is of great interest to note that this increased cost is primarily due to the cost of drilling the borehole(s) as opposed to the geophysical logging itself. The average cost for borehole geophysical logging reported by the California Department of Transportation (Caltrans) was only 8% of the cost of drilling. For context, the typical Caltrans logging suite includes caliper measurements, natural gamma measurements, electrical resistivity measurement, and in-situ compression and shear wave seismic velocity logging (Hughes, 2002).

A.2.3.1 Vertical Seismic Profiling (VSP)

Vertical seismic profiling, or VSP, is a technique for characterizing layered media using the wave velocities determined for those media. VSP can be conducted using the uphole or downhole configurations. Arsenault et al. (2012) note the downhole approach is most used. By recording the arrival of seismic waves at receivers at different depths, an average wave velocity for each ray path can be calculated.

VSP is commonly used to determine a value for the average shear-wave velocity to a depth of 30 m, Vs_{30}, a useful parameter in earthquake engineering applications (Moss, 2008). Building codes around the world (Martin & Diehl, 2004), including the National Building Code of Canada (NBCC) and the Ontario Building Code (OBC), reference Vs_{30} to guide the selection of a seismic site class. A value for Vs_{30} can be calculated by dividing 30 m by the sum of the vertical travel-times within the layers extending to 30 m (Arsenault, Hunter, & Crow, 2012).

Survey Configurations and Equipment

For this guideline, discussion regarding VSP is focused on uphole and downhole seismic surveying configurations. These methods typically involve the use of a vertical borehole (or probe) in tandem with a seismograph and recording computer, at least one surface or downhole 3-component geophone, and a source/triggering system (Arsenault, Hunter, & Crow, 2012).

The borehole is typically cased using PVC, which is grouted in place. From a data quality perspective, best results can be obtained from an uncased, fluid-filled borehole (Hughes, 2002) but this is not always possible depending on the stability of the boring. When the borehole is fluid-filled, hydrophones must be used. Seismometer contact with the borehole sidewalls can be achieved using air bladders, wedges, stiff springs, or mechanical expanders.

For downhole surveys, a 1-5 m source offset from the borehole is sufficiently far to reduce significant tube wave coupling to the casing but close enough to minimize non-vertical travel paths (refractive effects) (Arsenault, Hunter, & Crow, 2012). A typical downhole survey source is the use of a sledgehammer struck against a metal plate. The plate will be struck vertically to generally

P-waves, and at an angle to generate S-waves (Crow, et al., 2015). The geophones will be suspended within the borehole and moved up or down, typically at 0.5 to 1.0 m intervals, but this can be adjusted depending on the expected stratigraphy and layer thicknesses.

For uphole surveys, the source may consist of a clamped downhole shear-wave hammer for shallow surveys (< 100 m) or compressive sources such as an airgun, water-gun, or even small explosives (Arsenault, Hunter, & Crow, 2012).

An increasingly common form of downhole survey is the seismic cone penetration test (sCPT), which has benefits which include rapidity of testing, acquisition of other geotechnical data in tandem, and eliminating the need for drilling and casing a borehole to conduct the testing. This approach to downhole shear wave velocity characterization can thereby result in considerable cost reduction (Robertson, Campanella, Gillespie, & Rice, 1986). This method utilizes a polarized shear source at surface and a horizontal seismic detector behind the tip of the cone. The cone is typically advanced at 0.5 m to 1.0 m intervals and the difference in shear wave arrival times between measurement intervals is used to calculate the corresponding shear wave velocity. Though coupling with the formation is typically very good, the sCPT technique is limited to the depth of cone refusal (Hunter, et al., 2002).

Parallel seismic is another variation of downhole surveying which applies specifically to existing foundation elements. This technique involves impacting a part of the exposed foundation or a structure connected to the foundation and monitoring from within an adjacent borehole. The borehole should be drilled within 1.5 m from the element of interest and to a depth of at least 3 to 5 m below it. This technique is discussed more in **Section A.2.7.2**.

A.2.3.2 Crosshole (CH) Seismic

The following section makes extensive reference to ASTM D4428/D 4428M *Standard Test Methods for Crosshole Seismic Testing* (ASTM, 2000). The reader is strongly recommended to refer to this standard in its entirety for details pertaining to the preferred survey and data interpretation methodology, equipment specifications, and survey design parameters to generate the highest quality data.

A minimum of two, but ideally three, boreholes should be used for the survey. Each borehole should be a diameter of 165 mm or less. Boreholes to be used for CH testing purposes should be drilled in a line and spaced 3.0 m to 4.5 m apart, center-to-center, depending on the expected velocity of the subsurface materials at the study site. The aim of the CH seismic survey is to measure direct waves only, so center-to-center spacing greater than 6.0 m is not recommended. As the distance between boreholes increases, so too does the likelihood of measuring refracted waves generated along the interfaces between layers. Measurement of refracted waves will mask the presence of low velocity layers/zones, rendering the survey result less useful.

