

# **CONSIDERING GEOPHYSICAL METHODS IN THE GEOTECHNICAL SUBSURFACE EXPLORATION PROCESS: A GEOTECHNICAL PERSPECTIVE**

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## **ABSTRACT**

Geophysical methods have been used to investigate variations and intrinsic properties of materials for a number of applications and fields, including geotechnical engineering. While geophysical methods, and in-situ testing methods have been used for many geotechnical applications, they are not always routinely considered when developing geotechnical subsurface exploration programs for highway applications. Additionally, while geophysical methods may not always be the most appropriate investigation tools for project needs, understanding how geophysical methods can be used to meet the needs of the geotechnical engineer is central to providing recognizable value for the use of geophysical methods on highway engineering projects. This paper provides an overview of the fundamental purpose of geotechnical subsurface exploration and testing, and a geotechnical engineering perspective of how geophysics can be more effectively utilized for geotechnical site characterization.

## **INTRODUCTION**

Unlike in many other engineering fields where the engineer works with materials with well-controlled properties, the geotechnical engineer works with earth materials and natural conditions that can vary tremendously. As a result, the geotechnical engineer must be skilled at making interpretations of subsurface conditions and variations in earth materials for engineering purposes. The geotechnical engineer must also exercise good judgment in assigning engineering parameters that appropriately characterize the engineering properties and behavior of these earth materials, considering project requirements and anticipated stress conditions. Geotechnical subsurface exploration, laboratory testing and site characterization are critical steps needed to perform engineering analyses, make engineering assessments and recommendations, and produce and construct engineered designs.

In the United States, the geotechnical engineering community has long relied on drilling, soil and rock sampling, index testing and the Standard Penetration Test (SPT) as the primary methods to characterize subsurface conditions. Laboratory testing methods, such as direct shear, triaxial shear, consolidation and permeability, are also common when more reliable measurements of shear-strength, compressibility and hydraulic conductivity are needed. Developments in subsurface exploration and in-situ testing methods have lead to huge potentials for improving geotechnical site characterization. Even so, the geotechnical community has been slow to embrace these newer techniques. This is, in part, due to the lack of familiarity and confidence in the results of these newer techniques, and, in part, due to the empirical component of geotechnical work. When an empirical method is used, imperfect parameters can have considerable value if there is a large body of experience developed from them. In order to more cost effectively use the variety of techniques available for our geotechnical exploration and testing programs, we must understand how geotechnical subsurface information is used for design and construction.

Among the advances in subsurface exploration and testing are geophysical methods. The geophysical methods that were originally developed for the oil and mining industries have found application in geology and hydrogeology, the military, the environmental field, the utility industry and various engineering fields. Advances in data collection and processing have made geophysics more attractive as a potential tool for geotechnical engineering, but these developments do not address issues related to the fundamental purpose of geotechnical site characterization. The purpose of this paper is to

examine these issues, and provide a geotechnical perspective on how geophysics can be more effectively utilized and provide measurable value for geotechnical site characterization.

## **OVERVIEW OF GEOTECHNICAL AND CONSTRUCTION NEEDS FROM EXPLORATION**

Along with experience and engineering fundamentals, subsurface exploration and testing is essential to geotechnical engineering analyses, evaluations and construction considerations. At the most basic level, geotechnical engineers are tasked with providing safe and cost effective engineering solutions for earth features and structural support. As such, the subsurface exploration and testing program must provide an adequate characterization of subsurface conditions, engineering properties, and material behavior relative to project requirements and engineering performance. The term “adequate” here is relative. More economical solutions typically require less conservatism, and less conservative designs require greater reliability in design information and engineering parameters to maintain a safe and well performing structure. In other words, in order to affect more economical designs without increasing the owner’s risk, we must have increased reliability in the parameters that characterize our subsurface conditions and engineering parameters. Furthermore, in order to have increased reliability in the parameters we use for design, we must more accurately characterize site conditions and engineering properties, with less uncertainty. FHWA Geotechnical Engineering Circular #5: Evaluation of Soil & Rock Properties provides guidance on various methods used to obtain and interpret subsurface data with particular attention to assessment of data quality and selection of properties for design. The reader is encouraged to refer to this publication to gain more insight on recommended rationale for developing subsurface exploration and testing programs, evaluating data reliability, reconciling data, and selecting design parameters for engineering purposes. The need to consider the reliability of our geotechnical data has become more apparent in recent years as design methodology has been transitioning to Load and Resistance Factor Design (LRFD), where resistance factors reflect the reliability of the methods used in analysis.

