MoDOT Pavement Preservation Research Program
Volume IV. Pavement Evaluation Tools–Data Collection Methods

Prepared by
Neil Anderson, PhD, PEng
Lesley Sneed, PhD, PE
Brent Rosenblad, PhD, PE
Missouri University of Science and Technology
Department of Geosciences and Geological Sciences and Petroleum Engineering
Department of Civil, Architectural and Environmental Engineering
University of Missouri-Columbia Department of Civil and Environmental Engineering

Final Report Prepared for Missouri Department of Transportation
October 2015 Project TRyy1141 Report cmr16-004

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.
cmr 16-004

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
MoDOT Pavement Preservation Research Program. Volume IV, Pavement Evaluation Tools–Data Collection Methods

5. Report Date
August 3, 2015
Published: October 2015

6. Performing Organization Code

7. Author(s)
Neil Anderson, PhD, PEng; Lesley Sneed, PhD, PE; Brent Rosenblad, PhD, PE

8. Performing Organization Report No.
NUTC R300

9. Performing Organization Name and Address
Missouri University of Science and Technology

Department of Geosciences and Geological and Petroleum Engineering
1400 N. Bishop, Rolla, MO 65409

Department of Civil, Architectural and Environmental Engineering
1401 N. Pine St., Rolla, MO 65409

University of Missouri-Columbia
Department of Civil and Environmental Engineering
E 2509 Lafferre Hall
Columbia, MO 65211

10. Work Unit No.

11. Contract or Grant No.
MoDOT project #TRyy1141 (Task 3)
NUTC project #00039112
USDOT contract #DTRT06-G-0014

12. Sponsoring Agency Name and Address
Missouri Department of Transportation (SPR) http://dx.doi.org/10.13039/100007251
Construction and Materials Division
P.O. Box 270
Jefferson City, MO 65102

Center for Transportation Infrastructure and Safety/NUTC program
Missouri University of Science and Technology
220 Engineering Research Lab
Rolla, MO 65409

13. Type of Report and Period Covered
Final report (June 2012-August 2015)

14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at http://www.modot.org/services/or/byDate.htm. This report is available at http://library.modot.mo.gov/RDT/reports/TRyy1141/cmr16-004v4.pdf.

16. Abstract
The overarching goal of the MoDOT Pavement Preservation Research Program, Task 3: Pavement Evaluation Tools – Data Collection Methods was to identify and evaluate methods to rapidly obtain network-level and project-level information relevant to in situ pavement conditions to enable pavement maintenance decisions. The focus of these efforts was to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluations. Application of these technologies will ultimately enable pavement maintenance decisions that minimize cost and maintain/improve pavement quality. This report presents a summary of methods previously used by MoDOT to evaluate pavement condition, and a summary of methods investigated to evaluate pavement and subsurface conditions.

17. Key Words
Evaluation and assessment; Level of service; Maintenance equipment; Pavement maintenance; Pavement management systems; Pavement performance; Preservation; Rehabilitation (Maintenance)

18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	102	

MoDOT PAVEMENT PRESERVATION RESEARCH PROGRAM
MoDOT TRyy1141

FINAL REPORT

VOLUME IV
PAVEMENT EVALUATION TOOLS – DATA COLLECTION METHODS

August 3, 2015

Prepared for
Missouri Department of Transportation

by

Neil Anderson PhD, PEng
Department of Geosciences and Geological and Petroleum Engineering
Missouri University of Science and Technology

Lesley Sneed, PhD, PE
Department of Civil, Architectural and Environmental Engineering
Missouri University of Science and Technology

Brent Rosenblad, PhD, PE
Department of Civil and Environmental Engineering
University of Missouri-Columbia

EXECUTIVE SUMMARY

The overarching goal of the MoDOT Pavement Preservation Research Program, Task 3: *Pavement Evaluation Tools – Data Collection Methods* was to identify and evaluate methods to rapidly obtain network-level and project-level information relevant to in situ pavement conditions to enable pavement maintenance decisions. The focus of these efforts was to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluations. Application of these technologies will ultimately enable pavement maintenance decisions that minimize cost and maintain/improve pavement quality.

This report presents a summary of methods previously used by MoDOT to evaluate pavement condition, and a summary of methods investigated to evaluate pavement and subsurface conditions.

This study is sponsored by the Missouri Department of Transportation and the National University Transportation Center at the Missouri University of Science and Technology in Rolla, Missouri. This research was performed by the Missouri University of Science and Technology and the University of Missouri. The report fully documents the research.

AUTHOR ACKNOWLEDGEMENTS

The research reported herein was sponsored by the Missouri Department of Transportation (MoDOT) and the National University Transportation Center (NUTC) at the Missouri University of Science and Technology (Missouri S&T). The research was performed by Missouri S&T and the University of Missouri-Columbia. At Missouri S&T, the principal investigator was Neil Anderson, and the co-principal investigator was Lesley Sneed. The principal investigator at the University of Missouri-Columbia was Brent Rosenblad. The principal investigator for the overall project was David Richardson. Major contributions to the project were made by Evgeniy Torgashov, Abdallah Dera, Adel Elkrry, Aleksey Khamzin, Dan Iffrig, Mengxing Li, Stanley Nwokebuihe, and Aleksandra Varnavina. The assistance of each of these individuals is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Goal

The overarching goal of the MoDOT Pavement Preservation Research Program, Task 3: *Pavement Evaluation Tools – Data Collection Methods* was to identify and evaluate methods to rapidly obtain network-level and project-level information relevant to in situ pavement condition to enable pavement maintenance decisions. The focus of this effort was to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluation that will ultimately enable pavement maintenance decisions that minimize cost and maintain/improve pavement quality.

1.2 Objectives

The primary objectives of this task were to:

- Summarize state-of-the-art methods to collect pavement data (with focus on non-invasive imaging technologies)
- Compare and quantify pavement data collection methods in terms of applicability, relative ease, and relative cost, and identify potential improvements to current MoDOT data collection practices
- Recommend methods that will be selected for site specific pavement condition assessments in MoDOT Pavement Preservation Research Program, Task 4: *Site Specific Pavement Condition Assessment*

1.3 Scope of Work

The scope of work for this task was to collect and summarize techniques, especially non-invasive techniques, used by MoDOT and others to collect network-level and project-level data on pavement condition. These techniques were compared to evaluate the applicability and relative cost for various applications. This work also served to establish the assessment techniques and procedures evaluated in MoDOT Pavement Preservation Research Program, Task 4: *Site Specific Pavement Condition Assessment*.

The following work was performed in this task:

- Methods routinely used by MoDOT to assess pavement condition were examined.
- Commercially-available methods utilized by industry to assess pavement condition were examined.
- Methods currently being researched or under development to assess pavement condition were examined.
- Summary tables were developed to describe each technology in terms of applicability to network-level or project-level data production, type of pavement condition data collected (distress, structural capacity, surface characteristics), data collection method

(manual, automated, semi-automated), reliability, reproducibility, and other advantages, disadvantages, and limitations.

- Summary tables were developed to describe the planning and cost-related aspects of each technology such as crew size, cost per day, area per day, lane closure requirements, level of expertise in data acquisition and processing, etc.
- Methods were selected to conduct the site specific pavement condition assessments conducted in MoDOT Pavement Preservation Research Program, Task 4: *Site Specific Pavement Condition Assessment*. Equipment was procured and tested prior to the field investigations.

The methods that were investigated are summarized in Table 1.1.

1.4 Organization of the Report

Chapter 1 presents the goal, objectives, and scope of this task. Chapter 2 summarizes the methods that have been used by MoDOT for pavement evaluation based response from an electronic survey conducted of the MoDOT districts. The main content of this report is contained in Chapter 3, with summaries of each data collection method investigated in this task. The tables and figures provided in Chapter 3 are intended to provide MoDOT with a comprehensive yet concise description of each data collection method to enable decisions regarding which methods are appropriate for various types of pavement and subsurface investigations. Chapter 4 presents concluding remarks and recommended methods for the Task 4 investigations.

Table 1.1- Pavement/subsurface data collection methods and applicability

Method	Network-Level	Project-Level	Pavement	Subsurface
Stress Wave Methods				
Impact Echo (IE) using Portable Seismic Property Analyzer (PSPA)		x	x	
Multi-Channel Analyses of Surface Wave (MASW)		x	x	x
Conventional Refraction Seismic Surveying		x	x	x
Conventional Refraction Seismic Tomography Surveying		x	x	x
Refraction Microtremor (ReMi)		x	x	x
Ultrasonic Surface Wave (USW) using Portable Seismic Property Analyzer (PSPA)		x	x	
Electrical and Electromagnetic Methods				
Conventional Electrical Resistivity Tomography (ERT)		x		x
Electrical Resistivity Tomography (ERT) Using OhmMapper		x		x
Frequency-Domain Ground Conductivity Control		x	x	x
Time-Domain Ground Conductivity Control		x		x
Frequency-Domain Metal Detectors		x	x	x
Time-Domain Metal Detectors		x	x	
Gravity Method		x		x
Magnetic Method		x	x	
Infrared Methods				
Infrared Thermography (IR)	x	x	x	
Radar Methods				
Air-Launched Ground Penetrating Radar (GPR)	x	x	x	
High-Frequency Ground Coupled Ground Penetrating Radar (GPR)		x	x	
Low- to Intermediate-Frequency Ground Coupled Ground Penetrating Radar (GPR)		x	x	x
Deflection Methods				
Falling Weight Deflectometer (FWD)	x	x	x	
Rolling Dynamic Deflectometer (RDD)		x	x	
Rolling Wheel Deflectometer (RWD)	x		x	

2 PAVEMENT AND SUBSURFACE INVESTIGATION TOOLS PREVIOUSLY USED BY MoDOT

An electronic survey was conducted of the different MoDOT districts to determine which methods have been used to assess pavement condition. The survey period was 9/10/12 – 10/12/12. Responses were received from the Northeast, Northwest, Southeast, Southwest, Kansas City, and St. Louis districts, and the Construction and Materials Division. One additional response was received from an unspecified recipient. Results of the survey are summarized in Table 2.1.

Table 2.1- Methods used by MoDOT districts for pavement investigation - summary of 9/10/12-10/12/12 survey results

District	Methods Used
Northeast (1st Response)	GPR-Rarely ARAN-Yearly
Northeast (2nd Response)	PSPA-Rarely FWD-Rarely RWD-Rarely Portable Deflectometer-Rarely ARAN-Monthly Self-Potential-Rarely GPR-Rarely Resistivity-Rarely Seismic Reflection-Rarely Seismic Refraction-Rarely Infrared Thermography
Northwest	Heavy Vehicle Simulator-Rarely ARAN-Yearly
Southeast	FWD-Rarely ARAN-Yearly
Southwest	FWD-Yearly RWD-Rarely ARAN-Yearly GPR-Rarely Covermeter (Profometer) To determine steel mesh depth for diamond grinding candidate
Kansas City	FWD-Rarely RWD-Rarely ARAN-Yearly GPR-Rarely Infrared Thermography-Rarely
St. Louis	ARAN-Rarely Time Domain Reflectometery-Yearly Metal Detectors-Monthly GPR-Rarely Resistivity-Rarely Magnetic-Rarely
Construction and Materials Division	FWD-Yearly Portable Deflectometer-Rarely ARAN-Monthly Metal Detectors-Yearly GPR-Rarely Magnetic-Rarely
(Unknown respondent)	ARAN-Yearly Nuclear Densimeter-Monthly GPR-Rarely Resistivity-Rarely

3 PAVEMENT AND SUBSURFACE INVESTIGATION TOOLS

3.1 Introduction

In this document, pavement and subsurface investigation methods are organized by method type. Method types include stress wave methods (Section 3.2), electrical and electromagnetic methods (Section 3.3), infrared thermography (Section 3.4), radar methods (Section 3.5), and deflection methods (Section 3.6). Two tables are provided for each method, the first of which summarizes the deliverable, the data collection method, advantages and disadvantages, and applicability, and the second of which summarizes logistical and cost information.

3.2 Stress Wave Methods

Stress wave methods used for pavement and subsurface investigation include impact echo (IE), multi-channel analyses of surface wave (MASW), conventional refraction seismic, conventional refraction seismic tomography, refraction microtremor (ReMi), and ultrasonic surface waves (USW). A photo of a portable seismic property analyzer (PSPA) used to collect IE and USW data simultaneously is shown in Fig. 3.1. Fig. 3.2 shows photos of seismic equipment used to acquire multi-channel analyses of surface wave (MASW), conventional refraction seismic, conventional refraction seismic tomography, and refraction microtremor (ReMi) data.

Fig. 3.1–Photo of portable seismic property analyzer (PSPA) equipment used to acquire impact echo (IE) and ultrasonic surface wave (USW) data simultaneously.

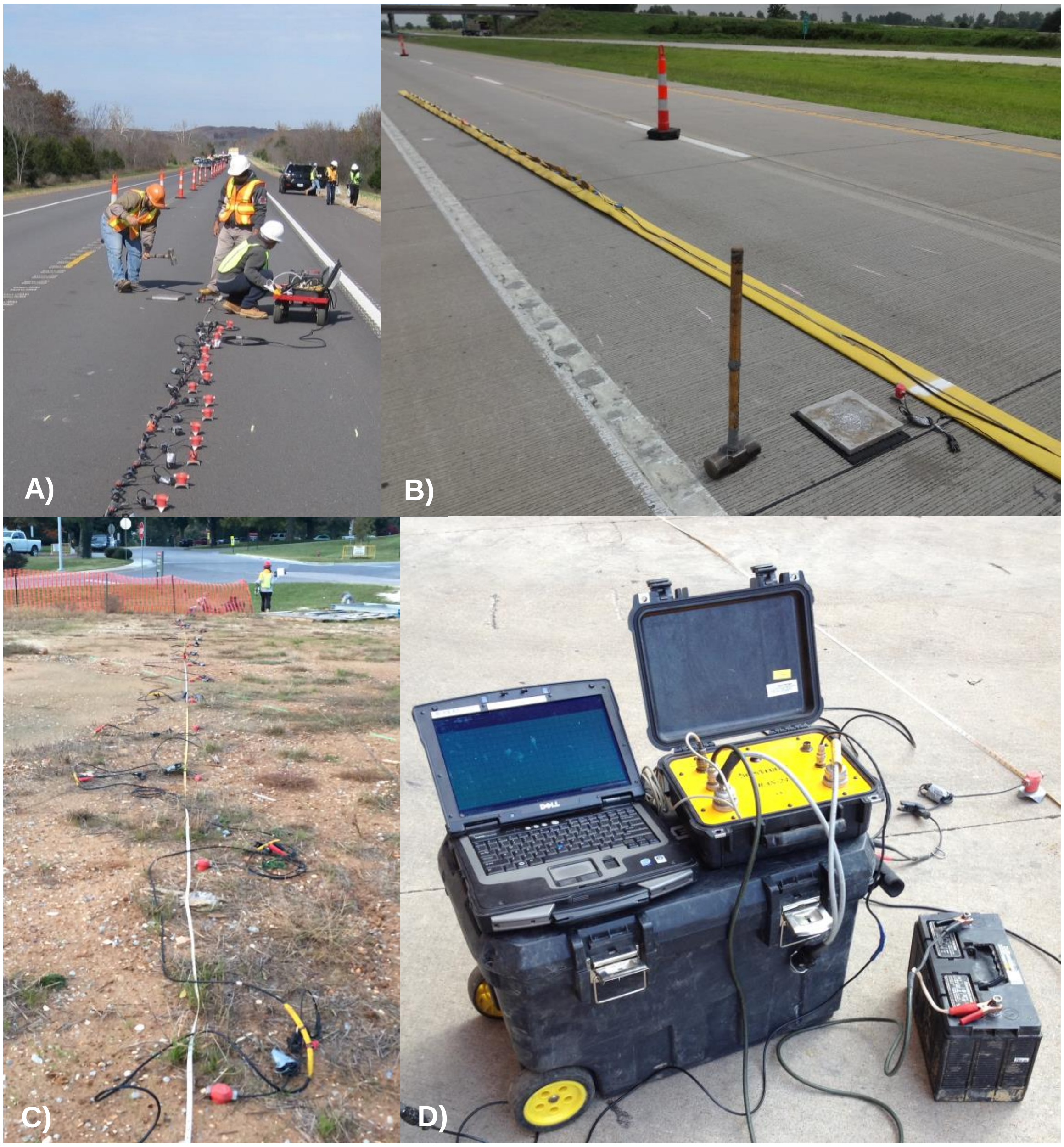

Fig. 3.2–Photos of seismic equipment used to acquire multi-channel analyses of surface wave (MASW), conventional refraction seismic, conventional refraction seismic tomography, and refraction microtremor (ReMi) data. A) Multi-channel MASW data being acquired on a paved roadway using a 24-channel geophone array with low-frequency (4.5 Hz) geophones mounted to base plates for paved surfaces; B) A 24-channel geophone streamer used on a paved roadway. A 20-lbs sledgehammer with metal plate used as an active acoustic source; C) A 24-channel geophone array with geophones mounted to spikes for soil. Current configuration can be used for multi-channel analyses of surface wave (MASW), conventional refraction seismic, conventional refraction seismic tomography, and refraction microtremor (ReMi) methods; D) A 24-channel seismograph powered by a 12-V battery and a laptop, used for multi-channel analyses of surface wave (MASW), conventional refraction seismic, conventional refraction seismic tomography, and refraction microtremor (ReMi) methods.