Though not strictly necessary, casing the boreholes is strongly recommended to preserve the borehole integrity. If casing is installed, it should consist of 75-mm or 100-mm inside diameter (ID) PVC pipe or aluminum casing with a bottom cap. The casing should be centered in the borehole with the aid of centralizers, then grouted in place to ensure good contact with the borehole sidewalls. The grout should be mixed to match the density of the surrounding material. A bottom cap with a one-way valve is encouraged to facilitate grouting, or grout may be tremied to the bottom of the borehole from the annular space between the casing and borehole sidewalls. Care must be taken to avoid disturbing the borehole wall. Anchoring the casing may be necessary to counter buoyancy during grouting. Resisting upward buoyancy from surface is not recommended, as the casing could bend and/or break.

Since the horizontal distance between boreholes is critical to calculating the wave velocity, accurate surveying of the verticality and horizontal distance between boreholes is required. The need for accurate surveying becomes more important as the depth of the boreholes increases.

A.2.4 Other Seismic Methods

A.2.4.1 Microtremor Techniques

Microtremors are weak, low amplitude vibrations present everywhere and occurring constantly. These ambient vibrations are too small to be perceivable by human senses but can be measured by sensitive equipment and subsequently amplified. In conventional seismic surveys, microtremors are regarded as noise but microtremor techniques utilize these weak vibrations as the primary input source (Okada, 2003). Utilizing microtremors as the signal source can be convenient since they are ubiquitous and can travel through the complete overburden thickness (U.S. EPA, 2024). Microtremor techniques are noted to be viable in urban areas and the depth of investigation can be down to hundreds of meters thanks to the typically low frequency of ambient vibrations (Jongmans, Ohrnberger, & Wathelet, 2005). Several variations in the measurement and analysis of ambient vibration wavefields are discussed below.

Microtremor Horizontal-to-Vertical Spectral Ratio (HVSR): This technique is carried out using a single seismometer and involves recording ambient noise or vibration (microtremors). A three-component seismometer is placed on the ground and left to record for up to an hour (Molnar, et al., 2022). The ratio of the horizontal to vertical Fourier spectra of the recorded noise is calculated (Perret, 2015) and typically presented as amplitude versus frequency curves (Dietiker B. , Pugin, Crow, Brewer, & Russell, 2024). The cost of data acquisition for this method is relatively low since only a single seismometer is required.

Applications of the HVSR method include mapping the site period, fundamental resonance frequency, f_0, and shear-wave velocity depth profiling (Molnar, et al., 2017). Other applications include estimating the properties of unconsolidated overburden sediments (U.S. EPA, 2024), the depth to bedrock, and mapping the bedrock surface. The maximum H/V spectral ratio has been found through empirical evidence and numerical simulation to generally occur at or close to the fundamental resonance frequency of sites when a strong impedance contrast exists between layers (Perret, 2015; U.S. EPA, 2024). The fundamental resonance frequency is related to the thickness and the average shear-wave velocity of a soil profile, so the HVSR method can be used to determine the shear-wave velocity of the soil profile, or *vice versa*, provided the other parameter is known (Perret, 2015).

A potentially significant advantage over conventional reflection and refraction techniques is that the direction of steeply dipping layers or basins can be estimated from HVSR data (Dietiker B. , Pugin, Crow, Brewer, & Russell, 2024).

Refraction Microtremor (ReMi): Microtremor array measurements (MAM) involve the analysis of the dispersion properties of Rayleigh surface waves to produce estimates of shear-wave velocity or rigidity profiles (Louie J. N., 2001). The dispersion curves of these surface waves are retrieved using array measurement analysis and wavefield transformation techniques to obtain a v_s profile (Jongmans, Ohrnberger, & Wathelet, 2005), like for MASW and SASW.

The refraction microtremor (ReMi) technique is a MAM method which uses the same setup as MASW or refraction but is a passive source method, meaning it relies on ambient energy in the environment from sources such as traffic. This ambient energy typically contains lower frequency data, permitting investigation depths of several hundred meters (Jongmans, Ohrnberger, & Wathelet, 2005). The depth of investigation is also a function of the array length and the resonant frequency of the sensors utilized for the measurements (Stephenson, Louie, Pullammanappallil, Williams, & Odum, 2005). Data is typically recorded over approximately 10 minutes (Geophysics GPR International Inc., 2019), followed by transformation and stacking ahead of the inversion process.

A study by Louie (2001) found that shear wave velocity could be estimated with 20% accuracy down to 100 m depth by using microtremor noise recordings along a 200-m long line using seismic refraction equipment. The ReMi method was able to produce average velocity estimates for 10-20 m depth intervals, but it cannot match the resolution possible using suspension loggers (Louie J. N., 2001).

Advantages of the ReMi method include the use of commonly available equipment and ambient vibrations as the source energy, thereby simplifying recording procedures. As a result, ReMi data acquisition can be more time efficient than MASW (Stephenson, Louie, Pullammanappallil, Williams, & Odum, 2005). Another advantage is that this technique can be used in noisy, urban areas since it utilizes the ambient noise that is present. In fact, this method works best in urban areas with noise coming from all directions and will be more challenging at sites that are too quiet (Louie, Pancha, & Pullammanappallil, 2017).

