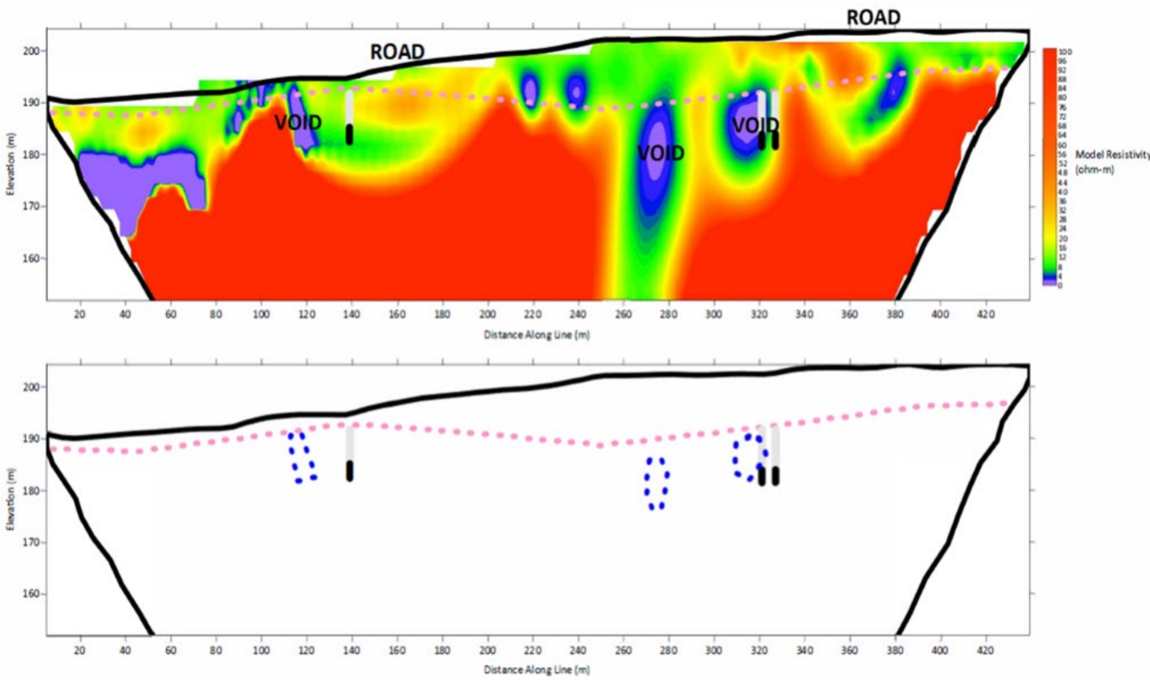
New Technologies for Detecting and Mapping Passages Beneath Missouri Roadways



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Final Report

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New Technologies for Detecting and Mapping Passages Beneath Missouri Highways

By
WSP USA Inc. and MS&T

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16. Abstract
The Missouri Department of Transportation (MoDOT) commissioned WSP USA Inc., in collaboration with the Missouri University of Science and Technology (Missouri S&T), to evaluate advanced, non-intrusive geophysical and remote sensing technologies for detecting and mapping subsurface passages beneath Missouri highways. Subsurface features such as karst voids, caves, sinkholes, and abandoned mine workings present ongoing risks to roadway safety, structural performance, and long-term maintenance, particularly in regions underlain by karst terrain and historic mining activity. This study was conducted to provide MoDOT with a practical, implementation-focused assessment of available subsurface investigation methods and to develop a risk-based framework for their application beneath active transportation corridors. Following a comprehensive literature review, technical evaluation, and review of practices employed by other state departments of transportation, a suite of geophysical and remote sensing methods was assessed. Evaluated technologies included Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), seismic refraction, and Multichannel Analysis of Surface Waves (MASW), microgravity, magnetometry, transient electromagnetic (TEM) surveying, Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR), muography, and selected borehole geophysical methods. Each method was evaluated based on depth of investigation, sensitivity to voids and weak zones, logistical constraints, suitability beneath paved roadways, and applicability to Missouri's geologic conditions. Results indicate that no single method is universally effective; however, ERT consistently provides the most reliable primary subsurface imaging for void detection in karst and mining-prone settings. Based on these findings, a phased, multi-method investigation framework is recommended to support proactive risk management, targeted verification, and informed decision-making for MoDOT's transportation infrastructure.

17. Key Words Subsurface void detection; Karst terrain; Abandoned mine workings; Highway infrastructure; Geophysical methods; Electrical Resistivity; Tomography (ERT); Ground Penetrating Radar (GPR); Seismic methods; Non-intrusive investigations; Risk-based investigation framework		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161	
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Acknowledgments

This research was conducted collaboratively by WSP USA Inc. and the Missouri University of Science and Technology (Missouri S&T). The project was led by a multidisciplinary team of geophysical and geotechnical professionals who contributed to the technical development, evaluation, and synthesis of advanced methods for detecting and mapping subsurface passages beneath Missouri highways.

The authors gratefully acknowledge the Missouri Department of Transportation (MoDOT) for sponsoring this research and for their continued commitment to advancing innovative, data-driven approaches to infrastructure safety and asset management. MoDOT's support, technical engagement, and forward-looking perspective were instrumental in shaping the direction and relevance of this study. The authors sincerely appreciate the guidance, insights, and constructive feedback provided by MoDOT's project team throughout the course of the work.

The authors also recognize the valuable contributions of colleagues at Missouri S&T, whose academic expertise, research support, and technical input strengthened the scientific foundation of this effort. Their collaboration helped ensure that the evaluation of geophysical and remote sensing technologies was grounded in both rigorous research and practical application.

In addition, the authors extend their appreciation to the broader WSP technical team, including geophysical, geotechnical, and data analytics staff, whose experience and support were essential to the completion of this project. Administrative and production support staff are also acknowledged for their assistance with coordination, document preparation, and quality control.

This project reflects the collective efforts of many individuals and organizations, and the authors are grateful for the collaboration and expertise that made this research possible.

Executive Summary

The Missouri Department of Transportation (MoDOT), recognizing the risks posed by karst terrain, abandoned mine workings, and other subsurface passages beneath highways, commissioned this research to evaluate geophysical and remote sensing technologies capable of detecting and mapping subsurface voids. Undetected features such as caves, sinkholes, voids, and legacy mine openings can lead to pavement settlement, structural distress, sinkhole collapse, and increased maintenance costs. Proactive identification and management of these hazards is critical to maintaining the safety, reliability, and long-term performance of Missouri's transportation infrastructure.

This research was conducted collaboratively by WSP USA Inc. and the Missouri University of Science and Technology (Missouri S&T) to provide MoDOT with a technically sound, implementation-focused evaluation of available subsurface investigation methods. The objective was to identify practical, field-deployable technologies that can be applied beneath active transportation corridors and to develop a recommended framework for their use within Missouri's unique geologic and operational context.

The primary objectives of this study were to:

- Evaluate geophysical and remote sensing methods capable of detecting subsurface passages beneath highways
- Assess the strengths, limitations, depth capability, and resolution of each method
- Review practices and lessons learned from other state DOT applications
- Identify the most reliable and practical methods for Missouri conditions
- Develop a phased, risk-based investigation framework for MoDOT implementation

A comprehensive literature review and technical assessment were conducted for the following methods:

- Electrical Resistivity Tomography (ERT)
- Ground Penetrating Radar (GPR)
- Seismic Refraction and Multichannel Analysis of Surface Waves (MASW)
- Microgravity
- Magnetometry
- Transient Electromagnetic (TEM) surveying

- Light Detection and Ranging (LiDAR) and Interferometric Synthetic Aperture Radar (InSAR)
- Muography (muon tomography)
- Selected borehole geophysical methods

Each method was evaluated with respect to depth of investigation, sensitivity to voids and weak zones, logistical constraints, suitability beneath paved roadways, and applicability to karst and mining-prone environments.

To supplement the technical evaluation, this study reviewed documented applications from other state DOTs, including Florida, Kentucky, Texas, Ohio, and Colorado. These examples demonstrate that no single geophysical method is universally effective for all subsurface conditions. Successful investigations typically rely on:

- A multi-method approach using complementary techniques
- Early screening and prioritization using existing data and remote sensing
- Targeted subsurface imaging supported by verification through drilling or borehole methods

In addition, the study draws on numerous WSP and Missouri S&T case studies from the United States and internationally. These projects illustrate real-world performance of geophysical methods for detecting voids, mapping mine workings, evaluating crown pillar stability, and assessing sinkhole risk.

Based on the combined literature review, DOT experience, and case studies, the following conclusions were reached:

- ERT is the most reliable primary imaging method for subsurface void detection beneath Missouri highways, particularly in karst terrain and historic mining districts.
- ERT provides consistent depth imaging and can distinguish air-filled voids, water-filled cavities, collapse features, and weak zones.
- GPR is effective for shallow investigations and rapid screening where soil conditions allow.
- Seismic methods (MASW and refraction) provide valuable information on bedrock depth, material stiffness, and fractured zones.
- Microgravity can identify large, deep density contrasts but requires specialized expertise and careful interpretation.

- LiDAR and InSAR are best suited for regional screening, surface deformation monitoring, and long-term asset management rather than direct subsurface imaging.

Based on these findings, a phased investigation framework is recommended for MoDOT:

1. Desktop Screening
    - Review Missouri Geological Survey's Geosciences Technical Resource Assessment Tool (GeoSTRAT) and geologic data. Refer to Section 2.2.9 for the details of the GeoSTRAT tool.
    - Evaluate LiDAR topography and historic records
2. Surface Reconnaissance
    - Field inspection of pavement distress and sinkhole indicators
3. Primary Imaging
    - Electrical Resistivity Tomography (ERT) as the primary subsurface method
4. Supplemental Methods (as needed)
    - GPR, seismic methods, microgravity, or remote sensing based on site conditions
5. Targeted Verification
    - Drilling and borehole geophysics to confirm void geometry and materials
6. Remediation and Confirmation
    - Stabilization followed by post-remediation confirmation surveys

This tiered approach allows investigation intensity to be scaled to site-specific risk and infrastructure vulnerability.

Adoption of the recommended framework will enable MoDOT to:

- Improve early detection of subsurface hazards
- Reduce uncertainty in design and maintenance decisions
- Prioritize resources using a risk-based approach
- Enhance long-term infrastructure resilience and safety

In summary, this research provides MoDOT with a comprehensive, practical roadmap for evaluating and managing subsurface void risk beneath Missouri highways. By prioritizing proven methods and integrating geophysical investigations into a phased framework, MoDOT can strengthen proactive risk management and support sustainable transportation infrastructure across the state.

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Acronyms and Abbreviations

Acronym/Abbreviation	Definition
%	percent
.kmz	Google Earth files
.shp	Shapefiles
1D	one dimensional
2D	two dimensional
3D	three dimensional
ACCA	American Cave Conservation Association
AOI	Area of Interest
ATV	Acoustic Televiewer
CCC	Country Club Circle
cm	centimeter
cps	counts per second
CPT	Cone Penetration Testing
CRF	Cave Research Foundation
DEM	Digital Elevation Models
DNAPL	dense non-aqueous phase liquid
DOT	Department of Transportation
DRMS	Department of Reclamation, Mining, and Safety
ERI	Electrical Resistivity Imaging
ERT	Electrical Resistivity Tomography
ft	feet
ft/s	feet per second
FTC	fluid temperature/fluid conductivity
FWI	Full Waveform Inversion
GeoSTRAT	Geosciences Technical Resource Assessment Tool
GIS	Geographic Information System
gpm	gallon per minute
GPR	Ground Penetrating Radar
GRM	Generalized Reciprocal Method
GSSI	Geophysical Survey Systems, Inc.
HPFM	Heat Pulse Flowmeter
Hz	hertz
InSAR	Interferometric Synthetic Aperture Radar
IP	Induced Polarization

kHz	kilohertz
Kn	kilonewton
KYTC	Kentucky Transportation Cabinet
lb	pound
LiDAR	Light Detection and Ranging
LMG	low mobility grouting
m	meter
m/s	meters per second
MASW	Multichannel Analysis of Surface Waves
MCA	Missouri Caves Association
MCKC	Missouri Caves and Karst Conservancy
MGS	Missouri Geological Survey
MHz	megahertz
mi^2	square mile
Missouri S&T	Missouri University of Science and Technology
mm	millimeters
MoDOT	Missouri Department of Transportation
MPBX	Multipoint Borehole Extensometers
MSI	Mount Sopris Instruments
MSS	Missouri Speleological Survey
N/A	not applicable
NSS	National Speleological Society
OTV	Optical Televiewer
PEG	propelled energy generators
POC	proof of concept
RVSP	Reverse Vertical Seismic Profiling
SAR	Synthetic Aperture Radar
SCP	Seismic Cone Penetrometer
SFM	Spinner Flowmeter
SPT	Standard Penetration Test
SRT	Seismic Refraction Tomography
TEM	Transient Electromagnetic
tTEM	Towed Transient Electromagnetic
UAV	Unmanned Aerial Vehicle
USEPA	United States Environmental Protection Agency
Vp	compressional wave velocity

Vs	shear wave velocity
WSP	WSP USA Inc.
XHT	Cross-hole Seismic Tomography

Chapter 1: Project Understanding and Objectives

Missouri's highway network is underlain by complex geological conditions, including regions with karst terrain and numerous caves and abandoned mines, posing significant risks to infrastructure stability. Undetected subsurface passages can lead to pavement settlement, sinkhole formation, and increased long-term maintenance demands.

This project aims to detect and map subsurface passages using advanced technologies by following a multi-phase approach that incorporates a comprehensive literature review, interim reporting of findings, and evaluation of each method's applicability to Missouri's unique geological conditions. Findings from this work will provide MoDOT with reliable, data-driven guidance for selecting and implementing appropriate detection and mapping methods.

Key project tasks include conducting a systematic review of current technologies, assessing the effectiveness of geophysical and remote sensing techniques under different geologic conditions, and comparing their performance in identifying subsurface anomalies. The study will also develop a decision-making framework to support MoDOT's infrastructure stability and environmental objectives. Ultimately, this project will deliver actionable recommendations and implementation strategies to enhance transportation safety, reduce maintenance costs, and proactively manage geotechnical risks associated with underground voids.

1.1 Scope of Services

The scope of services for this project includes the application of a multi-phase geophysical and geotechnical investigation program designed to identify, characterize, and assess subsurface anomalies associated with karst features, voids, and abandoned mine workings. Key elements include:

- Geophysical Surveys: Deployment of advanced technologies such as Electrical Resistivity Imaging (ERI), Ground Penetrating Radar (GPR), and seismic methods to map subsurface voids and heterogeneities. Utilizing remote sensing technologies such as LiDAR and drone imagery to complement initial assessments.
- Data Integration: Correlation of geophysical findings with existing geological, geotechnical, and historical data to develop robust subsurface models.
- Site-Specific Evaluations: Focused assessments at priority locations along MoDOT's roadway network where the risk of voids or sinkhole formation is elevated.
- Decision Support: Development of frameworks and criteria to guide mitigation strategies, rehabilitation planning, and future monitoring needs.

1.2 Objectives

The primary objectives of this project are to:

- Identify Best Methods for Detecting and Delineation of Subsurface Anomalies: Identify technologies for analyzing voids, abandoned mine workings, and karst features that pose risks to MoDOT infrastructure.
- Evaluate Method Performance: Compare and assess geophysical and remote sensing techniques to determine their effectiveness under Missouri's geologic conditions.
- Develop Decision-Making Frameworks: Provide MoDOT with practical tools and criteria for prioritizing risks, selecting remediation strategies, and planning long-term monitoring.
- Support Infrastructure Resilience: Deliver actionable recommendations that enhance transportation safety, reduce maintenance costs, and ensure compliance with regulatory and environmental objectives.

By meeting these objectives, the project will not only strengthen MoDOT's ability to proactively manage geotechnical risks but also provide a structured foundation for long-term infrastructure resilience. The outcomes will enable MoDOT to anticipate emerging subsurface challenges before they escalate, improve prioritization of maintenance and mitigation efforts, and ensure that available resources are applied where they will have the greatest impact. In addition, the project will support regulatory compliance and align with broader environmental and safety goals, ensuring that Missouri's transportation network remains dependable, cost-effective to maintain, and capable of supporting future growth.

Chapter 2: Background and Methodology

2.1 Introduction

This project adopts a structured and systematic approach to establish a detailed understanding of subsurface detection technologies and to evaluate their applicability to Missouri's transportation infrastructure. This effort will be delivered collaboratively by WSP and the Missouri University of Science and Technology (MS&T), leveraging academic rigor, practical field experience, and stakeholder engagement. The goal is to generate actionable insights that are both technically sound and aligned with MoDOT's operational needs.

This work will consist of three integrated phases: a comprehensive literature and technology review, case studies of past WSP projects where geophysical methods were applied, and a synthesis of findings and recommendations that inform MoDOT's path forward. Table 2.1 shows a comparison of geophysical techniques for subsurface characterization. Table 2.1 summarizes the main properties measured, advantages, limitations, and typical applications of each method. This provides a quick reference to highlight the strengths and constraints of the techniques, supporting the selection of appropriate methods based on the site conditions.

2.2 Geophysical and Remote Sensing Methods Overview

2.2.1 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a high-resolution electromagnetic method that employs radio waves in the frequency range of approximately 25–3000 MHz to generate images of subsurface structures (Daniels, 2000; USEPA, 2016d). It operates by transmitting radar pulses into the ground, which are reflected or scattered at interfaces where dielectric contrasts exist, often linked to variations in water content. The reflected signals are received by antennas and processed to produce continuous lateral and vertical subsurface profiles, enabling 2D and 3D characterization with high spatial resolution (ASTM, 2011a).

Due to its rapid data acquisition and non-destructive nature, GPR is widely recommended for mapping buried utilities, voids, fractures, tanks, embankments, archaeological remains, and shallow stratigraphy (USEPA, 1993; ASTM, 2011b; Everett, 2013). Depth of penetration relies on the center frequency of the antenna and subsurface conditions. GPR waves are highly attenuated by clay soils, so the penetration depth in clayey soils can be very shallow. The penetration depth can be increased by using lower frequency antennas, although lower frequencies have reduced resolution, and so cannot usually detect small targets. GPR is often used for shallow applications such as looking for utilities or environmental void detection; under favorable geologic conditions (drier soils without much clay) a 400 MHz antenna can usually penetrate to a depth of 12 feet (Mahdi, H., & Akhnoukh, A., 2016). For deeper investigations, such as mapping stratigraphy or identifying large-scale geohazards (e.g., sinkholes or large voids) where resolving small features is secondary to achieving maximum penetration depth, frequencies from ~25 MHz to 20 MHz are recommended.

The greatest advantages of GPR are its rapid data acquisition, real-time data interpretation, and small sampling footprint. Data can be acquired at walking speeds, and the small size of a GPR antenna allows data acquisition at sites that cannot support a longer cable-based method. GPR data require minimal processing for first interpretations, so data can be understood in real time in the field. GPR can also provide high-resolution subsurface images under favorable geologic conditions. Limitations to GPR include rapid attenuation in clayey soils and sensitivity to cultural noise from metallic debris, pipelines, and reinforced concrete (which can limit penetration depth). Additionally, if advanced data processing is desired for very precise depth estimates, this can require additional data collection in the field and expertise in data processing. Additional background information on the GPR method, including basic principles, field procedures, data processing, and case studies, is provided in Appendix B.

GPR systems may be deployed using either ground-coupled antennas, which are placed directly on or very near the ground surface, or air-launched (non-contact) antennas, which operate with a small stand-off distance above the ground. The discussion above primarily reflects ground-coupled GPR systems, which generally provide superior signal coupling, resolution, and depth of penetration. Air-launched systems are typically used for rapid, reconnaissance-level surveys and generally provide reduced penetration depth and resolution compared to ground-coupled antennas, particularly in clay-rich or conductive soils.

2.2.2 Electrical Resistivity Tomography (ERT)

Electrical Resistivity Tomography (ERT), also commonly referred to as Electrical Resistivity Imaging (ERI), is one of the most commonly used geophysical techniques in archaeological exploration, environmental site characterization, and engineering investigations (Griffiths, D. and Barker, R., 1994). It measures the subsurface distribution of electrical resistivity by injecting current into the ground through electrodes and recording potential differences at the surface. By alternatingly injecting current and measuring voltages at different electrodes, estimates of the apparent (or bulk) resistivity can be determined at different horizontal and vertical locations. Different combinations of current and voltage electrodes are referred to as electrode configurations, and different configurations provide advantages in lateral resolution or depth penetration. The most commonly used configuration for ERT surveying is the Dipole-dipole configuration, which achieves fairly high resolution in both the lateral and vertical dimensions.

One of the main strengths of ERT methods is the ability to generate both 2D and 3D images, which is done using advanced instrumentation and computational methods (Coggon, J., 1971; Koefoed, O., 1979). The inversion process, typically based on damped least-squares algorithms, minimizes the misfit between measured and modeled resistivity values, producing a cross-section model of the subsurface resistivity (Inman, J.R. 1975; deGroot Hedlin, C. & Constable, S.1990; and Farquharson, C.G. and Oldenburg, D.W. 1998), which can be related to geologic properties. Electrical resistivity is sensitive to saturation, mineralogy, porosity, particle size, and dissolved solids in groundwater. Thus, ERT can be used to map features such as stratigraphic boundaries, voids, contaminant plumes, and anthropogenic features such as tanks (ASTM, 2011b).

ERT can be an effective tool for mapping irregular bedrock topography and for identifying sinkholes and voids. ERT can provide high-resolution data, but the resolution of an ERT survey depends on the number and spacing of electrodes used. High-resolution data requires a large number of closely spaced electrodes, which can make data acquisition very time-consuming and may require multiple electrode cables. Penetration depth is also controlled by the length of the electrode array and is usually ~20% of the length of the electrode array. For this reason, spatial constraints may limit the applicability of this technique. Additionally, ERT can be sensitive to cultural noise, such as electrical lines or metal fences, so ERT is not generally suitable in urban areas (NJDEP, 2005). Finally, the method is more time-intensive than magnetometry or GPR and requires physical electrode installation, which may limit its use in areas with restricted ground access.

ERT provides reliable depth information and approximate delineation of geometry for detecting cave passages beneath highways and is suitable for identifying large-scale subsurface anomalies such as air-filled voids in limestone terrains. One advantage of ERT surveying for void detection is that ERT can usually distinguish between voids that are filled with air and voids filled with soil or water, as they have very different resistivities. However, like most geophysical methods, resolution decreases with depth, so ERT cannot find small, deep voids. Additionally, electricity tends to flow around highly resistive units, so these units (like air-filled voids) can be missed even at shallow depths if the voids are small.

Additional background on the ER method, including theory and applications for identifying subsurface voids, is provided in Appendix A, which includes the report titled "Electrical Resistivity Tomography: Overview and Applications for Identifying Subsurface Voids" by Cooke and Grote (Missouri University of Science and Technology).

2.2.3 Seismic Refraction

The seismic refraction method depends on the principle of ray tracing and usually assumes that seismic velocity increases with depth. When a seismic wave encounters a boundary, energy may be refracted along the boundary and back to the surface to be detected by geophones (Sheriff & Geldart, 1995). The Generalized Reciprocal Method (GRM) and other inversion techniques are commonly used to analyze first arrival travel times and estimate depths of refracting layers (Hales, 1958; Palmer, 1980). Seismic Refraction Tomography (SRT) is particularly useful for void detection as it uses much more data than simple layered refraction methods and can provide more detailed 2D or 3D information on subsurface velocities.

This method is often applied to determine depth to bedrock, thickness of overburden, groundwater table, or weathered rock profiles (Anderson, 2014). It can provide velocity information to infer lithology and strength (Dobrin, 1976; Telford et al., 1990).

Advantages of seismic refraction include direct sensitivity to mechanical properties of the subsurface. With recent improvements in instrumentation and modeling methods, it can detect small weak zones in the ground, such as voids, cavities, or sinkholes. Limitations can arise in complex geology where the background velocity decreases with depth, since the method assumes velocity increases with depth; using SRT helps to avoid this issue. In addition, external factors such as cultural noise, large survey areas, and interpretation complexity also present challenges.

2.2.4 Multichannel Analysis of Surface Waves (MASW)

Multichannel Analysis of Surface Waves (MASW) is a seismic method that utilizes the dispersive properties of Rayleigh waves to characterize subsurface stiffness and layering. By deploying a linear array of geophones and generating seismic waves through an active source, MASW records the frequency-dependent propagation velocities of surface waves. These velocity dispersions are then inverted to produce one- or two-dimensional shear wave velocity (Vs) profiles, which provide insights into soil stiffness, stratigraphy, and dynamic properties of the subsurface (Park et al., 1999; Xia et al., 2002).

MASW is particularly effective in shallow geotechnical and environmental applications, as shear wave velocity is a key parameter for assessing material stiffness, seismic site classification, and liquefaction potential. In karst terrains, MASW is especially valuable for identifying low-velocity zones that may correspond to voids, weakened rock, or zones susceptible to sinkhole development (Ivanov et al., 2013). The method provides rapid, non-intrusive subsurface characterization. Active MASW may be used to assess velocities to several tens of meters in depth, while passive methods may be used for investigations up to a kilometer in depth. Limitations include reduced resolution at greater depths, sensitivity to surface conditions such as rough terrain or strong heterogeneity, and the need for skilled data interpretation and advanced inversion methods to minimize errors in interpreting results (Foti et al., 2018).

2.2.5 Microgravity Surveys

Microgravity surveying is a passive geophysical method that measures minute variations in the Earth's gravitational field caused by differences in subsurface density. These variations can reveal the presence of voids, cavities, mine workings, and other anomalous features that pose risks to surface infrastructure. The method is non-intrusive and involves collecting high-precision gravity measurements at closely spaced stations across a survey area using portable gravimeters. Data are corrected for terrain, elevation, latitude, and instrument drift before being processed to produce residual gravity anomaly maps. Negative anomalies typically indicate low-density subsurface conditions, such as cavities or solution features, while positive anomalies can reflect denser materials such as infilled voids or mafic intrusions (Hinze et al., 2013).

