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Geophysical Methods for Determining the Geotechnical Engineering Properties of Earth Materials

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The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research.

Executive Summary

Surface and borehole geophysical methods exist to measure in-situ properties and structural characteristics of earth materials. Application of such methods has demonstrated cost savings through reduced design uncertainty and lower investigation costs. Routine use of geophysical methods, however, remains limited due to the specialized nature of the work and limited industry experience with its application to real-world projects. In an attempt to address that issue, Caltrans staff submitted a proposal for research aimed at developing a reference document describing the quantitative measurements of material properties that may be obtained using geophysical methods. In support, Caltrans staff surveyed the available literature to evaluate: 1) the current state of the practice regarding the use of geophysics for transportation projects, 2) the body of available literature that documents the use of geophysical methods to derive engineering properties of soil and rock, and 3) any standardized or recommended methods and procedures.

Summary of Findings

Numerous publications documenting advances in specific geophysical techniques or quantitative procedures for deriving specific physical properties from such methods are available. However, that information is widely dispersed in numerous publications, most of which would not be anticipated to be readily accessible or known to practicing civil and geotechnical engineers.

Many guidelines and a few standards on the use of geophysical techniques have been published nationally. Those guides and standards assume familiarity with the methods and quantitative interpretation aspects of the techniques are generally not addressed to a significant extent. Worldwide, efforts have been made to define best practices and to disseminate information on the application of geophysical methods for engineering problems. Those discussions tend toward basic, qualitative description of the methods. Quantitative descriptions of the properties actually measured or estimated by the techniques are kept to a minimum, either due to the purpose of the document or by the intended audience. The lack of engineering-based, quantitative discussions of geophysical applications creates a knowledge gap that may be bridged by this research proposal.

Current research on the topic is scarce. The Central Federal Lands Division of the Federal Highway Administration disseminates primarily qualitative information on geophysical methods through its interactive web site. The state of Florida is sponsoring research focused on geophysical techniques for assessing spatial variability in foundation properties, with emphasis on karst problems unique to Florida. Discussion of applications more relevant to California, such as seismic safety and slope stability, are still necessary. The Florida research is in its final stages, review of the results is recommended to avoid duplication of effort and to expand upon their findings.

Gaps in Findings

A considerable body of literature can be found that documents the use of geophysical techniques for qualitative assessment and quantitative measurement of earth material properties. Its content tends to fall within two extremes: 1) references that outline basic concepts for an entry-level audience and 2) published works that detail specific topics for experienced practitioners. Scarce in the literature are publications intended for those who possess an entry-level knowledge and wish to apply the methods, but are either not experienced practitioners or work in fields where advanced training in geophysical methods is unavailable or inappropriate. Also lacking are publications that are engineering-based: that first identify the physical parameters needed for adequate engineering and design, then describe the procedures and methods for obtaining that data. This project will make steps in filling that portion of the knowledge base.

Next Steps

Caltrans should consider: 1) implementing this research project in a phased approach, where tractable parameters are incorporated first and other methods worthy of further investigation or development are included in a subsequent phase or phases, 2) monitoring ongoing and future research for inclusion into this project and 3) pursuing cooperative agreements with the Central Federal Lands Division of the Federal Highway Administration for information transfer and pooling of resources.

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Background

Surface and borehole geophysical methods exist to measure in-situ properties and structural characteristics of earth materials (e.g., shear modulus, bulk density, porosity, fracture orientation, depth to bedrock, fault location). Application of such methods has demonstrated cost reduction through reduced design uncertainty and lowered investigation costs. Routine use of geophysical methods, however, remains limited due to the specialized nature of the work, exclusion of the methods in college engineering curricula and limited industry experience with its application to real-world projects. Numerous references on geophysical applications exist. However, a comprehensive summary of the available literature, describing the derivation of those physical parameters, needed by civil and geotechnical engineers for foundation design, that can be obtained from geophysical methods is unknown in the literature.

The Federal Highway Administration actively promotes the application of geophysical methods for cost-effective geotechnical site characterization. The Central Federal Lands Division of the FHWA has spearheaded an effort to disseminate information on the methods and their application through an interactive web-based publication, Application of Geophysical Methods to Highway Related Problems. This document, discussed in more detail below, provides basic knowledge of geophysics and nondestructive test (NDT) methods. Caltrans has identified a need to expand upon and complement that introductory work by developing a reference document for practicing engineers and geologists that describes in more detail the quantitative measurements of material properties that may be obtained using geophysical methods.