Microtremor array techniques are constrained by the assumption that the site is horizontally stratified and that the ambient vibrations being recorded primarily consist of surface waves (Jongmans, Ohrnberger, & Wathelet, 2005). However, it has been demonstrated that a collection of 1D ReMi profiles can be extended into 2D cross sections (Louie, Pancha, & Pullammanappallil, 2017).

A.2.4.2 Testing & Imaging Using Seismic Acoustic Resonance (TISAR)

Testing and Imaging using Seismic Acoustic Resonance (TISAR) is a seismic technique that was developed by Geophysics GPR International Inc. to produce high-resolution imaging of geological strata. It is reported to be capable of depths of investigation in the order of 70 m depending on the conditions (Situm, McClement, & Arsenault, 2011). The technique was originally conceived as an extension of the theory behind the well-known impact-echo method, which is used in non-destructive testing (NDT) of concrete structures. The TISAR survey configuration and data processing, however, differs from that of the impact-echo method. The TISAR technique was intended to be used for multi-layer geological systems with increasing or decreasing acoustic impedance (Arsenault & Chouteau, 2002). The acoustic impedance is equal to the product of the seismic velocity and the volumetric mass of the material.

TISAR is undertaken in the frequency domain and relies on the build-up of resonance signals, caused by the repeated reflection of a seismic impulse at interfaces between materials of different acoustic impedance. The frequency of the resonance signal can then be used in combination with the seismic velocity, as determined using other methods, to determine the depth of the reflecting interface and hence the thickness of the upper layer (Situm, McClement, & Arsenault, 2011). If multiple resonance frequencies are identified, the thickness of each corresponding layer can be determined in the same manner and by sequentially stripping the upper layer thicknesses from the overall depth (Wang, et al., 2024). This is illustrated schematically in **Figure A-6** below.

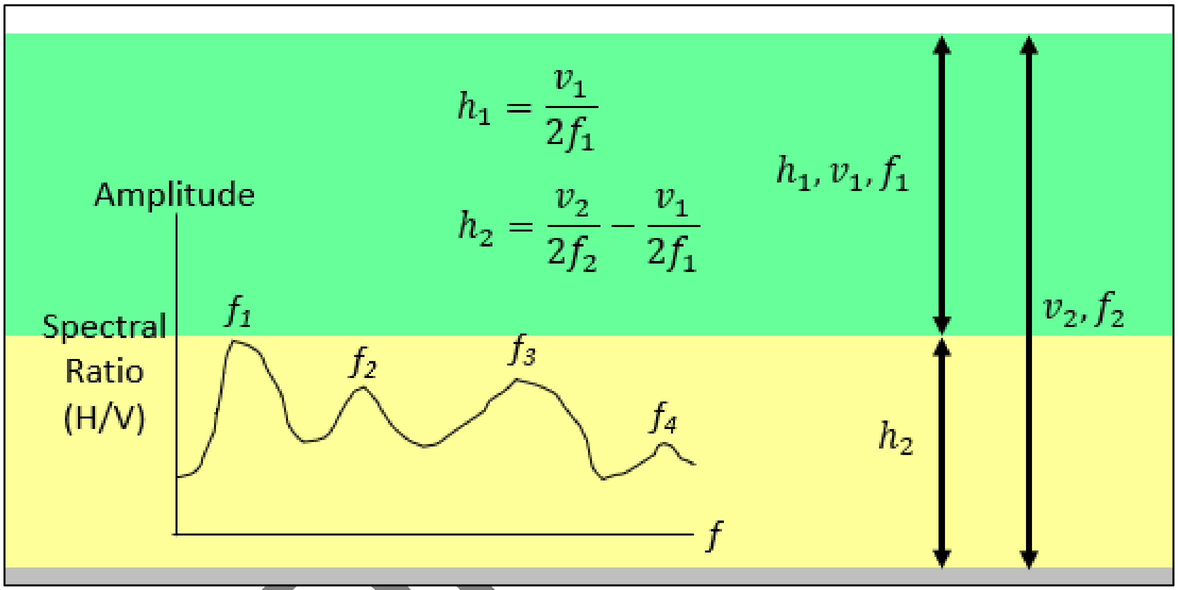

Figure A-6. Schematic depiction of the TISAR technique

The application of TISAR is like GPR in that it is typically used to produce a high-resolution image of relatively shallow geological media. However, TISAR is well suited to conductive subsurface environments which would severely limit the depth of investigation of GPR. TISAR is stated to be capable of achieving depths of investigation of up to 70 m and resolving layers as thin as 10 cm (Situm, McClement, & Arsenault, 2011).

Situm et al. (2011) state that it is typical to produce 18 records (or shot gathers) for each TISAR line. The shots are located between every second geophone and at various in-line offsets. The source of the seismic impulse energy does not differ from other seismic methods. Wang et al. (2024) show resonance frequencies derived from ambient noise recording at a single station is also viable.