Table 3.1–Impact echo (IE) surveying using a Portable Seismic Property Analyzer (PSPA) with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The typical deliverable of an impact echo (IE) survey conducted using a portable seismic property analyzer (PSPA) is a plot depicting variations in the ***thickness of the pavement***. The PSPA impact echo can provide reliable (typically $\pm$ 0.5 in.) thickness measurements for good quality asphalt or concrete pavement. However, where delamination or debonding is present, abnormally high thickness values will be output. Recorded impact echo data can also be analyzed visually in the frequency domain (plot of amplitude versus frequency). ***Pavement quality*** can often be inferred on the basis of the frequency domain signature of recorded impact echo data.
Utility of typical deliverable	The PSPA IE tool can be used to map variations in the thickness of new pavement and to estimate the thickness of existing pavements. The IE tool can provide reliable thickness measurements for good quality pavement. However, where delamination or debonding is present, abnormally high thickness values will be output. Recorded impact echo data can also be analyzed visually in the frequency domain. Pavement quality can often be inferred on the basis of the frequency domain signature of recorded impact echo data. The PSPA IE tool can be used to assess both existing and new pavements.
Reliability of typical deliverable	If good quality field data are recorded across good quality pavement, the thickness estimates are reliable in a relative sense. The PSPA instrument estimates pavement thicknesses based on the automated analyses of the frequency-domain IE data (frequency of reverberation of compressional wave reflection from the base of the pavement is identified) and the estimated compressional wave velocity of the pavement. Compressional wave velocities are estimated based on measured surface wave phase velocities and an assumed value of Poisson's ratio. If the pavement is poor quality, the incorrect frequency can be identified and/or an inaccurate compressional wave velocity can be estimated, leading to highly inaccurate depth estimates. Recorded impact echo data can also be analyzed visually in the frequency domain. Pavement quality can often be inferred on the basis of the frequency domain signature of recorded impact echo data. The visual interpretation of frequency domain IE data appears to be reliable in a qualitative sense.

Reproducibility of typical deliverable	Results are reproducible when data are acquired across good quality pavement. However, thickness estimates at a specific observation location on deteriorated concrete can vary if the orientation of the PSPA tool is varied, presumably because surface wave velocities and IE data can be directionally dependent (depending on the type of degradation).
Data collection method	IE data are acquired by placing the PSPA tool (see Fig. 3.1) on the paved surface and activating the high-frequency impact acoustic source. Reflections (and multiples thereof) from the base of the pavement and/or from the horizontal discontinuities within pavement are recorded by the receiver. The PSPA instrument estimates pavement thicknesses based on the automated analyses of the frequency-domain IE data (frequency of reverberation of compressional wave reflection from the base of the pavement is identified) and the estimated compressional wave velocity of the pavement. Compressional wave velocities are estimated based on measured surface wave phase velocities and an assumed value of Poisson's ratio.
Applicability for network-level investigations	The PSPA IE tool is not applicable to network-level investigations as data acquisition is relatively slow.
Applicability for project-level investigations	The PSPA IE tool is applicable to project-level investigations. The PSPA IE tool is not the most appropriate tool for mapping variations in thickness of new or existing pavements (for this purpose, the GPR tool is less expensive and more reliable, Tables 3.29-3.32). However, the PSPA IE tool can be used to identify areas of degraded pavement. Both existing and new pavements can be tested.
Advantages	Advantages to using the PSPA IE tool for pavement investigation include: • tool is non-invasive • limited potential for human error • tool is capable of generating reliable thickness estimates ($\pm$ 0.5 in.) across good quality asphalt or concrete pavement • field data are reproducible • data processing is automated except for the visual analyses of frequency domain IE data. Thickness estimates are output automatically without any input from the user. If the user wishes to analyze the frequency domain data, the user must access the appropriate files via a laptop. • tool can be used to identify poor quality pavement

Disadvantages	Disadvantages to using the PSPA IE tool for pavement investigation include: • data acquisition is relatively slow • PSPA IE method cannot always provide the reliable thickness estimates especially across degraded pavement • only thickness of uppermost pavement layer can be estimated • the maximum depth of the investigation for PSPA is 12 in. with the 6 in. sensor spacing
Recommendations	The PSPA IE tool is not the most appropriate tool for mapping variations in thickness of new or existing pavements (for this purpose, GPR tool is less expensive and more reliable, Tables 3.29-3.32). However, the PSPA IE tool can be used to identify areas of physically degraded pavement. Both existing and new pavements can be tested.

Table 3.2–Impact echo (IE) surveying using a Portable Seismic Property Analyzer (PSPA) with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, etc.).
Typical volume of data acquired per day	A 1-person field crew can normally acquire PSA IE data at 30 locations in an hour.
Crew size	Typically 1 person.
Typical acquisition costs per field day	Costs include crew time (typically 1 person) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a PSPA IE instrument are on the order of $350/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are required.
Typical processing costs per field day	Generally, the post-acquisition processing (uploading data from the PSPA instrument and plotting the same) takes about as long as acquiring the data. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor/interpreter is required, especially if frequency domain IE data are interpreted visually. The interpreter must be experienced and very familiar with pavement properties and pavement degradation.

Table 3.3–Multi-channel analyses of surface wave (MASW) surveying for geotechnical purposes with emphasis on data acquisition in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable of a "multichannel analyses of surface wave" (MASW) survey is a ***1-D shear-wave velocity profile*** of the subsurface often with superimposed geologic interpretations. Typically, the subsurface is imaged to a depth of approximately 100 ft or less (if sledge hammer, weight-drop, or other relatively small magnitude active sources are employed). If passive surface wave sources are utilized, the 1-D shear-wave velocity profile can be extended to depths of multiple hundreds of feet. 2-D shear-wave velocity profiles can be created by acquiring MASW field records at multiple locations along a traverse. The 1-D shear-wave velocity profiles generated for each location can be appropriately placed side-by each and contoured thereby generating a 2-D shear-wave velocity profile.
Utility of typical deliverable	The output 1-D shear-wave velocity profile can be of significant utility to those engaged in highway construction and/or maintenance. For example, a shear-wave velocity profile that extends to depths on the order of 100 ft can be used for earthquake site classification purposes. Although the interfaces between adjacent velocity layers on a 1-D shear-wave velocity profiles may not correlate to specific geologic contacts, the velocity assigned to each layer may be indicative of the ***dominant lithology of that layer*** (e.g. sand, clay, limestone rock, etc.). Also, the depth to the interface between an overlying layer with a shear-wave velocity consistent with that of soil and an underlying layer with a velocity consistent with rock can be indicative of the ***depth to top of rock.*** 2-D shear-wave velocity profiles can also be of significant utility. Variable depth to the top of rock, low velocity zones, lateral and vertical changes in lithology, etc., can often be inferred on the basis of the interpretation of the 2-D shear-wave velocity profiles.
Reliability of typical deliverable	If good quality MASW field data are recorded, and if the subsurface can be reasonably well-represented by a layered velocity model (this assumption is usually less valid in more structurally/stratigraphically complex areas), the output 1-D and/or 2-D shear-wave velocity profiles can be very reliable. If ground truth (typically borehole control) is available, the superposed geologic interpretations can also be highly reliable.

Reproducibility of typical deliverable	If the subsurface is stratigraphically and/or structurally complex, the output 1-D shear-wave velocity profile generated for a specific observation location can vary if the length and/or orientation of the geophone array are changed. However, if good quality field data are acquired, if the subsurface can be well-represented by a layered-velocity model, and if ground truth is available, experienced interpreters will produce very similar 1-D or 2-D shear-wave velocity profiles and comparable superposed geologic interpretations.
Data collection method	An array of geophones (typically 24) is placed on the ground surface at uniform intervals and connected to an engineering seismograph (see Fig. 3.2). The length of the array should be approximately equal to the desired maximum depth of investigation. If active MASW data are desired, an acoustic source is discharged off the end of the array (typically on the order of 20 ft depending on the length of array), and the generated surface wave signal is recorded as it passes through the geophone array. Active data are normally used to generate relatively high-resolution 1-D shear-wave velocity images of the upper 100 ft. If high-resolution images of the shallow subsurface (to depths significantly less than 100 ft) are required, shorter geophone arrays and lower magnitude acoustic sources can be employed. If passive MASW data (only) are desired, a field source is not employed. Rather, the user simply places a linear or symmetric array of geophones on the earth surface and records passive surface wave signal generated by non-active sources (includes traffic, distal earthquakes, quarry blasts, etc.). Passive MASW data are normally used to generate lower-resolution 1-D shear-wave velocity images extending to depths of multiple hundreds of feet. Combination active/passive MASW data can be acquired.
Applicability for network-level investigations	MASW surveys are not applicable to network-level investigations as data acquisition is relatively slow.
Applicability for project-level investigations	MASW surveys are applicable to project-level investigations. This tool can often be used to generate reliable 1-D and/or 2-D shear-wave velocity profiles of the subsurface. It is usually relatively easy to acquire good quality active MASW quality data even in acoustically noisy areas and across paved, rocky, frozen, muddied, graveled, or sandy surfaces. MASW data are usually easy to acquire in a DOT ROW because traffic is a good source of passive surface wave energy.

Advantages	Advantages to using MASW surveys to investigate DOT ROW include: • tool is non-invasive • limited potential for human error • tool is capable of generating reliable 1-D and 2-D shear-wave velocity profiles of the subsurface in areas where the subsurface is neither stratigraphically nor structurally complex • depth of investigation is typically on the order of 100 ft when active sources are employed, but much greater if passive sources are utilized • if ground truth is available, reliable geologic models can be generated • average shear moduli can be assigned to each “velocity layer” imaged • data can be acquired while it is raining as long as recording instrument is protected • data can be processed in the field • data processing is semi-automated and relatively fast • superimposed geologic interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas) • good quality data can often be acquired even in acoustically noisy areas and across paved, rocky, frozen, muddied, graveled or sandy surfaces
Disadvantages	Disadvantages to using MASW surveys to investigate DOT ROW include: • ground truth is required to accurately constrain geologic interpretations • reliability of interpretations decreases with depth and as the lateral and vertical heterogeneity of soil/rock increases • crew productivity decreases in adverse weather conditions • a suitable source of passive surface wave energy may not be present at survey site at time data are acquired
Recommendations	The acquisition of active MASW data is recommended at any location where general information about stratigraphy/structure/elastic modulus of shallow (depths < 100 ft) soils and/or rock is required. If high-resolution images of the shallow subsurface (to depths significantly less than 100 ft) are required, shorter geophone arrays and lower magnitude acoustic sources can be employed. If greater depths of investigation are required, the acquisition of combination active/passive MASW control is recommended.

Table 3.4–Multi-channel analyses of surface wave (MASW) surveying for geotechnical purposes with emphasis on data acquisition in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 3-person field crew using a sledge hammer source can usually acquire a single active or passive 1-D MASW data set in less than two hours. 2-D MASW data can be acquired much more rapidly if a land streamer and vehicle-mounted active source are employed. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 3 persons.
Typical acquisition costs per field day	Costs include crew time (typically 3 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for an engineering seismograph, geophones and cables are on the order of $350/day plus preparation and shipping. Vehicle-mounted source is extra.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Generally, it takes less time to process MASW data than it does to acquire the data. An experienced processor can usually process a single MASW data set in less than one hour. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.5–Conventional refraction seismic surveying with emphasis on data acquisition in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable is a non-tomographic (see Table 3.8; conventional seismic refraction tomography surveying) layered 2-D velocity-depth profile of the subsurface with superposed geologic interpretations. Each layer, with the exception of the uppermost layer, is generally assigned a uniform velocity (no lateral or vertical velocity variations within each layer). Both shear-wave and compressional-wave refraction seismic data can be acquired. Typically, the subsurface is imaged to a depth of 30 ft or less (if sledge hammer, weight-drop or other relatively small magnitude sources are employed). Low-velocity layers (low-velocity relative to velocity of overlying layers) and relatively thin high-velocity layers cannot be imaged.
Utility of typical deliverable	The output 2-D velocity-depth profile (shear-wave or compressional wave) of the shallow subsurface can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest can include, but are not limited to, the mapping/identification of the following: • variable depth to ***top of rock*** (and sometimes variable depth to the top of lithologic layers beneath top of rock) • ***interface between soil layers*** with significantly different acoustic properties • ***top of water table*** (compressional-wave data only) • bulk compressional-wave and/or shear-wave velocity of soil and rock layers (can be transformed into elastic modulus if density is known or can be estimated) • vertical variations in competence of soil/rock • vertical variations in soil/rock lithology • pattern, placement, density and offset of faults
Reliability of typical deliverable	If good quality field data are recorded, and if the subsurface can be reasonably well-represented by a layered earth model (this assumption is usually less valid in more structurally/stratigraphically complex areas), the output layered 2-D velocity-depth model can be very reliable. If ground truth is available, the superposed geologic interpretations can also be very reliable.
Reproducibility of typical deliverable	If good quality field data are acquired and if ground truth is available, experienced interpreters will produce very similar 2-D geologic interpretations.
Data collection method	An array of geophones (see Fig. 3.2) is placed at uniform intervals along the length of a traverse. The length of the array is normally about 6X the desired maximum depth of investigation. Acoustic sources are discharged at predetermined locations (generally nine or less,

	depending upon the number of geophones employed) within and off the ends of the geophone array. The geophones record the arrival time and magnitude of the first shear-wave or compressional-wave energy to reach each geophone (depending on type of survey) and a limited time-window of later-arriving acoustic energy. The arrival time of the first shear-wave or compressional-wave energy to reach each geophone after a source is discharged and the corresponding source-to-receiver separation is the only information utilized by the processor of conventional refraction seismic data.
Applicability for network-level investigations	Conventional refraction seismic surveying is not applicable to network-level investigations since data acquisition is relatively slow.
Applicability for project-level investigations	Conventional refraction seismic surveying is applicable to project-level investigations. This tool can often be used to generate reliable layered 2-D shear-wave or compressional-wave velocity-depth profiles of the shallow subsurface with superposed geologic interpretations. It can be difficult to acquire good quality data in acoustically noisy areas (e.g. in DOT ROW). It can also be difficult to acquire good quality data across paved, rocky, frozen, muddied, graveled or sandy surfaces (as geophones should be well-coupled to ground surface) and to depths exceeding 30 ft.
Advantages	Advantages of using conventional refraction seismic surveying for pavement investigation include: • tool is non-invasive • limited potential for human error • tool is capable of generating reliable velocity-depth images of shallow subsurface (upper 30 ft) in areas where the subsurface is neither stratigraphically nor structurally complex • velocities can be converted to elastic moduli • reliability can often be increased by decreasing the geophone spacing and/or increasing the number of source locations • maximum depth of investigation is typically on the order of 30 ft (unless a high-magnitude source is employed) • if ground control is available, reliable lithologic images can be generated • average elastic modulus can be assigned to each layer imaged (if density is known or can be estimated) • data can be acquired while it is raining as long as recording instrument is protected • field data are reproducible except in acoustically “noisy” areas • data processing is semi-automated and relatively fast (compared to refraction seismic tomography)

	• superposed geologic interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas)
Disadvantages	Disadvantages of using conventional refraction seismic surveying for pavement investigation include: • data acquisition is manual and relatively slow • it can be very difficult to acquire good quality field data across paved, rocky, graveled, sandy, frozen muddied, etc., ground surfaces because geophones need to be well-coupled to surface • resolution and reliability of velocity-depth image decreases rapidly with increasing depth, in large part, because non-tomographic processing is employed • low-velocity layers and thin high-velocity layers cannot be imaged • maximum achievable resolution is significantly less than that provided by the refraction seismic tomography method especially where the subsurface is either stratigraphically or structurally complex • data are normally processed back in the lab, not in the field • ground truth is required to accurately constrain geologic interpretations • reliability of interpretations decreases with depth and as the lateral and vertical heterogeneity of soil/rock increases • crew productivity decreases in adverse weather conditions
Recommendations	The acquisition of conventional refraction seismic data is recommended at any location where the subsurface is neither stratigraphically nor structurally complex and general information about stratigraphy/structure/elastic modulus of shallow (depths < 30 ft) soils and/or rock is required. Conventional refraction seismic can be a cost-effective tool for imaging the shallow subsurface between boreholes. If high-resolution images are required, or if significant lateral velocity variations are anticipated, refraction seismic tomography (Tables 3.7-3.8) is usually a better tool. The conventional refraction seismic method is not the most appropriate acoustic tool for defining pavement thickness, type, and condition.