Caltrans staff submitted a proposal for research toward the aforementioned goal. To support this proposal, Caltrans staff reviewed recent research, national and international guidance and related efforts of other state departments of transportation to determine:

- What is the current state of the practice regarding use of geophysics for transportation projects? What methods are used, for what purpose, and what results are obtained?
- What research is available or still needed to document the quantitative physical property measurements available using geophysical methods, and what, if any, standardized or recommended methods and procedures exist?
- At what phase (or phases) of project development is the use geophysical methods most appropriate?
- What are appropriate uses of the engineering parameters derived from geophysical measurements?
- What are the underlying assumptions behind specific geophysical methods and what limitations do those assumptions place on the derived engineering parameters?
- What methods exist to assure and assess the quality of geophysical data?
- For methods where no endorsed standards or guidance exist, is it possible to propose recommended approaches for their use?

Summary of Findings

We have organized our findings in the following sections: **Research in Progress; Best Practices, Design Guides and Additional Resources;** and **Related Research**. As this is a preliminary investigation for a topic where a considerable body of literature exists, not every available reference is included herein. We have instead attempted to limit our focus for this preliminary investigation to recent and most pertinent state, federal, international and industry literature.

Our key findings include:

Research in Progress

Research currently underway on the topic is scarce. The State of Hawaii has funded a project for the use of geophysical methods to assess subsurface voids and soil settlement. The Federal Highway Administration (FHWA) is funding work on improvements to impulsive soil shear testing. The FHWA is also funding development of Internet-based knowledge resources for dissemination of basic information for non-destructive evaluation and testing (NDE) of highway structures, similar to work they previously funded for geophysical methods (see Application of Geophysical Methods to Highway Related Problems discussion below). The Transportation Research Board is sponsoring research on high-speed, non-destructive testing for tunnel defects. One project in particular is worth note. Dr. Dennis Hiltunen is currently finalizing work for the state of Florida on the use of geophysical techniques for assessing spatial variability in foundation properties, with particular focus on karst problems unique to Florida. Our discussions with Dr. Hiltunen indicate that our proposal is not duplicative of his work but will dovetail and extend his efforts in that state for nationwide application. Dr. Hiltunen has expressed interest in participating in our research. We intend to monitor his results and hope to have his cooperation in extending his work.

Best Practices, Design Guides and Additional Resources

Many guidelines and a few standards on the use of geophysical techniques have been published by the American Society for Testing and Materials. Those guides and standards assume familiarity with the methods and tend toward discussion of field methodology and quality assurance. Quantitative interpretation aspects of the techniques are generally not addressed.

Worldwide, efforts have been made to define best practices and disseminate information on the application of geophysical methods for engineering problems. The Society of Exploration Geophysicists of Japan (SEG-Japan) has produced a standardization document aimed at introducing an ISO 9000 approach to geophysical investigations (see Application of Geophysical Methods to Engineering and Environmental Problems discussion below). In the United Kingdom, the Construction Industry Research and Information Association (CIRIA), in conjunction with the Geological Society of London and the British Geological Survey, published a comprehensive document on the application of geophysics for engineering (see Geophysics in Engineering Investigations discussion below). In the United States, the FHWA published an online web-based resource describing geophysical methods commonly used for highway infrastructure (Application of Geophysical Methods to Highway Related Problems, discussed below). The Transportation Research Board of the US National Academies published Circular E-C130 in 2008 that provides an overview of 12 geotechnical geophysical methods commonly applied to transportation projects. For all of these publications, the discussion tends toward basic, qualitative discussion of the methods. Quantitative descriptions of the properties actually measured or estimated by the techniques are kept to a minimum, either due to the purpose of the document (SEG-Japan) or by the intended audience (FHWA). It should be noted that the CIRIA document provides more quantitative discussion of theory and application, but not at the level envisioned for the subject of this Preliminary Investigation.