Microgravity is particularly effective for characterizing voids beneath highways, bridges, and critical infrastructure, where even small subsurface anomalies can lead to settlement or collapse. The method is non-destructive, relatively rapid once survey grids are established, and capable of detecting anomalies at depths of several tens of feet, depending on survey resolution (Eppelbaum et al., 2010). However, interpretation requires careful correction and modeling, as results can be influenced by near-surface density variations, cultural noise, or incomplete coverage. In practice, microgravity is often applied in conjunction with complementary geophysical methods such as electrical resistivity imaging or ground penetrating radar to confirm anomaly geometry and reduce interpretive uncertainty (Butler, 1984; Nabighian et al., 2005).

Overall, microgravity surveys provide a cost-effective reconnaissance tool for assessing potential subsurface hazards in karstic and mined terrains. For transportation agencies such as MoDOT, the technique offers a valuable means of identifying hidden voids that may compromise roadway safety, allowing for proactive risk management and targeted remediation planning.

2.2.6 Magnetometry

Magnetometry is one of the oldest and most widely employed near-surface geophysical techniques, particularly effective for detecting buried features that produce variations in the Earth's magnetic field. The method, which relies on measuring the local magnetic field influenced by both natural and anthropogenic sources, has been successfully applied in archaeological and cultural heritage studies to locate stone masonry, foundations, and ferrous materials that contrast magnetically with surrounding soils (Kvamme, K.L., 2006; Gaffney, C., 2008; Fassbinder, J.W., 2015; Garrison, E.G., 2016; and Fedi, et al., 2017).

Magnetometer surveys measure variations in the Earth's magnetic field to detect buried ferrous objects, geologic intrusions, and faults (Dobrin, 1976), using instruments such as proton-precession and fluxgate magnetometers.

For subsurface passage detection beneath highways, magnetometry provides rapid, non-intrusive data collection across large survey areas, with high sensitivity to shallow anomalies, making it a valuable reconnaissance tool for identifying voids or disturbed zones potentially associated with caves or abandoned mines. However, its performance may be reduced in areas with minimal magnetic contrast or where cultural noise (e.g., metallic debris, reinforced concrete, pipelines, or power lines) dominates the signal.

2.2.7 Light Detection and Ranging (LiDAR)

Light Detection and Ranging (LiDAR) is an active remote sensing technology that employs laser pulses to measure distances between a sensor and the Earth's surface, typically in the visible, ultraviolet, and near-infrared spectrum (Fujii, T., & Fukuchi, T. Eds., 2005). By recording the travel time of each emitted pulse and its reflection, LiDAR produces high-resolution, three-dimensional point clouds that can be processed into detailed digital elevation models (DEMs) and surface maps (Carter et al., 2012; Wehr & Lohr, 1999).

LiDAR has become a widely used tool in geotechnical and geomorphological applications due to its ability to capture subtle surface variations across large areas with inch-scale precision. When deployed from airborne or Unmanned Aerial Vehicle (UAV) platforms, LiDAR can rapidly survey complex terrain and provide high-density topographic data even in vegetated regions where traditional photogrammetry is less effective (Baltsavias, 1999; Glennie et al., 2013).

For subsurface hazard investigations, LiDAR is particularly valuable for detecting indirect indicators of instability such as subtle ground settlement, surface deformation, and sinkhole precursors. These features, often too small to be recognized in conventional surveys, can signal the presence of underlying voids, abandoned mine workings, or karst conduits that pose risks to transportation infrastructure (Sithole & Vosselman, 2004; Kromer et al., 2017; Ciglič et al., 2022; Gimmestad, G., Roberts D. 2023). The ability to monitor temporal changes through repeat LiDAR surveys also provides a means of assessing deformation trends and prioritizing mitigation efforts.

LiDAR is cost-effective to collect at a large scale, and large quantities of LiDAR are publicly available via the USGS LiDAR explorer. The availability of public data enables a "first pass" approach, where LiDAR can be used to screen and prioritize areas for follow-up analysis. LiDAR has been used to detect abandoned mine shafts at a large scale in Victoria, Australia (see Section 5.4 Case Study: Victoria Historic Mines Large-Scale Detection and Mapping; Silver et al., 2025a; Silver et al., 2025b).

LiDAR is limited to mapping surface expression and cannot directly image subsurface anomalies. Therefore, it is most effective when integrated with complementary geophysical methods such as ground penetrating radar or electrical resistivity imaging, which provide direct subsurface characterization.

2.2.8 Interferometric Synthetic Aperture Radar (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) is an advanced remote sensing technique that measures minute ground surface displacements by comparing the phase difference between two or more Synthetic Aperture Radar (SAR) images acquired at different times or slightly different positions. The method uses microwave signals transmitted toward the Earth's surface, with the backscattered signals recorded and processed to detect changes in path length corresponding to deformation, often at millimeter-scale accuracy. Much of the assessment of uplift or subsidence relies on interpreting the interferogram created from two InSAR images captured at different times. When there is displacement, a slightly farther or shorter portion of the wavelength is reflected. In the SAR image, the direction of ground movement is shown by the order of color changes in the fringes as they advance toward the deformation center.

InSAR is highly effective for monitoring subsidence, uplift, landslides, and other forms of ground instability, making it valuable for regional-scale infrastructure monitoring and early detection of hazards such as karst collapse, abandoned mine subsidence, or subsurface void migration.

Its non-intrusive nature, ability to cover hundreds of square kilometers, and capacity for retrospective analysis using archived SAR datasets are major strengths. However, accuracy can be affected by atmospheric effects, temporal decorrelation in rapidly changing land surfaces, and the need for stable reflectors such as buildings, bare rock, or infrastructure. These challenges can be mitigated by integrating InSAR with ground-based methods like electrical resistivity imaging or microgravity. In practice, InSAR provides a cost-effective, powerful complement to conventional geotechnical investigations, offering both long-term monitoring of deformation trends and proactive risk management through the identification of developing geohazards.

2.2.9 Geosciences Technical Resource Assessment Tool (GeoSTRAT)

The Missouri Geological Survey (MGS) has been engaged in systematic geoscientific surveys for more than a century, producing a wide array of maps and datasets that document the state's geology, hydrology, and natural resources. To organize and make this information broadly accessible, MGS developed the GeoSTRAT system, a web-based Geographic Information System (GIS) platform that integrates diverse geospatial data into a single, user-friendly interface.

GeoSTRAT is designed to serve multiple purposes, including hazard identification, environmental assessment, land-use planning, engineering design, and insurance evaluation. The platform compiles and continuously updates datasets such as geologic maps, stratigraphic layers, geologic structures, and records of karst activity (e.g., sinkholes, springs, dye tracing, losing/gaining streams, and caves). The geologic well logs are a helpful layer under the title, "well logs" that contain information for weathered zone, voids, and mud-filled voids. These datasets allow users to visualize both surface and subsurface conditions and to analyze potential geohazards or development constraints before initiating site investigations.

One of the key strengths of GeoSTRAT is its accessibility. Users can navigate the system through an online portal, eliminating the need for specialized GIS software on individual computers. Data are available for immediate visualization and, when needed, can be downloaded in standardized formats, such as shapefiles (.shp), or Google Earth files (.kmz) for integration into engineering, planning, or research workflows. This makes GeoSTRAT not only a repository of historical data but also a dynamic tool that supports ongoing decision-making processes.

While GeoSTRAT provides a powerful and cost-effective means of accessing geoscientific information, some regions may have relatively sparse survey coverage or datasets of variable resolution, and localized conditions may require supplemental site-specific investigations. Nevertheless, the system remains an essential starting point for geotechnical and environmental projects, providing a reliable framework for identifying potential hazards, reducing uncertainty, and guiding resource-efficient planning and design. (MDNR, 2025).

2.2.10 Transient Electromagnetic (TEM) Surveying

Transient Electromagnetic (TEM) surveying is a time-domain geophysical method designed to investigate subsurface electrical conductivity by measuring the decay of induced electromagnetic fields. During a TEM survey, a transmitter loop placed on the ground surface generates a controlled primary magnetic field. When the transmitter current is abruptly turned off, the collapse of the magnetic field induces eddy currents in the subsurface. The temporal decay of these eddy currents, recorded by receiver coils, reflects variations in conductivity with depth (Christiansen et al., 2006; Fitterman & Deszcz-Pan, 2001).

TEM techniques are particularly effective for mapping groundwater resources, saline intrusion, and conductive geologic units such as clays and weathered bedrock. In engineering and environmental applications, TEM has been applied to detect subsurface voids, abandoned mine workings, and stratigraphic boundaries in karst terrains, and even to study grain texture in aquifers making it a valuable complement to resistivity imaging and seismic surveys (Danielsen et al., 2003; Smith & Stanley, 2005). Compared to frequency-domain electromagnetic methods, TEM provides greater depth of investigation (tens to hundreds of feet) and improved sensitivity to resistivity contrasts, while maintaining rapid data acquisition in the field.

The advantages of TEM include its non-intrusive nature, ability to cover large areas efficiently, and robustness in detecting conductive anomalies beneath heterogeneous overburden. Limitations include reduced sensitivity to highly resistive targets (e.g., dry bedrock or air-filled voids), strong cultural noise interference from nearby infrastructure, and logistical requirements for deploying large transmitter loops in urban or confined settings. A typical TEM field setup is shown in Figure 2.1, where a transmitter loop (TX-Coil) is deployed on the ground surface, and receiver coils (RX-Coil) measure the decay of induced currents. The system includes positioning (GPS) and instruments for recording the electromagnetic response, allowing for rapid data collection over large areas.

One of the most recent adaptations of the traditional ground-based TEM geophysical tool is towed Transient Electro Magnetic (tTEM) designated for rapid data collection. The tTEM is good for shallow depths as it relies on the conductive materials, for example at a depth of 390 feet, there is no conductive material, so the method underperforms. When it is applied to conductive material that surrounds non-conductive materials, it limits the imaging of the non-conductive materials as a disadvantage. At the same time, water content impacts resistivity and subsequently tTEM application.

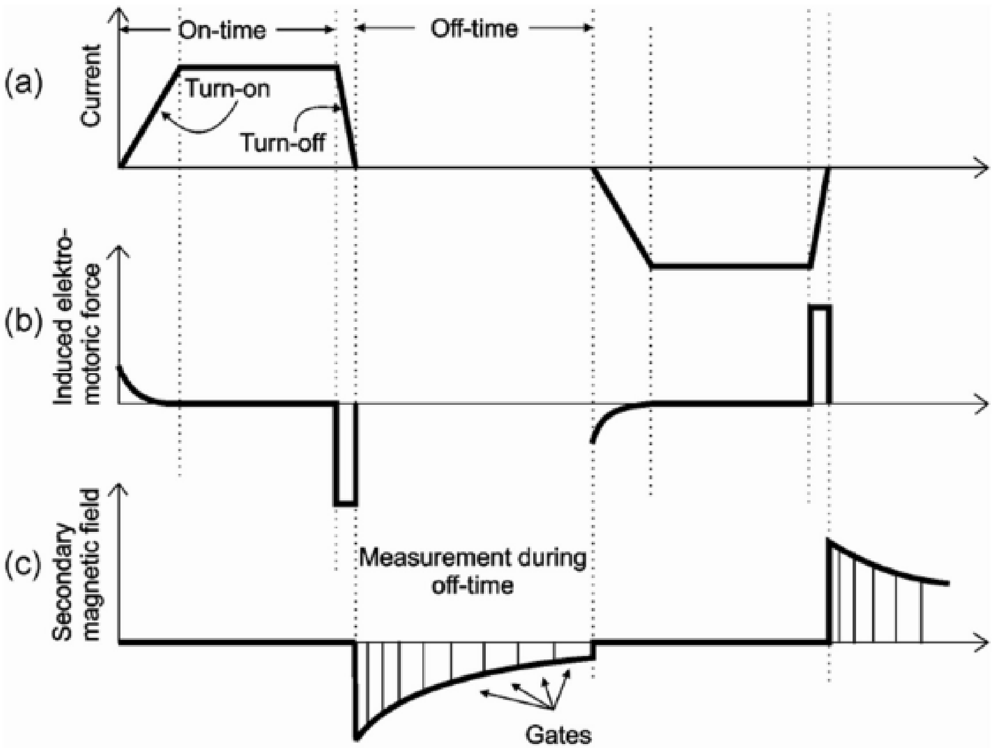

Figure 2.1: Typical field configuration of a transient electromagnetic (tTEM) survey system

2.2.11 Muography

Muography, also known as muon radiography, is an emerging geophysical imaging technique that uses naturally occurring cosmic-ray muons to detect and map subsurface density variations. Muons are high-energy subatomic particles generated when cosmic rays interact with Earth's atmosphere, and they continuously rain down on the Earth's surface. Because muons are highly penetrating, they can pass through hundreds of meters of rock. As muons travel through subsurface materials, they are attenuated at rates proportional to the density and thickness of the materials they traverse. By placing muon detectors in boreholes, tunnels, caves, or at the ground surface, scientists can measure variations in muon flux and reconstruct images that reveal low-density features such as caves, voids, fractured zones, and mine workings.

In karst and underground engineering applications, muography provides a non-intrusive, large-scale imaging capability that complements traditional borehole and surface geophysical methods. Unlike seismic or electrical techniques that require active energy sources, muography is entirely passive, silent, and capable of imaging large volumes of rock without disturbing the subsurface. This makes it particularly well-suited for detecting unknown cavities above tunnels, beneath infrastructure, and within carbonate bedrock prone to sinkhole formation. Muography has been successfully applied to cave detection, mine void mapping, and stability assessment of underground openings, and its ability to image entire rock masses offers promising applications for sinkhole hazard assessment, tunnel planning, and protection of critical infrastructure in karst regions such as Missouri.

2.2.12 Full Waveform Inversion (FWI)

Full Waveform Inversion (FWI) is a high-resolution seismic imaging method that utilizes the complete recorded wavefield, including amplitude and phase information, to reconstruct detailed subsurface velocity models. This technique operates by transmitting seismic energy into the ground and iteratively minimizing the difference between observed and simulated waveforms through nonlinear optimization (Tarantola, 1984; Virieux and Operto, 2009). This process enables continuous lateral and vertical characterization of subsurface features with spatial resolution approaching the scale of the seismic wavelength.

FWI is sensitive to the accuracy of the initial velocity model and the presence of low-frequency energy, which governs convergence and resolution. The method supports both 2D and 3D applications and can incorporate elastic, anisotropic, and attenuative effects to improve realism (Fichtner, 2010). When properly constrained, FWI is capable of resolving fine-scale geological features such as faults, stratigraphic interfaces, and fluid boundaries.

Limitations include high computational cost, sensitivity to cultural noise, and dependence on dense source-receiver coverage. Recent advancements, such as adaptive waveform inversion have improved robustness by mitigating sensitivity to amplitude mismatches and modeling errors (Warner and Guasch, 2016). Despite these constraints, FWI remains a cost-effective, nonintrusive tool for quantitative subsurface characterization when integrated with complementary geophysical methods.

Table 2.1: Comparison of Geophysical Methods and Remote Sensing Methods for Subsurface Investigation

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Ground Penetrating Radar (GPR)	▪ Dielectric Permittivity ▪ Electromagnetic Wave Reflections ▪ Moisture Contrasts	▪ High Imaging Resolution of Shallow Subsurface Features ▪ Fast Data Acquisition ▪ Non-Destructive ▪ Detects Voids/Utilities Beneath Pavements	▪ Attenuation in Clay-rich or conductive soils ▪ Requires relatively smooth ground or pavement access ▪ Limited depth of penetration (Typically 3-10 feet in conductive soils like wet clayey or conductive soils, and up to ~ 30-50 feet for dry resistive soils like dry sand or gravel). ▪ Sensitive to noise	▪ Dry, sandy soils ▪ Shallow stratigraphy ▪ Limestone with cavities ▪ Utility detection ▪ Void mapping ▪ Paved roads
Electrical Resistivity Tomography (ERT)	▪ Subsurface resistivity distribution	▪ Provides depth information in 2D/3D ▪ Sensitive to lithological changes, water content, and voids ▪ Capable of imaging large cavities in karst settings	▪ Resolution limited by electrode spacing ▪ Slower survey speed compared to GPR or magnetometry ▪ Requires ground disturbance for electrode installation ▪ Sensitive to noise	▪ Clay-rich media ▪ Limestone/karst terrain ▪ Deeper depths of penetration ▪ Most reliable for confirming void geometry and depth beneath critical infrastructure
Seismic Refraction	▪ Seismic velocity ▪ Acoustic interfaces ▪ Groundwater table	▪ Cost-effective ▪ Effective for shallow depths ▪ Can detect weathered bedrock	▪ Misinterpretation when low-velocity layers underlie high-velocity ones ▪ Limited to velocity increasing with depth ▪ Large survey length	▪ Bedrock profiling ▪ Overburden thickness ▪ Groundwater and shallow geologic mapping

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Microgravity Surveys	▪ Variations in the Earth's gravitational field ▪ Subsurface density contrasts	▪ Non-intrusive, passive method ▪ Effective for detecting voids, cavities, and karst features ▪ Sensitive to low-density anomalies beneath infrastructure ▪ Cost-effective reconnaissance tool for a large area	▪ Influenced by near-surface density variations (e.g., soil, fill, utilities) ▪ Requires careful correction for terrain, elevation, latitude, and instrument drift ▪ Interpretation can be complex and uncertain	▪ Karst terrains and mine workings ▪ Detecting hidden voids beneath highways, bridges, and dams ▪ Critical infrastructure assessments ▪ Large-area reconnaissance
Magnetometry	▪ Magnetic field strength ▪ Magnetic susceptibility contrasts	▪ Rapid, Non-intrusive ▪ Effective for detecting masonry, ferrous objects, and anthropogenic features ▪ Minimal preparation ▪ High coverage over large areas	▪ Limited depth sensitivity ▪ Less effective in non-magnetic lithologies ▪ Cultural noise from steel/pipes ▪ Cannot uniquely resolve anomalies	▪ Dry soil ▪ Shallow depths ▪ Sites with ferrous debris or masonry (e.g., buried drums, tanks)
Light Detection and Ranging (LiDAR)	▪ Surface elevations ▪ Terrain and landform variations ▪ Surface deformation and settlement indicators	▪ Provides high-resolution data with centimeter-scale accuracy (typically 6–12 inches). ▪ Effective for large-area surveys at relatively low cost. ▪ Performs well in forested and vegetated areas. ▪ Rapid data acquisition using airborne or UAV platforms. ▪ Public data widely available.	▪ Cannot directly image subsurface features; only provides surface expression. ▪ Effectiveness is reduced under cloud cover, rain, haze, or air traffic interference. ▪ Accuracy can be influenced by instrument drift, GPS error, or vegetation density. ▪ Public data has low resolution (point density) in some regions.	▪ Large area topographic mapping with high resolution ▪ Detecting surface deformation (e.g., subsidence and sinkhole) ▪ Detecting abandoned mining features ▪ Infrastructure monitoring for instability risk ▪ Repeated surveys for temporal change detection

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Interferometric Synthetic Aperture Radar (InSAR)	▪ Ground surface displacement over time ▪ Terrain elevation changes ▪ Subsidence and deformation patterns	▪ Non-contact, satellite- or UAV-based remote sensing ▪ Detects very small displacements (mm-level accuracy) over large areas ▪ Provides temporal monitoring (time-series deformation data) ▪ Cost-effective for regional and repeated surveys	▪ Accuracy reduced by vegetation cover, water, or atmospheric noise (clouds, humidity) ▪ Requires long observation periods and multiple images for time-series analysis ▪ Limited penetration (only surface deformation is detected) ▪ Requires cleaning data at the time to interpret it.	▪ Monitoring land subsidence (mining, groundwater withdrawal, urban areas) ▪ Tracking slope movements and landslides ▪ Infrastructure monitoring (roads, dams, pipelines) ▪ Regional-scale hazard mapping
Geosciences Technical Resource Assessment Tool (GeoSTRAT)	▪ Statewide geologic mapping ▪ Stratigraphic and geologic structures (faults, sinkholes, karst features) ▪ Hydrologic and environmental datasets ▪ Surface and subsurface geoscience information	▪ Provides a GIS-based platform integrating more than 100 years of Missouri geoscience data. ▪ Freely accessible online without specialized GIS software. ▪ Continuously updated with new datasets, ensuring relevance for ongoing projects. ▪ Supports visualization of regional and site-specific conditions.	▪ Data resolution and completeness vary depending on location and survey coverage. ▪ Some areas may have limited detail or outdated information. ▪ Lacks direct field measurements; relies on compiled datasets. ▪ Not a substitute for site-specific investigations, particularly in areas of critical development.	▪ Preliminary hazard screening (sinkholes, faults, karst collapse potential). ▪ Supporting environmental and land-use planning. ▪ Insurance and risk management applications. ▪ Educational and research purposes

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Transient Electromagnetic (TEM) Surveying	▪ Subsurface electrical resistivity ▪ Conductivity variations with depth	▪ Non-intrusive and rapid data collection ▪ Effective for mapping groundwater and conductive zones ▪ Provides 1D/2D models without electrode installation	▪ Resolution decreases with depth ▪ Sensitive to cultural noise (power lines, infrastructure) ▪ Requires careful data processing and inversion ▪ Less effective in highly resistive terrains	▪ Groundwater exploration Identifying conductive zones (e.g., clay layers, saline intrusion) ▪ Environmental and mining investigations ▪ Bedrock depth detection beneath overburden
Multichannel Analysis of Surface Waves (MASW)	▪ Shear wave velocity (Vs) profiles ▪ Soil stiffness and dynamic properties ▪ Seismic response characteristics with depth	▪ Non-intrusive and relatively low-cost ▪ Provides Vs profiles for seismic site classification ▪ Cover long survey lines with multi-channel arrays ▪ Useful for shallow-depth geotechnical studies	▪ Resolution decreases with depth, (typically 100-164 feet) ▪ Requires careful inversion and interpretation of curves ▪ Susceptible to noise in urban/traffic environments ▪ Less effective in highly heterogeneous ground conditions	▪ Soil stiffness profiling for foundation and embankment design ▪ Earthquake engineering and dynamic response analysis ▪ Mapping depth to bedrock or contrasting soil layers

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Muography	▪ Cosmic-ray muon flux attenuation through overlying materials ▪ Integrated density (areal density) along the muon travel path ▪ Density contrasts between geologic materials (e.g., air-filled voids vs. rock) ▪ Angular distribution of incoming muons (used to reconstruct density images)	▪ Passive technique – no energy source required (uses naturally occurring cosmic muons) ▪ Exceptional penetration depth (hundreds of feet depending on geometry) ▪ Effective for detecting large voids, caves, tunnels, and mines ▪ Works in urban or infrastructure-restricted environments (no vibration, no EM noise) ▪ Can image beneath thick, conductive, or heterogeneous materials where ERT or GPR struggle	▪ Long acquisition times (weeks to months) required for adequate resolution ▪ Low spatial resolution compared to near-surface geophysics ▪ Requires large detector systems and secure deployment locations ▪ Best results require known geometry and clear detector placement (below or adjacent to target) ▪ Limited effectiveness for small or shallow features ▪ Complex data processing and interpretation; limited number of experienced practitioners	▪ Cave and karst system detection beneath highways, dams, or urban areas ▪ Mapping abandoned mine workings and large subsurface voids ▪ Imaging beneath critical infrastructure (tunnels, levees, foundations) ▪ Volcanology (magma chambers, conduits, density changes) ▪ Archaeology (large chambers, pyramids, buried structures) ▪ Complementary method alongside ERT, seismic, and borehole geophysics for high-risk sites
Full Waveform Invasion (FWI)	▪ Subsurface velocity variations, full seismic wavefield (amplitude and phase)	▪ High-resolution imaging, resolves fine-scale features, supports 2D/3D modeling, nonintrusive	▪ Computationally intensive, sensitive to initial model and noise, requires dense source-receiver coverage	▪ Deep and shallow subsurface characterization, and fault mapping

2.3 Borehole Geophysics

For completeness, the following sub-sections provide details of the most common borehole geophysical methods which can be used to investigate subsurface voids. The most generally applicable methods include downhole televiewers, borehole cameras, sonar mapping, and cavity scanning. However, the best applicable method may differ depending on the size and extent of intersected subsurface voids.

2.3.1 Caliper Logging

Caliper logging is a fundamental borehole geophysical method used to measure the diameter and shape of a borehole as a function of depth. A caliper tool typically uses multiple spring-loaded mechanical arms or acoustic sensors that extend outward to contact the borehole wall, continuously recording changes in borehole radius while the probe is raised or lowered. These tools can typically travel up the borehole at 10 to 12 ft/min. The resulting log provides a detailed profile of borehole enlargement, contraction, and irregularity caused by geological features such as fractures, bedding plane partings, solution voids, soft clay seams, and zones of weathering. In karst and fractured rock environments, caliper logs are especially valuable for identifying potential voids, zones of collapse, washed-out intervals, and areas of instability that may not be apparent from drilling observations alone. The measurement collected by caliper logging gives the borehole diameter as indicated by the average deflection of three spring-loaded arms pressed against the wall of the borehole. Abrupt shifts to larger diameter (kicks) can indicate the locations where fractures intersect the borehole wall. However, the thickness of the caliper arms and the mechanical enlargement of fractures by drilling result in only a very approximate, qualitative relation between fracture aperture and the size of the caliper deflection (Long et al, 1996).

From a hydrogeologic and geotechnical standpoint, caliper logs serve both diagnostic and interpretive roles. Borehole enlargement often correlates with permeable fracture zones, solutionally enlarged joints, and water-bearing features, making caliper data useful for locating groundwater inflow points and identifying transmissive pathways. Caliper logs are also critical for quality control of other downhole geophysical measurements; borehole diameter changes strongly influence the response of tools such as resistivity, gamma, and neutron probes. In engineering investigations, caliper logs assist in evaluating borehole stability, selecting casing depths, and interpreting the reliability of core recovery, providing a baseline understanding of the mechanical and hydrologic behavior of subsurface rock and soil units.

2.3.2 Acoustic Televiewers

The Acoustic Televiewer (ATV) is an advanced imaging tool that produces high-resolution, oriented, 360-degree images of the borehole wall using reflected ultrasonic sound waves. The instrument emits an acoustic pulse that travels through the borehole fluid, reflects off the borehole wall, and returns to the sensor, with travel time and signal amplitude used to construct a continuous cylindrical image of the borehole interior. This imaging allows geoscientists to visualize fractures, bedding planes, foliation, cavities, and breakouts with precise depth control and spatial orientation. Because acoustic waves interact strongly with changes in rock texture and void space, ATVs are particularly effective in both open bedrock and water-filled boreholes, making them well suited for karst, fractured carbonate, and crystalline rock environments.