Table 3.6–Conventional refraction seismic surveying with emphasis on data acquisition in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 3-person field crew using a vehicle-mounted source can usually acquire one thousand lineal feet (or more) of conventional refraction seismic coverage (10 ft geophone spacing; 24-channel seismograph) in a single working day. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 3 persons.
Typical acquisition costs per field day	Costs include crew time (typically 3 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for an engineering seismograph, geophones, and cables are on the order of $350/day plus preparation and shipping. Vehicle-mounted source is extra cost.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Generally, it takes about as long to process conventional refraction seismic data as it does to acquire the data. An experienced processor can usually process a thousand feet of good-quality conventional refraction seismic coverage (10 ft geophone spacing/ 24-channel seismograph) in a single working day. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.7–Conventional refraction seismic tomography surveying with emphasis on data acquisition in a DOT ROW – description and applications

Description of deliverable	The deliverable is a tomographic velocity-depth image (2-D profile) of the subsurface with superposed geologic interpretations. Both shear-wave and compressional-wave refraction seismic data can be acquired. Typically, the subsurface is imaged to a depth of 50 ft or less (if sledge hammer, weight-drop or other relatively small magnitude sources are employed). Low-velocity zones and lateral velocity variations can be effectively imaged using this technology.
Utility of deliverable	The output 2-D velocity-depth profile (shear-wave or compressional-wave) can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest include, but are not limited to, the mapping/identification of the following: • variable depth to top of rock • lateral/vertical variations in the acoustic properties and lithology of rock • variations in rock quality and lithology • lateral/vertical variations in the acoustic properties and lithology of soil • top of rock • top of the water table (compressional-wave data only) • lateral and vertical variations in elastic moduli (assuming densities are known or can be estimated) • low-velocity zones • pattern, placement, density, and offset of faults • fractured rock
Reliability of deliverable	If good quality field data are recorded, and if the subsurface can be reasonably well-represented by a 2-D tomographic velocity/depth model (this assumption is usually less valid in more structurally/ stratigraphically complex areas), the output tomographic image can be very reliable. If ground truth is available, the superposed geologic interpretations can also be very reliable.
Reproducibility of deliverable	If good quality field data are acquired and if ground truth is available, experienced interpreters will produce very similar geologic interpretations.
Data collection method	An array of geophones (see Fig 3.2) is placed at uniform intervals along the length of a traverse. The length of the array is normally about 6X the desired maximum depth of investigation. Acoustic sources are discharged at multiple locations (generally twice as many source locations as the number of geophones employed) within and off the ends of the geophone array. The geophones record the arrival time and magnitude of the first compressional-wave or shear-wave acoustic

	energy (depending on type of survey) to reach each geophone and a limited time-window of later arriving acoustic energy. The arrival time of the first compressional-wave or shear-wave acoustic energy to reach each geophone after a source is discharged and the corresponding source-to-receiver separation is the only information utilized by the processor of refraction seismic tomography data.
Applicability for network-level investigations	Conventional refraction seismic surveying is not applicable to network-level investigations as data acquisition is relatively slow.
Applicability for project-level investigations	Conventional refraction seismic surveying is applicable to project-level investigations. Tool can often be used to generate a reliable layered 2-D tomographic velocity-depth image (2-D profile) of the shallow subsurface with superposed geologic interpretations. It can be very difficult to acquire good quality data in acoustically noisy areas (e.g. in DOT ROW). It can also be very difficult to acquire good quality data across paved, rocky, frozen, muddied, graveled, or sandy surfaces (as geophones should be well-coupled to ground surface) and to depths exceeding 50 ft.
Advantages	Advantages to using conventional refraction seismic surveying to investigate DOT ROW include: • tool is non-invasive • limited potential for human error • tool is capable of generating reliable velocity-depth images of shallow subsurface (upper 30 ft) in areas where the subsurface is neither stratigraphically nor structurally complex • both lateral and vertical velocity variations are effectively imaged • low-velocity zones are effectively imaged • reliability can often be increased by decreasing the geophone spacing and/or increasing the number of source locations • resolution can often be increased by decreasing the geophone spacing • maximum depth of investigation is typically on the order of 50 ft (unless a high-magnitude source is employed) • if ground control is available, reliable lithologic images of the subsurface can be generated (less so in stratigraphically/structurally complex areas) • lateral and vertical variations in velocity can be transformed into corresponding variations in the elastic moduli (if densities are known or can be estimated) • reliability can often be increased by decreasing the geophone spacing • maximum depth of investigation varies from tool to tool, but is

	typically on the order of 50 ft (unless a high-magnitude source is employed) • data can be acquired while it is raining as long as recording instrument is protected • field data are reproducible except in acoustically “noisy” areas • data processing is semi-automated • superposed geologic interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas)
Disadvantages	Disadvantages to using conventional refraction seismic surveying to investigate DOT ROW include: • data acquisition is manual and relatively slow • it can be very difficult to acquire good quality field data across paved, rocky, graveled, sandy, frozen muddied, etc., ground surfaces because geophones need to be well-coupled to surface • reliability of output velocity-depth image decreases with increasing depth and as the stratigraphic and/or structural complexity of the subsurface increases • data are normally processed back in the lab, not in the field • ground truth is required to accurately constrain geologic interpretations • reliability of interpretations decreases with depth and as the lateral and vertical heterogeneity of soil/rock increases • crew productivity decreases in adverse weather conditions
Recommendations	The acquisition of refraction seismic tomography data is recommended at any location where high-resolution acoustic images (depicting both lateral and vertical velocity variations) of the subsurface are required. Refraction seismic tomography can be a cost-effective tool for imaging the shallow subsurface between boreholes. The tool can also be used to map lateral and vertical variations in the acoustic properties of base, native soil, and underlying rock. It is not the most appropriate acoustic tool for mapping variations in the acoustic properties of asphalt and/or concrete pavements. If relatively low-resolution images will suffice, conventional refraction seismic (Tables 3.5-3.6) is often a more cost-effective tool.

Table 3.8–Conventional refraction seismic tomography surveying with emphasis on data acquisition in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 3-person field crew using a vehicle-mounted source can usually acquire about five hundred lineal feet (or more) of conventional refraction seismic coverage (10 ft geophone spacing; 24-channel seismograph) in a single working day. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 3 persons.
Typical acquisition costs per field day	Costs include crew time (typically 3 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for an engineering seismograph, geophones and cables are on the order of $350/day plus preparation and shipping. A vehicle-mounted source is usually necessary and extra.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Generally, it takes about as long to process refraction seismic tomography data as it does to acquire the same. An experienced processor can usually process a five hundred feet of good-quality conventional refraction seismic coverage (10 ft geophone spacing/ 24-channel seismograph) in a single working day. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.9–Refraction microtremor (ReMi) surveying for geotechnical purposes with emphasis on data acquisition in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable of a "refraction microtremor" (ReMi) survey is a 1-D shear-wave velocity profile of the subsurface often with superposed geologic interpretations. Typically, the subsurface is imaged to a depth of approximately 100 ft or less (if sledge hammer, weight-drop or other relatively small magnitude active sources are employed). If passive surface wave sources are utilized, the 1-D shear-wave velocity profile can be extended to depths of multiple hundreds of feet. 2-D shear-wave velocity profiles can be created by acquiring ReMi field records at multiple locations along a traverse. The 1-D shear-wave velocity profiles generated for each location can be appropriately placed side-by each and contoured thereby generating a 2-D shear-wave velocity profile.
Utility of typical deliverable	The output 1-D shear-wave velocity profile can be of significant utility to those engaged in highway construction and/or maintenance. For example, a shear-wave velocity profile that extends to depths on the order of 100 ft can be used for ***earthquake site classification*** purposes. Although the interfaces between adjacent velocity layers on a 1-D shear-wave velocity profiles may not correlate to specific geologic contacts, the velocity assigned to each layer may be indicative of the dominant lithology of that layer (e.g. sand, clay, limestone rock, etc.). Also, the depth to the interface between an overlying layer with a shear-wave velocity consistent with that of soil and an underlying layer with a velocity consistent with rock can be indicative of the ***depth to top of rock.*** 2-D shear-wave velocity profiles can also be of significant utility. Variable depth to the top of rock, low velocity zones, lateral and vertical changes in lithology, etc., can often be inferred on the basis of the interpretation of the 2-D shear-wave velocity profiles.
Reliability of typical deliverable	If good quality ReMi field data are recorded, and if the subsurface can be reasonably well-represented by a layered velocity model (this assumption is usually less valid in more structurally/stratigraphically complex areas), the output 1-D and/or 2-D shear-wave velocity profiles can be very reliable. If ground truth is available, the superposed geologic interpretations can also be highly reliable.

Reproducibility of typical deliverable	If the subsurface is stratigraphically and/or structurally complex, the output 1-D shear-wave velocity profile generated for a specific observation location can vary if the length and/or orientation of the geophone array are changed. However, if good quality field data are acquired, if the subsurface can be well-represented by a layered-velocity model, and if ground truth is available, experienced interpreters will produce very similar 1-D or 2-D shear-wave velocity profiles and comparable superposed geologic interpretations.
Data collection method	An array of geophones (see Fig. 3.2) (typically 24) is placed on the ground surface at uniform intervals and connected to an engineering seismograph. The length of the array should be approximately equal to the desired maximum depth of investigation. If active ReMi data are desired, an acoustic source is discharged off the end of the array (typically on the order of 20 ft depending on length of array) and the generated surface wave signal is recorded as it passes through the geophone array. Active data are normally used to generate relatively high-resolution 1-D shear-wave velocity images of the upper 100 ft. If high-resolution images of the shallow subsurface (to depths significantly less than 100 ft) are required, shorter geophone arrays and lower magnitude acoustic sources can be employed. If passive ReMi data (only) are desired, a field source is not employed. Rather, the user simply places a linear or symmetric array of geophones on the earth surface and records passive surface wave signal generated by non-active sources (includes traffic, distal earthquakes, quarry blasts, etc.). Passive ReMi data are normally used to generate lower-resolution 1-D shear-wave velocity images extending to depths of multiple hundreds of feet. Combination active/passive ReMi data can be acquired.
Applicability for network-level investigations	ReMi surveying is not applicable to network-level investigations as data acquisition is relatively slow.
Applicability for project-level investigations	ReMi surveying is applicable to project-level investigations. The tool can often be used to generate reliable 1-D and/or 2-D shear-wave velocity profiles of the subsurface. It is usually relatively easy to acquire good quality active ReMi quality data even in acoustically noisy areas and across paved, rocky, frozen, muddied, graveled or sandy surfaces. Passive ReMi data are usually easy to acquire in a DOT ROW because traffic is a great source of passive surface wave energy.

Advantages	Advantages to using ReMi surveys to investigate DOT ROW include: • tool is non-invasive • limited potential for human error • tool is capable of generating reliable 1-D and 2-D shear-wave velocity profiles of the subsurface in areas where the subsurface is neither stratigraphically nor structurally complex • depth of investigation is typically on the order of 100 feet when active sources are employed, but much greater if passive sources are utilized • if ground control is available, reliable geologic models can be generated • average shear moduli can be assigned to each “velocity layer” imaged • data can be acquired while it is raining as long as recording instrument is protected • data can be processed in the field • data processing is semi-automated and relatively fast • superposed geologic interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas) • good quality data can often be acquired even in acoustically noisy areas and across paved, rocky, frozen, muddied, graveled or sandy surfaces.
Disadvantages	Disadvantages to using ReMi surveys to investigate DOT ROW include: • ground truth is required to accurately constrain geologic interpretations • reliability of interpretations decreases with depth and as the lateral and vertical heterogeneity of soil/rock increases • crew productivity decreases in adverse weather conditions • a suitable source of passive surface wave energy may not be present at survey site at time data are acquired
Recommendations	The acquisition of active ReMi data is recommended at any location where general information about stratigraphy/structure/elastic moduli of shallow (depths < 100 ft) soils and/or rock is required. If high-resolution images of the shallow subsurface (to depths significantly less than 100 ft) are required, shorter geophone arrays and lower magnitude acoustic sources can be employed. If greater depths of investigation are required, the acquisition of combination active/passive ReMi control is recommended.

Table 3.10–Refraction microtremor (ReMi) surveying for geotechnical purposes with emphasis on data acquisition in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 3-person field crew using a sledge hammer source can usually acquire a single active or passive 1-D ReMi data set in less than two hours. 2-D ReMi data can be acquired much more rapidly if a land streamer and vehicle-mounted active source are employed. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 3 persons.
Typical acquisition costs per field day	Costs include crew time (typically 3 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for an engineering seismograph, geophones and cables are on the order of $350/day plus preparation and shipping. Vehicle-mounted source is extra.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Generally, it takes less time to process ReMi data as it does to acquire the data. An experienced processor can usually process a single ReMi data set in less than one hour. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.11–Ultrasonic surface wave (USW) surveying using a Portable Seismic Property Analyzer (PSPA) with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The typical deliverable of an ultrasonic surface wave (USW) survey conducted using a portable seismic property analyzer (PSPA) is a plot depicting variations in the average elastic modulus (Young's modulus) of the pavement as determined at multiple observation locations on the paved surface Plots depicting variations in Young's modulus with depth are also generated for each observation location.
Utility of typical deliverable	The average value of Young's modulus as determined at each observation location is indicative of the ***overall integrity*** of the pavement at that location. Plots showing variations in Young's modulus with depth at each observation location are indicative of variations in the integrity of the pavement with depth at the observation location. PSPA USW tool can be used to assess both existing and new pavements.
Reliability of typical deliverable	If good quality field data are recorded, the results are reliable in a relative sense. The PSPA tool outputs values of Young's modulus that are calculated based on the measured phase velocities of ultrasonic surface waves, average concrete or asphalt densities, and average values of Poisson's ratio for concrete or asphalt.
Reproducibility of typical deliverable	Results are reproducible (to within 3% according to manufacturer) if duplicate readings are taken with PSPA tool placed in exactly the same position. However, output at a specific observation location can vary if the orientation of the PSPA tool is varied, presumably because Young's modulus can be directionally dependent depending on the type degradation.
Data collection method	USW test data are acquired by placing the PSPA (see Fig. 3.1) on the paved surface and activating the high-frequency impact acoustic source four to six times. Prerecording impacts of the source are used to adjust the gains of the amplifiers in a manner that optimizes the dynamic range of the electronics. The outputs of the three transducers from the final three impacts are saved and stacked. The magnitude of surface wave generated by the source is recorded by two PSPA acoustic receivers. A phase velocity curve is automatically generated and a 1-D plot showing variations in Young's modulus with increasing pavement depth is output, as well as an estimate of the average Young's modulus for the pavement.