Essential to geotechnical site characterization is the understanding of its purpose: assessing conditions and determining properties for engineering design and construction needs. Project requirements, existing information and regional experience are considered to develop a subsurface exploration and testing program specific to project needs and anticipated conditions. The factual information obtained from the subsurface exploration and testing program is interpreted into a profile that distinguishes layers, conditions, earth materials, properties and significant features as they relate to engineering performance and behavior. The geotechnical engineering profile typically provides an interpretation of at least the following:

- Delineations of materials with significantly different engineering properties and behavior
- Discontinuities that affect engineering performance and construction
- Engineering (soil) and geologic (rock) descriptions of materials
- Physical engineering properties, indices and classifications that characterize shear-strength behavior, stiffness/compressibility, earth pressure and hydraulic behavior.
- Groundwater elevations/fluctuations/pressures
- State of stress and stress history

Proper engineering interpretation and selection of design parameters will not only consider the engineering properties and behavior of the subsurface materials, but will also consider the design application, construction methods, stress states, design life, structure criticality, material property variation and the reliability of the methods used to determine the engineering properties. If conditions are encountered that are different than those anticipated, then additional information is needed to resolve those differences. Often, the materials, features and conditions that pose the greatest risks, and the properties that have the greatest influence on the specific design application(s), require additional exploration, testing or monitoring to provide better accuracy and less uncertainty so that more reliable assessments and analyses can be conducted to achieve the most economical solutions.

In addition to design needs, the subsurface exploration and testing program must also consider construction needs. Again, the subsurface exploration and testing program must consider specific project requirements and anticipated conditions. Common construction needs include the following:

- Excavation and foundation installation method requirements, considering
  - Material types, consistencies (soil), potential obstructions, soundness and hardness (rock), discontinuity condition and orientation (rock-slopes), groundwater conditions
  - Effects of changes to effective stress state and excavation disturbance on engineering properties of earth materials
  - Effects of sound and vibration on the human and natural environment
- Potential earth material sources for construction fill considering project requirements and availability
- Fill placement requirements considering material type, material properties and project requirements
- Subgrade preparation requirements considering stability, settlement, and long-term performance.

Both designers and contractors rely on quality subsurface exploration data to achieve quality results. Designers rely on subsurface information to ensure their designs are constructible, to establish construction requirements relative to material properties and in-place conditions, and to control construction influences that could degrade or adversely impact their designs. Contractors rely on subsurface data and construction requirements in order to determine equipment and methods necessary for construction, and provide a bid for the contracted work. The more uncertainty there is in the subsurface data, the greater the risk of owner liability from “changed condition” issues arising during construction that may cause delays, project escalations (construction claims and redesign), and litigation or arbitration costs and delays.

Undoubtedly, the most common exploration method and in-situ test method currently used in geotechnical practice is the test-boring with Standard Penetration Tests (SPT). While the SPT is admittedly a relatively crude in-situ test that must be correlated to engineering properties, geotechnical engineers have developed a familiarity and comfort with this test. When used in conjunction with other methods that provide more reliable measures of engineering properties, the test (and sample) provides an effective tool to relate soils of similar engineering properties. Geotechnical borings provide a mechanism for valuable sampling and in-situ testing, however, geotechnical borings are limited in providing information related to lateral variation. As such, geotechnical engineers often must make interpretations and conservative judgments on lateral variations.