Numerous publications documenting advances in specific geophysical techniques or quantitative procedures for deriving specific physical properties from such methods are available in the literature. To keep this Preliminary Investigation to a manageable length, a sample of the pertinent research findings are included and discussed below as Additional Resources. The American Society of Civil Engineers discusses the use of borehole geophysical measurements for geotechnical studies and the in-situ derivation of soil stiffness and damping for seismic design and settlement. Mavko *et al.* summarize many

equations from the field of rock physics that are pertinent to this research topic. The California Department of Transportation (Caltrans) discusses derivation of seismic loading based on seismic velocities of soil and rock. Additional researchers present findings relating physical properties of soil porosity and Standard Penetration Test values to in-situ seismic velocities.

Related Research

This section includes research results from the related field of non-destructive testing (NDT). Although it is common and useful, for discussion purposes, to try to separate the fields of geophysics and NDT based on the materials measured (geophysics focuses on naturally-occurring earth materials and artificial fill structures using earth materials, NDT primarily on man-made structures and structural elements) in reality and practice the two fields are closely linked and share much in the way of theory, procedures and equipment. Included herein are findings from research on deterioration of concrete structures and road pavements utilizing resistivity, impact-echo and ground-penetrating radar techniques.

One notable publication included in this section summarizes the state of the practice of geophysics among state and provincial transportation authorities in North America. Those findings indicate lack of understanding and experience with regard to geophysical methods hinders its effective use among the states and provinces, pointing out continued need for training of transportation staff.

Gaps in Findings

A considerable body of literature exists that documents the use of geophysical techniques and non-destructive testing for qualitative assessment and quantitative measurement and estimation of the properties of earth materials. From this preliminary investigation, we find that the literature content tends to cluster at the ends of the knowledge spectrum. Many references can be found that outline basic concepts for an entry-level audience and a significant body of work exists that illuminates specific subjects on the topic for experienced practitioners. The literature is scarce in that middle ground for those who already possess an entry-level knowledge and wish to apply the methods, but are either not experienced practitioners, or work in related fields of geotechnical engineering or at project levels where advanced training in geophysical methods is inappropriate. Additionally, most of the literature is method-specific, describing the types of methods available, followed by discussion of the physical properties obtained from the technique. Noticeably scarce in the literature are publications that are engineering-based: that, first, identify the physical parameters needed for adequate engineering and design, then describe the procedures and methods for obtaining that data. This project will make steps in filling that portion of the knowledge base and also will help bridge the identified knowledge gap between engineering and geophysical practitioners.

Next Steps

Caltrans should consider:

- Implementing this research project. Consideration should be given to implementing this project in phases. The first phase can focus on inclusion of established and tractable geophysical relationships and identification of avenues for further study. The subsequent phase (or phases) may be used to establish validity of other, specific geophysical approaches and development of industry-consistent approaches for implementation.

- Monitoring the Research in Progress web site of the Transportation Research Board for ongoing results and resources related to the practice of geophysics and non-destructive testing for quantitative measurement of foundation properties.
- Monitoring the ongoing research of the Florida DOT under Contract BDK75 977-01 to determine how their results may be incorporated into this proposal. Enlisting the assistance of the principal investigator for that contract, Dr. Dennis Hiltunen, would be beneficial to this effort. Dr. Hiltunen has already expressed interest in participation.
- FHWA's Central Federal Lands Division currently serves as a de facto national center for dissemination of information in the field of geophysics for transportation projects. A possible outcome of this proposal may be cooperative publication and dissemination of the results via the Central Federal Lands existing Web resources. Continued contact and collaboration with FHWA is encouraged for information transfer, resource pooling and cooperative study.

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Research in Progress

Geophysical Testing of Rock and Its Relationship to Physical Properties
Florida Department of Transportation, Contract BDK75 977-01
http://rip.trb.org/browse/dproject.asp?n=17234
The primary objective of the project is to incorporate appropriate geophysical testing techniques into site characterization activities of the Florida Department of Transportation. Testing techniques will be proposed to characterize spatial variability in geotechnical engineering physical parameters of rock formations useful in the design of deep foundations. Secondary objective is to aid in implementation of LRFD design methodologies that explicitly account for spatial variability in design parameters. Summary of work in progress was presented in Hiltunen (2008), the reference is provided in the Best Practices, Design Guides and Additional Resources section below

Impulse Shear Testing of Foundation Soils for Earthquake Design
Federal Highway Administration, Transportation Pooled Fund Study TPF-5(031)
http://www.pooledfund.org/projectdetails.asp?id=22&status=6
Research is seeking to develop enhancements to an existing FHWA impulse shear testing device, to improve its ability to provide detailed information on the liquefaction resistance of soils subjected to large seismic forces. Enhancements will also be made to improve ease-of-use and cost effectiveness.