Applicability for network-level investigations	Not applicable to network-level investigations as data acquisition is relatively slow.
Applicability for project-level investigations	Applicable to project-level investigations. Tool can be used to map variations in pavement integrity. Both existing and new pavements can be tested.
Advantages	Advantages include: • tool is non-invasive • limited potential for human error • tool is capable of generating a reliable 1-D elastic modulus profile for the pavement as well as an average value of Young's modulus • maximum depth of investigation is typically on the order of 18 in. (with 6 in. sensor spacing) • field data are reproducible • data processing is automated
Disadvantages	Disadvantages include: • data acquisition is relatively slow • PSPA USW method cannot always provide the reliable modulus estimate, especially across the degraded sections of pavement • the interpretation of USW data for multi-layers pavement system can difficult • the maximum depth of the investigation for PSPA is 12 in. with the 6 in. sensor spacing.
Recommendations	The acquisition of PSPA USW control is recommended at any site where information about the physical integrity (Young's modulus) is required. Both existing and new pavements can be tested.

Table 3.12–Ultrasonic surface wave (USW) surveying using a Portable Seismic Property Analyzer (PSPA) with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters. Consultation between client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, etc.).
Typical volume of data acquired per day	A 1-person field crew can normally acquire PSPA USW data at 30 locations in an hour.
Crew size	Typically 1 person.
Typical acquisition costs per field day	Costs include crew time (typically 1 person) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a PSPA USW instrument are on the order of $350/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are required.
Typical processing costs per day	Generally, the post-acquisition processing (uploading data from the PSPA instrument and plotting the same) takes about as long as acquiring the data. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with pavement properties and pavement degradation.

3.3 Electrical and Electromagnetic Methods

Electrical methods used for pavement and subsurface investigation include electrical resistivity tomography (ERT). (Tomography refers to the process of imaging by sectioning using a penetrating wave.) Electromagnetic methods include frequency-domain ground conductivity control, time-domain ground conductivity control, frequency-domain metal detectors, time-domain metal detectors, gravity method, and magnetic method. Figs. 3.3 and 3.4 show photos of equipment used to collect ERT data. Figs. 3.5 and 3.6 show photos of frequency-domain ground conductivity control and time-domain ground conductivity control equipment, respectively. A frequency-domain metal detector is shown in Fig. 3.7, and a time-domain metal detector is shown in Fig. 3.8. A photo of gravity method equipment is shown in Fig. 3.9, and a photo of magnetic method equipment is shown in Fig. 3.10.

Fig. 3.3–Photo of electrical resistivity tomography (ERT) equipment.

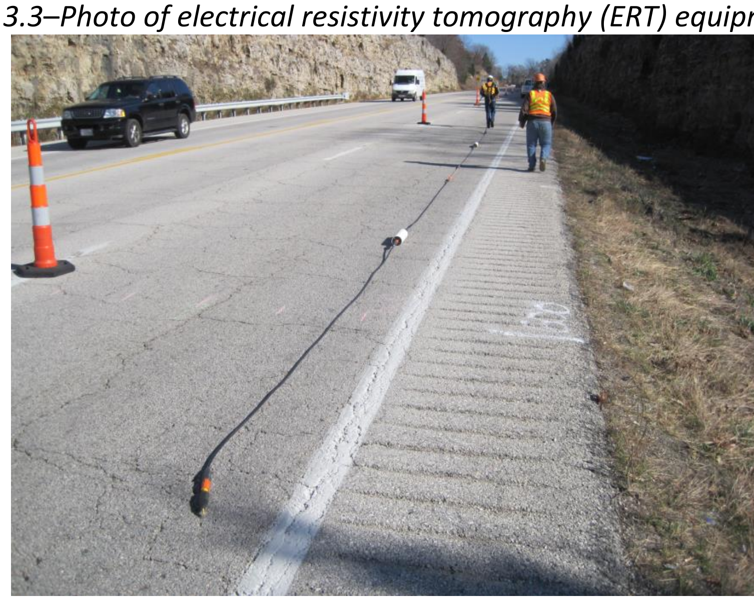

Fig. 3.4–Photo of OhmMapper equipment used to collect electrical resistivity tomography (ERT) data.

Fig. 3.5–Photo of frequency-domain ground conductivity control equipment (EM31-MK2, source: www.geonics.com).

Fig. 3.6–Photo of time-domain ground conductivity control equipment (Protem CM, source: http://www.geophysical.com).

Time-domain EM data are analyzed in the time domain (e.g. variations in amplitude of the received signal over time). Frequency-domain EM data are normally analyzed in the frequency-domain (amplitude spectrum; variations in spectral amplitude with frequency). Often time-domain tools emit a shorter duration EM source signal.

Fig. 3.7–Photo of frequency-domain metal detector equipment.

Fig. 3.8–Photo of time-domain metal detector equipment (GSSI Profiler EMP-400, source: http://www.geophysical.com).

Fig. 3.9–Photo of gravity method equipment (CG-5 Autograv Gravity Meter, source: www.scintrexltd.com).

Fig. 3.10–Photo of magnetic method equipment (G-859 Magnetometer, source: www.geometrics.com).

Table 3.13–Conventional electrical resistivity tomography (ERT) method with emphasis on the 2-D profiling in a DOT ROW – description and applications

Description of typical deliverable	The deliverable is a 2-D electrical resistivity tomography (ERT) image of the subsurface (ERT profile) with superposed geologic interpretations. The geologic interpretations are based on the assumption that measured variations in the resistivity of the subsurface at a specific study site reflect corresponding changes in lithology and moisture content. Interpretations are generally reliable, especially if ground truth is available to constrain and/or verify interpretations. 1-D resistivity data and 3-D electrical resistivity tomography data can also be acquired. ERT data can be acquired in water using specialized marine cables.
Utility of typical deliverable	An interpreted ERT profile can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest include, but are not limited to, the mapping/identification of the following: • variable ***depth to top of rock*** • variations in ***rock quality*** • variations in rock lithology • pattern, placement, and density of solution-widened joints • pattern, placement, density, and offset of faults • ***air-filled voids*** • water- and clay-filled vugs in karst terrain • ***top of water table*** • distribution of dry soil • ***distribution of moist soil*** • ***distribution of sandy-silty soil*** • ***distribution of clayey soil*** • ***seepage flow pathways***
Reliability of typical deliverable	Output of data processing: An uninterpreted ERT profile (output of automated processing) will be reliable if the field data are good quality and if the 3-D subsurface through which the current flows can be reasonably well represented by a 2-D ERT profile. This assumption is usually less valid in more structurally/ stratigraphically complex areas. The inversion software generates an error estimate for each output uninterpreted ERT profile. Deliverable: The ERT profile with superposed geologic interpretations will be most reliable if the uninterpreted ERT profile accurately depicts resistivity variations in the subsurface and if ground truth is available to constrain and verify the geologic interpretation.
Reproducibility of typical deliverable	The electrical resistivity of soil and rock will vary as the moisture content of the subsurface varies (mostly seasonally). This will cause

	corresponding changes in the resistivity values displayed on acquired ERT data. However, in most situations, the resultant geologic interpretation of the output ERT profile will not change in any significant way. If good quality ERT data are acquired and if ground truth is available, experienced interpreters will produce very similar 2-D geologic interpretations.
Data collection method	ERT data can generally be acquired (start to finish) along a 395 ft traverse (using 80 electrodes spaced at 5 ft intervals) in about 3-4 hours (see Fig. 3.3) . Data collection is slowed because electrodes (stainless steel spikes, typically 18 in. long) need to be manually inserted into the ground at multiple locations along the length of the traverse and connected to the resistivity meter using a cable. The recording of the ERT field data however, is fully automatic. Depths of investigation can be increased by increasing the length of the array; resolution can be increased by decreasing the electrode spacing.
Applicability for network-level investigations	ERT is not applicable to network-level investigations.
Applicability for project-level investigations	ERT is applicable to project-level investigations where detailed stratigraphic and/or structural information about the subsurface is required.
Advantages	Advantages of using ERT for investigating a DOT ROW include: • ERT data are relatively high resolution (compared to other geophysical methods capable of imaging the subsurface to depths in excess of 50 ft) • resolution can be increased by decreasing electrode spacing • depths of investigation can be increased by increasing array length • the subsurface can be imaged to depths (in all types of soil and/or rock) in excess of 100 ft unless site access is limited • ERT data can, with some degree of difficulty, be acquired across paved roadways and graveled ROWs • limited potential for human error • tool is non-invasive, except for insertion of metal electrodes • data collection is relatively rapid and automated (except for the insertion of electrodes and the coupling of cables) • processing of field data is automated (user input is required when data are noisy) • data can be processed and interpreted (preliminarily) on-site • field data are reproducible except in “noisy” areas • interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas)

	• limited potential for equipment error as instrument is self-testing
Disadvantages	Disadvantages of using ERT for investigating a DOT ROW include: • ground truth is required to accurately constrain geologic/hydrologic interpretations • resolution and reliability of data decrease with increasing depth • the array of electrodes must be approximately 5X the desired maximum depth of investigation • full depth coverage is achieved only beneath the central third of the array • reliability of interpretations decreases as the lateral and vertical heterogeneity of soil/rock increases • ERT data are not normally acquired while it is raining as moisture can damage non-waterproof cable electrode connections • rain, high humidity, and high temperatures and can damage the resistivity meter • it can be very difficult to couple electrodes to frozen ground • crew productivity decreases in adverse weather conditions • ERT field data quality can be adversely affected if traverses are located in close proximity to utilities or parallel to grounded fences or guard rails • elevation control along ERT traverses is required, if the elevation differences exceed 1 ft • ERT data can, with some degree of difficulty, be acquired across paved roadways and graveled ROWs; this typically requires the insertion of metal electrodes into cored holes, as the electrodes must be in contact with either moist base material or soil
Recommendations	The acquisition of 2-D ERT data is recommended at any location where detailed geologic control is required. The ERT tool is normally a good tool for imaging the subsurface between and beneath boreholes. If possible, the ERT array should be oriented perpendicular to the strike of linear features of interest.

Table 3.14–Conventional electrical resistivity tomography (ERT) method with emphasis on the 2-D profiling in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive ERT experience is qualified to design optimum ERT field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipate features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 4-person field crew can usually acquire 800-1000 lineal feet of continuous ERT coverage (5-ft electrode spacing) in a single working day. Acquisition rates will decrease if crew movement is impeded, if data need to be acquired across paved surfaces, if the ground surface needs to be moistened at electrode locations, if ponded water is present, if adverse weather conditions are encountered, etc.
Crew size	Typically 3-5 persons.
Typical acquisition costs per field day	Costs include crew time (typically 3-5 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for an automated electrical resistivity tomography system and 40 non-polarizing electrodes are on the order of $500/day plus preparation and shipping.
Level of expertise required to acquire ERT data	A skilled instrument operator is required. Experienced field hands are essential if efficiency is desired and because cables need to be connected correctly and in the proper sequence.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Good quality field data can be uploaded to a laptop and processed in the field (or back in the lab). Tomographic processing software automatically transforms the ERT field data acquired along a traverse into an optimum 2-D electrical resistivity image of the subsurface. Usually, the inversion of the apparent resistivity data does not require significant interactive input from the interpreter. However, some processing parameters can be interactively changed to enhance the output. Processing is relatively fast if data quality is good. Normally, it takes a single skilled processor about 4 hours (or less) to process the field data a crew acquires in a single field day. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.15–Electrical resistivity tomography (ERT) surveying using an OhmMapper tool with emphasis on 2-D profiling in a DOT ROW – description and applications

Description of typical deliverable	The OhmMapper tool can be used to acquire electrical resistivity tomography (ERT) data without the use of ground stakes used in the conventional method (Tables 3.13-3.14). The typical deliverable is a 2-D ERT image of the subsurface (ERT profile) with superposed geologic interpretations. The geologic interpretations are based on the assumption that measured variations in the resistivity of the subsurface at a specific study site reflect corresponding changes in lithology and moisture content. Interpretations are generally reliable, especially if ground truth is available to constrain and/or verify interpretations. 3-D ERT data can also be acquired using the OhmMapper.
Utility of typical deliverable	An interpreted 2-D ERT profile can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest include, but are not limited to, the mapping/identification of the following: • variable ***depth to top of rock*** • variations in ***rock quality*** • variations in rock lithology • pattern, placement, and density of solution-widened joints • pattern, placement, density, and offset of faults • ***air-filled voids*** • water- and clay-filled vugs in karst terrain • ***top of water table*** • distribution of dry soil • ***distribution of moist soil*** • ***distribution of sandy-silty soil*** • ***distribution of clayey soil*** • ***seepage flow pathways***
Reliability of typical deliverable	Output of data processing: An uninterpreted ERT profile (output of automated processing) will be reliable if the field data are good quality and if the 3-D subsurface through which the current flows can be reasonably well represented by a 2-D ERT profile. This assumption is usually less valid in more structurally/ stratigraphically complex areas. The inversion software generates an error estimate for each output uninterpreted ERT profile. Deliverable: The ERT profile with superposed geologic interpretations will be most reliable if the uninterpreted ERT profile accurately depicts resistivity variations in the subsurface and if ground truth is available to constrain and verify the geologic interpretation.

Reproducibility of typical deliverable	The electrical resistivity of soil and rock will vary as the moisture content of the subsurface varies (mostly seasonally). This will cause corresponding changes in the resistivity values displayed on acquired ERT data. However, in most situations, the resultant geologic interpretation of the output ERT profile will not change in any significant way. If good quality ERT data are acquired and if ground truth is available, experienced interpreters will produce very similar 2-D geologic interpretations.
Data collection method	2-D OhmMapper data (see Fig. 3.4) are normally acquired by dragging a coupled pair of transmitter/receiver dipoles along a traverse of interest. The maximum depth of investigation is a function of the separation between the dipole pair. Greater vertical and lateral resolution can be achieved by dragging the dipole pair along the traverse multiple times each time employing a different transmitter-receiver separation. The same enhanced vertical resolution can be achieved by coupling the transmitter dipole to multiple receiver dipoles (each with a different transmitter-receiver separation) and dragging the same along the length of the traverse. The OhmMapper transmitter and receiver dipoles do not need to be physically coupled to the ground. Where the surface is free of impediments, OhmMapper data can generally be acquired at a slow walking pace. The recording of data is fully automatic. The system can be coupled to a GPS unit.
Applicability for network-level investigations	The OhmMapper tool is not applicable to network-level investigations.
Applicability for project-level investigations	The OhmMapper tool is applicable to project-level investigations where detailed stratigraphic and/or structural information about the subsurface is required. OhmMapper data can be acquired across unreinforced pavements, exposed rock, compact gravels, etc. However, useful OhmMapper data cannot normally be acquired across reinforced pavements, adjacent to metal fences or guard rails, above underground metal utilities, or in proximity other metals.