Today, advances in geotechnical exploration and in-situ test methods provide many tools to help geotechnical engineers more reliably characterize subsurface conditions for engineering and construction needs. Many in-situ testing methods can directly provide detailed stratigraphy and direct measurements relating to such engineering properties and in-situ stress conditions as shear-strength properties, undrained shear-strength sensitivity, stress history, various moduli, in-situ void-ratio, groundwater table and water pressure, hydraulic properties, and at-rest lateral earth pressure. Geophysical methods can also provide valuable information for these properties and their lateral variations. However, direct in-situ testing and geophysical methods have been slow to move into the assembly of methods routinely considered when planning geotechnical subsurface exploration and testing programs. While both in-situ testing and geophysical methods are under-utilized, this paper focuses on the use of geophysical methods for geotechnical engineering. The following sections examine how geophysical methods could be more effectively used for geotechnical and construction subsurface exploration, and reasons why geophysical methods have been slow to move into routine consideration. The following sections also provide suggestions to increase the effective use of geophysical methods for geotechnical applications.

## GEOPHYSICAL METHODS AND GEOTECHNICAL APPLICATIONS

Geophysical methods have great appeal for geotechnical subsurface exploration. Surface methods can often provide data where data from traditional invasive methods are difficult to obtain, such as in deposits or fills composed of gravels, cobbles and boulders; over difficult terrain; and within contaminated sites. Many surface methods provide the ability to cover large linear tracks that make them particularly appealing for highway alignment construction. Downhole methods can identify lithologic units and hard-to-identify thin seams, density and porosity estimates, and seismic response information. In addition, mechanical wave methods work on principles conducive for determining elastic properties of soil and rock. Geophysical methods have been used successfully for geotechnical engineering applications that include establishing stratigraphy, depth to bedrock, depth to groundwater, rippability of rock, and locating discontinuities and anomalous conditions.

Functionally, geophysical methods have great potential in the following aspects of geotechnical subsurface exploration and testing:

- Preliminary surveys to assist with locating potentially problematic conditions
- Correlations to engineering properties, including those of particular interest, such as shear-strength and stress-strain behavior
- Identifying and delineating specific features of interest.

Preliminary surveys refer to explorations that cover large areas and assist the geotechnical engineer with positioning further exploration and testing where the preliminary survey results provide indicators that correlate to potential conditions of specific engineering significance, such as potentially weak or compressible soils. Figure 1 provides an example of how a preliminary geophysical survey can potentially help the geotechnical engineer identify areas to concentrate further exploration. The figure shows an electromagnetic survey of an alignment and an associated cross-section. However, one should note that the results of this survey are provided in terms of conductance. To the average geotechnical engineer, conductance has no meaning. The engineer is interested in those subsurface attributes, mentioned previously, that effect engineering performance for specific project needs. An electromagnetic survey may provide results in terms of conductance, but how would this correlate to conditions and engineering properties of specific interest to the geotechnical engineer? In order for this survey to have enough significance, or benefit, to the engineer – to overcome the inertia of business-as-usual – there must be a relation between conductance and those conditions and engineering properties of interest to the engineer.