High-Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings
Transportation Research Board, Project R06(G)
http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2672
Periodic inspection of highway tunnels is required to detect tunnel leaks, concrete deterioration (cracking, spalling, delamination, debonding), steel corrosion, and improper drainage. Tunnel inspection is a challenging problem, as tunnels typically service high volume traffic in a constricted environment. Minimizing tunnel closures and user delays must be carefully balanced with the need to conduct detailed inspections to ensure driver safety. Consequently, there is a need to identify and develop nondestructive test methods that are automated, quantitative and rapid, and that provide improved coverage compared to conventional visual inspections.

Characterization of Voids and Other Subsurface Deficiencies by Geophysical Methods
Hawaii Department of Transportation, Contract 55161
http://rip.trb.org/browse/dproject.asp?n=12848
Hawaii's roads, airfields and harbors often experience pavement deterioration due to the presence of cavities, loss of soil foundation and settlement of underlying loose or soft material. A major concern is that proper characterization of these subgrade deficiencies have typically been accomplished by drilling and excavation, which can be costly, ineffective and disruptive to the travelling public. The purpose of this study is to evaluate and test a range of remote sensing techniques and instruments and to choose the most versatile for implementation by the Hawaii Department of Transportation. The ultimate goal is to make available a cost effective and practical means of detecting cavities and other subgrade deficiencies beneath roadways and other surfaces.

Nondestructive Evaluation (NDE) Web Manual
Federal Highway Administration, Contract number unknown
http://rip.trb.org/browse/dproject.asp?n=20559
This research project seeks to develop the basic framework of a Web-based manual, comparing nondestructive evaluation (NDE) capabilities for bridges, pavements, and other ancillary structures. This document will complement and the earlier Application of Geophysical Methods to Highway Related Problems web manual, published in 2003 and discussed further in the next section.

Best Practices, Design Guides and Additional Resources

American Society for Testing and Materials
Standard Guide to Site Characterization for Engineering Design and Construction Purposes, ASTM D 420.
This guide provides recommendations and refers to ASTM methods by which soil, rock, and ground water conditions may be determined via sampling, in situ testing, or both. Discusses use of geophysical surveys as an integral part of site characterization and incorporates test methods D 4428 (crosshole seismic) and method G 57 (electrical resistivity) by reference.

American Society for Testing and Materials
Standard Guide for Planning and Conducting Borehole Geophysical Logging, ASTM D 5753
This guide discusses recommended documentation and general procedures necessary to plan and conduct a geophysical logging program for geotechnical investigations. It briefly describes the significance and use of borehole geophysics, the testing hardware, calibration and standardization procedures and report contents.

American Society for Testing and Materials
Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation, ASTM D 5777
This guide summarizes the recommended equipment, field procedures, and interpretation methods for the determination of depth, thickness and the seismic velocity of subsurface soil and rock or engineered materials using the seismic refraction method. The guide is applicable to mapping subsurface conditions for various uses including geotechnical investigations. Discussion is limited to acquisition and evaluation of compressional (P-wave) data.

American Society for Testing and Materials
Standard Guide for Conducting Borehole Geophysical Logging: Mechanical Caliper, ASTM D 6167
This guide provides recommended general procedures to conduct caliper logging of boreholes, wells, access tubes, caissons and shafts for geotechnical investigations. Caliper logging for mineral or petroleum exploration are excluded from the guide.

American Society for Testing and Materials
Standard Guide for Conducting Borehole Geophysical Logging: Gamma, ASTM D 6274
This guide covers the general procedures necessary to conduct logging of in-situ gamma ray emissions in boreholes, wells, access tubes, caissons, and shafts for geotechnical investigations. Logging via artificial sources (such as, neutron activation and gamma-gamma density logs), as well as gamma logging for minerals or petroleum applications, are excluded from discussion.

American Society for Testing and Materials
Standard Guide for Selecting Surface Geophysical Methods, ASTM D 6429
This guide covers the selection of surface geophysical methods for common application to site characterization. Brief descriptions of each geophysical method, along with field considerations and limitations are also provided.