Advantages	Advantages to using the OhmMapper to investigate DOT ROW include: • OhmMapper ERT data are relatively high resolution • resolution can be increased by acquiring data using a greater number of transmitter-receiver separations without increasing the maximum separation employed • the subsurface can be imaged to depths (in all types of soil and/or rock) to depths on the order of 30 to 50 ft (depending on conductivity of soil/rock) • OhmMapper ERT data can be readily acquired across non-reinforced pavements, graveled ROWs, rock, sand, etc., (areas where the acquisition of conventional ERT control would be difficult) • limited potential for human error • tool is non-invasive • transmitter and receiver dipoles do not need to be physically coupled to the earth's surface • data collection is relatively rapid (compared to the acquisition of conventional ERT data) and semi-automated • field data are reproducible except in "noisy" areas • interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas)

Disadvantages	Disadvantages to using the OhmMapper to investigate DOT ROW include: • data processing requires significant expertise (compared to the processing of conventional ERT data) • data cannot be processed and interpreted on-site • ground truth is required to accurately constrain geologic/hydrologic interpretations • resolution and reliability of data decrease with increasing depth • depths of investigation are generally limited to 30-50 feet depending on the conductivity of the soil/rock • reliability of interpretations decreases as the lateral and vertical heterogeneity of soil/rock increases • OhmMapper ERT data are not normally acquired while it is raining as moisture can damage electrical connections and instrumentation • transmitter and receiver dipoles can be “snagged” by surface debris or vegetation • it can be very difficult to couple electrodes to frozen ground • crew productivity decreases in adverse weather conditions • quality OhmMapper data cannot be acquired across reinforced pavements, adjacent to metal fences or guard rails, above underground metal utilities, or in proximity metals, etc. • elevation control along ERT traverses is required if elevation differences exceed 1 ft
Recommendations	The acquisition of 2-D OhmMapper ERT data is recommended at any location where detailed geologic control to depths of less than 30 ft is required. The OhmMapper tool is normally a good tool for imaging the subsurface between and beneath boreholes. If possible, the ERT array should be oriented perpendicular to the strike of linear features of interest. Quality OhmMapper data cannot be acquired across reinforced pavements, adjacent to metal fences or guard rails, above underground metal utilities, or in proximity metals, etc.

Table 3.16– Electrical resistivity tomography (ERT) surveying using an OhmMapper tool with emphasis on 2-D profiling in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive OhmMapper experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipate features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 2-person field crew can usually acquire thousands of lineal feet of continuous ERT coverage in a single working day (depending on target depth and resolution required). Acquisition rates will decrease if crew movement is impeded, if ponded water is present, if adverse weather conditions are encountered, etc.
Crew size	Typically 1-2 persons.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for an OhmMapper system with one pair of transmitter-receiver dipoles is on the order of $500/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Normally, it takes about as long to process OhmMapper data as it does to acquire the data. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A highly-skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.17–Frequency-domain ground conductivity control with emphasis on the 2-D profiling in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable is a 2-D non-tomographic conductivity image of the subsurface (2-D conductivity profile) with superposed geologic interpretations. The geologic interpretations are based on the assumption that measured variations in the conductivity of the subsurface at a specific study site reflect corresponding changes in lithology and moisture content. Interpretations are generally reliable, especially if ground truth is available to constrain and/or verify interpretations. 1-D and 3-D ground conductivity data can also be acquired. A variety of frequency-domain ground conductivity tools are commercially available. Some are designed to generate single-layered 2-D conductivity images of the subsurface; others are designed to generate multi-layered 2-D conductivity images of the subsurface. Herein, the focus is on a generic frequency-domain ground conductivity tool capable of generating multi-layered 2-D conductivity images (2-D conductivity profiles) of the subsurface.
Utility of typical deliverable	A 2-D conductivity profile can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest can include, but are not limited to, the mapping/identification of the following: • variable ***depth to top of rock*** • variations in ***rock quality*** • variations in rock lithology • pattern, placement, density and offset of faults • ***top of water table*** • distribution of dry soil • ***distribution of moist soil*** • ***distribution of sandy-silty soil*** • ***distribution of clayey soil*** • ***seepage flow pathways***
Reliability of typical deliverable	Output of data processing: At each designated observation location along the traverse, apparent conductivity acquired for a range of depths versus frequencies. The data acquired at each observation location are transformed into a 1-D conductivity profile using inversion software that assumes the subsurface is comprised of a finite number of uniform layers (one layer can be generated for each frequency). This assumption is usually less valid in more structurally/stratigraphically complex areas. Deliverable: The 2-D conductivity profile with superposed geologic interpretations will be most reliable if the conductivity profile accurately depicts conductivity variations in the subsurface (this

	assumption is usually less valid in more structurally/stratigraphically complex areas) and if ground truth is available to constrain and verify the geologic interpretations.
Reproducibility of typical deliverable	The electrical conductivity of soil and rock will vary as the moisture content of the subsurface varies. This will cause corresponding changes in the conductivity values displayed on 2-D conductivity profile. However, in most situations, the resultant geologic interpretation of the output 2-D conductivity profile will not change in any significant way. If good quality field data are acquired and if ground truth is available, experienced interpreters will produce very similar 2-D geologic interpretations.
Data collection method	Data collection methods vary depending on the number of frequencies employed, the sampling mode (automated or manual), and the specifics of the conductivity tool used. Frequency-domain ground conductivity meters (see Fig. 3.5) do not need to be coupled to the ground surface, allowing for relatively rapid data acquisition. Automated data collection at relatively high speeds (greater than 20 miles per hour) is possible (using some commercially-available instruments) if apparent conductivity data are acquired for only a minimal number of frequencies (typically three or less). In this case, the output of data processing at each observation location is a 3-layered (or less) 1-D conductivity profile. The final deliverable can be a fairly high-resolution conductivity image (with superposed geologic interpretations) of the shallow subsurface to a depth of say 5 ft or a relatively low-resolution conductivity image of the subsurface to a depth of 30 ft (depending on range of frequencies employed). If the objective is to generate the highest resolution image possible to the maximum depth possible, the operator generally has two options. Data can be acquired in automatic mode (normally requires multiple passes along traverse) until apparent resistivity data has been acquired for all possible frequencies (available for specific tool). Alternatively, the operator can acquire data (in semi-automatic mode) at each observation location for all possible frequencies (for specific tool). The first approach is usually faster.
Applicability for network-level investigations	Frequency-domain ground conductivity is applicable to network-level investigations. Ground conductivity tools can be used to map variations in the clay and/or moisture content of shallow soils and to variable depth to the top of the water table or shallow bedrock. Ground conductivity data can be acquired very rapidly (compared to electrical resistivity tomography data), but cannot be acquired (reliably) across reinforced pavements. Also it may be difficult to acquire reliable ERT data in proximity (~30 ft) to and along traverses

	parallel to metal guard rails or fences, etc. Also, ground conductivity images are generally much lower resolution than comparable electrical resistivity tomography images.
Applicability for project-level investigations	Frequency-domain ground conductivity is applicable to project-level investigations. Ground conductivity tools can be used to map variations in the clay and/or moisture content of shallow soils and to variable depth to the top of the water table or shallow bedrock. Ground conductivity images are normally much lower resolution than comparable electrical resistivity tomography images. Data cannot be acquired across reinforced pavements. Ground conductivity meters can be good tools for imaging the shallow subsurface between boreholes.
Advantages	Advantages of using frequency-domain ground conductivity to investigate a DOT ROW include: • tool is non-invasive and does not need to be coupled to the ground • data can be acquired very rapidly (relative to electrical resistivity tomography control) • data collection is automatic • limited potential for human error • ground conductivity tools are capable of generating relatively high-resolution conductivity images of shallow subsurface (upper 15 ft) • vertical resolution, in the shallow subsurface, can often be increased by increasing the number of frequencies employed • lateral resolution, in the shallow subsurface, can often be increased by increasing the number of frequencies employed and decreasing the spacing between sampling locations • maximum depth of investigation varies from tool to tool, but can be as high as 200 ft • ground conductivity data can be acquired across paved roadways (unreinforced only), graveled ROWs and frozen ground • data can be acquired while it is raining as long as instrument is protected • field data are reproducible except in "noisy" areas • interpretations, especially when constrained, are reliable (less so in stratigraphically/structurally complex areas) • many ground conductivity meters can also be used as metal detectors
Disadvantages	Disadvantages of using frequency-domain ground conductivity to investigate a DOT ROW include: • resolution and reliability of data decreases rapidly with increasing depth, in part, because non-tomographic processing is employed • maximum achievable resolution is significantly less than that

	provided by the electrical resistivity tomography tool especially at depths greater than about 15 ft • the processing of field data is time-consuming • multi-frequency field data cannot normally be processed or interpreted on-site • ground truth is required to accurately constrain geologic/hydrologic interpretations • reliability of interpretations decrease with depth and as the lateral and vertical heterogeneity of soil/rock increases • crew productivity decreases in adverse weather conditions • reliable data cannot be acquired in areas where surface or buried metal is present (proximity to utilities, metal fences, guard rails, rebar, etc.) as software misinterprets conductive metal as conductive soil • features characterized by high resistivity (e.g. air-filled voids) are not effectively imaged on ground conductivity profiles
Recommendations	The acquisition of frequency-domain ground conductivity data is recommended at any location where general information about variations in the clay and/or moisture content of the shallow (< 20 ft) subsurface is required or where estimates of the variable depth to the top of the water table or shallow bedrock are required. Ground conductivity meters can be good tools for imaging the shallow subsurface between boreholes. If high-resolution images are required (especially at depths greater than 15 ft) or if the target of interest is highly resistive, electrical resistivity tomography (Tables 3.13-3.14) is usually the better tool.

Table 3.18–Frequency-domain ground conductivity control with emphasis on the 2-D profiling in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive ground conductivity experience is qualified to design optimum field acquisition parameters. This includes the selection of the specific instrument employed. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 2-person field crew using a vehicle can usually acquire five thousand lineal feet (or more) of ground conductivity meter coverage (5 ft observation location spacing) in a single working day. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 1-2 persons, depending upon whether the operator walks or rides.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a multi-frequency ground conductivity meter are on the order of $350/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Generally, it takes much longer to process ground-conductivity data than to acquire the data. An experienced processor can usually process several hundred feet of multi-frequency ground conductivity meter coverage (5 ft observation location spacing) in a single working day. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.19–Time-domain electromagnetic (TDEM) ground conductivity control with emphasis on the 2-D profiling in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable is a 2-D non-tomographic conductivity image of the subsurface (2-D conductivity profile) with superposed geologic interpretations. The geologic interpretations are based on the assumption that measured variations in the conductivity of the subsurface at a specific study site reflect corresponding changes in lithology and moisture content. Interpretations are generally reliable, especially if ground truth is available to constrain and/or verify interpretations. 1-D and 3-D time-domain conductivity data can also be acquired.
Utility of typical deliverable	A 2-D conductivity profile can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest include, but are not limited to, the mapping/identification of the following: • variable depth to top of rock • variations in rock quality • variations in rock lithology • pattern, placement, density and offset of faults • ***top of water table*** • distribution of dry soil • ***distribution of moist soil*** • ***distribution of sandy-silty soil*** • ***distribution of clayey soil*** • ***seepage flow pathways***
Reliability of typical deliverable	Output of data processing: 1-D conductivity profiles are generated at each designated observation location along the traverse of interest. The 1-D inversion software assumes that the subsurface can be represented by a finite number of uniform layers. This assumption is usually less valid in more structurally/ stratigraphically complex areas. These 1-D conductivity profiles are placed at appropriate locations a horizontal axis (representing the length of the traverse) and collectively contoured. The final output of processing is a non-tomographic 2-D conductivity image (conductivity profile) of the subsurface. Deliverable: The 2-D conductivity profile with superposed geologic interpretations will be most reliable if the conductivity profile accurately depicts conductivity variations in the subsurface (this assumption is usually less valid in more structurally/ stratigraphically complex areas) and if ground truth is available to constrain and verify the geologic interpretation.

Reproducibility of typical deliverable	The electrical conductivity of soil and rock will vary as the moisture content of the subsurface varies. This will cause corresponding changes in the conductivity values displayed on 2-D conductivity profile. However, in most situations, the resultant geologic interpretation of the output 2-D conductivity profile will not change in any significant way. If good quality field data are acquired and if ground truth is available, experienced interpreters will produce very similar 2-D geologic interpretations.
Data collection method	Time domain electromagnetic (TDEM) conductivity meters (see Fig. 3.6) typically consist of two coils: a transmitter and a receiver. For a period of time, DC current is passed through the transmitter coil temporarily turning it into a powerful magnet with a field that energizes the subsurface through the zone of interest. At some preset time, the DC current is terminated as rapidly as possible, causing the associated magnetic field to collapse and transient currents to flow briefly. These transient currents generate secondary electromagnetic fields that are recorded (magnitude of induced voltage over time) by the receiver coil and transformed into a 1-D conductivity profile. Larger transmitter loops and higher magnitude currents are used to image the subsurface to greater depths. Coils are commonly placed on the ground surface, but do not need to be coupled to the ground surface. In other instances, coils are suspended from helicopters or fixed wing aircraft. Herein, the focus is on transmitter/receiver coils that are placed on the ground surface.
Applicability for network-level investigations	Not applicable to network-level investigations.
Applicability for project-level investigations	Applicable to project-level investigations. Time-domain conductivity tools are best used when there is a need to image the subsurface to depths that cannot be effectively realized using either frequency-domain conductivity meters (Table 3.17-3.18) or the electrical resistivity tomography method (Table 3.13-3.14). Data cannot be acquired across reinforced pavements. Ground conductivity meters can be good tools for imaging the shallow subsurface between boreholes.

Advantages	Advantages include: • tool is non-invasive and does not need to be coupled to the ground • data can be acquired very rapidly (relative to electrical resistivity tomography control, Table 3.13-3.14) • data collection is automatic • limited potential for human error • time-domain conductivity tools are capable of generating conductivity images of shallow subsurface to depths that cannot be effectively realized using either frequency domain conductivity tools or the electrical resistivity tomography method • lateral resolution can often be increased by increasing the number of observation locations along the length of the traverse • ground conductivity data can be acquired across paved roadways (without reinforcing steel), graveled ROWs and frozen ground • field data are reproducible except in "noisy" areas • interpretations, especially when constrained, are reliable (less so in stratigraphically/ structurally complex areas)
Disadvantages	Disadvantages include: • resolution and reliability of data decreases rapidly with increasing depth, in part, because non-tomographic processing is employed • the processing of field data is time-consuming • data cannot normally be processed or interpreted on-site • ground truth is required to accurately constrain geologic/hydrologic interpretations • reliability of interpretations decreases with depth and as the lateral and vertical heterogeneity of soil/rock increases • crew productivity decreases in adverse weather conditions • reliable data cannot be acquired in areas where surface or buried metal is present (proximity to utilities, metal fences, guard rails, rebar, etc.) as software misinterprets conductive metal as conductive soil • features characterized by high resistivity (e.g. air-filled voids) are not effectively imaged on ground conductivity profiles
Recommendations	The acquisition of time-domain conductivity data is recommended at any location where general information about the lithology subsurface is required to depths that cannot be effectively realized using either frequency domain conductivity tools (Table 3.17-3.18) or the electrical resistivity tomography method (Table 3.13-3.14). This can be a good tool for mapping the top of water table and the top of bedrock.

Table 3.20–Time-domain electromagnetic (TDEM) ground conductivity control with emphasis on the 2-D profiling in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive ground conductivity experience is qualified to design optimum field acquisition parameters. This includes the selection of the specific instrument employed. Consultation between client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 2-person field crew using a vehicle can usually acquire five thousand lineal feet (or more) of ground conductivity meter coverage (5 ft observation location spacing) in a single working day. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 1-2 persons, depending upon whether the operator walks or rides.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a multi-frequency ground conductivity meter are on the order of $350/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Generally, it takes much longer to process ground-conductivity data than to acquire the same. An experienced processor can usually process several hundred feet of multi-frequency ground conductivity meter coverage (5 ft observation location spacing) in a single working day. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

Table 3.21–Frequency-domain electromagnetic (FDEM) metal detectors with emphasis on real time scanning in a DOT ROW – description and applications

Description of typical deliverable	When a hand-held frequency domain electromagnetic (FDEM) metal detector is moved close to a buried or surface metal object (typically within a couple of feet or less, depending upon the size of the metal object and the depth range of the specific metal detector), the operator is acoustically alerted. The instrument emits a high pitched sound that increases in intensity with increasing proximity to the target. The user can use headphones so that the sound cannot be heard by passersby. On the basis of phase differences between the primary and secondary radiation, the type of metal can also be estimated. This information is displayed on the instrument panel.
Utility of typical deliverable	FDEM metal detectors can be used to ***locate small (key-size) to large pieces of metal*** in the shallow subsurface. Realizable depths of investigation are typically less than 2 ft. The type of metal can also be estimated. This information is displayed on the instrument panel.
Reliability of typical deliverable	FDEM metal detectors can be used to locate small to large pieces of metal in the shallow subsurface. Difficulties arise when the object of interest is too small or too deep to be imaged or when signal from the object of interest is effectively masked by the signal(s) generated from other proximal pieces of metal.
Reproducibility of typical deliverable	The instrument response is reproducible.
Data collection method	The operator moves the light-weight hand-held FDEM metal detector (see Fig. 3.7) rapidly across the ground surface. When the metal detector is in close proximity to a buried or surface metal object, the operator is acoustically alerted. The tool emits a high pitched sound which increases in intensity as it is moved closer to the target. The user can wear headphones so that the sound cannot be heard by passersby.
Applicability for network-level investigations	FDEM metal detectors are not applicable to network-level investigations.
Applicability for project-level investigations	FDEM metal detectors are applicable to project-level investigations. Tool can be used to locate shallow metal in the subsurface.