In applied geology and engineering practice, ATVs are indispensable for structural analysis and hydraulic characterization. The orientation data extracted from ATV images allow users to determine fracture strike and dip, identify dominant joint sets, and evaluate stress-induced features such as breakouts and drilling-induced fractures. These data are widely used in slope stability studies, tunnel design, dam foundations, and groundwater flow modeling. Because transmissive fractures are often visually distinguishable on ATV images, the method also plays a major role in selecting well screen intervals, locating packer test zones, and identifying potential contaminant migration pathways in fractured aquifers.

2.3.3 Optical Televiewers

The Optical Televiewer (OTV) is a downhole camera-based imaging tool that records true-color, high-definition photographic images of the borehole wall**.** Unlike acoustic systems, OTV relies on visible light and digital imaging to capture fine-scale geological details such as lithologic color variations, mineral bands, bedding laminations, fossil content, and small fractures. The result is a continuous, oriented, unwrapped image of the borehole wall that closely resembles a virtual core. This visual realism makes the OTV particularly valuable in sedimentary environments, carbonate rocks, and well-cleaned boreholes where the borehole fluid is clear and the wall surface is stable.

OTV data are frequently used in lithologic classification, stratigraphic correlation, and detailed fracture mapping**.** In karst studies, optical televiewer images can directly show solution features, cavities, and sediment infill, allowing researchers to characterize cave-forming processes and identify zones of enhanced permeability. The orientation capability allows fracture strike and dip to be measured directly from the images, supporting groundwater modeling, geotechnical design, and resource characterization. OTV logs are commonly integrated with caliper, resistivity, and acoustic televiewer data to produce a comprehensive interpretation of subsurface structure and hydrogeologic behavior.

2.3.4 Electrical Resistivity

Downhole electrical resistivity logging measures the ability of subsurface materials to resist the flow of electrical current**,** providing critical information about lithology, porosity, and fluid content. The tool introduces an electrical current into the surrounding formation through electrodes, and the resulting voltage response is used to calculate resistivity as a function of depth. High resistivity values typically indicate competent, dry, or crystalline rock, while low resistivity values often correspond to clay-rich units, saturated zones, or formations containing conductive groundwater. In karst and fractured environments, sharp changes in resistivity frequently highlight solution features, water-filled fractures, and zones of enhanced permeability.

In groundwater and engineering applications, resistivity logs are essential for aquifer delineation, contaminant investigations, and subsurface characterization**.** They are commonly used to distinguish between clay, shale, limestone, dolomite, and sandstone, and to identify freshwater versus mineralized water zones. When combined with caliper and televiewer logs, resistivity data help confirm whether fractures and voids observed visually are hydraulically active. This integrated approach is particularly valuable in sinkhole investigations, foundation design, and tunnel planning, where identifying transmissive karst features can significantly influence engineering decisions and risk assessments.

2.3.5 Fluid Temperature/Fluid Conductivity (FTC)

Fluid temperature logs are useful for delineating water-bearing zones and fluid into or out of the borehole by abrupt shifts in values or by slight changes in slope compared to the regional geothermal gradient, which is approximately 1-degree Fahrenheit per 100 feet of depth. Fluid conductivity is directly proportional to the concentration of dissolved solids in the borehole fluid and can also be used to delineate fluid flow into or out of the borehole as well as a general indicator of water quality in the borehole. These measurements apply to the fluid (water) in the borehole and may not be the same as the temperature and resistivity of the rocks surrounding the borehole.

2.3.6 Heat Pulse Flowmeter (HPFM)

The heat pulse flowmeter measures small vertical flow components at given depths in the borehole. This measurement gives the vertical flow at a given depth in the borehole where the probe is held stationary long enough for all effects of probe movement on the fluid column to have faded. The measurement gives the time required for vertical flow to move a thermally tagged parcel of water a known distance (2 cm) up or down after heating by capacitor discharge onto an electrical grid. The probe measures flow through a cylindrical measurement section where the annulus surrounding this cylinder is blocked by a flexible disk, the diverter.

Flowmeter response times are converted to flow rates using calibration curves provided by Mount Sopris Instruments (MSI). Upward flow is detected by the upper thermistor and reported as a positive value, while downward flow is detected by the lower thermistor and reported as a negative value. The heat pulse flow meter has a low flow detection limit of about .03 gallon per minute (gpm) or 0.15 feet/minute (MSI, 2026). The upper flow detection limit is associated with the thermal inertia of the thermistors, which cannot respond quickly enough to detect flow if the flow exceeds about 1.0 gpm or 13 feet/minute in either direction (up or down).

2.3.7 Spinner Flowmeter (SFM)

The Spinner Flowmeter (SFM) can determine the direction of flow based upon the direction of the spinning motion of the impeller. The impeller assembly uses a point and cup system much the same as a jeweled bearing to reduce friction and allow for smooth spinning of the impeller assembly. This assembly is attached to a magnetically driven encoder that produces 256 points per revolution. The SFM generates two data channels, an up-channel and a down-channel. It can be run under ambient and stressed conditions, trolling and stationary, to identify permeable flow zones within the aquifer. The raw data produced by the SFM is inherently noisy and usually has a filter applied, commonly a moving average filter in the range of seven to seventeen measurements based on depth sample interval. Therefore, as with other geophysical logs, more prominent changes in the log are relatively significant, and smaller drifts in the logs may not be of hydrogeologic significance. In the stationary data collection, the SFM is positioned at the desired depth and placed in time-drive to record data for approximately one minute. If the flow is up-flow at this location, then the up-channel records 0 counts per second (cps) and the down-channel records flow in cps. If the flow is down-flow, then the up-channel records flow in cps and the down-channel records 0 cps.

When collecting data in trolling mode, the SFM is trolled down and up the borehole at a specific, constant speed. While trolling down, up-flow will appear as increased counts on the down-channel and the up-channel records 0 cps. If there is down-flow, then the up-channel records 0 cps and the down-channel records reduced cps. While trolling up, up-flow will appear as reduced cps on the up-channel and the down-channel records 0 cps. If there is down-flow, then the up-channel records increased cps and the down-channel records 0 cps.

2.3.8 Sonar/Acoustic Scanning

Sonar/Acoustic scanning is a nonintrusive acoustic technique used to characterize subsurface features in aquatic or saturated environments. The method operates by emitting sound pulses from a transducer and measuring the time and intensity of echoes reflected from submerged surfaces or stratigraphic interfaces. These reflections are processed to generate continuous profiles of bathymetry, sediment layers, or buried objects, depending on the frequency and configuration of the system.

High-frequency systems (e.g., >200 kHz) provide enhanced resolution for shallow targets, while lower-frequency systems (e.g., <50 kHz) offer greater penetration for deeper or more attenuative media. The vertical resolution and depth of penetration are governed by pulse duration, beam angle, and substrate composition. Borehole sonar systems are specialized for mapping underground voids as long as they are flooded, and some can image within a range of 6 inches to 330 feet (Imagenex, 2022).

Sonar scanning is effective for delineating borehole geometry, identifying washouts, detecting fractures, and characterizing fluid-filled features along the borehole wall. It is particularly suited for conditions where optical tools are ineffective, such as in turbid, sediment-laden, or low visibility borehole fluids. Limitations include reduced performance in highly attenuative formations, sensitivity to acoustic noise from drilling equipment or fluid movement, and the need for postprocessing to correct for tool centralization, borehole deviation, and signal scattering. Despite these constraints, sonar mapping remains a rapid and cost effective method for high resolution borehole imaging, supporting applications such as casing integrity evaluation, fracture mapping, lithologic interpretation, and geotechnical assessments for foundation and groundwater investigations.

2.3.9 Borehole Camera

The borehole camera is a visual logging tool used to obtain direct imagery of borehole conditions, lithologic contacts, fractures, and construction features. The system typically consists of a downward or side viewing camera lowered into the borehole, with integrated lighting to illuminate the borehole wall in water or air-filled conditions. The camera is held stationary or advanced at a controlled rate to ensure clear imaging and to minimize disturbances from tool movement or fluid turbidity.

Borehole camera surveys provide real time visual confirmation of features identified by other geophysical logs, including voids, open fractures, sediment intrusions, casing defects, and changes in borehole diameter. This method is particularly effective in situations where physical sampling is limited or where optical access is required to verify subsurface conditions. Performance is influenced by water clarity, lighting conditions, and borehole geometry, and image quality may be reduced in highly turbid or debris- filled intervals. Additional- postprocessing may be required- to correct for lens distortion, tool rotation, and variations in borehole fluid properties. Borehole camera surveys are less useful in flooded conditions due to suspended particulate matter in water, often becoming limited to an inspection of the breakthrough conditions or confirmation of the presence and depth of backfilling in the void space (M. Pak et al, 2017).

Despite these limitations, borehole camera logging remains a rapid and cost effective technique for qualitative subsurface assessment. It is widely used for evaluating borehole integrity, confirming stratigraphic boundaries, documenting construction conditions, and supporting geotechnical and hydrogeologic investigations where visual inspection enhances interpretation of complementary geophysical data.

2.3.10 Cavity Scanning

Cavity scanning is a borehole geophysical technique used to identify and characterize voids, enlarged zones, and irregularities along the borehole wall. The method typically employs a laser-based scanning tool that rotates within the borehole, measuring radial distances to the borehole wall to generate a continuous 360degree profile. These measurements are compiled to produce detailed cross-sectional images and three-dimensional representations of borehole geometry.

Cavity scanning is particularly effective for detecting washouts, karst voids, solution features, and zones of mechanical instability that may not be evident from conventional caliper or optical logs. The technique provides quantitative information on cavity size, shape, and orientation, supporting geotechnical assessments where borehole stability or subsurface voids pose engineering concerns. For the cavity scanner to capture a successful scan, the void must not be flooded, and the air must be free of excessive dust. When an underground void is backfilled through holes drilled from the surface, the air in the void often becomes very dusty, which can prevent the laser from penetrating to the floors and walls. The resulting scan would then only show an erroneous spherical cloud of points around the head of the unit.

Despite these limitations, cavity scanning remains a high resolution and nonintrusive method for evaluating borehole integrity and identifying subsurface voids. It is widely used in foundation investigations, karst assessments, tunnel and mine hazard evaluations, and other applications where accurate characterization of borehole enlargement or void development is critical to project design and risk management.

2.3.11 In-Seam Logging

In-seam logging is a specialized borehole geophysical technique used to characterize the geologic, structural, and hydrologic conditions within coal seams or other laterally continuous stratigraphic units. The method typically employs seismic or geophysical transmitters and receivers placed within the seam to measure wave propagation, attenuation, and travel times along the coal horizon. These measurements provide information on seam continuity, fracture density, gas content, and the presence of voids or weakened zones.

In-seam surveys are particularly effective for detecting geologic anomalies such as faults, partings, washouts, and zones of increased permeability that may influence mine planning, gas migration, or ground stability. The technique supports both crosshole and single hole configurations, with data processed to generate seam parallel velocity profiles and structural interpretations. Performance may be reduced in highly heterogeneous seams, areas with significant gas saturation, or where tool coupling with the borehole wall is poor, which can limit signal quality and reduce the reliability of velocity and attenuation measurements.

2.3.12 Borehole Radar

Borehole radar can be used in a single hole or cross-hole configuration. A Single hole method has the transmitter and receiver in the same hole while the cross-hole method has the transmitter in one hole and receiver in another. According to Haeni, F. P. et al, 2002 single-hole and cross-hole radar have also been used for water-supply investigations in the northeastern United States, as well as to investigate fractures, cavities and lithologic changes. This method is based upon the propagation of electromagnetic waves in a frequency range from 10 to 2000 megahertz. Conductivity and permittivity influence the propagation of electromagnetic waves. In rock, porosity, saturation and conductivity of the fluid affect conductivity. While conductivity is a widely used property of rock, permittivity is used less frequently outside of radar. The relative permittivity of minerals remains low (4-9), while freshwater has a permittivity of 81.

Water content thus has a large effect on permittivity. Borehole radar has a range of 1 to 50 meters, depending on conductivity.

Borehole radar gathers data by first sending a pulse into the surrounding borehole, which is then reflected back to the receiver or transmitted further when encountering materials with different electromagnetic properties. Radar reflection profiles are built out by taking radar scans at differing positions up and down the borehole. In karstic regions, borehole radar tomography (cross-hole) is used to identify voids. While a single-hole radar scan would have an effective range of a few feet due to the high conductivity of the rock, a survey using the cross-hole method would increase the range by nearly 3 times.

Table 2.2: Comparison of Borehole Geophysical Methods for Subsurface Investigation

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Caliper Logging	▪ Continuous measurement of borehole size and shape	▪ Identification of washouts and voids	▪ Cannot measure voids larger than a fixed diameter	▪ Dry or fluid filled borehole intersecting smaller voids
Acoustic Televiewer	▪ Acoustic reflectivity ▪ Travel Time ▪ Orientation	▪ Provides an accurate image of structural features, providing aperture size, depth, and orientation ▪ 360-degree image	▪ Cannot be used without fluid in the borehole ▪ Magnetic minerals and steel casing can affect borehole image	▪ Fluid filled boreholes
Optical Televiewer	▪ Borehole image ▪ Orientation	▪ 360-degree image of borehole	▪ Limited use in fluids that block image collection	▪ Water filled or dry boreholes
Electrical Resistivity	▪ Subsurface resistivity distribution	▪ Provides detailed and localized information on subsurface resistivity variations	▪ Best used in conjunction with caliper and televiewer logs to confirm results ▪ Affected by adverse borehole conditions ▪ Requires borehole fluid	▪ Fluid filled boreholes containing zones of clay filled or empty voids

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Fluid Temperature/Fluid Conductivity	▪ Temperature ▪ Electrical Conductivity	▪ Can be collected under non-pumping, pumping, and injection conditions ▪ Locates inflow/outflow zones and zones of vertical fluid flow ▪ Helps interpret electric logs	▪ Does not indicate the direction of borehole fluid flow under ambient conditions ▪ Requires borehole fluid	▪ Often used as the first tool in a full logging suite ▪ Water filled and fractured boreholes
Heat Pulse Flowmeter (HPFM)	▪ Interval or fracture-specific flow rates ▪ Transmissivity and hydraulic head	▪ Provides direction of fluid flow vertically ▪ Measure flow rates below common lower flow rate limits	▪ Smaller velocity features may be undetected near high velocity features ▪ Requires no flow in the annular space between the casing and the borehole in cased holes ▪ Minimum and maximum detectable flow-rates are tool specific	▪ Low flow, fluid filled boreholes
Spinner Flowmeter (SFM)	▪ Interval or fracture specific flow rates	▪ Provides direction of fluid flow vertically ▪ Measures high flow rates	▪ Not ideal for low flow rates ▪ Suitable in clean fluid environments due to damage from abrasive particles ▪ Not ideal for pulsating flows	▪ Low to high flow, fluid filled boreholes

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
Sonar Mapping	▪ Delineation of borehole geometry	▪ Effective in turbid, sediment-laden, or low-visibility borehole fluids ▪ High resolution borehole imaging and fracture mapping	▪ Requires a fluid filled borehole ▪ Reduced performance in highly attenuative formations ▪ Sensitivity to acoustic noise ▪ Post-processing requirements ▪ Must be fully inserted into void to map	▪ Fluid filled boreholes intersecting voids
Borehole Camera	▪ Borehole image	▪ Quick and cost-effective ▪ Confirms drilling conditions or non-visual downhole methods	▪ Not useful when suspended particulate matter blocks visuals	▪ In boreholes to quickly confirm conditions
Cavity Scanning	▪ Acoustic/Laser scanning of borehole or encountered voids	▪ Provides a continuous 360-degree profile ▪ Quantitative information of cavity size, shape and orientation ▪ Does not need to be fully inserted into the void to map	▪ Void must not be flooded and air must be free of excessive dust	▪ Dry boreholes intersecting voids

Method	Properties Measured	Advantages	Limitations	Best Uses/Media
In-Seam Logging	▪ Wave propagation ▪ Attenuation ▪ Travel time	▪ Effective at detecting faults, partings, and washouts ▪ Supports both single-hole and cross-hole configurations	▪ Cross-hole methods have a larger radius of data collection ▪ Reduced performance in highly heterogenous seams ▪ Reduced performance when tool coupling is limited	▪ Identification of voids within seams
Borehole Radar	▪ Dielectric Permittivity ▪ Electromagnetic Wave Reflections	▪ High range ▪ Supports both single-hole and cross-hole configurations	▪ High variability of range depending on material ▪ Water content has a large effect on permittivity	▪ Karstic regions

Chapter 3: Survey of Other State DOT’s

3.1 Introduction

Practices of geophysics methods along the different states across the United States vary from single method application to the integration of multiple methods, depending on project needs and site conditions. These methods are commonly applied with the purpose of detecting voids beneath roadways and other transportation infrastructures. This literature review identifies these common practices such as the use of seismic, resistivity, ground penetrating radar, and some innovative approaches that have enhanced the ability of DOTs to evaluate subsurface conditions and mitigate potential risks.

3.2 Detection of Sinkholes using Full Waveform Inversion (FWI)

The Florida Department of Transportation has funded research, called 2D Full Waveform Inversion (FWI) code, developed to detect voids and subsurface layers. The algorithm is capable of conditioning seismic data and processing it efficiently in the field, reducing the need for extensive post-processing. This code identifies the initial velocity profile of seismic waves to finally invert the filtered data into more accurate subsurface images.

The method was applied along existing highways, as a result, the code was effective in correctly detecting the depth and diameter of known voids. Additional testing was performed in areas with non-existent voids, where validation was conducted using invasive methods like the Standard Penetration Test (SPT) and Cone Penetration Testing (CPT). In these applications, seismic signals were acquired using various geophone arrays, including a load-cell geophone on a sled at 120 feet/24 (channel seismic system) and the source of waves was either a sledgehammer 67 to 89 KN (15-20 pounds) or Propelled Energy Generators (PEG) (40 pounds). Even though the success of the application, limitations were noted. For example, synthetic analyses showed that a void could only be detected if it was located within or close to the geophone spread. If the test line is at least one diameter from the void, the void becomes non-existent or distorted. To improve detection reliability, multiple lines are required to set up around the suspected void zones.

To further evaluate the effectiveness of the FWI method, synthetic models of S-wave and P-wave velocities were developed and tested at different frequencies. The results illustrate how inversion performance changes with frequency, highlighting improvements in resolution and detection accuracy at higher frequencies. Figure 3.1 presents a comparison between the true velocity model, the initial model, and the inversion results at 12 Hz and 23 Hz, demonstrating how FWI can refine subsurface imaging and identify potential voids (McVay M., Tran K, Wasman S., Sullivan B., Siriwardane D. (2016)).

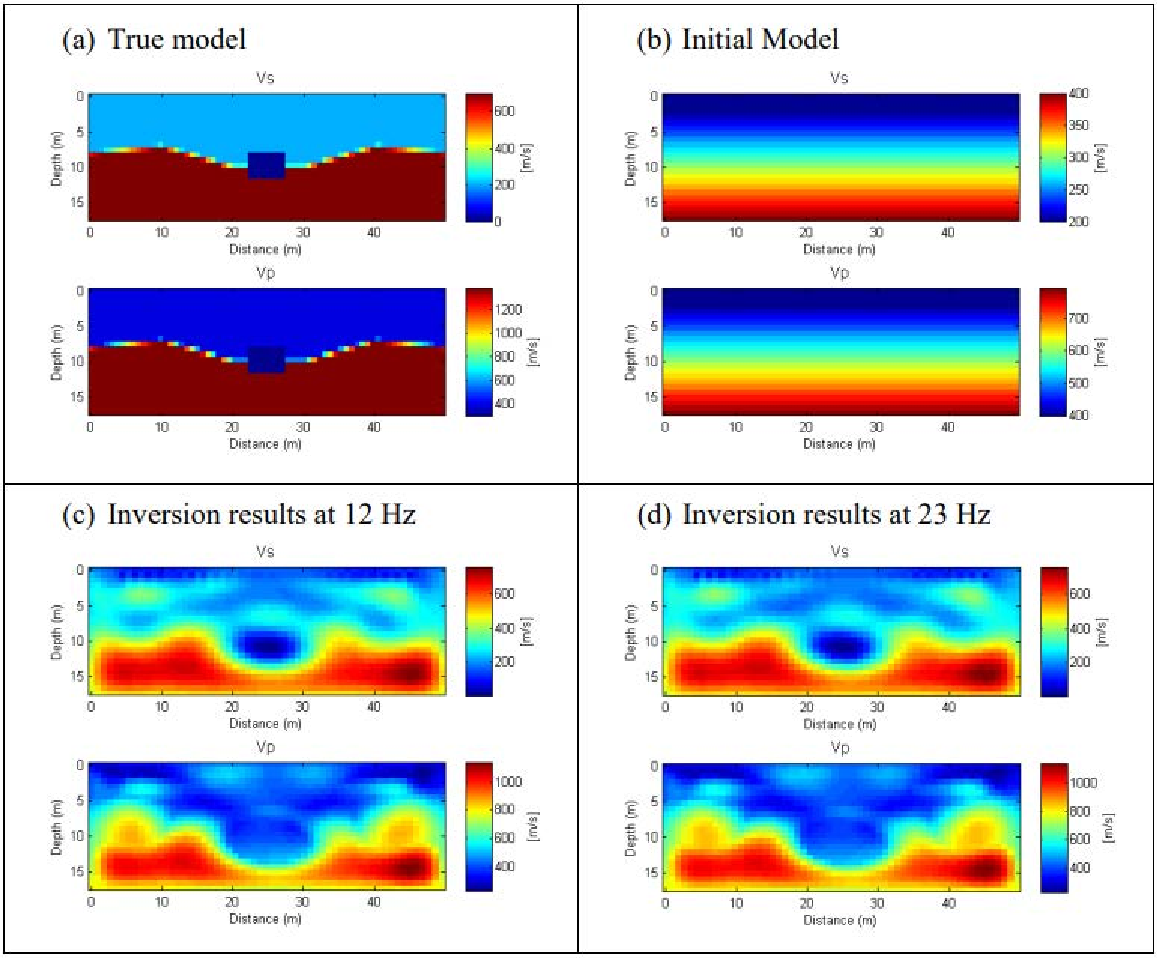

Figure 3.1: Synthetic model of S-wave and P-wave velocities (m/s): (a) line 1 true mode; (b) initial model; (c) inverted model at 12 Hz; and (d) inverted model at 23 Hz.

3.3 Conclusions

The study evaluates the effectiveness of 2D Full Waveform Inversion (FWI) for subsurface void detection. Since 2D FWI only analyzes along a single survey line, adjacent anomalies may be overlooked. Therefore, to address this limitation, a 3D forward model with synthetic data was applied to simulate testing at different offsets from a void. Results showed that FWI can reliably detect voids when data is collected directly above them (up to ~3 diameters depth). Voids may still be identified near their edges; however, detection becomes minimal when the survey line is located at least one diameter away from the void.

3.4 Evaluations of Geophysical Methods in Kentucky

The Kentucky Transportation Cabinet (KYTC) has supported the research of geophysical methods (including ERT, conductivity, microgravity, GPR, seismic reflection/refraction, cross hole tomography, electromagnetic techniques and others) primarily at the desktop evaluation level. Following an evaluation by experienced professionals, KYTC identified ERT and microgravity as the most promising methods for field application.

To implement the evaluation program, KYTC engaged two organizations to evaluate the effectiveness of the selected geophysical techniques in supporting a new highway alignment in south-central Kentucky. The work was distributed as summarized in Table 3.1.

Table 3.1: Characteristics of areas of study

Field Site	General Geology	Method
KY 101	Mississippian (Ste. Genevieve Limestone, Girkin Formation, Golconda Formation)	ERT, Microgravity
US 31-W	Mississippian (St. Louis Limestone, Ste. Genevieve Limestone)	Microgravity
KY 61	Mississippian (St. Louis Limestone, Ste. Genevieve Limestone)	ERT, Microgravity
US 27	Mississippian (St. Louis Limestone)	ERT, Microgravity

ERT proved to be an effective technique for investigating of karst features such as caves and voids, which typically present as high-resistivity anomalies. This method is especially useful for detecting subsurface irregularities; however, attention must be given to electrode spacing, as shallow-depth anomalies may be missed if the array is not designed appropriately. While the method requires substantial field effort and data processing, the detailed subsurface profiles it generates make it a worthwhile investment for karst terrain investigations. Technical limitation is that ERT cannot detect fine voids, as the volume averaged response of resistivity measurements and karst terrain may obscure smaller features or lead to misinterpretation of profiles. Some important findings are summarized below according to each geophysical method:

ERT was performed to locate existing subsurface features at one of the three sites KYTC designated for ERT. The equipment used was an AGI Sting R1 Earth resistivity meter. The data was analyzed in RES2DINV software, which iteratively calculates resistivity values to produce a three-dimensional model of the subsurface. The interpreted model revealed karst features at an average depth of 80 feet, with resistivity anomalies ranging from 50 to 200 ohm-m. Two types of anomalies were identified:

- Cup-shaped anomalies: inferred as depressions filled with clay (low resistivity) highly weathered that potentially can create a continuous subsidence, but not a major collapse.

- Shaft anomalies: interpreted as shafts filled with unconsolidated material that represents a higher concern as they do not possess any support and consequently are more prone to collapse.

Figure 3.2 presents an example of ERT results obtained, illustrating the subsurface resistivity distribution and highlighting anomalies associated with potential karst features. Figure 3.2 demonstrates how ERT can be used to visualize subsurface conditions and assist in the interpretation of voids or weak zones. Additionally, ERT surveys were also conducted at two other locations. These surveys further demonstrated the capability of ERT to delineate subsurface anomalies associated with karst terrain.