American Society for Testing and Materials
Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation, ASTM D 6431
This guide summarizes the equipment, field procedures, and interpretation methods to estimate the depth, thickness, and resistivity of subsurface layers using the direct current (DC) resistivity method. This guide is limited to the commonly used arrays for sounding and profiling (including modifications for specific applications): Schlumberger, Wenner and dipole-dipole.

American Society for Testing and Materials
Standard Guide for Using the Ground Penetrating Radar Method for Subsurface Investigation, ASTM D 6432
This guide summarizes the recommended equipment, field procedures, and interpretation methods for the assessment of subsurface materials using the impulse Ground Penetrating Radar (GPR) Method. The guide is limited to commonly used approaches to GPR measurements from the ground surface.

American Society for Testing and Materials
Standard Guide for Using the Frequency Domain Electromagnetic Method for Subsurface Investigation, ASTM D 6639
This standard guide summarizes the recommended equipment, field procedures, and interpretation methods applicable to mapping subsurface conditions using frequency domain electromagnetic (FDEM) methods. The guide is limited to instruments using coplanar transmitting and receiving coils and does not include coaxial or asymmetrical coil orientations that are sometimes used for special applications.

American Society for Testing and Materials
Standard Guide for Conducting Borehole Geophysical Logging: Electromagnetic Induction, ASTM D 6726
This guide provides recommended general procedures to conduct electromagnetic-induction logging of boreholes, wells, access tubes, caissons, and shafts for geotechnical investigations. Induction logging for minerals or petroleum applications is excluded.

American Society for Testing and Materials
Standard Guide for Conducting Borehole Geophysical Logging: Neutron, ASTM D 6727
This guide presents recommended general procedures to conduct neutron porosity logging of boreholes, wells, access tubes, caissons, and shafts for geotechnical investigations. Neutron soil moisture measurements made using neutron moisture gauges, and neutron logging for minerals or petroleum applications is excluded.

American Society for Testing and Materials
Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar, ASTM D 4748
This test method presents a standardized application of GPR for nondestructive determination of the thickness of the upper layers of a pavement (the bound layers), consisting of materials such as bituminous, concrete, Portland-cement concrete, roller-compacted concrete, and stabilized bases.

Federal Highway Administration Report FHWA-IF-04-021, 2003
Application of Geophysical Methods to Highway Related Problems
http://www.cflhd.gov/agm/index.htm
This provides basic knowledge of geophysics and nondestructive test (NDT) methods for solving specific transportation related problems such as design, planning, construction, or remediation. A broad range of practical methods are presented, including most traditional geophysical methods. These have been adapted to provide solutions more specific to a variety of engineering problems. The document is divided into two parts. Part 1 provides a range of geophysical imaging and NDT methods that can be used to solve particular highway-related problems. Part 2 provides more comprehensive discussions of the geophysical methods and theory. The document also provides an extensive bibliography for further information on the subjects presented.

Hiltunen, D., 2008
Geophysical Testing of Rock and Its Relationship to Physical Properties,
2008 Geotechnical Research in Progress Meeting, Florida Department of Transportation State Materials Office,
http://www.dot.state.fl.us/statematerialsoffice/geotechnical/conference/grip/2008/15_geophysicaltesting.pdf
To improve definition of subsurface conditions in karst terrain, this project seeks to identify and develop geophysical techniques to supplement site characterization of rock and reduce use of invasive investigation methods. This work attempts to relate geophysical parameters to rock properties and quality

of rock useful for directly estimating physical properties such as unit side resistance for drilled shafts, SPT N-values, and q_u, with the added goal of decreasing uncertainty by extending parameters to a larger volume via geophysics.

Transportation Research Board, Transportation Research Circular E-C130, 2008
Geophysical Methods Commonly Employed for Geotechnical Site Characterization
http://pubsindex.trb.org/view.aspx?id=873642
This circular presents an overview of 12 geotechnical geophysical methods commonly applied to transportation projects. Discussion is also devoted to the selection of appropriate geophysical methods and geophysical contractors.

US Department of Transportation, Federal Highway Administration, Report No. FHWA/OH-2003/007-1, 2003 (Ohio Department of Transportation, Mine Research Project GUE 70-14.10)
Guidelines for Geophysical Investigations of Mines under Highways

This document presents proposed guidelines for evaluating active and abandoned mine hazards beneath highways based on investigations conducted along Interstate Route 70 (IR-70) under contract with the Ohio Department of Transportation. The findings established the usefulness of an integrated geophysical testing approach using surface GPR, seismic shear wave reflection, and cross-hole GPR measurements in conjunction with existing geologic and hydrogeologic information.