Advantages	Advantages of using FDEM metal detectors in DOT ROW investigations include: • tool is non-invasive and does not need to be coupled to the ground surface • data can be acquired very rapidly • small metal objects (key size) can be located in shallow subsurface • tool responds only to the presence of conductive metal • metal objects can be located in real time • data processing is not required • type of metal can be estimated • experience operators are not required • limited potential for human error • field data are reproducible • data can be acquired in adverse field conditions • data can be acquired underwater
Disadvantages	Disadvantages of using FDEM metal detectors in DOT ROW investigations include: • limited depths of investigation (generally < 2 ft) • resolution decreases rapidly with depth • ground truth (shallow excavation) is required to accurately identify object • data are not digitally recorded • signal from the object of interest can be effectively masked by the signal(s) generated from other proximal pieces of metal
Recommendations	The FDEM metal detector is recommended at any site where there is a need to locate shallow (depths < 2 ft) metal rapidly and in real time.

Table 3.22–Frequency-domain electromagnetic (FDEM) metal detectors with emphasis on real time scanning in a DOT ROW – logistics and costs

Preplanning requirements	Familiarity with hand-held frequency domain metal detectors is desirable. Operator should understand the strengths and limitations of various commercially-available instruments. It may be necessary to move metal objects on the surface away from the area of interest as they constitute sources of noise. Information about the probable sizes, depths and types of metal targets of interest should be conveyed to the operator. Locations of metal utilities should be marked to minimize potential for misinterpretation.
Typical volume of data acquired per day	A 1-person field crew can scan more than a thousand square feet (or more) of ground in a single day (depending upon objective). Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 1 person.
Typical acquisition costs per field day	Costs include crew time (typically 1 person) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a multi-frequency ground conductivity meter are on the order of $175/day plus preparation and shipping.
Level of expertise required to acquire data	Familiarity with hand-held frequency domain metal detectors is desirable.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Audible data are interpreted in real time. No additional processing costs are incurred.
Level of expertise required to process and interpret data	Audible data are interpreted in real time. Familiarity with hand-held frequency domain metal detectors is desirable.

Table 3.23–Time-domain electromagnetic (TDEM) metal detectors with emphasis on real time scanning in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable of a time-domain electromagnetic (TDEM) metal detector survey is a plan view map of a study depicting variations in the conductivity (or some variant thereof) of the shallow (to depths of less than 15 ft) subsurface. Anomalously high conductivity values are generated by metals. On the basis of visual analyses of the conductivity map, the size, orientation, and approximate depth of the causative feature can usually be estimated. In many instances, the operator is often able to identify specific features of interest (underground metal tanks or metal utility lines, for example) based on the nature of the anomalies. Data can also often be interpreted in real time as they are displayed on the instrument screen.
Utility of typical deliverable	TDEM metal detectors can be used to locate small to ***large pieces of metal*** in the shallow subsurface. Maximum realizable depths of investigation are typically less than 15 ft (for larger metal objects). In certain instances, the nature of the causative feature can be inferred based on the size, orientation and magnitude of the conductivity anomaly.
Reliability of typical deliverable	Time-domain metal detectors can be used to locate small to large pieces of metal in the shallow subsurface. Difficulties arise when the object of interest is too small or too deep to be imaged or when signal from the object of interest is effectively masked by the signal(s) generated from other proximal pieces of metal.
Reproducibility of typical deliverable	The instrument response is reproducible.
Data collection method	TDEM metal detectors (see Fig. 3.8) typically consist of two coils: a transmitter and a receiver. TDEM metal detector coils are relatively small (a few inches to a few feet in diameter, with larger coils providing for lower resolution by greater depths of investigation). To allow for rapid investigations over relatively large areas, the coils are typically coupled to a GPS system and mounted on a mobile wheeled or hand held. Data are often acquired along parallel traverses to ensure rapid and full coverage. Data can be acquired per unit time or per unit distance. Anomalies can be identified in real time (displayed on instrument screen as acquired). Most often, data are recorded and posted on a contoured base map.
Applicability for network-level investigations	Not applicable to network-level investigations.

Applicability for project-level investigations	Applicable to project-level investigations. Tool can be used to locate metal in the shallow subsurface.
Advantages	Advantages include: • tool is non-invasive and does not need to be coupled to the ground • data can be acquired very rapidly and automatically • data can be interpreted in real time and/or digitally recorded, downloaded and posted on a contoured base map • small to large metal objects can be located in shallow subsurface depending upon specifics of instrument employed • tool responds mostly to the presence of metal • data processing is not required (downloading and contouring mostly) • data interpretation is usually straightforward • limited potential for human error • data are recorded digitally • field data are reproducible • data can be acquired in adverse field conditions • data can be acquired underwater
Disadvantages	Disadvantages include: • limited depths of investigation (generally < 15 ft depending on size of target and specifics of instrument) • resolution decreases rapidly with depth • ground truth (shallow excavation) is often required to accurately identify object of interest • signal from an object of interest can be effectively masked by the signal(s) generated from other proximal pieces of metal
Recommendations	The time-domain metal detector is recommended at any site where there is a need to locate shallow metal. The tool is especially useful if acquired data need to be recorded, posted and contoured.

Table 3.24–Time-domain electromagnetic (TDEM) metal detectors with emphasis on real time scanning in a DOT ROW – logistics and costs

Preplanning requirements	Previous field experience with time-domain metal detectors is essential. Contractor must also understand the strengths and limitations of various commercially-available time-domain metal detectors. Information about the probable sizes, depths and types of subsurface metal objects of interest should be conveyed to the operator/contractor so that appropriate field acquisition parameters can be identified. It may be necessary to move metal objects on the surface away from the area of interest. Locations of metal utilities should be marked to minimize potential for misinterpretation.
Typical volume of data acquired per day	A 1-person field crew can assess several thousand square feet (or more) of ground in a single day (depending upon objective). Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 1 person.
Typical acquisition costs per field day	Costs include crew time (typically 1 person) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a multi-frequency ground conductivity meter are on the order of $175/day plus preparation and shipping.
Level of expertise required to acquire data	Although the tool is fairly user friendly, previous experience with time-domain metal detector to be employed is essential.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	A skilled operator can download, post and contour data recorded at a typical work site in less than a couple of hours (if GPS control is available). Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor/interpreter is required. The interpreter must be experienced and must understand the nature of the feature(s) of interest to the client.

Table 3.25–Gravity method with emphasis on imaging the subsurface in a DOT ROW – description and applications

Description of typical deliverable	The typical deliverable is a 2-D density image of the subsurface with superposed geologic interpretations. The geologic interpretations are based on established or inferred density/lithology relationships. 3-D density images with superposed geologic interpretations can also be generated.
Utility of typical deliverable	An interpreted 2-D density image of the subsurface can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest include, but are not limited to, the mapping/identification of the following: • variable ***depth to top of rock*** • ***air-filled voids***
Reliability of typical deliverable	An interpreted 2-D density image (output of processing) can be very reliable if the gravity field data are good quality and if the observed residual gravity anomaly (after applying elevation and latitude corrections) is generated by a single known variable (such as variations in the thickness of soil). In this case, if the densities of the soil and shallow rock are known (or can be accurately estimated), the gravity data can be used to generate a 2-D image depicting variations in soil thickness. If the residual gravity anomalies are generated by more than one variable (such as variations in soil thickness and shallow air-filled voids) the gravity data cannot normally be transformed into a reliable 2-D image depicting both variations in soil thickness and the location of air-filled voids. The resolution of the gravity tool is significantly less than that provided by many other imaging tools.
Reproducibility of typical deliverable	Field data are reproducible. If the gravity field data are good quality and if the observed residual gravity anomaly (after applying elevation and latitude corrections) is generated by a single known variable (such as variations in the thickness of soil), experienced processors/interpreters will produce similar 2-D geologic interpretations.
Data collection method	2-D gravity data are normally acquired at predetermined locations along the length of a traverse (see Fig. 3.9). The gravimeter must be placed on the ground surface and levelled. The coordinates of each observation location (relative or absolute) must be determined with a very high degree of precision. Drift corrections must also be applied to acquired data.

Applicability for network-level investigations	The gravity method is not applicable to network-level investigations.
Applicability for project-level investigations	The gravity method has limited applicability to project-level investigations because of the tool's relatively low resolution and because residual gravity anomalies are often caused by multiple indistinguishable variables (depth to rock, air-filled voids, clay-filled vugs, water-filled vugs, metallic mineralization, etc.).
Advantages	Advantages of using the gravity method to investigate DOT ROW include: • tool responds only to density variations in the subsurface • tool is non-invasive • limited potential for human error • theoretically, the subsurface can be imaged to any depth • instrument does not need to be coupled to earth surface • data can be readily acquired across pavements, graveled ROWs, rock, sand, etc. • transmitter and receiver dipoles do not need to be physically coupled to the earth's surface
Disadvantages	Disadvantages of using the gravity method to investigate DOT ROW include: • data processing requires significant expertise • accurate assumptions about cause of observed gravity anomalies (e.g. depth to top of rock) are required • precise surveying control is required • data cannot be processed and interpreted on-site • ground truth is required to accurately constrain geologic/hydrologic interpretations • resolution and reliability of data decrease with increasing depth • reliability of interpretations decreases as the lateral and vertical heterogeneity of soil/rock increases
Recommendations	The acquisition of gravity data is not recommended for routine subsurface imaging in DOT ROW. Other imaging tools provide much higher resolution and require fewer accurate assumptions about the nature of the subsurface.

Table 3.26–Gravity method with emphasis on imaging the subsurface in a DOT ROW – logistics and costs

Preplanning requirements	Only a contractor with extensive gravity meter experience is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipate features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 1-person field crew can usually acquire 100 gravity readings in a single working day. Acquisition rates will decrease if crew movement is impeded, if ponded water is present, if adverse weather conditions are encountered, etc.
Crew size	Typically 1-2 persons.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a gravity meter is on the order of $235/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are not required unless data are to be acquired across roadway or immediately adjacent to roadway.
Typical processing costs per day	Normally, it takes about as long to process gravity meter data as it does to acquire the data. Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A highly-skilled data processor is required. The interpreter must be experienced and very familiar with the subsurface geology in the study area.

3.4 Infrared Thermography

A photo of infrared thermography equipment is shown in Fig. 3.11.

Fig. 3.11–Photo of infrared thermography equipment (FLIR A615 infrared camera, source: www.flir.com).

Table 3.27–Infrared Thermography (IRT) with emphasis on imaging the subsurface in a DOT ROW – description and applications

Description of typical deliverable	The typical output of an infrared thermography (IRT) survey is a suite of infrared images covering every square foot of paved surface of interest. The IRT tool is a hand-held or vehicle-operated system (see Fig 3.11) that transforms the thermal energy radiated from a paved surface in the infrared band of the electromagnetic spectrum into a visible image; each energy level is represented by a color or grey level.
Utility of typical deliverable	IRT images of asphalt pavements are frequently acquired while the asphalt is being placed to ***identify areas of thermal segregation***. Thermal segregation may be indicative of problems that may decrease the integrity and life-span of the asphalt pavement. IRT images of ***existing pavements (including bridge decks) are acquired to identify areas where the pavement is deteriorated***. For example, infrared thermography senses temperature differences that exist when the concrete pavement is warming because areas where the concrete is delaminated heat up more rapidly than areas where the concrete is intact. The stored images are normally analyzed/ interpreted off-site and used to generate a detailed deterioration map complete with qualitative assessments of the severity of delamination.
Reliability of typical deliverable	If good quality IRT data are acquired, areas of thermal segregation in newly-placed asphalt can be readily defined. If good quality IRT data are acquired, areas of significant degradation can be identified on interpreted IRT maps. The acquisition of good quality IRT data can be problematic.
Reproducibility of typical deliverable	The acquisition of good quality IRT data across existing pavements is weather-dependent. Significant temperature differences between delaminated and solid areas are normally established only on sunny or partially sunny days when the bridge deck is warming up (morning) or cooling (evening). Temperature differences are primarily related to the amount of sun, not the ambient air temperature, so inspections can be undertaken even in cool weather. The paved surface must be dry and clean (of sands and deicing salts), and wind must be less than 25 miles per hour to prevent heat from being dissipated. Shaded areas on the paved surface can be misinterpreted as “cooler” areas. Tarred areas can generate anomalies. Heat flow patterns across newly-placed asphalt will vary as the ambient air temperature varies.

Data collection method	Infrared thermography (IRT) data are usually collected in a series of passes across the paved surface (see Fig. 3.11), with each pass covering a width of between 12 and 15 ft. The operator can review the infrared video data in real-time so that selected areas that appear delaminated on the IR image (higher in temperature than surrounding areas) can be marked and immediately tested (if/as needed) to confirm the presence of delamination (or in the case of newly placed asphalt, the cause of thermal segregation).
Applicability for network-level investigations	IRT is not applicable to network-level investigations.
Applicability for project-level investigations	IRT is applicable to project-level investigations. The tool can be used to identify areas and extensiveness of thermal segregation. The tool can also be used to identify areas where existing pavements are deteriorated.
Advantages	Advantages to using IRT for investigation include: • tool is non-invasive and does not need to be coupled to the ground • data can be acquired very rapidly and automatically • data can be interpreted in real time and/or digitally recorded, downloaded and posted on a contoured base map • limited (if any) data processing is required (downloading and contouring mostly) • data interpretation is usually straightforward for an experienced interpreter • limited potential for human error • data are recorded digitally • field data are reproducible
Disadvantages	Disadvantages to using IRT for investigation include: • good quality IRT data can only be acquired under optimum weather conditions (temperatures must be dropping or rising rapidly and wind must be less than 25 miles per hour to prevent heat from being dissipated) • existing paved surfaces must be dry and clean (of sands and deicing salts) • shaded areas on existing paved surfaces can be misinterpreted as “cooler” areas • tarred areas on existing pavements can generate anomalies
Recommendations	The acquisition of IRT data is recommended to monitor thermal segregation. The tool could be used in support of GPR and/or PSPA investigations.

Table 3.28–Infrared thermography method with emphasis on imaging the subsurface in a DOT ROW – logistics and costs

Preplanning requirements	Only an experienced contractor is qualified to design optimum field acquisition parameters. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of IRT data acquired per day	A 2-person field crew can usually acquire thousands of square feet of continuous IRT coverage in a single working day (depending on target depth and resolution required). Acquisition rates will decrease if crew movement is impeded, if adverse weather conditions are encountered, etc.
Crew size	Typically 1-2 persons.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a IRT camera is on the order of $100/day plus preparation and shipping.
Level of expertise required to acquire IRT data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are normally required.
Typical processing costs per day	Normally, minimal processing is required.
Level of expertise required to process and interpret infrared thermography data	A skilled data processor/interpreter is required. The IRT signature of pavement can be affected by previous repairs, shadows, ponded water, etc. The interpreter may need to consider these variables.

3.5 Radar Methods

Radar methods used for pavement and subsurface investigation include air-launched ground penetrating radar (GPR), high-frequency ground-coupled GPR, and intermediate- or low-frequency ground-coupled GPR. Fig. 3.12 shows a photo of high-frequency air-launched GPR equipment mounted to a vehicle, and Fig. 3.13 shows a photo of high-frequency ground-coupled GPR equipment. Fig. 3.14 shows a photo of intermediate- or low-frequency GPR equipment.

Fig. 3.12–Photo of twin air-launched (horn) ground penetrating radar (GPR) antennae mounted to vehicle.