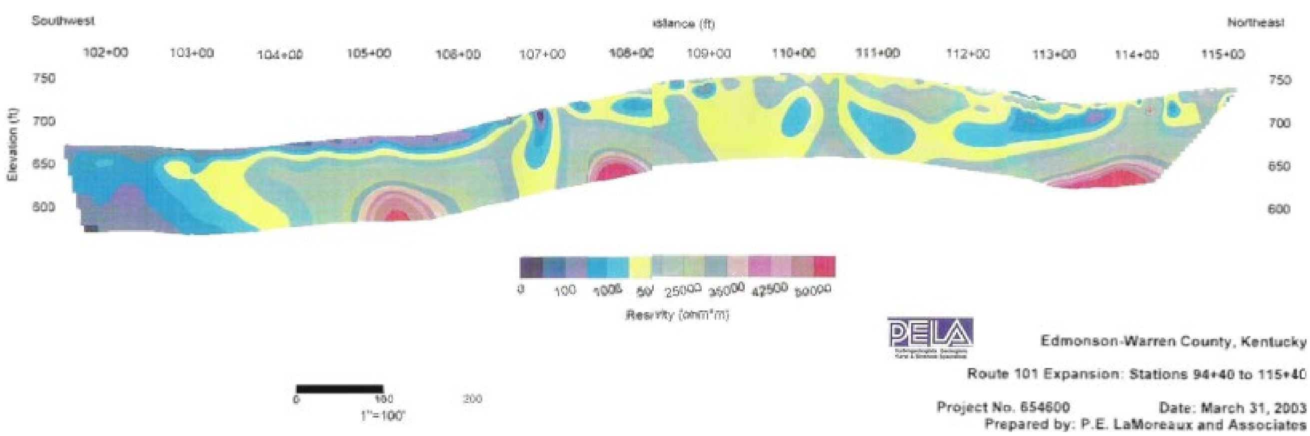

Figure 3.2: ERT result along KY 61

ERT methods were used at two other sites in response to a prominent zone of sagging to characterize anomalies junction with cave exploration. KTC used the following configurations for the ERT traverses at each site:

Table 3.2: ERT setup at KY 61 and US 27

Field Site	ERT Configuration
KY 61	- Dipole-Dipole (for horizontal resolution) - 3 lines (Southside, median, northside) - RES2DIV (software interpretation) - 20-foot and 23-foot electrode spacing (Depth of penetration approximately 100 feet)
US 27	- Dipole-Dipole (for horizontal resolution) - 4 lines (denoted A, B, C, D) - RES2DIV (software interpretation) - 20-foot and 23-foot electrode spacing (Depth of penetration of 100 feet and 115 feet, respectively)

The electrical resistivity at the three lines had low percentage of errors and displayed consistent results. The resistive area on the northside of KY 61 (Figure 3.3) was interpreted as dry, competent bedrock or non-conductive void and hence does not represent a concern of geohazard. The electrical resistivity on the south side and median areas were interpreted as voids or pinnacles of bedrock because they were isolated.

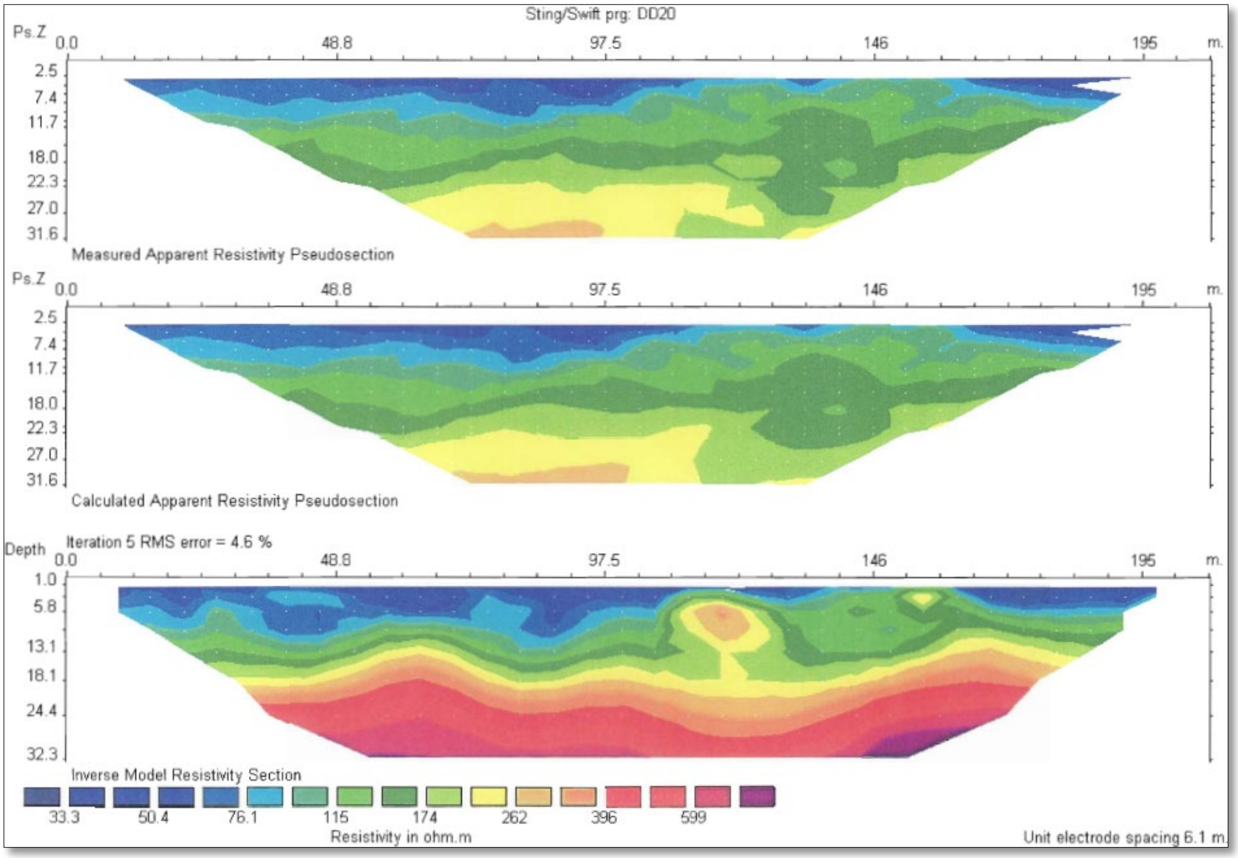

Figure 3.3: Electrical Resistivity profile along the north traverse

Microgravity measurements were applied at all four study sites. Data were corrected for instrument drift, earth tides, reference ellipsoid, free-air effect and Bouguer Slab density. These corrections are essential for isolating true subsurface density variations from background noise. Although microgravity provides valuable information for detecting density contrasts; however, field data collection and analyses takes a significant amount of time as well as highly trained professionals to apply the necessary corrections and ensure accurate interpretation. A summary of field investigations by each party is presented in the following section.

The results of the microgravity survey for the lowermost survey grid are illustrated in Figure 3.4, which presents Bouguer-corrected microgravity data with background trends removed. In Figure 3.4, blue and green zones indicate low-gravity anomalies, while red zones represent high-gravity anomalies. The anomalies marked “A,” “B” and “C’ correspond to areas of reduced density.

This application demonstrated the effectiveness of microgravity in detecting subtle variations in subsurface density but also highlighted its limitations: the non-uniqueness of solutions and the requirement for careful correlation with independent geophysical methods (such as ERT) to increase reliability.

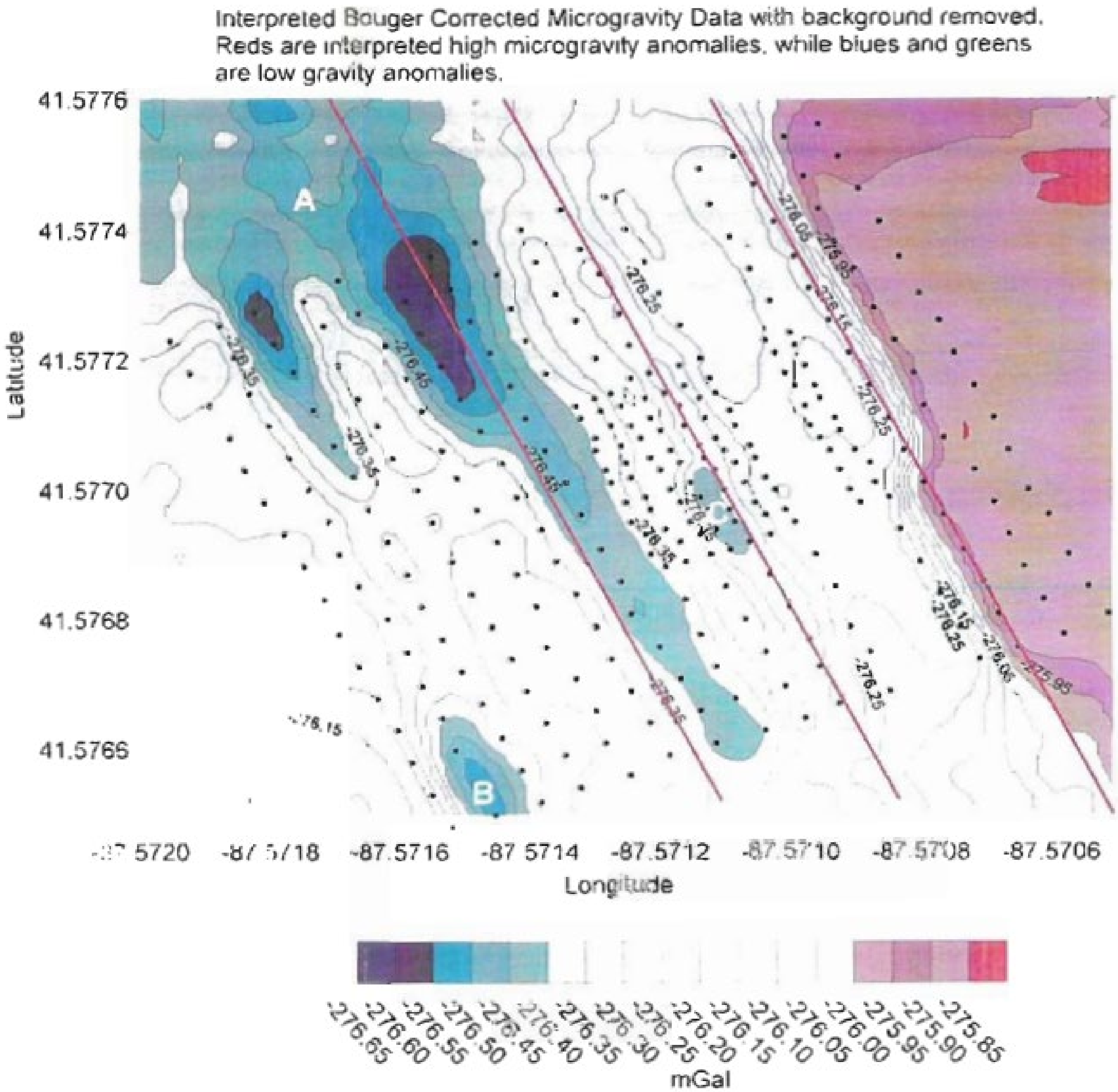

Figure 3.4: Bouguer-Corrected Microgravity results from KY 101 Survey Grid

The other sites were analyzed to investigate a sinkhole collapse in the sites as ERT survey. The technical committee have followed the next configuration to perform the investigation.

Table 3.3: Microgravity configuration at field sites

Field Site	Microgravity configuration
US 31-W	-Bouguer gravity technique
	-3 traverse (1,2,3)
	-10-foot spacing
	-OASIS Montaj (software interpretation)
KY 61	-Bouguer gravity technique
	-2 traversers (south and median)
	-10-foot spacing
	-OASIS Montaj (software interpretation)
US 27	-Bouguer gravity technique
	-4 traversers (A, B, C, and D)
	-10-foot spacing
	-OASIS Montaj (software interpretation)

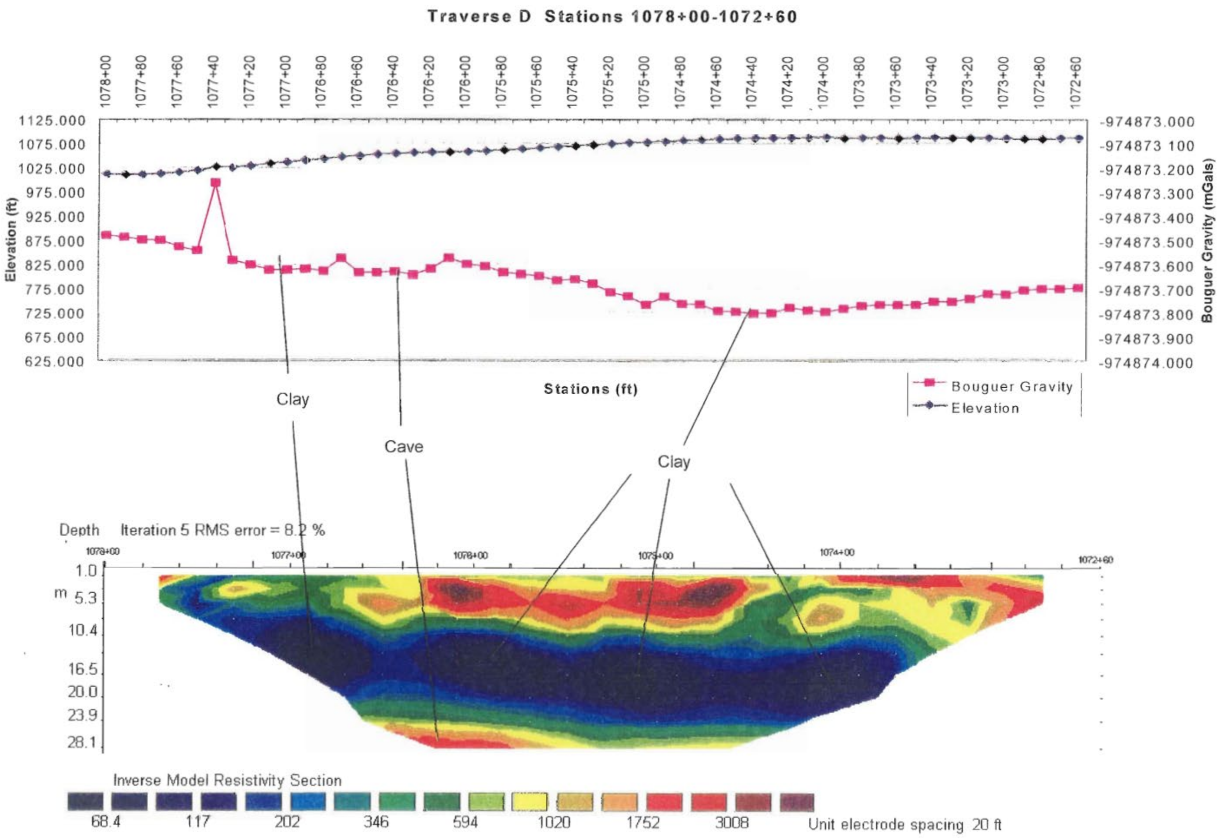

Figure 3.5: Microgravity and ERT at traverse D along US 27

Low gravity anomalies found at both traverses along US27, as shown in Figure 3.5. The size of the anomaly ranged from 40 to 60 microgals and a decrease in gravity was observed towards the end of traverse. Gravity was able to delineate shallow bedrock that agreed with the ERT survey at same location. At this site gravity surveys proved effective, but without the complementary information from the ERT, interpretation would be more general.

3.5 Conclusions

The evaluation of geophysical methods conducted at four Kentucky sites demonstrated that ERT and microgravity are effective tools for characterizing karst terrain and identifying potential subsurface hazards. ERT provided detailed resistivity profiles capable of detecting both shallow and deep anomalies, while microgravity surveys highlighted density variations that may indicate voids or highly weathered zones. Although each method has inherent limitations, such as the volume-averaging effect in ERT and the non-uniqueness of microgravity interpretations, the combined application of both techniques offered complementary results, increasing confidence in the detection of subsurface anomalies. Overall, the study confirmed that integrated geophysical surveys provide valuable guidance for transportation planning in karst-prone regions.

3.6 Evaluation of Geophysical Methods in Texas

The Texas Department of Transportation has studied the effectiveness of several geophysical methods for void detection, including ERT, Multichannel Analysis of Surface Waves (MASW), GPR and FWI. Their findings indicated that ERT is the most effective for localizing voids, although it underperforms in characterization of the void properties such as diameter and shape. MASW, on the other hand, demonstrated strengths in relatively realistic field conditions.

FWI was also shown to perform adequately in practical applications. GPR provided promising results; however, it was noted that further validation was not included in the scope of the project. Theoretically, GPR can detect voids with depth constraints, but its performance depends heavily on operator efficiency. Two sites were selected in Texas, for the application of these geophysical methods. The first site was a small flat project site studied in June 2021. The second site was evaluated later in December 2021 with the validation phase included drilling boreholes.

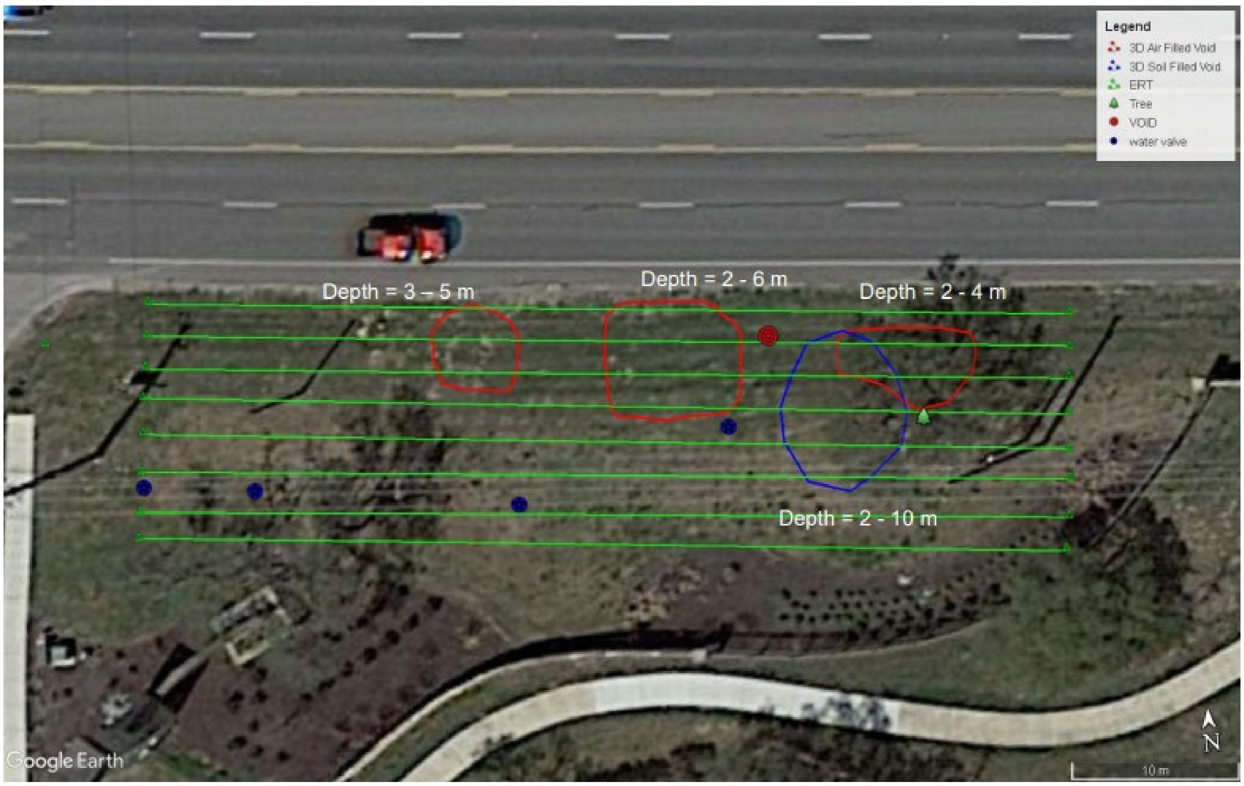

Figure 3.6: Surface map of suspected void locations based on pseudo-3D ERT

Applying ERT in Texas, a total of 9 lines (A-I) were completed. The survey identified several high resistivity and low resistivity anomalies, some of which correspond to underground utilities. These anomalies highlighted the importance of complementary drilling methods for validation.

MASW was also carried out in the same area as the ERT. A total of 48 4.5 Hz geophones were laid out per array line at 1-meter spacing. The source of waves generator was a sledgehammer with 5 shots at each point. Data collection was affected by background noise due to traffic on the highway.

FWI testing was performed using an array of 64 4.5 Hz geophones at each vertex of a 14m by 14m grid located in same array of the ERT application, spaced at 2m. Similar to MASW, five sledgehammer shots were applied at each location, and an additional shot was placed at the center of the grid. However, technical limitations in coding and processing restricted the full completion of the analysis.

GPR was conducted by a contractor with the survey line covering a shorter distance than ERT, starting at approximately 60. 7 feet (18.5 meters) from the left side of the ERT lines. In practice, the GPR data provided acceptable performance, though with some limitations. The GPR did not capture the full extent of the air-filled void, as shown by the ERT (Figure 3.6). This illustrates how ERT captured the full range of the anomaly, whereas GPR only detected its edges.

The drilling confirmed that ERT provided more accurate representation of void boundaries compared to GPR. The GPR performed reasonably well across most of the survey lines and showed agreement with ERT in identifying void-related anomalies (Figure 3.7).

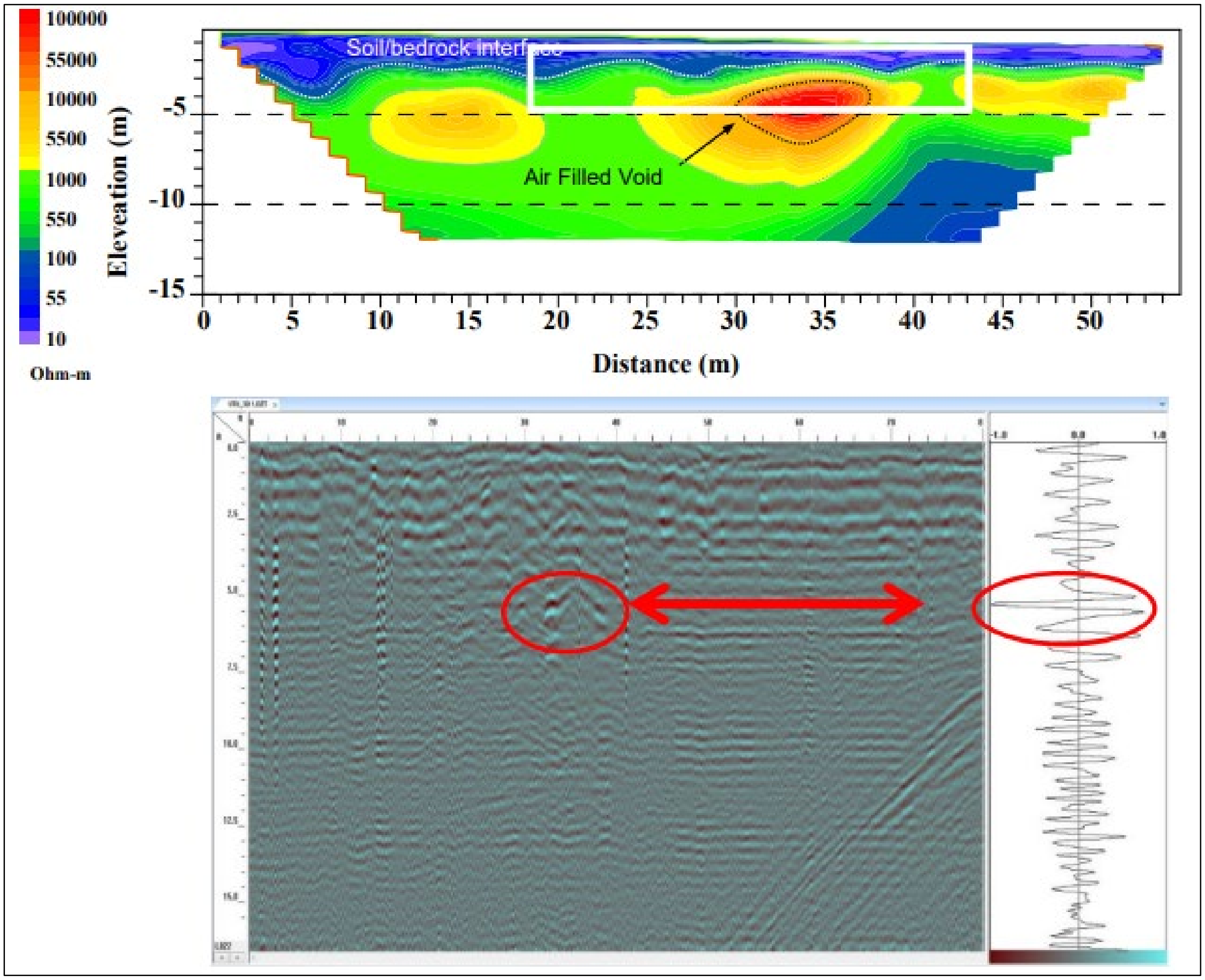

Figure 3.7: Results comparing ERT and GPR detecting air filled void

3.7 Conclusions

In summary, ERT proved effective in detecting subsurface anomalies to a depth of 65.6 feet (20 meters) in this configuration. The main limitation lies in distinguishing between materials that can have similar resistivity as voids. GPR complemented the ERT results but tended to capture only the edges of anomalies, while MASW and FWI provided additional supporting information. Overall, ERT was considered to be the most reliable field technique in this scenario, with the results aligned closely with drilling. To further improve reliability, future studies should consider integrating computational approaches such as FWI to reduce bias and enhance subsurface characterization (Mingwei C., Tairan L., Loukas K. (2024)).

3.8 Detection of Underground Voids in Ohio

The Ohio study aimed to evaluate non-intrusive geophysical techniques that might be effective in delineating subsurface voids. The primary scope of the study was to analyze different geophysical methods through theoretical assessments, followed by field evaluations. GPR was indicated as the most promising geophysical method to fulfill the task of void detection and was therefore selected for testing in real conditions.