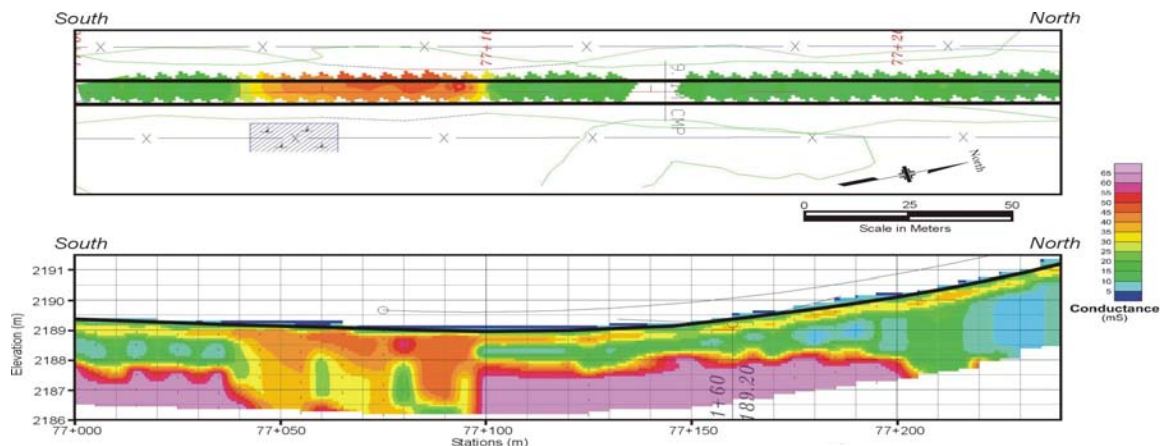


Figure 1: Example of geophysical (EM) survey that could potentially be used to focus further geotechnical exploration, provided a significant relationship exists between the geophysical properties measured and engineering properties or conditions of interest to the geotechnical engineer

Geophysical methods have a large potential for future development in the area of engineering correlations. This is particularly obvious for mechanical wave methods that rely on principles and measurements that correspond well with elastic strain, and would be well suited for stress-strain relationships for elastic behavior. Correlations to engineering properties have been developed from the results of seismic, electrical resistivity and nuclear methods, although they are not well used for geotechnical applications. These methods, and others, have great potential for new and better correlations to engineering properties.

According to NCHRP Synthesis 357 (2006), the most utilized type of geophysical applications are those that target, or otherwise attempt to distinguish, specific geologic or man-made features of interest. This could be identifying significant stratigraphic differences, top of bedrock, groundwater, significant discontinuities, karst features, boulders or massive differentially weathered rock, or other features, all of which are interpreted features that can be of interest to the geotechnical engineer and contractor. The key word, here, is *interpreted*; these features are interpreted from the results of geophysical measurements. Figure 2 displays a color-coded cross-section from a seismic tomography survey denoting differences in seismic velocity. The cross-section suggests some significance in the differences between the displayed velocities. The problem, again, becomes the significance of these differences to the geotechnical engineer or contractor. The geophysical measurements taken in the field and processed by the computer are generally not presented in terms of what the geotechnical engineer or contractor specifically requires. In this case, the cross-section shown in Figure 2 corresponds to a proposed new roadway alignment along an existing roadway slope. A retaining wall has been proposed to allow the new alignment to extend further out on the existing slope. For the proposed alignment section shown, the geotechnical engineer would be specifically interested in several aspects related to both design and construction. Among the necessary engineering evaluations, the geotechnical engineer would need to evaluate the global stability of the proposed reinforced wall system. For this, the geotechnical engineer must evaluate potential failure mechanisms with appropriate shear-strength values of bearing and retained earth materials. In addition, the geotechnical engineer would have to consider how the proposed design could be constructed. For this, the engineer would be interested in the excavation requirements necessary to excavate material and maintain stability for the temporary excavation necessary to construct the wall. The stability of the temporary excavation would also be dependent on shear-strength parameters, although for different stress states than those for the completed wall design. However, the geophysical data presented in Figure 2 is displayed in terms of velocity and not in terms of what the geotechnical engineer ultimately needs.

As a final point illustrated in Figure 2, the distinction between factual data and interpretation can often also be blurred. The factual geophysical measurements are processed and modeled to provide a displayed interpretation. For example, Figure 2 shows velocity of material at any of an infinite number of locations, which is an interpretation of velocities measured (factual) between a dozen or two receivers. Interpretations hold inherent liabilities when relied upon or abused as having factual significance. The distinction between factual data and interpretation must be clearly maintained, as should the expectations that the results are directly related to those conditions and engineering properties of interest to the geotechnical engineer and contractor.