A.2.5 NDT of Existing Foundations

There are several methods that have developed specifically around evaluating the integrity and capacity of existing concrete foundation elements without extracting or damaging the foundation in whole or in part. These tests are known as non-destructive test (NDT) methods. A few of the most common NDT methods which rely on acoustic (seismic) energy are described below.

A.2.5.1 Stress-Wave Methods

Surface acoustic NDT techniques are applied from the exposed top or side of a foundation element. These techniques involve generating a stress-wave, which will travel through the foundation element. These methods can be used to estimate the length of a foundation consisting of a material with a known wave velocity, or to identify possible deficiencies in the material based on observed reflections and/or slower-than-expected pulse velocities. The surrounding soils will also influence the measured response. Longer foundations and softer or more dispersive surrounding soils will both increase signal attenuation (Hertlein & Davis, 2006).

The response of the stress-wave is measured as it reflects and returns to one or more transducers coupled to the foundation. The placement of the transducers will dictate which path taken by the stress-wave is being measured. For applications to foundation elements, only indirect or semi-direct transmission will be possible since access will restrict placement of the transducers to the same or adjacent faces of the foundation element, respectively. Indirect and semi-direct transmission are less sensitive than direct transmission, which involves the transducers being placed on directly opposite faces. The signal amplitude produced by indirect transmission is approximately 2-3% of that produced by direct transmission (International Atomic Energy Agency, 2002).

The success of surface acoustic NDT techniques depends on the length-to-diameter ratio of the foundation element, soil properties, and the depth and type of anomaly (Hertlein & Davis, 2006). According to Hertlein and Davis (2006), experienced operators can reliably detect and quantify defects in the order of 10-15% of the shaft cross-sectional area using surface NDT techniques. The authors noted at the time that previous guidance via the FHWA's 1993 publication, "Drilled Shafts: Construction Procedures and Design Methods" suggested limited reliance on these techniques. The capability cited by Hertlein and Davis was attributed to advancements in experience, hardware and signal quality, data acquisition, and analytical algorithms over a span of 10 years since the 1993 FHwA publication.

Impulse Echo

The most common stress-wave method used for investigating drilled shafts or previously installed concrete foundations is the impulse echo method (Rausche, 2004). This method is also commonly referred to as sonic echo, seismic, seismic reflection, sonic, echo, pile integrity testing (PIT), and TNO-Wave (Hertlein & Davis, 2006).

Standardized test procedures for this method are provided in ASTM D5882, "Standard Test Method for Low Strain Integrity Testing of Piles" (ASTM, 2016). A light hammer is used to generate a compressive stress wave which will propagate as a bar (extensional) wave and generate reflections in response to changes in impedance. Impedance is a function of the elastic modulus and the density of the material through which the stress wave propagates. Changes in impedance can be expected where there are changes in the pile cross-section, pile material density, or the lateral resistance provided by the surrounding soil.

The return of the compressive stress wave energy is monitored at surface. The detected energy is called the response signal. Monitoring for the return of the response signal is accomplished using one or more accelerometers affixed to the exposed portion of the foundation. A sampling rate of 10 kHz and recording time of 100 ms is appropriate for most piles.

If the velocity of the material is known and accounting for the relative position of the hammer blow and sensors, the time taken for the response signal to travel through the foundation and return to the sensor can be used to determine the distance to the tip of the pile or intermediate reflectors, which could indicate the presence of defects. Alternatively, if the length of the pile is known, one can instead calculate the velocity of the material to provide an indication of its density and condition (Hertlein & Davis, 2006). This concept is illustrated below in **Figure A-7**.

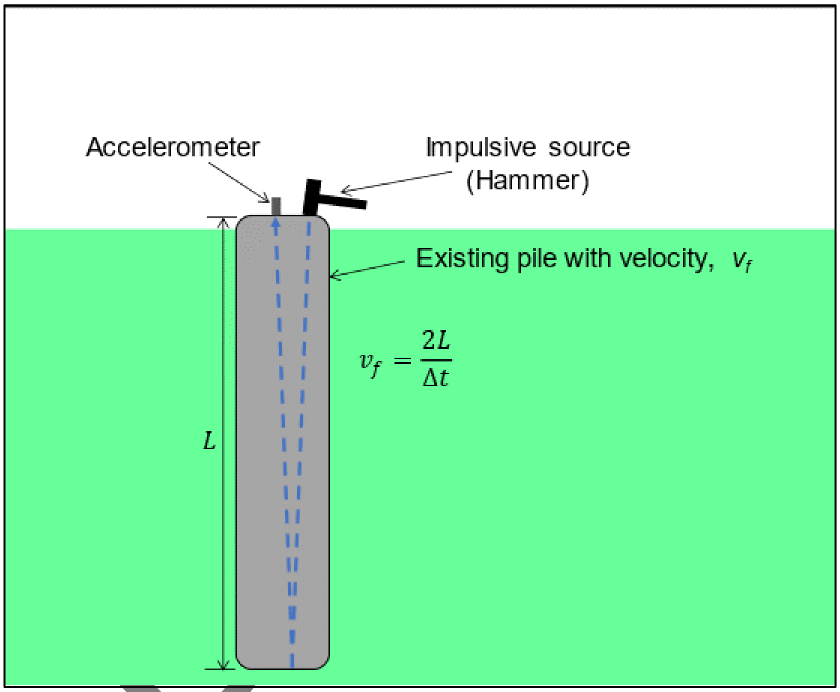

Figure A-7. Schematic of the Impulse Echo method for estimating pile length or condition