A literature review grouped the available methods into three categories (Electrical, potential field, and seismic methods). Synthetic GPR data was first utilized based on assumptions of void depth, size, and surrounding material properties. Results demonstrated that GPR could reliably detect voids; however, the method's accuracy was limited to shallow depths and the electrical properties of surrounding soils and rocks. A key limitation identified was that this method can only penetrate shallow depths, and it was expected to have a maximum depth of penetration of 25 feet in Ohio Limestone.

Field experiments were conducted at three sites. The types of antennas used for these experiments were the Geophysical Survey Systems, Inc. (GSSI), 80 MHz monostatic and GSSI multiple low frequency 25-120 MHz adjustable- frequency bistatic configuration. Depending on site conditions, GPR was able to detect not only karst voids but also abandoned powerlines, guardrails, and even buried vehicles. While some noise was present, such as interference from overhead powerlines, the system consistently provided valuable data. At selected sites, GPR demonstrated penetration depths of 5 to 50 feet (Table 3.4), highlighting its utility in mapping karst development and voids beneath roadways.

Figure 3.8 illustrates the application of GPR along Interstate 470 in Ohio, showing a distinct anomaly consistent with a subsurface void. This highlights both the effectiveness of GPR for karst environments and the importance of comparing results across multiple geophysical methods to improve reliability.

Table 3.4: Ground penetration setup and penetration depth

Field site	**Local geology**	**Antenna Frequency**	**Estimated depth of penetration (feet)**
I-470, Belmont County	Shaly limestone, coal	80 MHz MLF	10
		40 MHz	15
I-70, Guernsey County	Limestone, sandstone, shale, coal	80 MHz MLF	10
	Limestone	80 MHz MLF	40

SR-33 in Logan County		60 MHz	>50

Field investigation using gravity and magnetic methods were also carried out, though both presented challenges in terms of data acquisition and interpretation. In the case of gravity surveys, data collection was complex, it requires many closely spaced points and acquisition times (setting up a single point can last 15 minutes). Additionally, the cultural noise due to the heterogeneity of surrounding material and the presence of shallow geologic features reduced the quality of the data. Assumed data was modeled in analytical solutions of spherical and cylindrical voids surrounded by coal and limestone at desktop level. In the case of magnetic surveys, the small magnetic susceptibility of spherical and cylindrical voids is not favorable to detect voids. However, if voids are situated within ferrous materials this method may be effective.

In the third category, seismic methods (including both reflection and refraction) were assessed separately. Seismic surveys can detect voids based on contrasts in acoustic impedance, and researchers applied synthetic forward modeling to simulate potential detection scenarios. The results showed that accurate vertical and horizontal location are needed to detect subsurface anomalies, with a frequency range of 100-200 Hz penetrating 100 meters below ground surface. This method is susceptible to free oscillation of resonance of the void walls, anomalous amplitude attenuations and delayed signal arrival times. Refraction can detect both air-filled and water-filled voids; however, data interpretation may be biased, as saturated zones can exhibit similar characteristics to water-filled voids. Seismic methods are highly dependent on the source energy to transmit the higher frequency of waves and obtain acceptable resolution. Geophones may need to be closely spaced and interference from traffic on the highway also affects data collection.

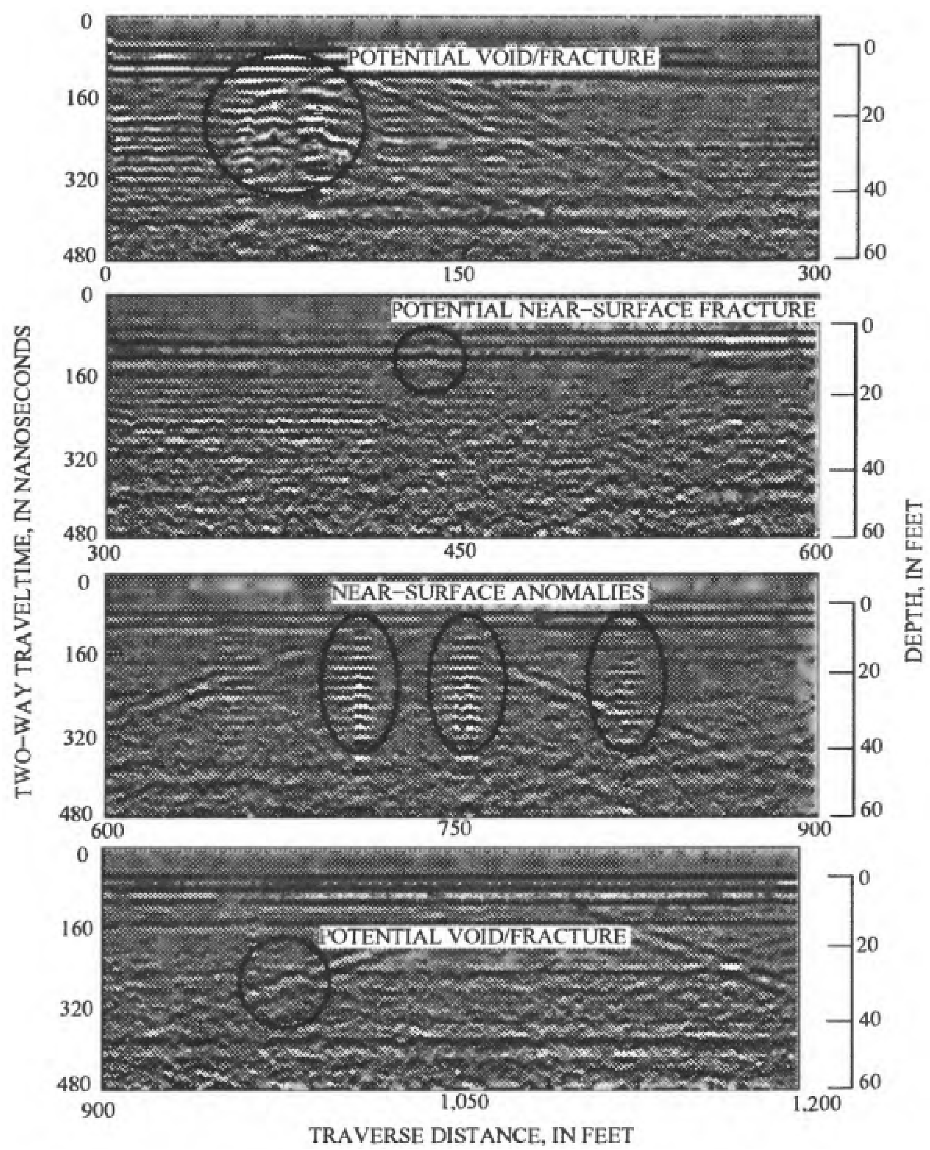

Figure 3.8: GPR application in Ohio

3.9 Conclusions

The Ohio Department of Transportation has supported research to assess three different categories of geophysical methods (electrical, potential field (gravity and magnetic) and seismic methods). Among these, GPR has proven to be the most effective due to its speed, cost-efficiency, and capability to detect voids beneath roadways. Although electrical resistivity, gravity, and seismic reflection methods have also demonstrated good results in obtaining void profiles, their effectiveness is often limited by more complex data collection and interpretation requirements. Overall, GPR was identified as a practical and efficient tool for roadway void detection, though complementary methods may still be needed for comprehensive site characterization (Munk, J., Sheets, R. (1997)).

3.10 Detection of Mine Workings and Voids in Colorado

The Colorado Department of Reclamation, Mining and Safety (DRMS), in collaboration with various engineering consultants, conducted an extensive geotechnical-geophysical investigation in the Country Club Circle (CCC) neighborhood of Colorado Springs to evaluate subsurface instability associated with historic room and pillar coal mine workings. The area, underlain by the abandoned Rapson Coal Mine at depths of approximately 50-100 feet, had experienced decades of settlement, trough subsidence, and sinkhole occurrences affecting residential properties and local infrastructure. To address these issues, a comprehensive investigative program was developed integrating surface and borehole geophysics, exploratory drilling, downhole imaging, and targeted ground modification.

The geophysical evaluation began with Multichannel Analysis of Surface Waves (MASW), which was deployed along multiple streets within the neighborhood to provide reconnaissance level characterization of shallow subsurface conditions. MASW identified velocity anomalies consistent with disturbed ground or weakened zones near the mining horizon; however, its depth of investigation was reduced due to the presence of a thick near surface sand layer that attenuated seismic energy. To obtain higher resolution imaging of mine workings, Reverse Vertical Seismic Profiling (RVSP) was carried out using an air gun seismic source and surface receiver arrays centered on borehole CCC3. RVSP produced detailed 2D reflection images revealing disrupted reflection events associated with voids or rubble zones and providing a clearer differentiation between intact coal pillars and mined out entries. The seismic interpretation helped refine the location of historic workings and guide additional drilling to confirm void conditions.

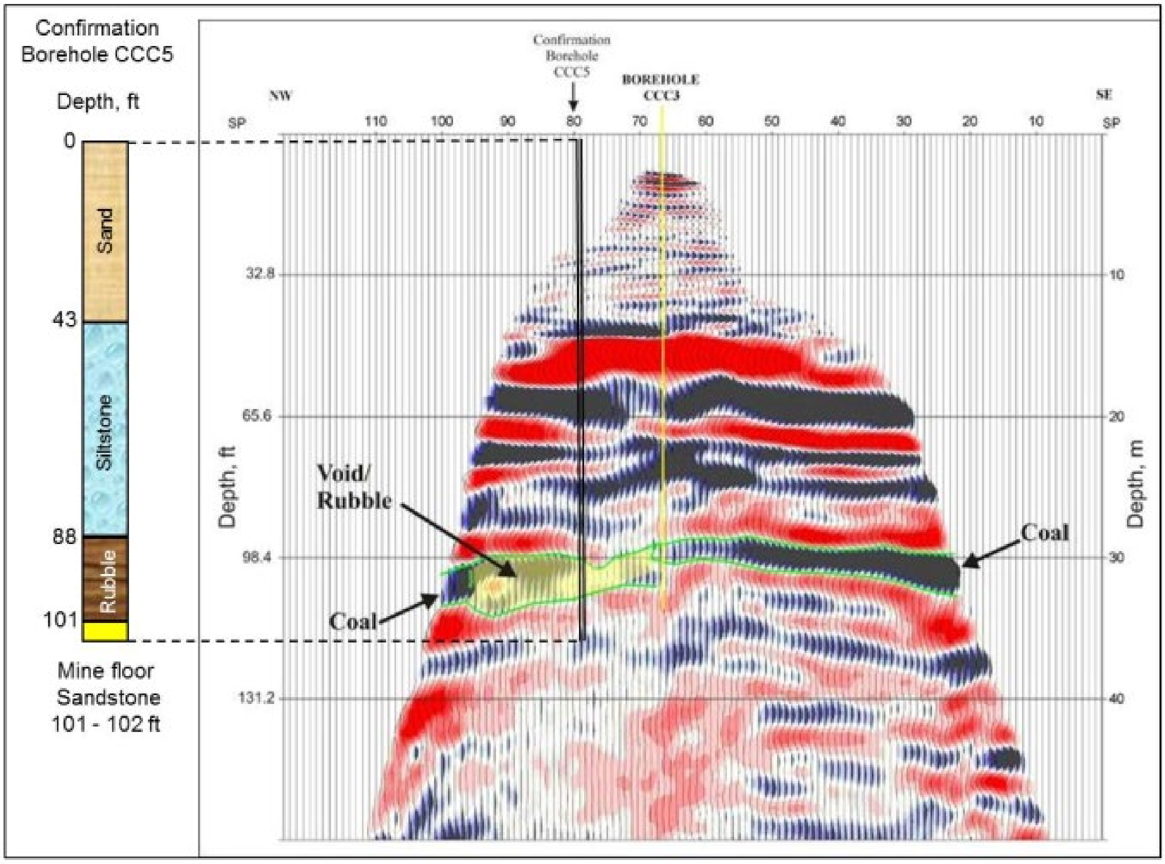

Figure 3.9: RVSP data interpretation obtained at borehole CCC3

Exploratory boreholes were drilled throughout the project area to ground truth geophysical anomalies and obtain site specific subsurface data. Thirteen borings totaling over 1,160 feet of drilling were completed, including Standard Penetration Tests (SPTs), coal seam identification, and geophysical logging (gamma, density, and resistivity). Multiple borings encountered both air filled and water filled voids or rubble zones, confirming the geophysical interpretations. To characterize the geometry and volume of these voids, advanced downhole imaging technologies were used. Cavity laser scanning from boreholes CCC6 and CCC13 produced detailed three-dimensional models of haulage ways and rooms, showing a primary entry approximately 230 feet long with dimensions of roughly 10 feet in width and 6 feet in height. Video imaging corroborated the presence of intact and collapsed areas, timbers, rubble banks, and roof separations, while sonar mapping was attempted but limited in debris filled water bearing voids. These combined datasets allowed the investigative team to reconcile the mapped subsurface conditions with historic mine maps, revealing discrepancies of up to 25 feet in the recorded locations of entries and workings.

Microgravity methods were not used in this Colorado case study; instead, the focus was on seismic and imaging-based approaches because of their higher effectiveness in the site's sandy overburden and bedrock contrast conditions. Cross-hole Seismic Tomography (XHT) was later applied to assess the effectiveness of mitigation techniques. Although XHT successfully identified low velocity zones corresponding to voids, its ability to resolve precise shapes or treatment extents was limited due to the low velocity of foamed sand infill relative to surrounding rock. Nevertheless, the method provided valuable before and after comparisons, confirming general improvements in treated areas.

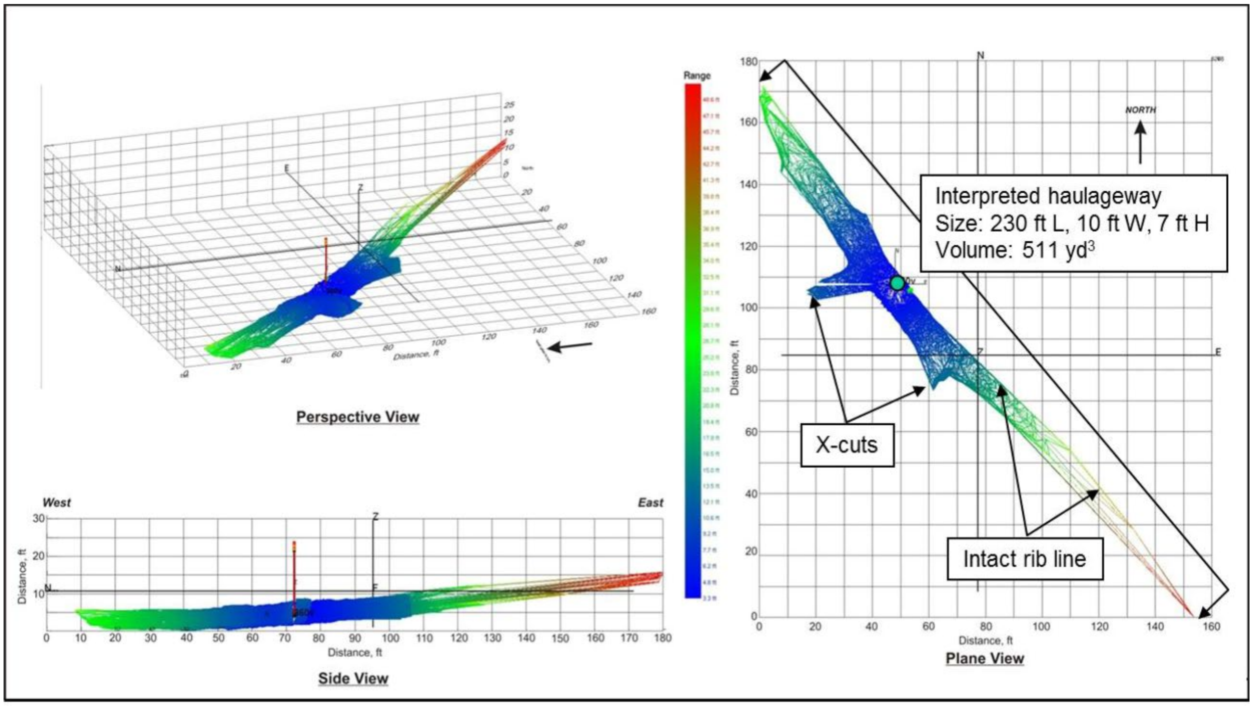

Figure 3.10: 3D Laser interpretation showing void space from borehole CCC6

Following the investigation, DRMS implemented a two-part mitigation strategy consisting of Low Mobility Grouting (LMG) beneath affected homes and foamed sand slurry backfilling of large mine openings. LMG was used to densify loose ground and fill smaller discontinuous voids directly beneath structures, with grouting volumes averaging roughly 348 cubic yards per house. Foamed sand slurry, produced by mixing engineered foam with damp sand onsite, was gravity fed through boreholes into large haulage ways.

Video monitoring from nearby boreholes confirmed that the slurry flowed effectively across long distances and filled voids to the quantities estimated from laser scans. This approach proved to be approximately half the cost per cubic yard of LMG and was highly suitable for stabilizing major openings. Subsequent drilling and grouting confirmed the improved conditions, although some grout movement into adjacent crosscuts indicated interconnected mine geometry consistent with the earlier geophysical interpretations.

3.11 Conclusions

The Colorado investigation demonstrated that integrating multiple geophysical techniques with exploratory drilling and advanced downhole imaging provides a robust strategy for identifying and characterizing underground mine voids in residential settings. MASW and RVSP offered effective non-intrusive detection, while laser and video imaging delivered precise geometric and visual confirmation of void conditions. The coordinated application of LMG and foamed sand slurry provided targeted ground improvement and long-term stabilization. Although each method had limitations, such as MASW depth restriction, sonar interference in rubble zones, and limited XHT resolution, the combination of approaches substantially reduced uncertainties and guided cost-effective mitigation. Overall, this case highlights the value of multi method geophysical frameworks for managing legacy mine hazards beneath developed infrastructure. (Hanna, K., Pfeiffer, J., Hodges, S., Amundson, A.L., Palladino, R., & Szynakiewicz, T. (2013)

Chapter 4: Societies, Surveys, Foundations and Associations in Missouri

4.1 National Speleological Society (NSS)

The National Speleological Society (NSS) is the largest and most influential speleological (caving) organization in the United States, dedicated to scientific cave study, exploration, conservation, education, and responsible access. Formed in 1941 as a national nonprofit, its mission includes advancing the understanding of caves and karst systems, protecting cave environments and their natural contents, and fostering fellowship among people who study and explore these environments. The NSS works to protect caves, promote ethical caving practices, and disseminate research and technical knowledge to both specialists and the public.

Exploration & Survey: NSS sponsors and supports volunteer cave explorations across the U.S., including systematic survey and mapping projects via its local chapters (called *grottos*). Grottos in Missouri (e.g., Stygian Grotto, Springfield Plateau Grotto, Chouteau Grotto) organize field trips, coordinate survey projects, and contribute data to state surveys and archives.

Scientific Research & Conservation: Through committees and divisions, NSS funds small research projects, conservation grants, and land protection efforts (e.g., *Save-the-Caves* grants supporting local conservation).

Education & Outreach: The NSS publishes *NSS News* and other periodicals, offers training workshops (e.g., cave rescue and conservation), and holds annual conventions featuring talks on geology, hydrology, biology, archaeology, and more.

Partnerships: The NSS partners with federal and state land management agencies on cave management and research.

Operation & Structure: The NSS is governed by a Board of Governors and funded by membership dues, donations, publication sales, and grants. It includes *grottos* (local clubs), *regions* (geographic groupings of grottos), and specialty sections for focused interests (e.g., cave diving, photography).

Publications & Findings: NSS publishes *NSS News*, the *Journal of Cave and Karst Studies* (peer-reviewed science), and various manuals and bulletins. Members can access decades of archived research.

Where to Access / Contact

- Address: 6001 Pulaski Pike, Huntsville, AL 35810-1122
- Website: caves.org
- Email: nss@caves.org
- Phone: (256) 852-1300

4.2 Cave Research Foundation (CRF)

The Cave Research Foundation (CRF) is a national nonprofit organization that focuses on cooperative cave research and long-term resource protection. Although it isn't Missouri-specific, the CRF has a strong collaborative role in cave science and resource management, especially where federal parks and public lands are concerned. Members of the CRF work with agencies (e.g., National Park Service) to assist in cave inventory, mapping, ecological monitoring, and resource planning — often volunteering thousands of hours to these efforts.

4.2.1 Activities and Scope

- Research & Management Partnerships: CRF teams work with organizations like the NPS and local partners to study cave geology, hydrology, biology, and long-term changes, and help manage significant cave resources.
- Survey & Documentation: Volunteers systematically survey cave passages and produce detailed maps and environmental datasets used in scientific work and management planning.
- Conservation & Interpretation: CRF promotes policies and practices that protect cave environments and interprets cave science for managers and visiting publics.
- Operation & Structure: CRF operates through volunteer scientists and cave explorers. It partners with government and academic institutions on formal agreements to work within parks and other lands.
- Where to Access Findings:
    - CRF reports, maps, and research summaries are distributed to partners and often published through cooperating agencies or specialty publications.

4.3 Missouri Cave and Karst Conservancy

The Missouri Caves and Karst Conservancy (MCKC) is a statewide nonprofit land trust founded in 1992 with a mission to protect, manage, and educate about caves and karst landscapes in Missouri. It focuses on ensuring long-term conservation of cave and karst resources — including natural features, wildlife habitat, and sensitive hydrological systems — while balancing responsible access for exploration and research.

4.3.1 Activities and Scope

- Land & Cave Protection: MCKC acquires, holds, and manages cave properties by purchase, easement, lease, or donation to ensure they remain conserved and accessible.
- Resource Stewardship: Members assist landowners with cave management practices, conservation planning, and stewardship that protects fragile karst ecosystems.
- Education & Outreach: MCKC provides educational materials and workshops about karst and cave conservation to Missourians and the broader caving community.
- Supporting Exploration: The conservancy ensures that caves remain available for ethical exploration, survey, and scientific use by qualified researchers and cavers.
- Affiliations
  - MCKC works closely with the NSS, MSS, American Cave Conservation Association (ACCA), Missouri Caves Association (MCA), and other conservation partners.
- Where to Access Findings & Permits
  - MCKC provides cave lists, permit request forms, trip reports, and conservation resources on its website.
- Contact & Info
  - Address: P.O. Box 190456, St. Louis, MO 63119
  - Website: mocavesandkarst.org

4.4 Missouri Speleological Survey (MSS)

The Missouri Speleological Survey, Inc. (MSS) is the statewide coordinating body and repository for speleological research and data in Missouri, with a strong focus on mapping, recording, and conserving cave information. Established in 1956, MSS works with individuals, clubs (often NSS grottos), and agencies to expand knowledge of Missouri’s more than ~7,900 documented caves.

4.4.1 Activities & Scope

- Cave Survey & Mapping: MSS collects, reviews, and archives cave survey data and maps submitted by cooperators (individuals and grottos), contributing to one of the most complete cave inventories in a U.S. state.

- Publications: It publishes the journal Missouri Speleology, a bi-monthly newsletter, and various county or project-specific cave maps and reports that cover geology, hydrology, and biota.

- Data Repository: MSS maintains one of the most extensive cooperative cave files in cooperation with the Missouri Geological Survey and Resources Assessment Division.

    - Conservation Advocacy: The survey encourages protection of cave environments and supports policy frameworks that preserve their natural conditions.

- Operation & Structure: MSS is governed by a board made up of representatives from affiliated organizations (mainly NSS grottos and conservancies). Meetings three times per year set policy and coordinate survey projects.

- Where to Access Findings:

    - Published maps and reports can be purchased or requested through the MSS website and are often used by researchers, land managers, and academic institutions.

- Contact & Info

    - Website: mospeleo.org

4.5 American Cave Conservation Association (ACCA)

The American Cave Conservation Association (ACCA) is a national nonprofit focused on education, conservation, and protection of caves, karst landscapes, and groundwater resources across the United States. While not Missouri-specific, ACCA's programs and expertise support karst conservation efforts nationwide and are often resources for Missouri groups.

4.5.1 Activities and Scope

- Education & Outreach: ACCA develops curricula, interpretive programs, workshops, and educational materials to teach the public, school groups, and land managers about karst systems and cave protection.

- Conservation Projects: The association participates in habitat restoration, cave gating to protect sensitive species, and cleanup initiatives in karst areas.
- American Cave Museum: ACCA operates interpretive facilities like Hidden River Cave and the American Cave Museum in Kentucky to inform visitors about caves and their ecosystems.
- Publications: ACCA produces *American Caves Magazine* and *ACCA News*, communicating conservation science, policy updates, and best practices.
- Operation & Structure: ACCA is governed by a board and funded through memberships and donations. Membership benefits include newsletters, access to educational events, and voting privileges in organization governance.
- Where to Access Findings & Materials
  - Publications and educational resources are available through ACCA's website.
- Contact & Info
  - Address: P.O. Box 409, Horse Cave, KY 42749
  - Website: caveconservation.com
  - Phone: (270) 786-1466

4.6 Missouri Caves Association (MCA)

The Missouri Caves Association (MCA) is a regional association of show caves in Missouri and neighboring Arkansas. Its mission is to promote public appreciation, tourism, and stewardship of show caves - caves open to visitors with interpretive tours and public access.

4.6.1 Activities and Scope

- Explorer & Visitor Programs: MCA runs programs like the *Cave Explorer's Club* where visitors collect stamps or badges by touring multiple caves in Missouri and Arkansas, encouraging public engagement with karst heritage.
- Networking & Events: MCA brings together show cave owners and operators to share best practices in conservation interpretation, safety, and tourism.
- Operation: MCA functions as an association of businesses and public cave attractions. It operates through member collaboration and public outreach efforts to promote caving experiences.
- Where to Access Findings & Info

- While not focused on scientific publications, MCA offers resources for visitors and educators about cave tourism and conservation through its website and partner sites.

- Contact & Info
  - Typically, reachable through its Explorer's Club contact (e.g., c/o Bridal Cave Fun Department, Camdenton, MO)

4.7 Missouri Department of Natural Resources (MoDNR)

The Missouri Department of Natural Resources (MoDNR), particularly the Missouri Geological Survey (MGS), provides governmental science, information, and policy support on karst landscapesand groundwater systems within the state. The MGS also investigates the state's geology, providing geologic and hydrologic information and expertise to aid economic development, infrastructure considerations, and environmental decision-making regarding site remediation, contaminant migration, subsurface investigations, and geologic hazards. Geologic Hazards can include sinkholes, mine shafts, abandoned mine lands, etc.