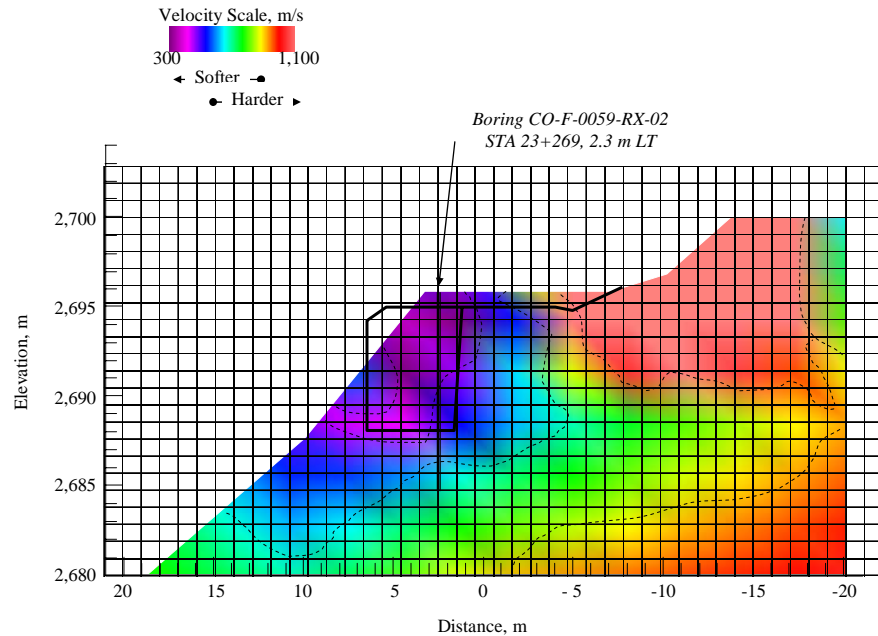


Figure 2: Cross-sections from a Seismic Tomography Survey that illustrates the need to clearly distinguish and indicate interpretation from factual data

If geophysical methods are to be effectively considered in geotechnical exploration and testing programs, those providing geophysical services must recognize the engineering significance for which the services are being requested. Likewise, the geotechnical engineer must recognize the limitations of the methods used, assumptions used in the interpretations, and correlations between the geophysical measurements and the conditions and engineering properties of interest. Clear communication and coordination between the geophysicist and the end-users is essential to ensure requirements can be accomplished, expectations met, and meaningful and valuable data for engineering and construction purposes can be obtained.

### ADDING VALUE TO ENGINEERING PROJECTS AND OVERCOMING INERTIA

It is easy to say that the appropriate inclusion of geophysical methods into geotechnical subsurface exploration and testing programs provides value, but it can be much more challenging to show quantitatively. To find the value added from geophysical methods for geotechnical application, one needs to look, again, at how exploration and testing information is used, and explore the interests of the various project stakeholders.

As stated previously, geotechnical engineers are tasked with providing safe and cost effective solutions. Essential to this, is the reliability of subsurface data relative to engineering performance and construction needs. Put simply, the reliability of our subsurface data directly affects the level of conservatism to which projects are designed and liability for construction claims is accepted; both can greatly affect project costs. In addition, economic demands on infrastructure in recent years have accentuated the need for quicker construction and longer performing structures. However, the road to progress may not be as straightforward as it appears.