A.2.5.2 Downhole Techniques

Downhole techniques involve lowering sensors to the desired test intervals, thereby avoiding any conditioning and damping of the response signal by the soil surrounding the foundation element (Hertlein & Davis, 2006). Hence, downhole techniques are independent of foundation length constraints associated with surface stress-wave techniques. Downhole techniques include cross-hole sonic logging (CSL), gamma-gamma logging, and parallel seismic testing. Both CSL and gamma-gamma logging require access tubes within the pile, typically placed during pile installation or, through considerably more effort and expense, by coring the length of an existing pile. As one of the intents of this document is to provide guidance on assessing existing piles while preserving them for reuse, the following discussion focuses on parallel seismic testing, which can be applied to existing piles of varying size and condition.

The parallel seismic method involves drilling a borehole in the soil or rock in parallel with an existing pile, within approximately 1 m. The borehole can be uncased, if the overburden is stable, or cased with PVC pipe. Steel casing can also be considered but is not recommended if magnetic or electrical methods are also being considered. If casings are used, the annular space should be fully grouted to ensure the casing is well-coupled to the surrounding strata. To provide acoustic coupling with the surrounding media, the casing can be filled with water if using hydrophone(s) (Hertlein & Davis, 2006). Alternatively, electro-mechanical bow-springs or other similar devices can be used to press the geophone into the side of the casing.

A major advantage of the parallel seismic method over other stress-wave methods involving measurement at surface is that its accuracy is not dependent on an assumed wave speed (Rausche, 2004).

To conduct parallel seismic testing, a geophone (or hydrophone) is lowered into the prepared borehole and then the existing pile head or a coupled feature is struck with a hammer to generate an acoustic pulse. The acoustic pulse will travel down the pile, generating headwaves at the soil-structure interface. This process is shown schematically in **Figure A-8**.

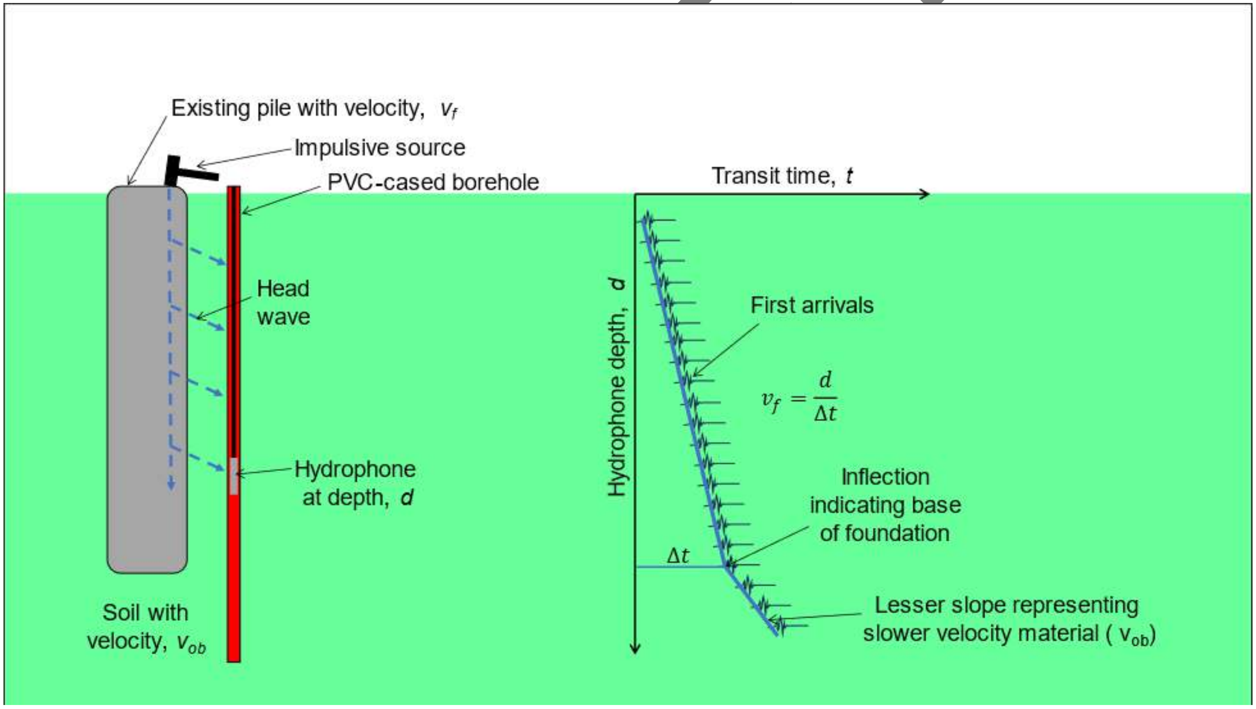

Figure A-8. Schematic depiction of the parallel seismic technique, with field setup (left) and example data (right) showing the identification of the base of an existing pile

After recording, the geophone is raised to the next vertical station and the test is repeated. Testing can be repeated at the same increments to allow for stacking to enhance the signal-to-noise ratio (Hertlein & Davis, 2006).