4.7.1 Activities and Scope

- Geologic Information & Mapping: MoDNR produces statewide karst maps, fact sheets, and data layers that help researchers, planners, and land managers understand cave distributions, sinkholes, and karst aquifer behavior.

- -A resource for the maps would be the Missouri Mine Map Repository: Missouri Mine Map Repository | Missouri Department of Natural Resources. The Repository houses more than 2,000 maps of underground and some are georeferenced.

- Technical Publications: The department publishes informational brochures (e.g., *Missouri - The Cave State*) detailing karst processes, cave formation, and conservation implications.

- Data Portals: Tools like GeoSTRAT provide searchable datasets that include cave and sinkhole records, aiding scientific research and resource planning.

- Cross-Agency Collaboration: MoDNR frequently collaborates with nonprofit cave organizations (MSS, NSS, MCKC) to share data and provide archival services for cave maps and surveys.

- Where to Access Findings & Info
  - Address: 111 Fairgrounds Road, Rolla, MO 65402
  - Website: Geology | Missouri Department of Natural Resources

- Phone: 573-368-2100 (main) or 800-361-4827 (toll-free)
- Email: geology@dnr.mo.gov
- Publications: Available through document search or GeoSTRAT portal

Chapter 5: Case Studies of WSP / Missouri S&T Projects

To demonstrate the practical application of geophysical and geotechnical methods for subsurface characterization, this chapter presents a series of case studies drawn from WSP's and Missouri S&T's project portfolios. Each case highlights the use of advanced technologies to identify and mitigate risks associated with underground voids, abandoned mine workings, and karst features. By examining these projects, we illustrate how integrated geophysical investigations provide actionable insights to support infrastructure protection, regulatory compliance, and long-term risk management. These examples not only underscore WSP's and Missouri S&T's technical expertise but also demonstrate the direct relevance of our experience to MoDOT's objectives of enhancing transportation safety and resilience.

5.1 Case Study: Closure Planning of the Historic Mine at Quanah, Texas

WSP USA Inc. provided geotechnical and geophysical services related to the closure of the historic shallow gypsum mine located near Quanah, Texas. The project aimed to evaluate the risk of sinkhole development that could impact a county road, which overlies and is adjacent to historic shallow gypsum mine workings. This assessment formed part of a phased investigation program designed to identify and mitigate subsurface hazards associated with legacy underground mining.

5.1.1 Objectives

The primary objective was to conduct a non-intrusive geophysical investigation to delineate the presence of underground voids, weak zones, and bedrock variations that could influence surface stability. Results were intended to guide decisions for roadway safety and long-term closure planning.

5.1.2 Employed Methods and Field Procedures

Three complementary geophysical methods were deployed:

- GPR: Used a 160-MHz antenna system to detect shallow anomalies and reflectors indicative of near surface voids or disturbed zones.
- ERI: Conducted using stainless steel electrodes and automated switching to evaluate subsurface resistivity contrasts, with profiles processed and contoured using Oasis Montaj software.
- MASW: Acquired seismic data with a 24-channel seismograph and sledgehammer source to determine shear-wave velocities (Vs), providing stiffness and depth information for subsurface layers.

Two mobilizations were conducted between October 2023 and March 2024. During the initial mobilization, GPR, ERI, and MASW lines were performed, though heavy rainfall influenced some ERI results. The second mobilization completed additional lines to achieve full coverage. MASW proved particularly valuable, producing velocity profiles interpreted using Building Seismic Safety Council (BSSC, 2003) standards to distinguish soil, weathered rock, and bedrock.

5.1.3 Key Findings

Figure 5.1 presents representative MASW-derived shear wave velocity profiles. The MASW results delineate variations in subsurface stiffness and identify the locations of the mine drifts which pass underneath the nearby road. Together, these datasets provided corroborating evidence for the presence of historical mine workings and supported the interpretation of potential collapse-prone zones beneath the road.

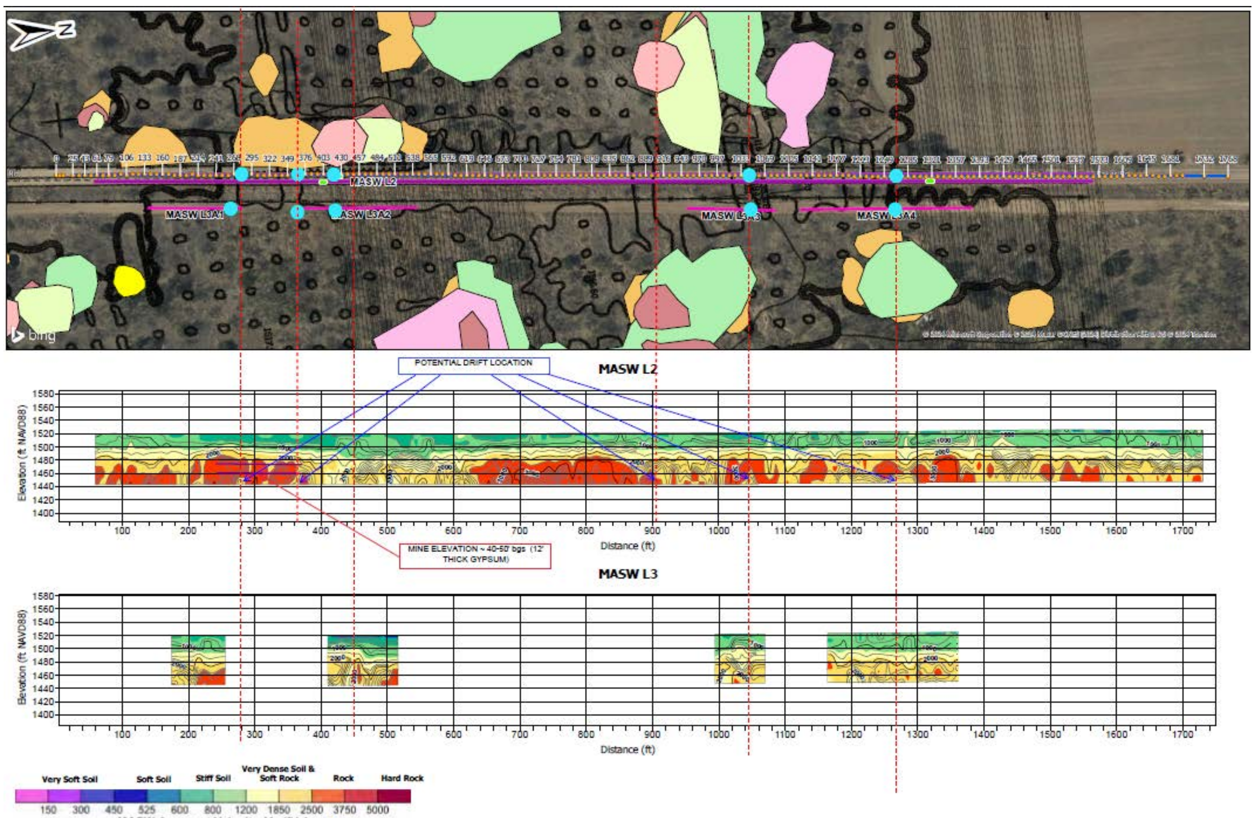

Figure 5.1: Representative MASW profiles along the road, illustrating shear wave velocity contrasts indicative of historical gypsum mine workings.

Key findings from the ERI and MASW surveys are:

- Overburden thickness ranged from 20 to 60 feet, modeled as two layers: stiff soil (600–1200 feet/s Vs) and denser soil (1200–1850 feet/s Vs).

- Bedrock was defined at approximately 1850 feet/s Vs, with the surface elevation undulating between 1500 and 1480 feet.

- Zones of irregular, low-velocity material were identified and interpreted as potential indicators of historical underground gypsum workings or alluvial channels.

- ERI profiles supported MASW results, showing overburden thicknesses up to 40 feet in places, with weak zones consistent with collapse features.

- GPR anomalies highlighted localized shallow reflectors, further supporting the presence of disturbed subsurface conditions.

5.1.4 Limitations

As with most geophysical investigations, results are interpretive and must be correlated with borehole or direct investigation data. Heavy rainfall during ERI surveys reduced data quality.

5.1.5 Outcome and Value

The combined use of GPR, ERI, and MASW provided an integrated evaluation of subsurface conditions, identifying areas with potential voids and collapse risk beneath the road. These results enabled the client and county stakeholders to prioritize risk management measures and inform future stabilization or remediation planning. The project demonstrated WSP’s capability in applying multi-method geophysics to mine closure and infrastructure protection challenges.

5.2 Case Study: Mine Void Detection Using Geophysics – Port Clinton, Ohio

WSP (formerly Golder Associates) completed a geophysical investigation along State Route 2 near Port Clinton in Ottawa County, Ohio, to assess subsurface stability risks associated with historic underground gypsum mines. The study area overlies mine workings located between 70 and 90 feet deep, where collapse features and karst-related voids in dolomitic limestone posed potential hazards to the highway infrastructure. The project was commissioned to delineate voids, characterize mine-related subsurface anomalies, and support risk mitigation strategies.

5.2.1 Scope of Work

The investigation was conducted on State Route 2 in Port Clinton, Ottawa County, Ohio, in August 2010, covering 2.4 miles. The investigation relied on ERI to map mine workings and karst features beneath the roadway. The work program included:

- Geophysical Surveying: Four continuous ERI lines were completed, with a total survey length of 2.4 miles (12,560 feet).

- Instrumentation: A 112-electrode system was deployed at 10-foot electrode spacing, allowing for a resolution of approximately 200 feet depth and 10-foot lateral detail.
- Geologic Model Development: A conceptual geologic model was constructed by calibrating ERI results to known stratigraphy and available mine records.
- Subsurface Characterization: Two primary layers were identified – an unconsolidated overburden underlain by dolomitic bedrock.

Table 5.1: ERI Configuration

Field site	ERI Configuration
-State Route 2, Port Clinton, Ottawa County, Ohio. Subsurface geology: dolomitic limestone	- Dipole-Dipole array - 4 lines - AGI's EARTHIMAGER (software interpretation) - 10-foot spacing - 112 electrode system (Depth of penetration of 200 feet)

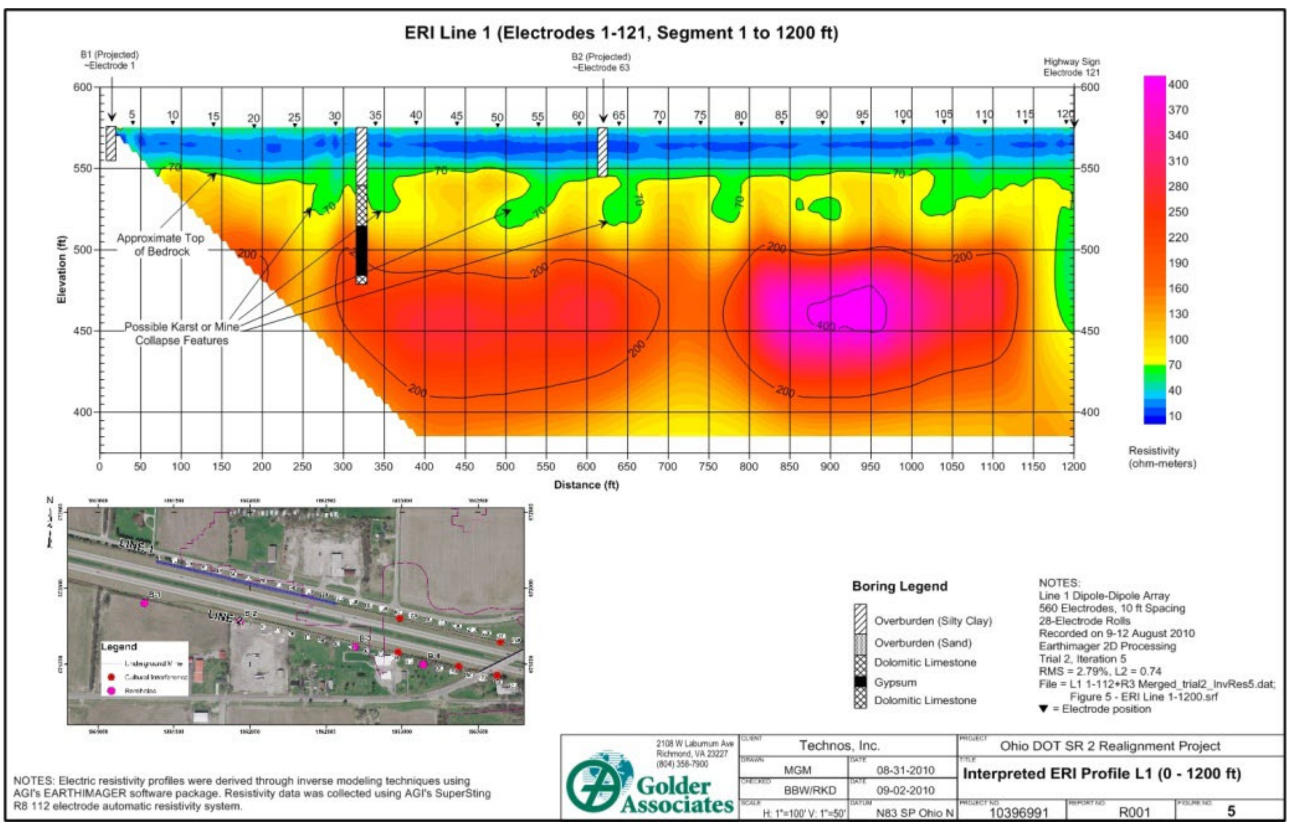

Figure 5.2: ERI cross-section from the Port Clinton, Ohio survey. Low-resistivity anomalies (purple/blue) are interpreted as mine voids and collapse features within the dolomitic limestone bedrock beneath State Route 2

5.2.2 Key Findings

Representative ERI results are shown in Figure 5.2, where low-resistivity anomalies (purple and blue zones) indicate potential collapse structures and mine voids beneath the roadway. Key findings include:

- The bedrock displayed high resistivity values (up to 400 ohmmeters), while surficial deposits exhibited resistivity less than 70 ohmmeters.
- Low-resistivity anomalies, typically 30–50 feet wide and extending more than 30 feet deep, were detected at and below the bedrock interface.
- These anomalies were interpreted as karst voids and collapse features linked to historic gypsum mining activity and zones of increased fracturing and groundwater porosity.

Concentrations of anomalies corresponded with suspected mine elevations, highlighting areas at higher risk for future subsidence.

5.2.3 Outcome and Value

The investigation provided crucial data for DOT planners and geotechnical engineers, allowing them to identify specific roadway sections where subsurface instability posed the greatest risks. ERI profiles supported predictive modeling of void locations and informed subsequent decision-making for maintenance, monitoring, and potential remediation of affected infrastructure.

5.2.4 Project Significance

This project demonstrated WSP’s ability to apply advanced geophysical imaging methods to detect and characterize mine voids beneath transportation corridors. The Port Clinton study showcased how electrical resistivity surveys can be used as a cost-effective and non-intrusive tool for identifying subsurface hazards, directly contributing to highway safety and long-term infrastructure resilience.

5.3 Case Study: Caledonia Mines #1 and #2, Ontario, Canada

WSP conducted a multi-phase geotechnical and geophysical investigation at the historic Caledonia Mines #1 and #2 in Ontario, Canada. These mines, originally operated between 1905 and 2004, were room-and-pillar operations with extensive underground workings located beneath public infrastructure, railways, private farmland, and residential developments. The project was initiated to evaluate mine hazards, crown pillar stability, and long-term remediation options as part of closure planning.

5.3.1 Scope of Work

WSP developed and implemented a staged mine hazard investigation strategy that combined desktop review, borehole drilling, crown pillar assessments, and geophysical surveys. The phased program included:

- Geophysics: ERI and drone-based subsidence mapping to delineate underground voids and crown pillar geometry.
- Drilling and Core Logging: More than 30 cored and non-cored boreholes, with crown pillar characterization and rock mass quality classification (Q-system).
- Instrumentation: Installation of Multipoint Borehole Extensometers (MPBX) to monitor crown pillar displacement.
- Stability Assessment: Scaled-span and unraveling assessments to quantify crown pillar performance, supported by geophysical and geomechanical data.
- Void Investigation: Borehole sonar and cavity monitoring surveys (wet and dry) to confirm geometry and water conditions of underground workings.

5.3.2 Key Findings

ERI data revealed anomalies interpreted as voids up to 9 m wide, located directly beneath critical infrastructure (Figure 5.3). These results provided key data to support further crown pillar stability assessments and remediation planning. Additionally:

- Crown pillar thickness ranged from 3 m to 10 m, with rock mass quality varying from “Poor” to “Good.”
- Overburden depths were 13–19 m, consisting of silts and clays, with seasonal flooding observed in the underground voids.
- Subsidence features, including surface sinkholes up to 8 m wide and 4 m deep, were documented on farmland.

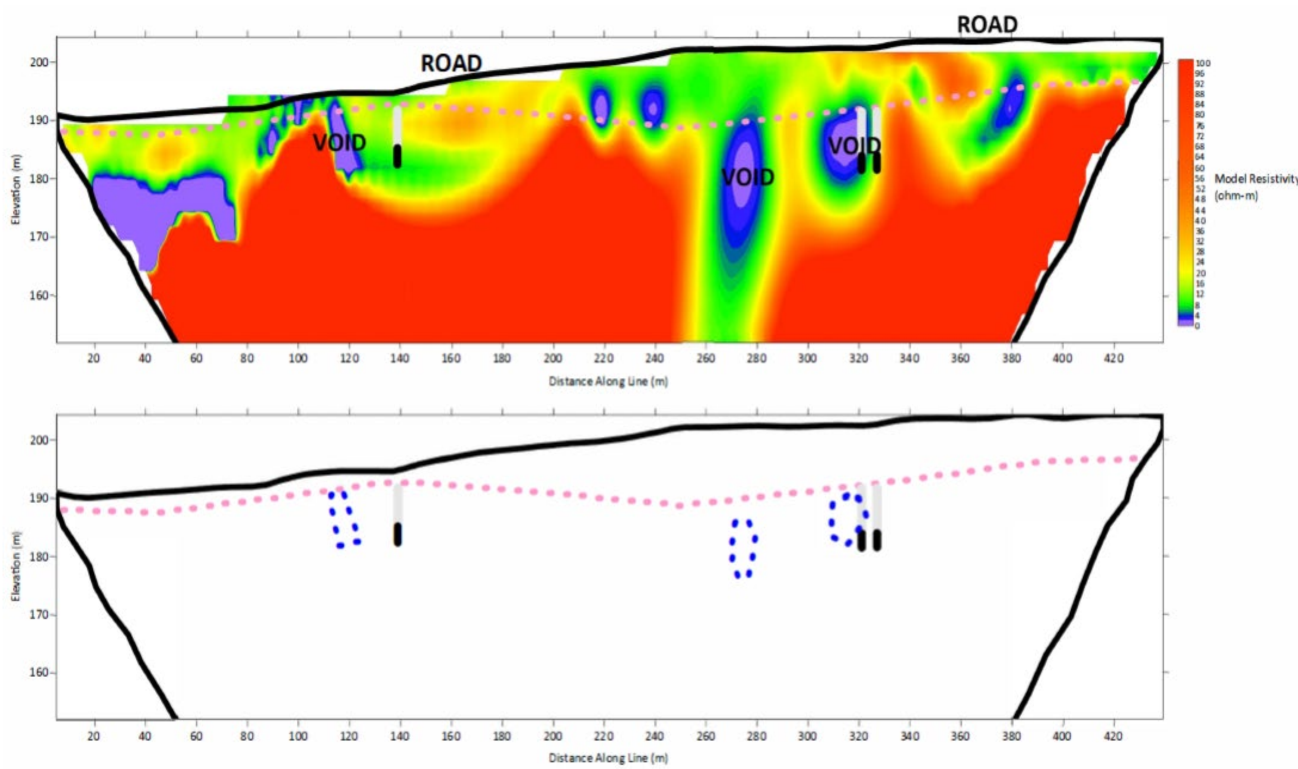

Figure 5.3: Preliminary ERI results from the Caledonia Mines investigation. Low-resistivity anomalies (blue zones) interpreted as voids beneath surface infrastructure, supporting subsurface hazard identification and remediation planning.

5.3.3 Project Outcome

WSP developed a conceptual filling and rehabilitation strategy to mitigate risks, including:

- Backfilling voids with clean gravel under controlled angles of repose.
- Staged remediation planning, beginning with localized stabilization followed by major filling campaigns.
- Ongoing monitoring through extensometers and drone surveys.

5.3.4 Project Significance

This project showcased WSP's ability to integrate geophysics, drilling, and geomechanical assessments to evaluate subsurface hazards in complex legacy mine environments. The Caledonia Mines investigation directly informed closure planning, regulatory compliance, and rehabilitation design for infrastructure protection. It also demonstrates WSP's expertise in applying advanced geophysical tools such as ERI and cavity laser scanning to support subsurface characterization and risk mitigation.

5.4 Case Study: Historic Mines Large-Scale Detection and Mapping, Victoria, Australia

5.4.1 Objectives

The project aimed to address the legacy of Victoria's gold rush era (1850s–1910s), which left hundreds of thousands of abandoned mine shafts, many hidden beneath vegetation. The primary objective was to develop and deploy a fully automated, large-scale AI detection method to uncover previously undocumented mine shafts across Victoria, Australia, supporting the Victorian Government in managing legacy mining sites and informing the public about associated risks.

5.4.2 Scope of Work

The project covered the areas of Victoria where high-resolution LiDAR had already been collected by the Department of Transport and Planning, enabling analysis and automated processing. The last phase included a new LiDAR collection zone, where the insights from previous phases directly informed the LiDAR collection and processing.

The project included four phases with corresponding Areas of Interest (AOIs) summarized in Table 5.2.

Table 5.2: Scope of Victoria Historic Mines Project

Region	Land Area	File Size	LiDAR Point Density	DEM Resolution	Purpose
AOI1, Golden Plains Region	5,996 km^2	9 TB	17 ppm^2	0.5 m	Develop and evaluate an automated method to find historic mine shafts and estimate their depth, using LiDAR and DEMs as input data.
AOI2, all areas of Victoria with LiDAR over 8 ppm^2	85,995 km^2	22 TB	Varying, at least 8 ppm^2	Varying, mostly 1 m	Scale up the automated method to a larger area (approximately 40% of Victoria)
AOI3, Goldfields Region (subset of AOI2)	25,463 km^2	7.4 TB	Varying, at least 8 ppm^2	Varying, mostly 1 m	Refine the method to produce a higher-quality output dataset for the Central Goldfields region.
AOI4, Cobungra-Dargo (high country)	7,635 km^2	4.7 TB	12 ppm^2	0.5 m	Apply the method to a new LiDAR collection zone in high country terrain.
TOTAL (AOI1+ AOI2 + AOI4)	**99,626 km^2 (38,466 mi^2)**	**35.7 TB**			

5.4.3 Methodology

Figure 5.4 gives an overview of WSP's custom-built system for detecting historic mining activity.

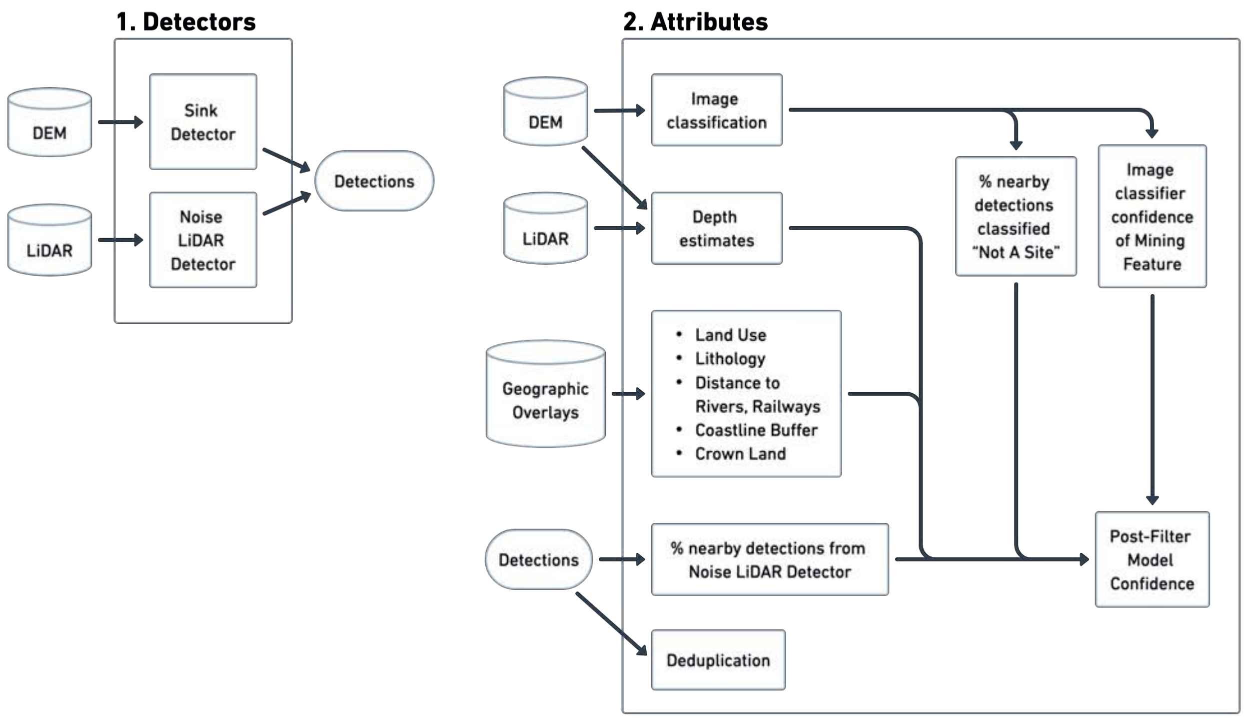

Figure 5.4: Overview of Historic Mines Detector System

Two detectors detect mine shafts and shallow workings: the sink detector and the noise LiDAR detector.