The owners of our highway systems (the public represented by transportation agencies) expect safe and reliable transportation infrastructure at the best value. As such, owners have a vested interest in reducing claims, reducing project costs, increasing structural life, and reducing congestion by accelerating project delivery and construction, while not compromising safety. Construction costs account for the

majority of total project costs, which are typically on the order of 80 to 90 percent. Geotechnical exploration and testing programs typically account for less than 5 percent of total construction costs. At a minimum, these programs provide information necessary for the geotechnical engineer for design and construction needs. Deliberative, well-planned and executed exploration and testing programs provide an opportunity for increasing the reliability of engineering parameters used for design and reducing uncertainty. This can have a significant impact in producing more economical designs and reducing the chances of construction claims at a fraction of the total project costs if the exploration and testing methods are appropriately selected, and the engineering parameters are validated and used appropriately. An unfortunate reality is that many geotechnical engineers lack familiarity and comfort with these newer exploration and testing methods, and rely heavily on the exploration and testing methods of which they are familiar, predominantly the Standard Penetration Test. In addition, geotechnical engineers, like other civil engineers, are predisposed to err on the side of safety in the absence of more reliable data. Familiarity with geophysical methods, and other exploration and testing methods, and confidence in results through validation and successful use is necessary before geotechnical engineers will make recommendations or produce designs that are less conservative without compromising safety and increasing personal liability. This suggests an inertia that must be overcome if we are to take advantage of the value provided by increased reliability of subsurface data.

To overcome this inertia and to provide incentive for the value that can be provided by increased reliability of subsurface data, the following suggestions are provided.

**Increase reliability of geotechnical exploration and testing:** The geophysical and geotechnical communities should consider developments to address needs specific to geotechnical engineering and construction, and consider using geophysics appropriately, where the results will provide less uncertainty and more reliability. More reliable correlations to engineering properties and behavior of soil and rock that have significant impact on geotechnical design and construction could also be developed. In addition, standards for testing could be developed that encourage consistency and help establish expectations. The significance in the reliability of data has become more apparent as design methodology shifts toward LRFD and reliability based design.

**Demonstrate value:** The geophysical and geotechnical communities should conduct examination studies to support and demonstrate reduction in uncertainty for geotechnical and construction projects. The geophysical and geotechnical communities should also conduct and publish prediction versus actual studies to quantify cost savings.

**Build familiarity and confidence:** Confidence in geophysical methods will come, in part, with increased reliability of geotechnical data through standards, correlations, further developments and appropriate use. In addition, studies that demonstrate value will help build confidence with results from geophysical methods, while quantifying and publishing cost savings will provide incentive. Familiarity, in large part, must come from using these methods and their results in practice with recognizable success.

**Protect against misuse:** One of the most effective way to lose confidence with any technology is to have it misused with adverse consequences. Clear communication between geophysicist, geologist, geotechnical engineer and contractor is essential for setting and meeting expectations. Clearly distinguishing factual data from interpretation, and establishing standards for presenting complex factual data would help protect owners, and any others involved with a project, from liabilities related to frivolous construction claims.

## SUMMARY

Geophysical methods have tremendous potential for geotechnical applications. Understanding the needs of the geotechnical engineer is key to effective use of geophysical methods for geotechnical applications. The quality of a geotechnical engineer's work depends heavily on the quality and appropriateness of their subsurface exploration and testing programs. Results from geophysical methods are commonly presented in units of which geotechnical engineers are not commonly familiar, and are generally not correlated to those engineering properties and conditions of which the geotechnical

engineer specifically needs for analysis and evaluation for design and construction. The greatest potential benefits of well planned and executed subsurface exploration and testing program can be greater reliability of engineering parameters and less uncertainty of subsurface conditions, which can result in more economical designs and less claims and delays during construction. These are the benefits that have the greatest value, and would be where geophysical methods could be used most effectively. In order to more effectively utilize geophysical methods, the following suggestions are provided:

**Increase reliability of geotechnical exploration and testing:** The geophysical and geotechnical communities should consider developments to address needs specific to geotechnical engineering and construction, and consider using geophysics appropriately, where the results will provide less uncertainty and more reliability. More reliable correlations to engineering properties and behavior of soil and rock that have significant impact on geotechnical design and construction could also be developed. In addition, standards for testing could be developed that encourage consistency and help establish expectations. The significance in the reliability of data has become more apparent as design methodology shifts toward LRFD and reliability based design.

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