An important assumption is that the borehole is parallel to the foundation element. If the distance between the borehole and the foundation remains constant, the travel times for the signal to reach the geophone will depend on the length of the foundation through which they have passed. With the geophone depth also being known, the velocity of the foundation material can be evaluated. Furthermore, the length of the foundation can be determined if a disproportionate change in travel time is noted beyond a certain geophone depth (Hertlein & Davis, 2006). The change of velocity should be confirmed for several more increments to determine whether the cause is the end of the foundation or if a defect has been encountered.

A.2.6 Seismic Data Processing

The objective of seismic data processing is to improve seismic resolution through the selective enhancement of signal energy recognition amidst other recorded energy.

The sequence in which seismic data is processed primarily consists of deconvolution, stacking, and migration. Deconvolution is the compression of seismic wavelets into more discrete “spikes” and suppression of reverberating wave trains, which improves *temporal resolution*. Stacking is the process of compressing redundant data across multiple shots and stations to the plane of zero-offset, which enhances the *S/N ratio* by amplifying correlated signals and suppressing uncorrelated noise. Migration involves collapsing diffractions and correcting the locations of dipping events based on the wave equation, which improves *lateral resolution*. Additional processing steps such as the application of filters, gain, or corrections can be undertaken throughout this sequence to improve the effectiveness of these principal steps (Yilmaz, 2001).

There are numerous techniques that are not described herein. Interested readers are referred to the selected reference materials listed in **Section 1.2** for additional reading. Instruction concerning the application of data processing techniques is also beyond the scope of this document and requires the skilled and experienced judgement of a qualified geophysicist.

Enhancing Signal-to-Noise Ratio

Raw data records collected during seismic surveys are expected to include energy from the source (signal), assuming an active method was undertaken, and energy from background sources. Techniques have been developed to facilitate recognizing the signal energy at both the data acquisition stage as well as post-acquisition.

Proper survey design should consider selection of appropriate offset distances and locations to promote the detection of the wave types that are of interest. For seismic surveys utilizing shear wave sources, opposite source polarity records are recommended to permit superimposition of the toward and away shot records. This technique can greatly assist with identifying the arrival of shear wave energy. For the MASW method, near-field and far-field effects can (and should) be minimized by optimizing the field configuration and/or selective offset and frequency processing (Park, Miller, & Xia, 1999).

Post-acquisition, there are several common techniques used to enhance the signal-to-noise ratio. These include stacking, filters, and gain control. These techniques were previously introduced in **Section A.1.2.3** when discussing GPR data and further details concerning their application should be referenced there. Everett (2013) explains that the signal (S) to noise (N) ratio improvement from stacking n traces can be described by Equation 11, assuming the noise is random:

$$\frac{S}{N}(n) = \sqrt{n}\frac{S}{N}(1) \tag{11}$$

Equation 6 shows there is a diminishing return in improvements to the SNR as the number of records increases. It also shows a small number of records being stacked can produce an appreciable improvement in the SNR. For example, stacking only n = 4 records would produce a 100% improvement in the SNR. The effort required to collect this relatively small number of records is entirely justifiable compared to the effort which typically goes into setting up the spread.

Analytical Techniques

Depending on the seismic method being used, different analytical techniques may be needed to support interpretation. For refraction methods, analytical techniques include the Generalized Reciprocal Method (GRM) (Palmer, 1981) and Hawkins' method (Hawkins, 1961) for computing the thicknesses and velocities of overburden layers and bedrock below each geophone location.

Inversion is the process by which seismic data is transformed into earth properties such as elastic impedances and densities, which are then used to predict lithologies and other material characteristics (Russell & Hampson, 2006). The objective of seismic inversion is to construct an earth model which satisfies the measured seismic data. Seismic inversion results are non-unique and judgement or tie-in with other data, such as borehole logs, is needed to corroborate a model.

Frequency wavenumber (f-k) techniques and spatial autocorrelation (SPAC) techniques are used to determine the dispersion curves for SASW, MASW, ReMi, and other methods involving ambient vibration wavefields. Frequency wavenumber techniques assume the validity of a plane wave signal model. The most commonly used f-k technique for microtremor analysis is the CAPON high-resolution f-q approach. This approach involves the evaluation of a cross spectral matrix (CSM). SPAC techniques assume the existence of a spatially and temporally stationary stochastic wavefield. A single valued phase velocity at a given frequency is obtained by inverting the averaged spatial autocorrelation coefficients which are determined for each pair of stations (Jongmans, Ohrnberger, & Wathelet, 2005).