Mavko, G., Mukerji, T., and Dvorkin, J., 2003
The Rock Physics Handbook: Tools for Seismic Analysis in Porous Media
Cambridge University Press, 328 p.
This textbook summarizes the state of rock physics in 76 concise articles describing relationships between the physical properties of rocks and their observable geophysical responses. Though primarily focused on seismic relationships, one chapter is devoted to electrical properties. The book is intended to provide practical solutions for real problems faced by geologists, geophysicists and engineers, and covers such topics as Vp-Vs relationships, wave attenuation, modulus estimation, porosity and density.

The Advisory Committee on Standardization, 2004
Application of Geophysical Methods to Engineering and Environmental Problems
Society of Exploration Geophysicists of Japan, 302 p.
This English translation of an original Japanese text is the result of collaboration between the Society of Exploration Geophysicists of Japan and the Australian Society of Exploration Geophysicists. The book provides recommended procedures for many geophysical techniques appropriate for geotechnical investigations, in an attempt to achieve parity with ISO 9000 standards. Standardized approaches to such methods as seismic refraction and reflection, electrical resistivity, ground penetrating radar and microtremor inversion are proposed to assist in worldwide application consistency and performance improvement.

Crosby, JW; Konstantinidis, B and Davis, P, 1981,
Geotechnical Applications of Borehole Geophysics,
American Society of Civil Engineers Journal of the Geotechnical Engineering Div, Vol. 107 No. GT10
Borehole geophysics is used widely in studies of nuclear power plant sites, waste disposal problems, and local and regional geohydrology, Though most investigations are oriented toward stratigraphic correlation, there is a wealth of semi-quantitative or quantitative data, often overlooked (e.g., moisture content, density, and porosity), that can be obtained from properly engineered borings.

Michaels, P, 2004
Design of Geophysical Surveys in Transportation,
Proceedings of the Conference on Geotechnical Engineering for Transportation Projects, Geo-Trans 2004, ASCE Geotechnical Special Publication No. 126
Transportation engineers who augment traditional subsurface geotechnical surveys with engineering geophysics are better prepared to avoid costly delays and redesign of projects due to differing site conditions. The author presents design strategies that incorporate constraints imposed by transportation projects, such as right-of-way, noise from traffic and the need to avoid traffic interruptions. Case histories taken from bridge and highway projects including beam steering, broadside shooting, and non-traditional designs are presented.

Anderson, NL, Cardimona, S and Newton, T, 2003
Application of Innovative Nondestructive Methods to Geotechnical and Environmental Investigations,
Missouri University of Science and Technology, Rolla, Missouri
http://library.modot.mo.gov/RDT/reports/Ri98014/RDT03008a.pdf
This report presents results of several projects conducted for the Missouri Department of Transportation that utilized nondestructive geophysical methods. Methods included ground penetrating radar (GPR), shallow seismic reflection, electromagnetic induction (EM), and electrical resistivity. Case studies addressed karst-related voids and sinkholes, underground storage tanks, bridge scour, and abandoned underground mines. Geophysics successfully assessed roadway and subsurface conditions with nondestructive, continuous profiles. A protocol for evaluating the utility of ten commonly employed geophysical methods is provided in this report to aid in the selection of appropriate methods.

Michaels, P, 1998
In Situ Determination of Soil Stiffness and Damping,
American Society of Civil Engineers Journal of Geotechnical and Geoenvironmental Engineering, Vol. 124 No. 8
Determination of in situ dynamic soil properties is fundamental to the prediction of the seismic behavior of foundations and soil embankment structures. Both elastic (stiffness) and inelastic (damping) values are required for computational analysis. This paper demonstrates how to collect in situ field data and solve for stiffness and damping values, and includes both synthetic and field data examples that illustrate the method.

Foti, S, Lai, C and Lancelotta R, 2002
Porosity of fluid-saturated porous media from measured seismic wave velocities
***Geotechnique*, 52, p 359-373.**
This paper presents a procedure for determining in-situ porosity of saturated soils using their P- and S-wave velocities. Their model assumes an undrained porous medium and has shown agreement with laboratory data from undisturbed samples collected at two locations in Italy.