- The Sink Detector uses a combination of hydrological processing and classical computer vision to detect potential shafts. Shafts are hydrological sinks: water can flow into them but cannot flow out.

The Noise LiDAR Detector finds clusters of noise points below ground level to detect potential shafts. This is used to capture shafts where LiDAR misclassification renders the DEM inaccurate.

A machine learning image classifier model is used to get an initial classification of each detection as mining or non-mining.

The model was trained using labelled examples of mining and non-mining detections. These were labelled via desktop review of the DEM.

The system calculates many other attributes of the detections (e.g. depth, land use, categorization of nearby detections by the image classifier, etc.)

All attributes are passed to a statistical model to produce a final probability that the site is a mine. Detections below a probability threshold are filtered out.

System performance was evaluated two ways:

- Precision: The percent of detections that are true positives. This was measured using a held-out set of labelled examples (not used for model training).
- Recall: The percent of mines that the system detects. This was measured using field-verified mining features from the Geological Survey of Victoria.

5.4.4 Key Findings

Data quality is key, as reflected in all key findings:

Outcomes are improved by using spatial overlays to screen out particular land uses. Logged areas in forests, plantations and built-up areas all produce false detections that can be screened out with the right overlay.

High ground point density is critical. LiDAR may have high point density overall, but if dense vegetation may impact ground point density, DEM quality, and overall results.

LiDAR misclassification can cause both false positives and false negatives.

Where low noise points are misclassified as ground points, they create apparent “holes” in the DEM, which the system incorrectly picks up as mining activity.

Where ground points in mine shafts are misclassified as noise, the mine shaft will be shallow or smoothed over in the DEM. These sites can be detected by finding clusters of LiDAR noise points below ground level; however, this comes at the cost of additional false positives due to actual noise.

These problems are uncommon, accounting for a small number of errors relative to the number of real shafts detected. They can be reduced further when the LiDAR classification is reviewed and improved as part of the project.

5.4.5 Project Outcome and Value

- The method was applied to 38,466 mi^2 of land (equivalent to about 55% of Missouri), processing over 30TB of data.
- 224,000 sites were detected, including both mine shafts and shallow workings.
- Precision ranged from 84–95%, and recall from 64–92%, depending on input data quality.
- The Geological Survey of Victoria reported a “100% hit rate” in field verifications.
- 204,000 detected sites from the first two regions have already been made public, significantly improving the accuracy and completeness of known shaft locations.

- The project methodology and results were published in two technical reports (Silver et al., 2025a; Silver et al., 2025b).

5.4.6 Project Significance

This project pioneered a new, scalable method for detecting abandoned mine shafts, setting a benchmark for digital innovation in legacy mining risk management.

The project delivered transformative outcomes for the client:

- Enabled rapid, large-scale analysis that would have been unfeasible with manual or desktop methods.
- Greatly improved the safety and management of legacy mining sites.
- Supported the client's mission to inform the public and empower communities and land managers with accurate, accessible information.
- Fostered further collaboration and expansion into new regions due to the client's trust in the results.

5.5 Case Study: Proof of Concept LiDAR-based Mine Detection in Old Lead Belt

WSP applied the LiDAR-based mine shaft detection method to a Proof of Concept (POC) area, the Old Lead Belt (see Figure 5.6 for POC area extent). The method is described in Section 5.4 Case Study: Victoria Historic Mines Large-Scale Detection and Mapping. The POC used publicly available DEM data from the USGS 3D Elevation Program. Publicly available DEM data coverage includes most of Missouri, so the POC could easily be extended to the whole state.

Figure 5.5 illustrates the benefit of LiDAR-based methods over imagery for detecting mine workings. It shows some detected mine workings close to US 67, a location of potential interest to MoDOT. The mine workings are clearly visible on the elevation model and are automatically detected. However, they are obscured by vegetation in the satellite imagery.

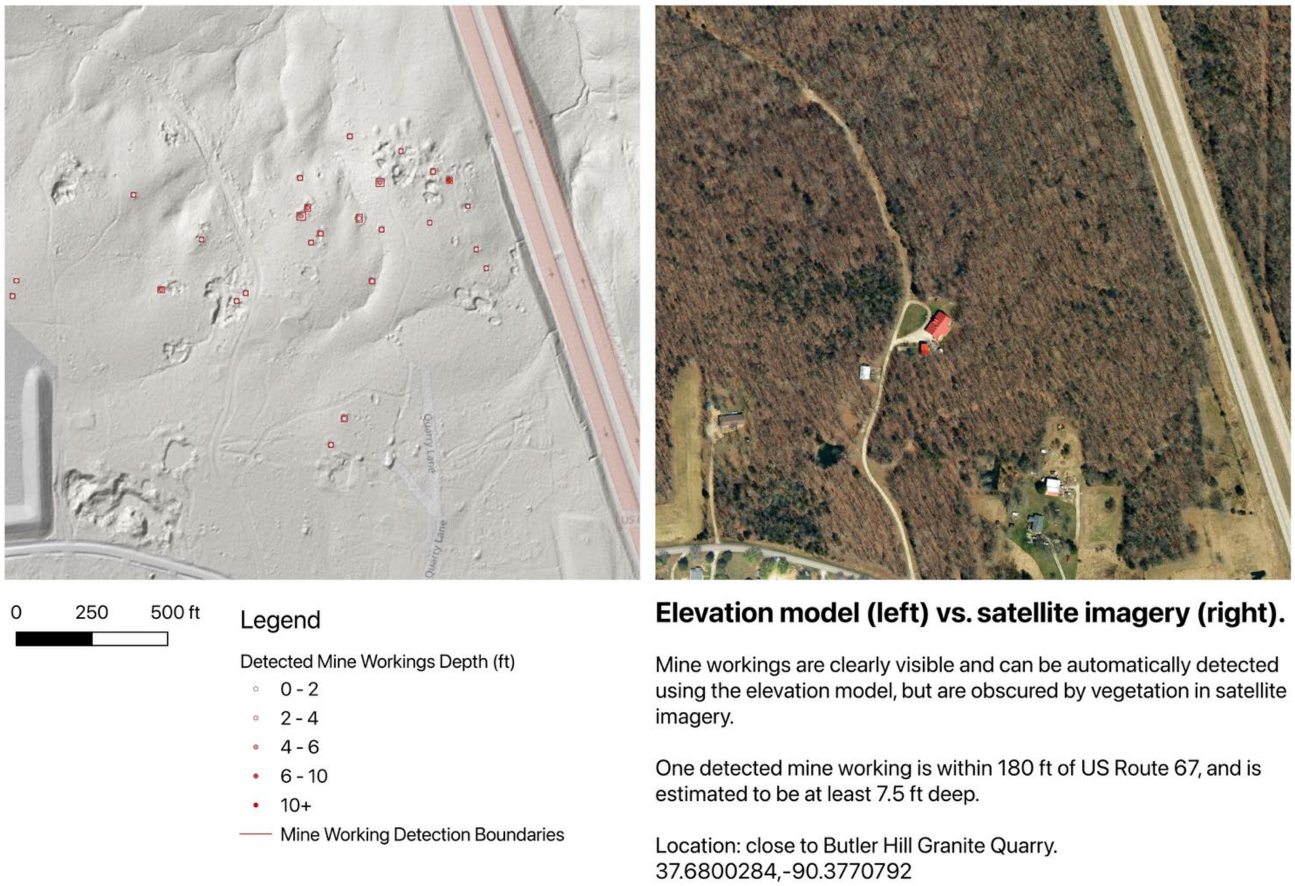

Figure 5.5 LiDAR vs. imagery for mine working detection

Figure 5.6 provides an overview of the POC area, as well as two detail maps that show the system successfully detecting shallow workings and karst dolines. The large dolines are filtered out; however, the system could easily be adapted to detect them as a separate landform.

This POC illustrates the effectiveness of LiDAR-based methods as a screening method for finding mine workings at a large scale, including in areas close to major roads. It could easily be extended to cover any area with available DEMs, i.e. most of Missouri.

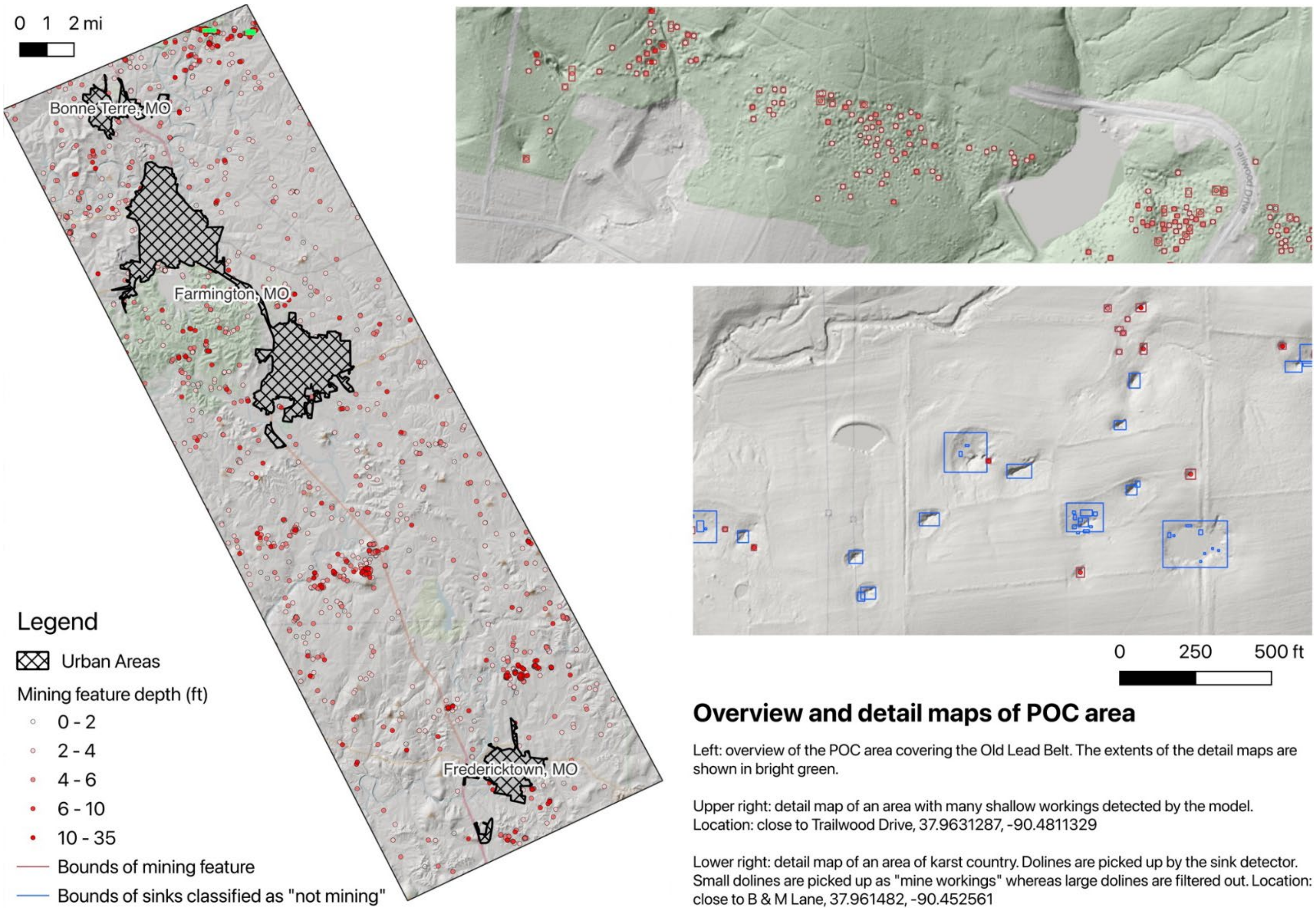

Figure 5.6: Proof of Concept of LiDAR-based mine detection in the Old Lead Belt

5.6 Case Study: Manitoba Mines-Crown Pillar Thickness Evaluation

5.6.1 Objectives

The primary objective was to conduct a non-intrusive geophysical investigation to delineate the presence of underground voids, weak zones, and other subsurface anomalies that may pose a risk to road construction over the mine. Results were intended to guide decisions for geotechnical drilling and roadway design.

5.6.2 Scope of Work

WSP carried out subsurface characterization in relation to an abandoned underground gold mine.

5.6.3 Methodology

Due to the remote location of the survey area and standing water over much of the planned roadway, the ERI method was selected as the primary method for void detection:

- ERI: Performed using stainless steel electrodes and automated switching to evaluate subsurface resistivity. Utilized the dipole-dipole and strong gradient arrays to achieve data density and lateral resolution for void detection and crown pillar thickness estimation. Resistivity data was used to evaluate bedrock features representative of mine voids and estimations of crown pillar thickness.

One mobilization was completed in May, 2012, with ERI profiles positioned over the abandoned mine working based on historical mine maps and exploratory drilling information. A total of eleven ERI transects were completed over the area of interest with the position of each subsequent line adjusted based on in-field interpretation of previous profiles to ensure proper line placement, depth of investigation, and acquisition parameters (i.e., electrode spacing).

5.6.4 Key Findings

Figure 5.7 presents representative ERI resistivity sections collected over the project area with bedrock anomalies of interpreted voids highlighted. The highlighted features represent mined areas, sections of interpreted mine void collapse, and areas of thin or compromised crown pillar. These results were used to develop a targeted drilling program that used vertical and angled borings to confirm void depths and crown pillar thickness.

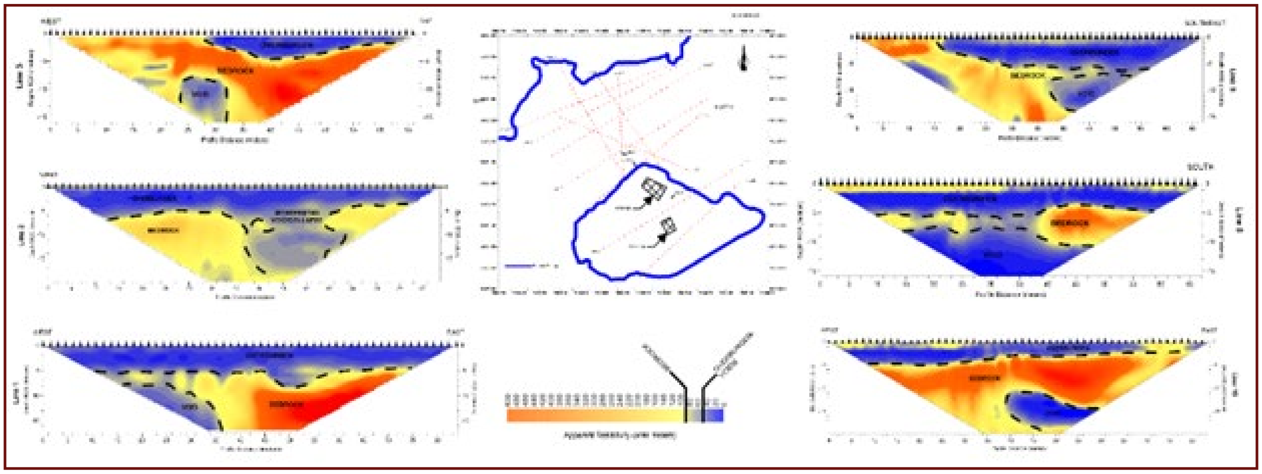

Figure 5.7: Representative ERI Resistivity Profiles

Resistivity profiles collected over the area of proposed roadway construction. Profiles of intact voids with a thick crown pillar are in the top left and bottom right. ERI profiles characteristic of a thin or potentially compromised crown pillar are shown in the bottom left and upper right panels. An interpreted collapse feature is observed in the left center panel, where the thin crown pillar has collapsed with infill of overburden and bedrock material.

Key findings from the geophysical survey were:

- Overburden thickness ranged from 20 to 40 feet with variations in bedrock topography interpreted from ERI results.
- Zones of irregular, low resistivity were interpreted as mine voids and collapse features within the area of investigation.
- Reliable estimates of thin or absent crown pillar were made from ERI results and were integral in the design of the geotechnical drilling program.
- Maps of void areas, thin or absent crown pillar, and proposed confirmatory drilling locations were provided based on results.

5.6.5 Limitations

As with all geophysical investigations, results were interpretive and subsequently correlated with borehole data obtained following the ERI survey. The presence of standing water limited access in some areas of ERI data coverage and also limited options for the deployment of other techniques (i.e., MASW) that could be used to evaluate the stiffness of the overburden soils and provide confirmation of voids interpreted from ERI results.

5.6.6 Project Outcome and Value

The use of ERI provided an accurate picture of subsurface conditions, identifying areas with interpreted voids and those with thin or compromised crown pillars. These results enabled informed and strategic decision-making on the design of a geotechnical drilling program. The project demonstrated WSP's capability in applying a non-intrusive geophysical technique to characterize the subsurface and maximize the drilling and exploration budgets with a targeted approach.

5.6.7 Project Significance

The project successfully characterized various voids and similar features that have the risk of subsiding beneath the planned road. The project clearly integrated geophysical methods together with the WSP expertise to complete subsurface characterization by providing ERI profiles.

5.7 Case Study: Contaminant Fate and Transport Karst Investigation

5.7.1 Objectives

The primary objective was to conduct a non-intrusive geophysical investigation to delineate the presence of underground voids, weak zones, and bedrock variations that may act as groundwater preferential pathways. Results were intended to guide decisions for roadway safety and long-term closure planning.

5.7.2 Scope of Work

WSP USA Inc. provided geophysical services related to the subsurface characterization of a former retail petroleum location in St. Clair, MO, where impacts to the subsurface had been reported, with data gaps noted on the fate and transport of these impacts. The site was in an area of known karst, divided by a mapped fault, and along a ridge that separates the drainage of the Meramec and Bourbeuse Rivers.

5.7.3 Methodology

Three complementary geophysical methods were deployed:

- Seismic Refraction Tomography (SRT): Acquired seismic data with a 24-channel seismograph and sledgehammer source to determine compressional-wave velocities (Vp), providing top of bedrock information throughout the project area.

- Electrical Resistivity Imaging (ERI): Performed using stainless steel electrodes and automated switching to evaluate subsurface resistivity and induced polarization (IP) contrasts. Data was collected with the dipole-dipole array to provide data with good lateral resolution with this array being optimal for the collection of IP data. Resistivity data were used to evaluate bedrock features representative of karst and structural features with IP data used to evaluate for the is of dense non-aqueous phase liquid (DNAPL) within these features.

- Multi-channel Analysis of Surface Waves (MASW): Acquired seismic data with a 24-channel seismograph and sledgehammer source to determine shear-wave velocities (Vs), providing stiffness and depth information for areas of fault offset identified along a key ERI profile.

- Borehole Geophysical Logging: Used fluid temperature/fluid resistivity, natural gamma, and 3-arm caliper instruments to map fractures within existing bedrock groundwater monitoring wells to provide a qualitative evaluation of flow into the borehole.

One mobilization was completed in July 2013, with ERI profiles positioned to avoid subsurface utilities identified during previous environmental field investigations. SRT data was used to provide bedrock information over utility corridors and over faulted areas to confirm bedrock surface topography. A total of six ERI transects and five seismic refraction profiles were completed with borehole geophysics completed in five existing bedrock monitoring wells. The supplemental MASW line was collected over an interpreted fault offset along the primary resistivity profile.

5.7.4 Key Findings

Figure 5.8 presents representative ERI resistivity and IP sections in conjunction with SRT and MASW-derived velocity profiles. The resistivity cross-sections highlight low-resistivity and IP anomalies in bedrock consistent with impacted clay-filled karst, while the SRT and MASW results delineate fault offsets and bedrock topography variations. Together, these datasets provided evidence for the presence of karst features that were part of the data gaps analysis for contaminant fate and transport across the site. These anomalies represent potential source areas outside of the primary release.

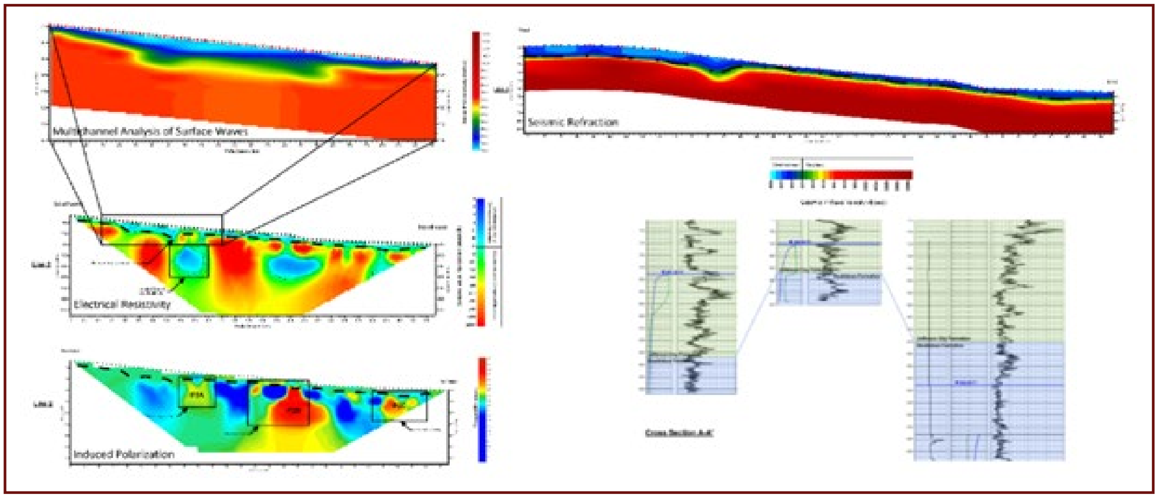

Figure 5.8: Representative ERI Resistivity Profiles

Profiles collected over the fault with low resistivity anomalies (left center) interpreted as clay-filled karst features. Induced polarization (IP) anomalies (left bottom) over the same features were characteristic of chargeability anomalies associated with DNAPL impacts. The supplemental MASW profile (top left) confirmed bedrock surface variations over the area adjacent to the fault. Seismic refraction results (right top) over an area of known utilities illustrating bedrock offset at the fault and borehole geophysical results (right bottom) showing unit correlation and fault offset.

5.7.5 Limitations

As with most geophysical investigations, results are interpretive and must be correlated with borehole or direct investigation data. The presence of utilities limited ERI data coverage with some borehole limitations related to performing the survey within wells that had not been properly developed prior to logging.

5.7.6 Project outcome and value

The combined use of ERI (resistivity and IP), SRT, MASW, and borehole logging provided an integrated picture of subsurface conditions, identifying areas with potential voids and representative of potential contaminant fate and transport. These results enabled informed and strategic decision-making on the location of future monitoring wells and the design of a remedial system capable of capturing areas of impact previously unidentified through drilling alone. The project demonstrated WSP's capability in applying multi-method geophysics to environmental data gaps analysis and conceptual site model development.

5.8 Case Study: 3D Geophysical Characterization of Sinkhole Structure in Greene County, Missouri

5.8.1 Objectives

MS&T completed geophysical surveys of a sinkhole near US 60 in Greene County, Missouri using ERT and MASW techniques. The objective of the surveys was to determine if the sinkhole was at risk of catastrophic collapse, since this would endanger nearby infrastructure.

5.8.2 Scope of Work

MS&T conducted this project in 2019 in Greene County, Missouri, which is an active karst area with many sinkholes and subsurface voids. Two geophysical techniques, ERT and MASW, were used to better understand sinkhole development and were verified through borehole validation.

5.8.3 Methodology

- Sixteen parallel ERT lines were acquired across and in proximity to an active sinkhole. ERT lines were separated by 6.1 m and were acquired with an AGI R-8 Supersting multichannel resistivity array. Each ERT line had 168 electrodes, and data were acquired using the dipole-dipole configuration. Each line was initially processed as a 2D resistivity profile using Res2DInv software. Then, the sixteen 2D data files were combined into a 3D data file and inverted using Res3DInv software. The 2D data sets were used to generate pseudosections (cross-sections of resistivity) for comparison with 1D borehole and MASW data, while the 3D data sets were used to generate resistivity depth slices at different elevations to better understand the sinkhole structure.

- MASW data were acquired at nine locations using a Seistronix RAS-24 24-channel seismograph with geophones spaced at 2.5 ft intervals. MASW data were processed using SurfSeis software to provide a 1D profile of shear wave velocity at each location.

- One borehole was advanced to the bedrock surface using a hollow-stem auger and HQ core barrels to core through bedrock.

5.8.4 Key Findings

Figure 5.9 shows data acquired along one ERT line (line 2), along with co-located MASW results and the borehole log. Both axes on the ERT profile are given in meters. Low resistivity values (shown in blue) indicate areas of soil. Figure 5.9 shows:

- Bedrock topography in this area is highly irregular; steep bedrock troughs and knobs are common.

- The two MASW shots acquired along this line correlated well with the ERT data. Rapid increases in shear wave velocity (indicating the transition from soil to bedrock) in the 1D MASW profile corresponds to the soil-bedrock interface indicated by rapid changes in resistivity in the ERT profile.

- The ERT data agree well with the borehole log (CH –1), as the soil-bedrock interface in both techniques occur at the same depths.