Fig. 3.13–Photo of high-frequency ground-coupled ground penetrating radar (GPR) equipment.


Fig. 3.14–Photo of intermediate- or low- frequency ground penetrating radar (GPR) equipment.

Table 3.29–Air-launched ground penetrating radar (GPR) surveying with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The typical deliverable of an air-launched ground-penetrating radar (GPR) survey across pavement is an interpreted 2-D GPR image (horizontal axis: distance; vertical axis: depth) of the pavement depicting various pavement layers, embedded rebar, debonded layers, etc. Typically, the pavement is imaged to a depth on the order of 1.5 ft.
Utility of typical deliverable	An interpreted 2-D GPR profile (2-D GPR image) acquired across pavement can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest can include, but are not limited to, mapping/identification of the following: • ***thickness of pavement layers*** (asphalt layers, concrete layers, base, to depths on the order of 1.5 ft) • ***The thickness of new pavements can be measured to within 3-5%; the reliability of thickness estimates for existing pavements deceases as pavement quality decreases*** • ***variations in asphalt quality*** • ***variations in concrete quality*** • ***delaminations*** • ***debonding*** • ***moisture content of base*** • ***pattern, placement density (spacing) of reinforcing steel*** • ***location of buried utilities*** • ***depth to sub-grade*** • ***depth to top of rock***
Reliability of typical deliverable	A 2-D GPR profile with superposed interpretations will be most reliable if ground truth is available to constrain and verify the interpretations. In certain instances, real variations in pavement layer thicknesses can be misinterpreted as apparent variations in thickness and erroneously attributed to variations in pavement quality.
Reproducibility of typical deliverable	The electrical properties (dielectric permittivity) of pavement layers will vary slightly as the moisture content of the pavement varies (seasonally; after rain; when frozen). This will cause corresponding changes in the appearance of the output 2-D GPR profile. However, in most situations, the resultant interpretation of the output 2-D conductivity profile will not change in any significant way. If good quality GPR field data are acquired, and if ground truth is available, experienced interpreters should produce very similar interpretations.

Data collection method	Air-launched GPR (see Fig. 3.12) data are normally acquired at highway speeds using one or more pairs of high-frequency antennae (in bi-static mode) mounted to the front or rear of a vehicle. If two pairs of antennae are used, GPR control can be acquired simultaneously along two parallel traverses. As the vehicle is driven along the segment of roadway to be surveyed, GPR data (traces) are acquired at predetermined distance intervals. GPS data are acquired simultaneously so that the locations at which all GPR data are acquired can be determined with a high degree of precision. If the roadway is relatively long, the GPR data are often collected in manageable section lengths.
Applicability for network-level investigations	Air-launched GPR surveys are applicable to network-level investigations. GPR data can be acquired at highway speeds and used to generate essentially continuous interpretable images of lengthy segments of roadway.
Applicability for project-level investigations	Air-launched GPR surveys applicable to project-level investigations. However, if very high resolution images are required, a high-frequency ground-coupled GPR antenna is often more suitable (see Tabled 3.31-3.32). If greater depths of investigation (>1.5 ft) are required, an intermediate- to low-frequency ground-coupled GPR antenna should be employed (see Tables 3.33-3.34).
Advantages	Advantages of using air-launched GPR surveying for pavement investigation include: • tool is non-invasive and does not need to be coupled to the pavement surface • lane closures are not required • data can be acquired very rapidly (highway speeds) • data collection is essentially automatic • limited potential for human error • lateral resolution can often be increased by increasing the number of traces acquired per unit distance • data can be acquired across all types of paved roadways • data can be acquired while it is raining as long as the GPR antennas are protected • field data are reproducible • processing is relatively straightforward and semi-automated • interpretations, especially when constrained, are reliable • data are displayed as acquired (QC purposes and limited real time interpretations)

Disadvantages	Disadvantages of using air-launched GPR surveying for pavement investigation include: • limited depths of investigation (< 1.5 ft) • number of traces acquired per unit distance decreases as vehicle speed increases • images are generally lower resolution than those generated by comparable ground-coupled antennae • post-acquisition processing may be required • data, in part because of the large volume acquired, must be processed and interpreted in the lab • ground truth (limited core control) is required to accurately constrain interpretations
Recommendations	The acquisition of air-launched GPR data is recommended along any segment of paved roadway location where information about pavement layer thicknesses or pavement layer quality is desired. If very high-resolution GPR images are required, a high-frequency ground-coupled GPR antenna may be more suitable (see Tables 3.31-3.32). If greater depths of investigation (> 1.5 ft) are required, an intermediate- to low-frequency ground-coupled GPR antenna should be employed (see Tables 3.33-3.34).

Table 3.30–Air-launched ground penetrating radar (GPR) surveying with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design an air-launched GPR survey. This includes selection of acquisition parameters and selection of the specific instrument employed. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.).
Typical volume of data acquired per day	A 2-person field crew using a commercial vehicle can acquire air-launched GPR data at highway speeds.
Crew size	Typically 2 persons; a driver and an operator.
Typical acquisition costs per field day	Costs include crew time (typically 2 persons) plus travel time and equipment usage fee. An air-launched GPR system must be mounted on a dedicated vehicle. Hence, this tool is not normally rented on a per day basis. Rather, an air-launched GPR system is normally owned and operated by established professionals who specialize in pavement assessment. Daily acquisition costs are estimated to be on the order of $2000.
Level of expertise required to acquire data	A highly-skilled experienced instrument operator is required. The operator must be able to mount both the GPR and GPS systems on the vehicle and interface the data.
Lane closure requirements	Lane closures are not required.
Typical processing costs per day	Generally, it takes much longer to process air-launched data than to acquire the data. An experienced operator can usually process/interpret multiple miles of roadway GPR data in a single working day (depending on the quality of the GPR data, the availability of ground truth, the complexity of the interpretations, pavement variability, etc.). Costs include the processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A highly-skilled experienced data processor/interpreter is required. Data are interpreted visually and with the aid of sophisticated, yet user-friendly, software. The interpreter must be experienced with the interpretation of pavement GPR data.

Table 3.31–High-frequency ground-coupled ground penetrating radar (GPR) surveying with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The typical deliverable of a high-frequency (> 1000 Hz) ground-coupled ground-penetrating radar (GPR) survey across pavement is one or more interpreted 2-D GPR images (horizontal axis: distance; vertical axis: depth) of the pavement depicting various pavement layers, embedded rebar, debonded layers, etc. If a 1500 MHz antenna is employed, maximum realizable depths of investigation will be on the order of 1.5 ft.
Utility of typical deliverable	An interpreted 2-D GPR profile (2-D GPR image) acquired across pavement can be of significant utility to those engaged in highway construction and/or maintenance. Interpretations of interest can include, but are not limited to, the mapping/identification of the following: • ***thickness of pavement layers (asphalt, concrete, base, typically to depths on the order of 1.5 ft)*** • ***variations in asphalt quality*** • ***variations in concrete quality*** • ***delaminations*** • ***debonding*** • ***moisture content of base*** • ***pattern, placement density of reinforcing steel*** • ***voids*** • ***location of buried utilities*** • ***depth to sub-grade*** • ***depth to top of rock***
Reliability of typical deliverable	The 2-D GPR profiles with superposed interpretations will be most reliable if ground truth (boring control) is available to constrain and verify the geologic interpretation. In certain instances, real variations in pavement layer thicknesses can be misinterpreted as apparent variations in thickness and erroneously attributed to variations in pavement quality.
Reproducibility of typical deliverable	The electrical properties (dielectric permittivity) of pavement layers will vary slightly as the moisture content of the subsurface varies (seasonally; after rain; when frozen). This will cause corresponding changes in the appearance of the output 2-D GPR profile. However, in most situations, the resultant interpretation of the output 2-D conductivity profile will not change in any significant way. If good quality GPR field data are acquired and if ground truth is available, experienced interpreters will produce very similar interpretations.

Data collection method	Ground-coupled GPR data are normally acquired at walking speeds using a wheeled push-cart (Fig 3.13). GPS data can be acquired simultaneously, so that the locations at which GPR data were acquired can be determined with a high degree of precision.
Applicability for network-level investigations	Ground-coupled GPR is not applicable to network-level investigations.
Applicability for project-level investigations	Ground-coupled GPR is applicable to project-level investigations. If greater depths of investigation are required, an intermediate- to low-frequency ground-coupled GPR antenna should be employed (Tables 3.33-3.34).
Advantages	Advantages for using ground-coupled GPR for pavement investigation include: • tool is non-invasive and does not need to be physically coupled to the ground; rather it is pushed or pulled across the ground surface • generates very high-resolution images of pavement • data can be acquired rapidly (walking speeds) • data collection is essentially automatic • limited potential for human error • lateral resolution can often be increased by increasing the number of traces acquired per unit distance • data can be acquired across all types of paved roadways • data can be acquired while it is raining as long as instrument is protected • field data are reproducible • processing is relatively straightforward and semi-automatic • interpretations, especially when constrained, are reliable • data are displayed as acquired for QC purposes • visual interpretations can frequently be made in real time
Disadvantages	Disadvantages for using ground-coupled GPR for pavement investigation include: • limited depths of investigation (typically less than 1.5 ft) • lane closures are required • post-acquisition processing may be required • data must normally be processed and interpreted in the lab • ground truth (limited core control) is required to accurately constrain interpretations

Recommendations	The acquisition of high-frequency ground-coupled GPR data is recommended along any segment of paved roadway location where information about pavement layer thicknesses and condition are required. If greater depths of investigation (> 1.5 ft) are required, an intermediate- to low-frequency ground-coupled GPR antenna should be employed (Tables 3.33-3.34).

Table 3.32–High-frequency ground-coupled ground penetrating radar (GPR) surveying with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Only a contractor with extensive ground conductivity experience is qualified to design optimum field acquisition parameters. This includes the selection of the specific instrument employed. Consultation between the client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.). Testing will require lane closures.
Typical volume of data acquired per day	A 2-person field crew can usually acquire several thousand lineal feet (or more) of high-frequency ground-coupled GPR in a single working day. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 1-2 persons.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a high-frequency GPR unit are on the order of $350/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are normally required.
Typical processing costs per day	Generally, it takes much longer to process GPR data than to acquire the data. An experienced processor can usually process/interpret at least one thousand feet of good quality high-frequency GPR data in a single day (depending on the quality of the GPR data, the availability of ground truth, the complexity of the interpretations, pavement variability, etc.). Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor/interpreter is required. Data are interpreted visually and with the aid of sophisticated, yet user-friendly, software. The interpreter must be experienced with the interpretation of pavement GPR data.

Table 3.33–Low- to intermediate-frequency ground-coupled ground penetrating radar (GPR) surveying with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The typical deliverable of a low- to intermediate-frequency ground-coupled ground-penetrating radar (GPR) survey across pavement is a suite of interpreted 2-D GPR images (horizontal axis: distance; vertical axis: depth) of the pavement and underlying sediment. If an intermediate-frequency antenna (~400 MHz) is employed, maximum realizable depths of investigation are on the order of 6 ft. If a 100 MHz antenna is employed, maximum realizable depths of investigation can be on the order of 25 ft or more (depending on the electrical properties of pavement and underling soil/rock).
Utility of typical deliverable	An interpreted 2-D GPR profile acquired across pavement can be of significant utility to those engaged in highway construction and/or maintenance. If an intermediate-frequency (~400 MHz) antenna is employed, interpretations of interest can include, but are not limited to, the mapping/identification of the following: • ***approximate thickness of pavement layers (asphalt, concrete and base)*** • ***moisture content of base*** • ***location of buried utilities*** • ***depth to sub-grade*** • ***depth to top of rock*** If a low-frequency (~100 MHz) antenna is employed, the GPR image may extend well into the sub-grade or underlying bedrock (depths on the order of 25 ft depending on the electrical properties of the pavement and underlying soil/rock). However, resolution in the upper section of pavement will be significantly reduced.
Reliability of typical deliverable	The 2-D GPR profiles with superposed interpretations will be most reliable if ground truth is available to constrain and verify the geologic interpretation.
Reproducibility of typical deliverable	The electrical properties (dielectric permittivity) of pavement layers will vary slightly as the moisture content of the subsurface varies (seasonally; after rain; when frozen). This will cause corresponding changes in the appearance of the output 2-D GPR profiles. However, in most situations, the resultant interpretation of the output 2-D conductivity profile will not change in any significant way. If good quality GPR field data are acquired and if ground truth is available, experienced interpreters will produce very similar interpretations.

Data collection method	Ground-coupled GPR data are normally acquired at walking speeds using a wheeled push-cart. GPS data can be acquired simultaneously, so that the locations at which GPR data were acquired can be determined with a high degree of precision.
Applicability for network-level investigations	Not applicable to network-level investigations.
Applicability for project-level investigations	Applicable to project-level investigations. However, if high resolution images are required, a high-frequency ground-coupled GPR antenna may be more suitable.
Advantages	Advantages include: • tool is non-invasive and does not need to be physically coupled to the ground; rather it is pushed or pulled across the ground surface • generates moderate-resolution images of pavement • data can be acquired rapidly (walking speeds) • data collection is essentially automatic • limited potential for human error • lateral resolution can often be increased by increasing the number of traces acquired per unit distance • data can be acquired across all types of paved roadways • data can be acquired while it is raining as long as instrument is protected • field data are reproducible • processing is relatively straightforward and semi-automatic • interpretations, especially when constrained, are reliable • data are displayed as acquired for QC purposes • visual interpretations can frequently be made in real time
Disadvantages	Disadvantages include: • limited depths of investigation (typically < 25 ft or less in Missouri) • lane closures are required • post-acquisition processing may be required • data must normally be processed and interpreted in the lab • ground truth (limited core control) is required to accurately constrain interpretations
Recommendations	The acquisition of low- to intermediate-frequency ground-coupled GPR data is recommended along any segment of paved roadway location where information about pavement layer thicknesses and condition are required. If depths of investigation of less than 1.5 ft (only) are required, a high-frequency ground-coupled GPR antenna should be employed (Table 3.31-3.32).

Table 3.34–Low- to intermediate-frequency ground-coupled ground penetrating radar (GPR) surveying with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Only a contractor with extensive ground conductivity experience is qualified to design optimum field acquisition parameters. This includes the selection of the specific instrument employed. Consultation between client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements (depth of investigation, desired lateral and resolution, area of interest, nature of anticipated features of interest in the subsurface, etc.). Testing will require lane closures.
Typical volume of data acquired per day	A 2-person field crew can usually acquire several thousand lineal feet (or more) of low- to intermediate-frequency ground-coupled GPR in a single working day. Acquisition rates will decrease if crew movement is impeded.
Crew size	Typically 1-2 persons.
Typical acquisition costs per field day	Costs include crew time (typically 1-2 persons) plus travel time and equipment rental and/or usage fee. Published daily rental costs for a low- to intermediate-frequency GPR unit are on the order of $350/day plus preparation and shipping.
Level of expertise required to acquire data	A skilled instrument operator is required.
Lane closure requirements	Lane closures are normally required.
Typical processing costs per day	Generally, it takes much longer to process ground-conductivity data than to acquire the same. An experienced processor can usually process/interpret several hundred feet of good quality low- to intermediate-frequency GPR data in a single day (depending on the quality of the GPR data, the availability of ground truth, the complexity of the interpretations, pavement variability, soil/rock variability, etc.). Costs include processor's time and software rental and/or usage fee.
Level of expertise required to process and interpret data	A skilled data processor/interpreter is required. The interpreter must be experienced and very familiar with pavements and the subsurface geology in the study area.

3.6 Deflection Methods

The most common deflection-based method for pavement investigations is the falling weight deflectometer (FWD). In recent years, equipment and methods have been developed to collect deflection data “on-the-fly” from a moving platform. These methods include: the rolling dynamic deflectometer (RDD), and the rolling wheel deflectometer (RWD). Images of the FWD, RDD, and RWD are shown in Figs. 3.15 through 3.17. Overviews of these methods are presented in Tables 3.35 to 3.40.

Fig. 3.15–Photo of falling weight deflectometer (FWD) equipment.

Fig. 3.16–Photo of rolling dynamic deflectometer (RDD) equipment.