Andrus, R and Stokoe, KH, 1997
Liquefaction Resistance Based on Shear Wave Velocity
Evaluation of Liquefaction Resistance of Soils, National Center for Earthquake Engineering Research (NCEER) Workshop Proceedings, January 5-6 1996, Salt Lake City, Utah, p 89-128
This paper recommends revisions to the current simplified procedures for evaluating liquefaction potential of granular soils using small-strain S-wave velocity relationships. They propose application of a modified relationship between S-wave velocity and cyclic-stress ratio that they argue provides accurate prediction of liquefaction potential for 95% of their available case histories.

California Department of Transportation, 2006
Seismicity and Foundation Performance, Seismic Design Criteria, Version 1.4
The Caltrans Seismic Design Criteria specify minimum design requirements to meet performance goals established for ordinary standard bridges (as specifically defined in that document). Derivation of seismic loading is achieved by a deterministic approach that utilizes measurement of shear wave velocity of soil and rock. Standardized response curves may be used for many sites, but some foundation conditions require site-specific evaluation.

Imai, T, and Tonouchi, K, 1982
Correlation of N Value with S-wave Velocity and Shear Modulus,
Proceedings of the Second European Symposium on Penetration Testing, Amsterdam, 24-27 May 1982
This paper presents a relationship between CPT N-values and S-wave velocity and small-strain shear modulus from over 400 boreholes throughout Japan, which is useful in obtaining correlative velocity data for earthquake engineering from sites where velocity information is otherwise unavailable.

McDowell, PW, Barker, RD, Butcher AP, Culshaw, MG, Jackson, PD, McCann, DM, Skipp, BO, Matthews, SL and Arthur, JCR, 2002
Geophysics in Engineering Investigations,
Construction Industry Research and Information Association, Geological Society Engineering Geology Special Publication 19, London
The goal of this reference is to provide guidance for civil and geotechnical engineers on the use of geophysical investigations for engineering design and construction efforts, the use of geophysics for measurement of engineering parameters and its use for environmental investigations. Descriptions and applications of methods are provided, with additional emphasis on planning, staffing and management of the investigation process.

Nazarian, S and Diehl, J, 2000
Use of Geophysical Methods in Construction,
Proceedings of sessions of Geo-Denver 2000, American Society of Civil Engineers Geotechnical Special Publication No. 108, Reston, Virginia
This publication presents a collection of peer-reviewed papers showing practical applications of geophysical methods to solve construction-related problems, such as utility engineering, site reconnaissance, and anomaly detection. Geophysical techniques that may be used as economical and rapid quality control or process control tools for construction are presented. The publication also demonstrates how geophysical methods can be used post-construction to monitor system condition or detect deterioration. Several papers are dedicated to new methods or improvements to existing methods.

Burns, SE and Mayne, PW, 1996
Small- and High-Strain Measurements of In Situ Soil Properties Using the Seismic Cone Penetrometer
Transportation Research Record 1548
http://trb.metapress.com/content/652556788527764u/
This work was originally developed using seismic cone penetration tests, but has direct application to other geophysical methods that measure shear-wave velocity by providing economical assessment of the low-strain shear modulus of soil deposits. Their modulus degradation scheme to derive large-strain moduli from low-strain measurements has application to static monotonic loading of soils and is accepted by the FHWA.

Related Research

Transportation Research Board, NCHRP Synthesis 357, 2006
Use of Geophysics for Transportation Projects
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_357.pdf
The report summarizes the state of the practice regarding use of geophysics among US state DOT's and Canadian provincial transportation ministries. Results showed that a majority of the respondents utilize geophysics on five or fewer projects a year, with utilization increasing over time. The majority of respondents reported satisfactory results from geophysics, with a success/failure ratio of 7:1 consistent among all respondents. Lack of understanding and experience with regard to geophysical methods continues to hinder usage for transportation projects among the states and provinces, pointing out continued need for training of transportation staff.

Transportation Research Board, NCHRP Research Results Digest 213, 1995
Nondestructive Testing of Unknown Subsurface Bridge Foundations--Results of NCHRP Project 21-5
This digest summarizes the evaluation of existing and new nondestructive testing technologies for determining characteristics of unknown subsurface bridge foundations. Foundation depth information, in particular, is needed for performing an accurate scour evaluation of bridges. Research focused on those methods judged having the most promise of solving the unknown depth-of-bridge-foundation problem, and included Ultraseismic, Parallel Seismic, Spectral Analysis of Surface Wave, and Induction Field testing. Initial NDT studies of 20 bridge sites with known foundations were conducted to determine the accuracy of testing methods. The results, though deemed interesting, were determined by NCHRP to be insufficient for incorporation into general practice and a final NCHRP report was not published. However, the unedited final report is available for loan by contacting NCHRP@nas.edu.