A.3 Other Geophysical Methods

Gravity, magnetic, and radiometric methods are discussed in the following sections. These methods are less commonly used for civil engineering applications but may be worth considering for specific circumstances.

A.3.1 Gravity Methods

Gravimetry is the measurement of the intensity of earth's gravitational field. As with other potential fields, the detection of anomalies in the gravitational field intensity can be used to infer changes in subsurface conditions across a surveyed area. The gravitational field intensity can be expected to increase in the presence of a greater mass (i.e., higher density). In gravimetry, the gravitational field intensity is measured in gals, where one gal is equal to an acceleration of one centimeter per second squared. A specialized type of accelerometer known as a gravimeter is typically used for these studies (Lowrie, 2007). It is important to note, these instruments measure gravity differences rather than the absolute strength of the gravitational field (Milsom, 2003).

For relatively shallow geotechnical and foundations engineering applications involving relatively small masses or cavities (as opposed to plate tectonics, mountains, and geoidal sciences), the magnitude of the expected gravitational field anomalies is in the order of microgals (Eastern Research Group, Inc., 1993). Hence, a class of instrument capable of measuring with repeatability in the order of microgals, known as microgravimeters, are used for these applications. While these instruments can be sensitive to 0.01 microgals, accuracy is unlikely to be better than about 0.03 microgals (Milsom, 2003) and reading error may be up to 0.08 to 0.10 microgals (U.S. Army Corps of Engineers, 1995). Potential sources of reading error are listed below:

- Moving, releveling, and unclamping the meter
- Soft footing material below the gravimeter plate, such as snow
- Wind
- Ground movement or vibration

Nevertheless, gravimetry can be an effective option where large contrasts in mass are expected within the survey area. Such contrasts might be caused by the presence of (large) voids, tunnels, buried trenches or valleys, or dipping soil or bedrock layers.

Due to the required high degree of precision, considerable care must be taken when setting up the survey (Hunt, 2007) and correcting the field data for site conditions and noise. The following corrections may need to be applied to the field data and are discussed at length by Lowrie (2007):

- Drift (instrument) correction
- Tidal correction
- Terrain correction
- Bouguer plate correction
- Free-air correction
- Isostatic correction
- Eötvös correction
- Latitude correction

A site with variable surface topography and near-surface densities would be considered unsuited for this type of survey due to the added difficulty of the necessary corrections. The U.S. Army Corps of Engineers (1995) estimates such a site would produce 0.25 to 0.86 microgals of difficult-to-reduce error. For comparison, a sample calculation for a 1-m thick sheet with a density contrast of 2,000 kg/m^3 indicated a gravitational anomaly of 0.84 microgals (U.S. Army Corps of Engineers, 1995).

Other limitations discussed by the U.S. Army Corps of Engineers (1995) include:

- **Non-uniqueness:** the same gravitational anomaly caused by a large, buried mass may be produced by several smaller masses closer to surface.
- **Depth vs. Size:** as the mass of interest becomes deeper, the mass must become increasingly large to be detected (i.e., differentiated from noise). A practical limit is approximately 2 m depth per 1 m of diameter for a 1.0 g/cc density contrast.

Gravimetric surveys are relatively expensive primarily due to the high cost of a gravimeter and the need for precise surveying to relate the readings to a reference system (Milsom, 2003).

A.3.2 Magnetic Methods

A.3.2.1 Nuclear Magnetic Resonance (NMR)

Nuclear Magnetic Resonance (NMR) is a geophysical tool first used in the 1960s for oilfield exploration and more recently adapted for hydrogeological investigation. It involves the application of a strong magnetic field to induce precession of nuclei in a uniform orientation corresponding to the direction of the magnetic field. This precession will also be at an angular frequency, ω_0, proportional to the strength of the magnetic field, B_0. The Larmor equation describes this proportionality using the gyromagnetic ratio, γ, as shown in Equation 12:

$$\omega_0 = \gamma B_0 \tag{12}$$

The gyromagnetic ratio is unique to each element. The NMR technique exploits this phenomenon by subsequently subjecting the nuclei to radio-frequency energy. This results in nuclei of different elements resonating at different frequencies, allowing these elements to be identified (Bushberg, Seibert, Leidholdt Jr., & Boone, 2020).

This method can be applied at surface, but it is far more commonly applied in open or non-metallic cased boreholes via wireline or push-tool methods. NMR tools can acquire data at various radii, which can allow one to assess the radius of the disturbed zone and the hydrogeologic characteristics of the undisturbed soil or rock (Interstate Technology & Regulatory Council, 2019).

Uses include quantifying total porosity, pore-size distribution, permeability, and saturation. NMR can differentiate between mobile and bound porosity fractions, as well as between water and certain petroleum hydrocarbons. Indirect inference of lithologies (soil or rock types) can be made based on the porosity characteristics quantified using NMR (Interstate Technology & Regulatory Council, 2019).