Fig. 3.17–Photo of rolling wheel deflectometer (RWD) equipment (www.fhwa.dot.gov).

Table 3.35–Falling weight deflectometer (FWD) surveying with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The falling weight deflectometer (FWD) is a device used to infer pavement properties and condition by measuring pavement deflections on a point-by-point basis (Fig. 3.15). The FWD method consists of dropping a weight from a fixed height onto a pavement system to simulate the load of moving traffic. The peak applied load and peak deflections are measured. Geophones are positioned at multiple radial distances from the impact point to record the deflection basin caused by the falling weight. The deflection basin measured by the geophones can be used in a variety of ways to infer the properties and condition of the pavement system. Deliverables from the field test consist of peak deflection values from multiple weight drops at each test location. Processing and interpretation of the FWD data can vary significantly depending on the desired parameters and the method and assumptions used in the analysis. The FWD is often used as a means to determine pavement stiffness parameters and assess pavement quality.
Utility of typical deliverable	Deflection values from the FWD provide qualitative information on the composite stiffness of the pavement system. Large deflection values indicate poor quality pavement and/or subgrade materials. Interpretation of the FWD data can be used to develop estimates of modulus values for the individual pavement layers through back-calculation procedures. Simple empirical relationships can also be used to estimate composite pavement stiffness values. Testing across joints and cracks in rigid pavements can be used to assess load transfer efficiency of the joint or detect voids under the pavement.
Reliability of typical deliverable	The deflection data acquired from the field measurements are reliable if sources of error can be minimized. Sources of error may include improper calibration of the sensors, poor seating of the load plate on the pavement surface, and random errors in the data acquisition due to factors such as road noise, environmental conditions, and electrical equipment variability. Repeat weight drops can be performed and averaged to minimize the effect of random errors. Maintenance of equipment is also important to minimize errors. For example, worn load bumpers can alter the impact pulse and affect the results and interpretation of the data.
Reproducibility of typical deliverable	Reproducibility of the results can be assessed by performing repeat weight drops at the same location. Typically, the variability in deflection values may be on the order of 0.05 mils but is site and equipment dependent. Greater variability is expected if the equipment is removed and repositioned due to different seating conditions.

Data collection method	Collection of FWD data is automated. The operator selects the appropriate plate size and drop heights for the site of interest and positions the equipment at the point of interest (see Fig. 3.15). The operator controls the sequence of weight drops for each site. The FWD device performs the desired sequence and records the load level, receiver response at each location, and other information such as position and temperature (air and pavement).
Applicability for network-level investigations	FWD could be applied to network-level investigations. However, due to the time involved and the need for lane closure, FWD measurements for network level analysis must be collected at large spatial intervals (e.g. 600 ft apart or more). FWD for network level applications may provide valuable structural information (to supplement functional parameters such as roughness) about the pavement that could be used for pavement management planning.
Applicability for project-level investigations	FWD is most often used for project-level applications to provide detailed information about the structural properties of the pavement. This information may be used to select and design appropriate pavement rehabilitation strategies.
Advantages	Advantages include: • can be used to back-calculate modulus values of pavement layers • can be modified for various pavement types and thicknesses • non-invasive and non-destructive • limited potential for human error • field data are reproducible, and data collection is automated • could be used in network level applications (with sparse spatial sampling) to provide structural parameters which supplement functional parameters used in pavement management programs • can be used in project-level applications to provide parameters for design and selection of rehabilitation strategies
Disadvantages	Disadvantages include: • temporary lane closures are required • measurements are made only at discrete locations • back-calculation of modulus depends on several assumptions and is not a unique solution (requires iteration or inversion) • improper load plate or sensor seating can return inaccurate results • data acquisition is relatively slow for network-level assessment
Recommendations	The FWD is an appropriate tool for project-level applications to provide structural information (both qualitative and quantitative) that can be used in selection and design of pavement rehabilitation strategies. FWD may also be valuable for network-level pavement management programs but must be collected with much greater intervals between measurement points.

Table 3.36–Falling weight deflectometer (FWD) surveying with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Only a contractor with extensive experience is qualified to design optimum field acquisition parameters and acquire the data. Consultation between client and contractor is critical because acquisition parameters are identified on the basis of the client's requirements and needs. Testing will require lane closures.
Typical volume of data acquired per day	A two-person field crew can normally acquire FWD data at 15 to 20 locations in an hour. Data collected include receiver output, load level, temperature and location information. The typical deliverable is the peak load and peak deflection at each receiver location from multiple weight drops at each location.
Crew size	Typically two persons. One person operates and controls the equipment with assistance in positioning the equipment from the second person. Can be performed with a single operator.
Typical acquisition costs per field day	Approximately $250/hr to collect field data.
Level of expertise required to acquire data	An experienced instrument operator is required to perform the measurement. Consistent data collection procedures must be followed to produce reliable results.
Lane closure requirements	Lane closures are required.
Typical processing costs per day	Cost to process the field data and produce the deliverable of peak displacement at each receiver location is negligible. The time and cost of further processing of data to produce values such as modulus and load transfer efficiency depend greatly on the desired parameters and methods used to calculate the values.
Level of expertise required to process and interpret data	The extent of processing and interpretation of FWD data varies greatly depending on the methods used and parameters that are needed. Values such as load transfer efficiency and forward calculations using empirical methods are performed with a spreadsheet and do not require significant time or expense. Back-calculation of modulus values from FWD data requires specialized software and an experienced operator to achieve reliable results.

Table 3.37–Rolling dynamic deflectometer (RDD) surveying with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	Rolling dynamic deflectometer (RDD) data are acquired "on-the-fly" using a modified Vibroseis truck with a rolling source and rolling sensors. A dynamic force of about 10 kips (peak to peak) is superimposed on a static hold-down force of about 10 kips. The constant frequency (typically 30 Hz) dynamic force is generated from the vibrating mass of the Vibroseis and applied to the pavement through a pair of rolling wheels. Four wheel-mounted geophones (resonant frequency of 2 Hz) located between the source wheels, as well as 2 ft, 3.18 ft, and 4.67 ft from the source move along with the Vibroseis truck. The geophones record particle velocity along the pavement profile. Data processing produces a continuous profile of pavement deflections (averaged over intervals of about 2 ft) from each of the geophones. The deliverable from RDD testing is a continuous profile of pavement deflection produced from the moving load of the RDD and expressed in mils/10 kips. A deflection profile is provided for each of the geophones used to record the pavement motions.
Utility of typical deliverable	The continuous profile provides a much greater spatial resolution (deflection values about every 2 ft) of pavement deflection than is typically achieved with FWD measurements. The data are used qualitatively to ***detect and delineate regions of high deflection (indicating possible pavement problems) in both rigid and flexible pavements, and quantitatively to calculate load transfer efficiency (LTE) at joints and cracks.*** Differential deflections between receivers straddling a joint are used to determine if the joint is transferring load efficiently. Poor slab support is characterized by large mid-slab deflections and low differential deflections. Most of the published RDD applications have been for rigid pavements.
Reliability of typical deliverable	The deliverable is reliable if sources of error can be minimized. Distance measurement is subject to cumulative errors over long distances and should be checked with other known distance measures along the profile. Direction of travel is typically along the length of the pavement in one lane. It is important that the truck maintain a consistent distance from the pavement edge throughout the process of collecting data. Surface conditions are important as they may produce erratic deflection outputs if the surface is excessively rough. The measurement is not affected by road noise and can be performed next to an active lane of traffic.

Reproducibility of typical deliverable	If sources of error are minimized, the results should be reproducible. No detailed study quantifying the reproducibility and variability of the deflection profiles is available in the literature.
Data collection method	Data collection is automated. The RDD truck (see Fig. 3.16) operates at speeds of 1-3 miles per hour and requires either a lane closure or rolling lane closure. After the RDD sensors are positioned under the truck at the start of the planned profile, the data collection is largely automated as the truck is driven down the lane with the source continuously vibrating and the rolling sensors recording the pavement movements. A two-man crew is used to collect the data (one drives the truck and the other monitors the quality of the data collection and notes features of interest along the profile).
Applicability for network-level investigations	Due to the relatively slow operating speed (1-3 mph) and the need for lane closures, the RDD is not typically applied to network-level investigations where hundreds of miles need to be evaluated at highway speeds. However, data collection rates allow for 10 to 12 miles of pavement to be evaluated in a single day, so coverage is greater than typical project-level tools such as the FWD. The RDD could be used to sample sections of pavements for network-level decision making.
Applicability for project-level investigations	The RDD is appropriate for project–level investigations where detailed coverage of the pavement section of interest is desired. It will test and evaluate every joint or crack and provide a quality assessment of pavement support. Further development of the technology may provide quantitative assessments of soil and pavement properties.
Advantages	Advantages include: • Provides continuous record of pavement deflection • non-invasive and non-destructive • largely automated data collection • field data are reproducible • data processing is largely automated • provides information on pavement quality, subgrade support, joint efficiency and variability in properties along pavement section
Disadvantages	Disadvantages include: • data interpretation is largely qualitative at this point (i.e. high versus low deflection); does not provide modulus values • operating speed requires lane closures • RDD is not a commercial product at this time. There are only two in existence, both operated by the Texas Department of Transportation. Work must be contracted out, or a new device must be built.

Recommendations	The RDD is an appropriate tool for project-level pavement assessment purposes. The RDD can be used to evaluate pavement quality for planning of pavement rehabilitation. The equipment is not in widespread use, and research is still being conducted to evaluate the effectiveness of the RDD for different applications. Published studies have shown good results assessing joints in rigid pavements. There are few published studies of application to flexible pavements.

Table 3.38–Rolling dynamic deflectometer (RDD) surveying with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Testing requires lane closures or moving lane closures with crash trucks located ahead and behind the RDD. At this time, RDD testing is only performed by personnel from the University of Texas so arrangements must be made to transport the equipment from Texas to the site. Testing will require lane closures.
Typical volume of data acquired per day	A two-person field crew can normally acquire RDD data at 1-3 miles per hour speeds. Multiple channels of data are acquired, including: distance, load, and deflection values from Receivers 1 through 4.
Crew size	Typically two persons. One person drives; one person oversees data recording and assesses data quality and pavement features.
Typical acquisition costs per field day	At this time the cost to operate the RDD at sites outside of Texas may be prohibitive in some cases due to the cost to transport the equipment from Texas. Aside from transport costs, operation of truck costs about $250/hour.
Level of expertise required to acquire data	A skilled driver and operator are required to operate this equipment. At this time, only personnel from the University of Texas operate the RDD so this work must be contracted out.
Lane closure requirements	Lane closures are required, although moving lane closure can also be performed in some cases.
Typical processing costs per day	Data processing to produce the deflection profile is largely automated and is not a significant additional cost.
Level of expertise required to process and interpret data	Although data processing is largely automated, the interpreter must be experienced and very familiar with the pavement site tested and the operation of the equipment to assess the quality of the results.

Table 3.39–Rolling wheel deflectometer (RWD) surveying with emphasis on the assessment of pavements – description and applications

Description of typical deliverable	The Rolling Wheel Deflectometer (RWD) is a recently developed experimental system for acquiring deflection data at highway speeds. The RWD uses a specially designed semi-truck (Fig. 3.17) that can measure pavement deflections caused by one-half of an 18-kip single axle load. The truck is equipped with a laser array system for measuring pavement deflection that is mounted to the underside of the truck on an aluminum beam. The beam contains 4 lasers that use a spatially coincident method to determine deflections at the location of the tire and at several points spaced about 8.5 ft apart. The truck operates at highway speeds and produces a profile of pavement deflections (in mils) under the weight of the loaded truck versus distance.
Utility of typical deliverable	The RWD is designed to be a network-level device to collect pavement deflection data at highway speeds. The utility of the RWD is primarily as a qualitative network-level screening tool to identify poor pavement regions where detailed analysis with other methods should be performed.
Reliability of typical deliverable	The RWD is still an experimental device and the reliability of the results are still being assessed. Assessments of the reliability of the RWD deflections have been mixed. Some studies have shown good correlations with other methods, while others have shown poor correlations. For example, a 2010 study of RWD testing on Virginia highways showed poor correlations between RWD deflections and deflections from FWD measurements. The same study also showed variability in the RWD results with changes in surface type.
Reproducibility of typical deliverable	Reproducibility of the RWD results is still being assessed. Studies have produced different findings regarding the reproducibility of the results.
Data collection method (automated, semi-automated, manual)	Data collection is automated and is performed at highway speeds.
Applicability for network-level investigations	The RWD is a network-level assessment tool that is designed to rapidly screen pavements for pavement management applications and identify regions in need of detailed study using methods such as the FWD.
Applicability for project-level investigations	Not applicable to project-level studies.

Advantages	Advantages include: • Operates at highway speed (no lane closure); 200 to 300 lane miles per day • non-intrusive and non-destructive • automated data collection • screening tool for network level assessment of pavements
Disadvantages	Disadvantages include: • reliability and repeatability is questionable • tool is still in research and evaluation stage • not in widespread use • provides only a relative and qualitative assessment of pavement condition • large spatial averaging (e.g. one average deflection value in 0.1 mile) of results due to variability in the measurement • not used to calculate engineering parameters
Recommendations	The RWD is still in the research and evaluation stage, and the reliability of the method is still being studied.

Table 3.40–Rolling wheel deflectometer (RDD) surveying with emphasis on the assessment of pavements – logistics and costs

Preplanning requirements	Pavement assessment using the RWD needs to be contracted out to the operator of the RWD equipment.
Typical volume of data acquired per day	Site and project dependent.
Crew size	Not available
Typical acquisition costs per field day	Not available
Level of expertise required to acquire data	A skilled instrument operator is required. Pavement assessment using the RWD would be contracted out to the operator of the RWD equipment.
Lane closure requirements	Lane closures are not required.
Typical processing costs per day	Data are processed automatically as they are acquired.
Level of expertise required to process and interpret data	Interpretation is qualitative and mainly used to identify regions of high-deflection indicating the need for further study with project-level tools such as the FWD.

4 CONCLUDING REMARKS

4.1 Summary

This task was used to identify and evaluate methods to rapidly obtain network-level and project-level information relevant to in situ pavement condition to enable pavement maintenance decisions. The focus of these efforts was to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluation. These technologies will ultimately enable pavement maintenance decisions that minimize cost and maintain/improve pavement quality. Noninvasive imaging methods reviewed in this task are summarized in Table 1.1, including the applicability of each method to project- and/or network-level investigations, and applicability to pavement and/or subsurface investigations.

4.2 Recommended Methods for Task 4 Investigations

Based on the assessments conducted in this task, the non-invasive imaging technologies recommended for the Task 4 investigations are summarized in Table 4.1. These methods were selected to evaluate and demonstrate the applicability to project-level and/or network-level roadways.

Table 4.1 - Summary of non-invasive technologies recommended for Task 4 project-level and network-level investigations

Non-invasive Imaging Technology	Project-level Roadways	Network-level Roadways	ARAN compatible
Ultrasonic Surface Waves (USW)	Yes	No	No
Impact Echo (IE)	Yes	No	No
Ground-coupled Ground Penetrating Radar (GPR) (400 MHz and 1500 MHz)	Yes	No	Yes
Electrical Resistivity Tomography (ERT)	Yes	No	No
Multichannel Analyses of Surface Waves (MASW)	Yes	No	No
Falling Weight Deflectometer (FWD)	Yes	No	No
Rolling Dynamic Deflectometer (RDD)	Yes	No	No
Air-launched Ground Penetrating Radar (GPR)	No	Yes	Yes

In the Task 4 Appendix A, Guidance Document, (Section 9), pavement-specific applications for each of the eight recommended non-invasive technologies are presented.

Each of the recommended technologies could be utilized effectively by appropriately trained MoDOT personnel. Only the GPR technologies are compatible with the ARAN vehicle. The ultrasonic surface wave, impact echo, ground penetrating radar and electrical resistivity tools are readily stored and can be transported to a work site in a pick-up truck. The falling weight deflectometer and rolling dynamic deflectometer require dedicated vehicles. The field data acquired using all eight technologies are readily processed using commercially-available software and a laptop or desktop computer.