US Department of Transportation, Federal Highway Administration, Report No. FHWA-NH-RD-13733E, 2006
Integrated Geophysical Methods for Geotechnical Subsurface Investigations
This research summarizes the New Hampshire Department of Transportation's (NHDOT) efforts to supplement conventional test borings and exploration techniques through the use of geophysics on several geotechnical projects. The report presents case histories (of variable success) utilizing resistivity imaging and seismic refraction in conjunction with test borings and ground penetrating radar to characterize subsurface conditions. These geophysical investigative techniques have helped alleviate some of the uncertainties that arise when making subsurface interpretations based solely on conventional exploration methods.

Transportation Research Board, NCHRP Project 21-06, 2009
Corrosion in the Soil Environment: Soil Resistivity and pH Measurements
The objectives of this research were twofold: (1) develop recommended test methods for practical laboratory and field measurements of soil resistivity and pH that yield more precise, accurate values than existing methods; and (2) develop correlation factors to compare the results of these recommended methods with the historical record of data obtained with the previously existing methods.

Transportation Research Board, SHRP-2 Report S2-R01-RW, 2009
Encouraging Innovation in Locating and Characterizing Underground Utilities
http://onlinepubs.trb.org/onlinepubs/shrp2/shrp2_S2-R01-RW.pdf
This report presents the findings of the first two phases of SHRP 2 Project R01. The project identified existing and emerging technologies for underground utility location and characterization, and developed recommendations for subsequent research in this area. The report provides a review of locating practices and recommended improvements. A third phase was added to this project to develop decision support

software for identifying effective utility-locating methods for particular environments. The software will expand on capabilities already developed under the R01 project.

Nondestructive Testing to Identify Concrete Bridge Deck Deterioration
Transportation Research Board, Project R06(A)
http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2558
Over the past decade, technologies such as ground penetrating radar (GPR), infrared thermography, and scanning impact-echo have been developed for bridge deck condition assessment. These technologies, however, are not widely adapted or accepted. This project will attempt to survey availability and suitability of these techniques for dissemination to state DOT's.

Characterization of New and Old Concrete Structures Using Surface Resistivity Measurements
Florida Department of Transportation, Contract BD546-08
The results of this research will provide test methods to be used by construction inspection personnel for final acceptance of concrete structures. It is anticipated that this test method will eliminate much of the need for intermediate testing of individual concrete properties during the course of construction.

Using both Infrared and High-Speed Ground Penetrating Radar for Uniformity Measurements on New HMA Layers
Transportation Research Board Project R06(C)
http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2562
This project will attempt to demonstrate infrared and GPR technologies to assess HMA density and segregation over nearly 100% coverage of the constructed surface area, and to make recommendations for incorporating the technologies into existing DOT specifications for construction QA.

Nondestructive Testing to Identify Delaminations between HMA Layers
Transportation Research Board, Project R06(D)
http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2563
The main objective of this study is to identify and develop nondestructive testing (NDT) techniques that are capable of identifying and determining the extent and depth of delaminations and discontinuities in hot mix asphalt (HMA) pavements. The researchers shall determine key indicators that may be used to identify potential areas of delamination including lack of bond, stripping, and other causes. The NDT techniques developed under this project should provide rapid results with near 100% continuous coverage of the pavement area.

Transportation Research Board, NCHRP Report 626, 2008
NDT Technology for Quality Assurance of HMA Pavement Construction
Nondestructive test methods, including lasers, ground-penetrating radar, falling weight deflectometers, penetrometers, and infrared and seismic technologies, have significantly improved and show potential for use in the quality assurance of HMA pavement construction. The report summarizes results of a comprehensive field experiment to determine the effectiveness and practicality of promising NDT technologies for evaluation of unbound and bound pavement layers during or immediately after placement. The results identified several NDT technologies with potential for immediate implementation in a quality assurance program for HMA pavement construction, including individual HMA, base, and subgrade layers.