The vertical resolution of NMR is typically in the order of 0.2 m for direct push tools to 0.5 m for wireline conveyed tools. Data acquisition at smaller intervals is accomplished by overlapping and averaging data across intervals. The radius of investigation measured from the center of the tool ranges between 0.15 m to 0.50 m depending on the model. Logging is typically conducted at rates of 15 m/hr or less (Interstate Technology & Regulatory Council, 2019).

Advantages of NMR include its ability to quantify key parameters of hydrogeologic interest without the use of a radioactive source and from within existing PVC-cased monitoring wells (Interstate Technology & Regulatory Council, 2019). These traits may be highly favourable in sensitive environments with existing well infrastructure.

The borehole or well depth and diameter must be accounted for when evaluating the practicality of using NMR. A selection of NMR probes presented by the ITRC (2019) after Spurlin et al. (2019) varied between about 1.2 m to 2.2 m long and 45 mm to 133 mm in diameter.

A.3.2.2 Magnetometer Surveys

Magnetometry involves measuring the magnetic field strength, in nanoTesla (nT), and comparing to the theoretical magnetic field strength predicted by the International Geomagnetic Reference Field (Lowrie, 2007). The difference, referred to as the magnetic anomaly, can be plotted and used to identify variations in the subsurface. The intensity of the magnetic field corresponding to a dipole is inversely proportional to the square of the distance from the dipole and proportional to the volume of the object (Quesnel, Langlais, Sotin, & Galdeano, 2008). In concept, this is highly similar to gravity methods. However, in practice, the sensitivity required of magnetometers is much less than that of gravimeters since the magnetic properties of earth materials can differ by several orders of magnitude (Milsom, 2003).

The magnetization of a material is a vector defined as the magnetic moment per unit volume and is proportional to the magnetic field to which it is exposed. This proportionality is defined as the material's susceptibility, and it can be negative or positive. The material is defined as diamagnetic if the magnetization is negative, or as paramagnetic if the magnetization is positive. The susceptibility of most natural materials is very low, and observable magnetization in rock is generally attributed to the magnetite, pyrrhotite, or maghemite mineral content (Milsom, 2003). It is important to note that these minerals can become permanently magnetized during formation of the rock or due to later processes. This phenomenon is referred to as remanent magnetization. The total magnetization is the sum of the remanent magnetization, locked in from a past magnetic field, and the induced magnetization, from a present magnetic field (Lowrie, 2007).

Magnetometer surveys are typically used to detect magnetic ores or rocks, and seldom for engineering studies (Hunt, 2007). However, magnetometry may be useful in settings such as southern Ontario, where sediments may contain magnetic minerals due to their being derived in part from the Canadian Shield. Coarse-grained soils are also noted to generally have higher percentages of magnetic minerals than fine-grained soils (Dietiker B. , Pugin, Crow, Brewer, & Russell, 2024). Lastly, it is worth considering the application of magnetometry to investigations focused on locating utility infrastructure, foundations, reinforced slabs, tunnels, or other structures containing ferromagnetic materials in the form of reinforcing steel.

A.3.3 Radiometric Methods

Gamma-Gamma Density Logging (GDL) is an NDT technique used in civil engineering to investigate the integrity of concrete from within a borehole. The borehole may be cased with PVC or steel and can be filled with water or left empty (i.e., filled with air) (Wightman, Jalinoos, Sirles, & Hanna, 2004). GDL is also used in the oil and gas industry, with applications which include logging stratigraphic changes with depth and estimating relative and absolute porosity (U.S. EPA, 2024).

The GDL technique allows for changes in average bulk density of a nearby material to be detected, hence indicating the presence of anomalies such as voids, fractures, or defects. The change in bulk density is inferred from the intensity of reflected radiation returning to the sensor. A radioactive source is used to emit gamma rays into the material being investigated. The source is commonly Cesium-137 or Cobalt-60 (U.S. EPA, 2024). A detector containing a sodium- or cesium-iodide scintillation crystal is used to detect the gamma ray photons which are reflected by the surveyed material. The intensity is described in terms of counts per second (cps) (Wightman, Jalinoos, Sirles, & Hanna, 2004).

The gamma photons emitted from the source will bounce off the electrons, undergoing a process known as Compton scattering. Compton scattering results in the gamma photons losing energy.

If the energy of the gamma photons drops below 0.5 MeV, they can be captured by the material via photo-electric absorption. This process will result in a reduced quantity of gamma photons reaching the detector (U.S. EPA, 2024). Denser materials possess greater electron density; hence, the measured gamma intensity is inversely proportional to the bulk density of the material. To quantify the data obtained using the GDL technique, a factor to relate gamma intensity to density must be obtained by calibrating the probe using a test block of a known bulk density (Wightman, Jalinoos, Sirles, & Hanna, 2004).

The effective radius of GDL is limited to approximately half of the distance between the source and the detector (Wightman, Jalinoos, Sirles, & Hanna, 2004). The depth of investigation will also decrease as bulk density increases (U.S. EPA, 2024).