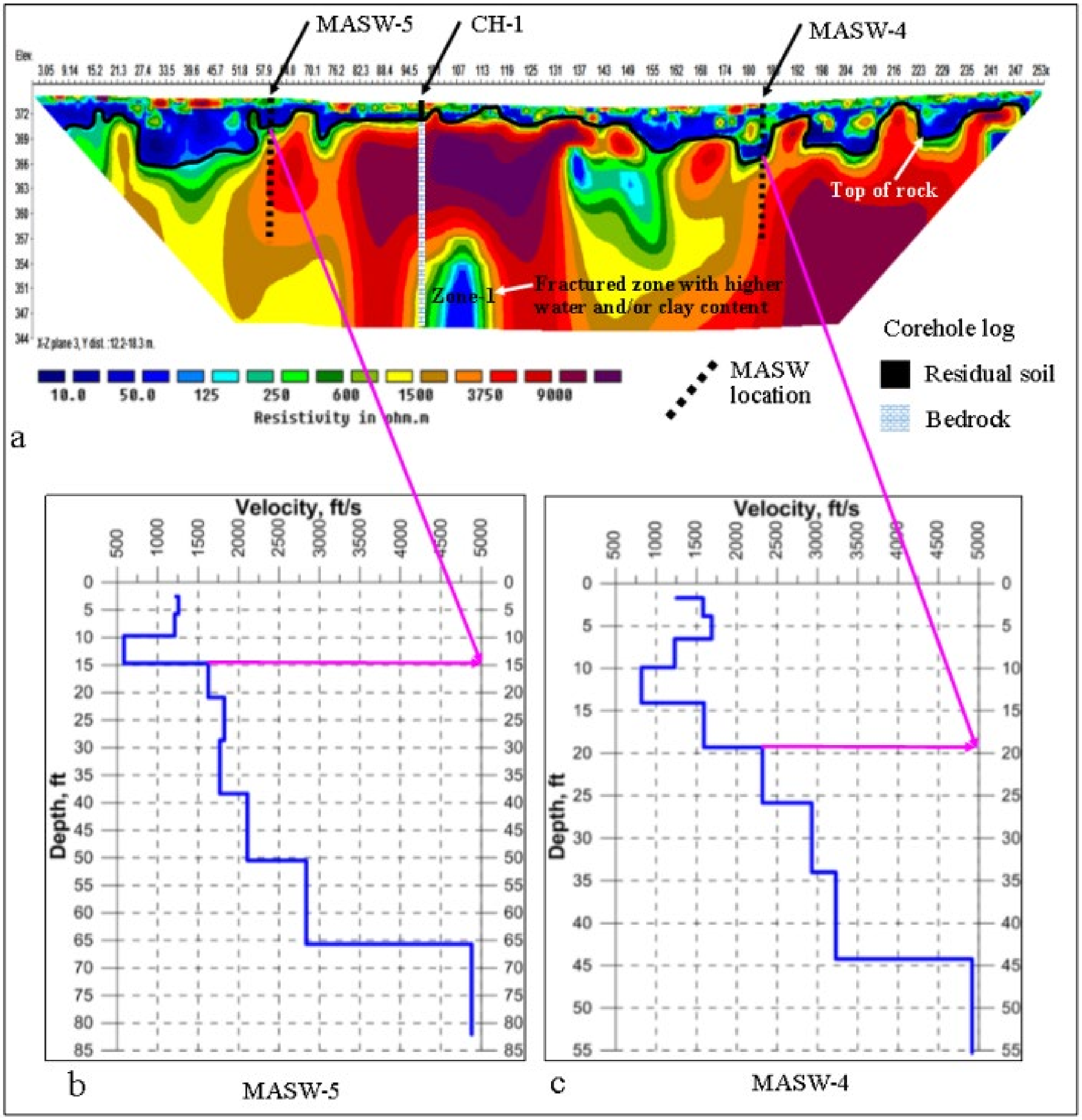

Figure 5.9: a) ERT profile along line 2, b) 1D shear wave profile from MASW at location 5, c) 1D shear wave profile from MASW at location 4.

Figure 5.10 shows 3D ERT data created by processing sixteen 2D profiles. Data are displayed as a series of 16 depth slices, and the location of the sinkhole is shown by a black circle on the surface in Figure 5.9a. Figure 5.10a shows the uninterpreted data, while Figure 5.10b shows the location of the sinkhole in all depth slices as well as features that are interpreted as solution widened joints. This figure shows that:

- 3D ERT data can image sinkhole geometry, including changes in sinkhole width with depth.

- 3D ERT data can delineate solution-widened joints that are filled with water or moist clay/soil (joint sets 1-3 in Figure 5.9b). Note that the width of these joint sets changes as a function of depth.
- The solution-widened joints are lower resistivity, indicating water flow through these joints.

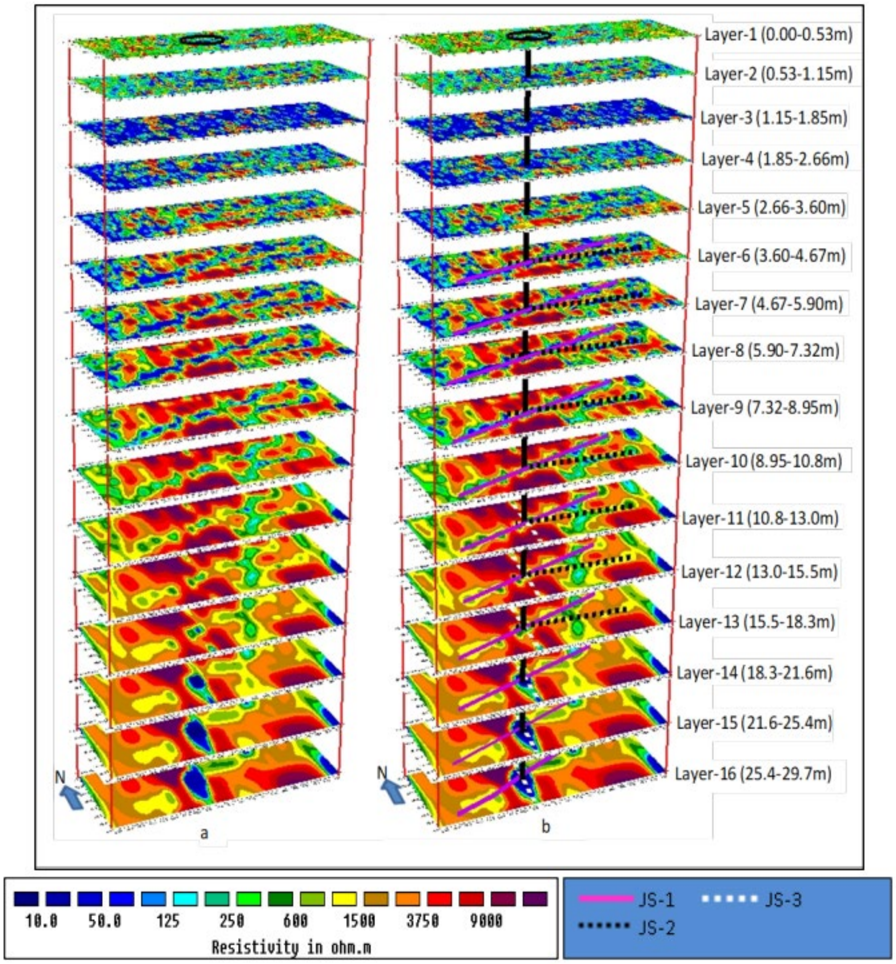

Figure 5.10: a) A series of 16 uninterpreted resistivity depth slices and b) resistivity slices with sinkhole location and interpreted joint sets shown.

5.8.5 Project Outcomes and Findings

This project provided data that allowed MoDOT engineers to assess the risk posed by an active sinkhole and to make decisions about methods for stabilizing the subsurface at this location. The ERT data showed the development of the sinkhole along solution-widened joints and indicated that the sinkhole is filled with soil and is developing slowly, and so is not at risk of catastrophic failure. Also, the 3D ERT depth slices showed the locations of the solution-widened joints that were funneling soil and water into the sinkhole and thus creating zones of weakness that could later manifest as surface subsidence.

Identification of the flow pathways to the sinkhole allows engineers to reduce drainage through these joints and thus mitigate piping and subsidence hazards.

5.8.6 Project Significance

The project demonstrated Missouri S&T's ability to perform 3D geophysical surveys using multiple geophysical methods to reveal complex subsurface structures. The 3D ERT data successfully identified the joint sets draining into an active sinkhole, and MASW data were useful for constraining ERT data and increasing confidence in data interpretation. Missouri S&T has the expertise to use these tools to identify hazards to infrastructure and to find economical methods for hazard reduction.

5.8 Case Study: Analysis of the Potential of MASW for Large-Scale Geologic Mapping in Urban Areas – I-70 corridor in St. Louis ,Missouri

5.8.7 Objectives

In this project, Missouri S&T was commissioned by MoDOT to determine if MASW could be used for large-scale geologic mapping in an urban area. The location was downtown St. Louis, where sources of electrical and magnetic noise made other techniques ineffective.

5.8.8 Scope of Work

This work was conducted along a 6,400 ft transect in St. Louis, Missouri. MASW data were acquired by MS&T and were compared to boring logs and Seismic Cone Penetrometer (SCP) data provided by MoDOT.

5.8.9 Methodology

MASW data were acquired by Missouri S&T in May 2003 along a 6,400 ft segment of I-70 in downtown St. Louis. Data were acquired using a Seistronix RAS-24 24-channel seismograph with 4.5-Hz geophones spaced at 10-ft intervals. A 20-lb sledgehammer and metal plate were used as the source. The station interval was 40 ft for the entire length of the traverse, resulting in more than 160 separate traces (vertical shear wave velocity profiles). MASW were compared to boring logs and SCP data that were available at a few locations near the MASW profile.

MASW data were processed using Surfeis software to create a 1D shear wave velocity profile at each station. The values of velocity with depth for all stations were also combined into a single data set and contoured to create a 2D profile of shear wave velocity along the traverse. Individual profiles were compared to the nearest boring logs and SCP data.

5.8.10 Key Findings

Figure 5.11 shows the 2D profile of shear wave velocity along the length of the traverse. The data extended to a depth of 100 ft, but Figure 5.11 truncates the data at a depth of 50 ft, since the zone of interest (the soil bedrock interface) occurs in this depth range. Figure 5.12 compares individual MASW profiles to the nearest boring logs (Figure 5.12a and Figure 5.12b) and SCP data (Figure 5.12c and Figure 5.12d). These figures show that:

- The bedrock surface near I-70 is highly irregular, with the depth to bedrock varying from 20 ft to 40 ft below ground surface.
- MASW profiles agree well with boring logs, with notable increases in velocity when bedrock is encountered.
- MASW profiles agree reasonably well with SCP data. Differences in velocity values may be due to 1) differences in measurement scale, 2) differences in location (boreholes were ~50 ft from the MASW traverse), or 3) differences in measurement technique.

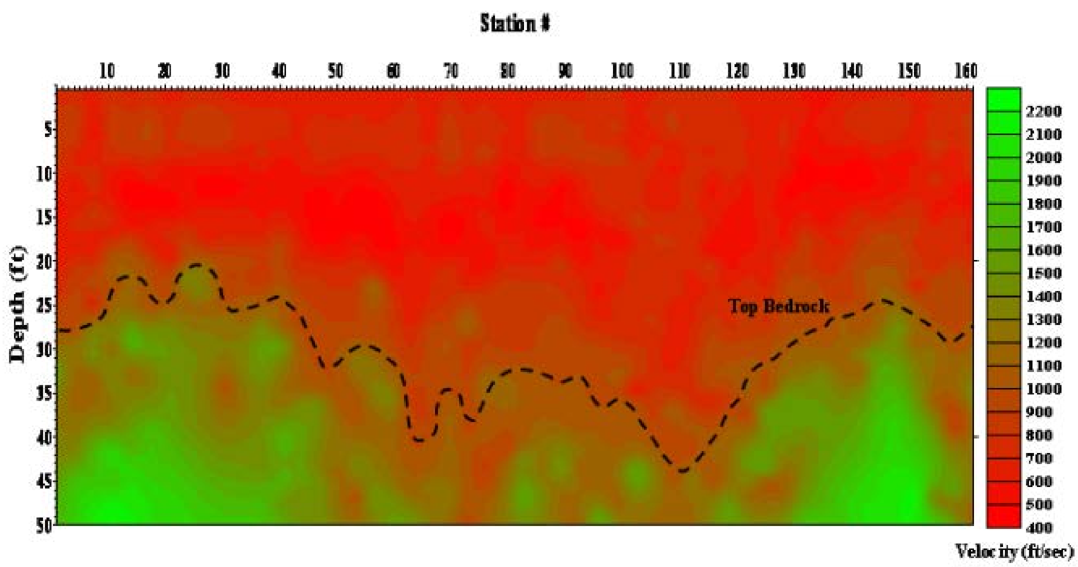

Figure 5.11: 2D profile of shear wave velocity along I-70.

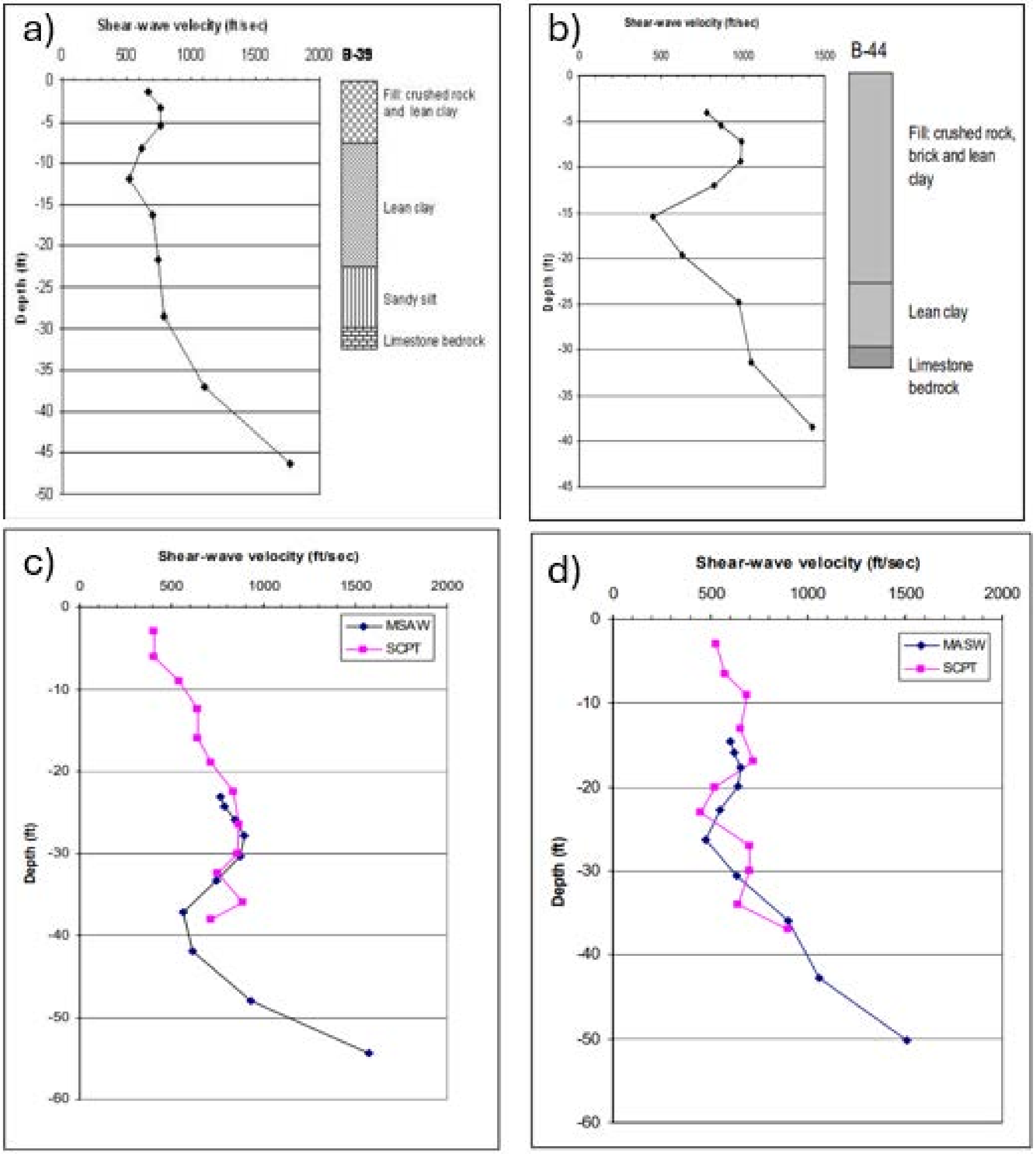

Figure 5.12: a) and b) Shear wave velocity at boreholes 39 and 44, respectively and c) and d) Shear wave velocity and SCP at MASW stations 1 and 140, respectively

5.8.11 Project Outcomes and Value

This project showed that MASW is an effective technique for mapping subsurface features in urban environments that limit most geophysical techniques. MASW techniques show profiles of velocity with depth that agree well with conventional coring and SCP techniques, but MASW resolution decreases with depth, so MASW cannot detect deep, thin layers that may be visible on SCP logs.

5.8.12 Project Significance

This project shows that Missouri S&T has the capability to do large-scale geophysical mapping, even in challenging urban environments. Shear velocity mapping using MASW can be used to find variable depth to bedrock or subsurface voids that can pose a hazard to infrastructure, and MASW techniques can be employed in areas where other geophysical techniques may not be successful.

Chapter 6: Recommendations

Based on the literature review, evaluation of geophysical methods, review of other State DOT practices, and WSP and Missouri S&T case studies, the following recommendations are provided to guide MoDOT's implementation of subsurface void detection and karst risk assessment beneath highway infrastructure.

6.1 General Strategy

Missouri's variable geology requires a tiered, multi-method investigation framework rather than relying on a single geophysical technique for evaluating suspected subsurface void conditions beneath highways. Subsurface conditions in Missouri's karst and mining-prone regions are highly heterogenous, and no individual method consistently provides sufficient resolution, depth of penetration, and reliability across all site conditions.

Geophysical investigations should be selected based on site-specific geology, anticipated void depth and size, overburden thickness and soil type, access constraints, and required confidence level. A multi-method approach improves detection reliability, reduces false positives, and supports risk-informed decision making.

Remote sensing methods, such as the recently developed LiDAR-based methods discussed in Sections 5.4 and 5.5, should be considered as a highly-effective tool for screening large areas and identifying targets for further investigation via geophysical methods.

6.2 Recommended Investigation Framework

For suspected void conditions beneath highways, the following phased framework is recommended:

6.2.1 Phase 1 – Desktop Screening

Desktop screening represents the initial step in the investigation process and is intended to identify potential void-related risk indicators prior to field activities. This phase compiles and evaluates available geological, topographic, historical, and maintenance data to establish a preliminary understanding of site conditions. Early identification of karst features, historic mine workings, surface depressions, or documented settlement allows investigation efforts to be focused efficiently and proportionally to risk.

Key desktop screening activities include:

- Review of GeoSTRAT and Missouri Geological Survey datasets
- Evaluate LiDAR topography for depressions

- Review historic mine maps
- Assess maintenance history and settlement records

6.2.2 Phase 2 – Surface Reconnaissance

Surface reconnaissance provides field-based confirmation of conditions identified during desktop screening and allows refinement of site-specific risk indicators. This phase focuses on direct observation of pavement performance, surface deformation, drainage patterns, and geomorphic features that may suggest subsurface void development. Documenting visible distress, localized settlement, cracking patterns, or sinkhole indicators help prioritize areas for targeted geophysical investigation and reduce uncertainty prior to subsurface imaging.

Primary surface reconnaissance tasks include:

- Field walkover assessment
- Pavement distress mapping
- Visual inspection of drainage and sinkhole indicators

6.2.3 Phase 3 – Primary Imaging

ERT is recommended as the primary subsurface imaging method for void detection beneath Missouri highways, particularly in karst terrain and historic mining areas.

ERT demonstrated:

- Reliable depth imaging capability
- Sensitivity to lithologic contrasts and void zones
- Effective delineation of karst features
- Consistent validation through drilling in other DOT case studies
- Applicability to both natural karst voids and mine workings

ERT provides two-dimensional or three-dimensional subsurface resistivity distributions, allowing identification of air-filled voids (high resistivity anomalies), water-filled cavities (low resistivity anomalies), weak or weathered zones, and mine collapse features.

MoDOT is advised to prioritize ERT for:

- Suspected karst voids in limestone terrain
- Mine void delineation in historic mining districts
- Investigation of settlement-prone highway corridors
- Pre-design subsurface characterization in high-risk zones

6.2.4 Phase 4 – Supplemental Methods (As Needed)

Supplemental geophysical methods may be applied when additional resolution, depth refinement, or confirmation is required beyond the primary imaging results. These methods are selected based on site-specific conditions to enhance reliability and reduce uncertainties prior to subsurface verification.

The following supplemental techniques may be implemented as needed:

GPR

GPR is recommended for:

- Shallow investigations (<15–20 feet, depending on soil conductivity)
- Pavement-level anomaly detection
- Rapid corridor screening
- Utility mapping and near-surface void detection

GPR is particularly useful for early screening of pavement distress areas, however, GPR should not be used as a standalone method in conductive soils or where deeper voids are anticipated. GPR is most effective when paired with ERT or seismic methods.

Seismic Methods (MASW / Refraction)

Seismic methods are recommended to:

- Define bedrock depth
- Identify weakened or fractured zones
- Provide stiffness characterization
- Support structural assessment of overburden and bedrock

MASW is particularly valuable for profiling shear wave velocity, which assists in identifying the competent rock, weathered zones, and collapse-prove zones. Seismic refraction is effective for mapping bedrock surfaces but should be used with caution where velocity inversion conditions may exist. Seismic methods are recommended where structural characterization is required in addition to void detection.

Microgravity

Microgravity may be considered for:

- Cost-effective large-area reconnaissance
- Detection of larger density contrasts
- Investigation of suspected deep mine workings

Microgravity requires experienced interpretation and careful correction for near-surface effects. It should be implemented only where qualified geophysical interpretation resources are available. Microgravity is best suited for large void detection rather than small, shallow cavities.

Remote Sensing Applications

LiDAR and InSAR are recommended to be used as regional and asset-management tools rather than direct subsurface imaging techniques, it is recommended for:

- Regional screening for karst-related depressions
- Surface deformation monitoring
- Identification of subsidence trends
- Prioritization of field investigations

These technologies provide valuable spatial context but do not replace subsurface imaging methods. Remote sensing supports corridor prioritization and long-term monitoring programs.

6.2.5 Phase 5 – Targeted Verification

Targeted verification represents the critical step in confirming the presence, geometry, and material characteristics of suspected subsurface voids identified during prior investigation phases. This phase transitions from indirect geophysical interpretation to direct subsurface confirmation, reducing uncertainty and providing the data necessary for engineering evaluation and design. Verification activities are focused and proportional to identified risk and anomaly significance.

Primary verification activities include:

- Drilling and borehole imaging/cavity scanning tools
- Confirmation of void geometry
- Material characterization

6.2.6 Phase 6 – Remediation and Confirmation

Where verification confirms void presence or instability risks, remediation measures are implemented to restore structural integrity and mitigate future subsidence. This phase integrates engineering design, construction stabilization, and post-remediation validation to ensure effectiveness. Follow-up confirmation ensures that corrective actions meet performance objectives and that residual risk is minimized.

Remediation and confirmation measures may include:

- Grouting or stabilization as required
- Post-construction geophysical confirmation survey

This framework supports risk-based decision making and scalable investigation intensity.

6.3 Long-Term Strategy

Over the long term, management of subsurface void risk in Missouri requires sustained integration of remote sensing and geophysical information into infrastructure planning and lifecycle decision-making. Rather than treating void detection as a project-specific activity, long-term strategy involves maintaining institutional knowledge, continuously improving data quality, and embedding subsurface risk considerations into reconstruction, rehabilitation, and expansion programs.

Establishing a centralized repository of geophysical investigations and confirmed void conditions allows trends to be evaluated over time and supports refinement of risk models. As additional data are collected, predictive capabilities improve, enabling more informed prioritization of capital investments in vulnerable corridors. Periodic reassessment of high-risk regions, supported by evolving technologies, further strengthens resilience against progressive subsurface deterioration.

A long-term approach ensures that subsurface hazard management becomes an ongoing component of transportation system stewardship, enhancing reliability, reducing lifecycle costs, and supporting sustainable infrastructure performance across Missouri.

Chapter 7: Limitations

This report provides an evaluation of geophysical and remote sensing technologies for detecting subsurface voids, karst features, and abandoned mine workings beneath Missouri highways. The findings and recommendations are based on literature review, review of other state DOT practices, and selected case studies. As such, the conclusions presented herein are conceptual and programmatic in nature and are subject to the limitations presented below.

7.1 Scope of Evaluation

The assessment is based on published research, agency experience, and documented case studies rather than new field investigations conducted specifically for this study, unless otherwise noted. Technology performance has been evaluated at a summary level to inform method selection and framework development. Therefore, the recommendations are not intended to replace project-specific geotechnical investigations, detailed design analyses, or site-specific engineering judgment.

7.2 Geophysical Method Limitations

Geophysical methods are indirect investigation tools that infer subsurface conditions based on contrasts in measurable physical properties. Detection capability depends on sufficient contrast between a target feature and surrounding materials. In environments where physical properties are similar, anomalies may be subtle or indistinguishable.

Resolution decreases with depth, and smaller or deeper voids may not be detected reliably. Data quality may be influenced by cultural interference such as traffic, buried utilities, pavement reinforcement, and other surface infrastructure. Additionally, soil moisture, electrical conductivity, lithologic variability, and seasonal groundwater conditions can significantly affect method performance.

7.3 Interpretation Uncertainty

Interpretation of geophysical data involves professional judgment and is subject to uncertainty. Anomalies identified in imaging results may represent voids, fractured zones, lithologic changes, utilities, construction artifacts, or natural heterogeneity. Distinguishing among these possibilities requires experience and, in most cases, corroborating information. The application of two or more geophysical methods can help reduce this uncertainty. For this reason, geophysical results should be considered screening and targeting tools.

7.4 Site-Specific Variability

Missouri's geologic conditions are highly variable and subsurface conditions may change significantly over short distances. Method performance can vary depending on depth to bedrock, overburden thickness, clay content and conductivity, groundwater presence, and accessibility constraints. As a result, findings from one corridor or region may not be directly transferable to another. Investigation approaches must be tailored to individual project conditions rather than applied uniformly statewide.

7.5 Use of Report

This report is intended to support MoDOT in developing a structured framework for evaluating and implementing geophysical technologies. It is not a substitute for project-specific geotechnical investigations, engineering design documentation, or regulatory approvals. Application of the concepts and recommendations contained herein should be performed by qualified professionals in consideration of site-specific conditions.

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Appendix A: Electrical Resistivity Tomography: Overview and Applications for Identifying Subsurface Voids

This appendix is provided as a separate, standalone document.

Appendix B: Ground Penetrating Radar (GPR): Overview, Principles, and Applications

This appendix is provided as a separate, standalone document.

Appendix C: Multichannel Analysis of Surface Waves (MASW)

This appendix is provided as a separate, standalone document.

Appendix D: Seismic Refraction

This appendix is provided as a separate, standalone document.