



## INTEGRATING METHODS FOR SUBSURFACE CHARACTERIZATION IN SUPPORT OF LINEAR INFRASTRUCTURE PROJECTS

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### Abstract

Integrated subsurface characterization utilizing classical subsurface point investigation methods (i.e., borings) and continuous characterization methods (i.e., geophysical survey) has been used very successfully for design of linear infrastructure projects such as pipelines, levees and tunnels. Challenges that road and rail infrastructure projects often face in developing a good understanding of the subsurface conditions along long alignments on often variable subsurface conditions can be addressed in the same manner. Although point investigation methods are invaluable in sampling and analyzing the variation of subsurface material properties they are also limited by the “hit and miss” approach with respect to identifying localized variations of subsurface materials. Unidentified localized variations such as caverns in karst environments, unknown faults, collapsible or expansive soils, variable depth to bedrock and groundwater could be easily missed by point explorations and significantly impact design and construction cost and schedule. Airborne electromagnetic survey, land and marine geophysical surveys, gravity surveys and other geophysical methods can provide continuous information on subsurface conditions. With ground truthing using direct soil sampling point investigation methods they provide additional confidence in the resulting subsurface characterization. Several geophysical methods and examples of utilizing integrated subsurface characterization approach for linear infrastructure projects are presented in this paper.

*Keywords: subsurface, site investigation, geophysics, integrated approach*

### 1 Introduction

Developing a complete and thorough subsurface characterization is an important factor in design and construction of any significant civil engineering project, most significantly those covering large distances of variable subsurface conditions. Surprises in the construction phase are rarely positive, and in most cases costly, both in terms of money and schedule delays. Traditionally, subsurface characterization for large area projects has been based mostly on the site-specific data collected by advancing borings or cone penetrometer tests (CPTs) at preselected spacing and using the collected data to interpret the subsurface conditions between. As the subsurface variability increases, the spacing of subsurface exploration needs to decrease in the effort to better characterize the encountered variability. Even with a relatively close spacing, there is always a chance that some critical location will be missed by point explorations. During recent years, subsurface characterization efforts have been moving into the direction of increased use of geophysical characterization techniques to develop a more complete picture of the subsurface conditions. Technological developments in the collection of geophysical

data have also allowed relatively rapid collection of geophysical data over large project areas. Using modern computer tools, integration of the data from direct soil sampling and characterization methods (such as borings and CPTs) and data collected using geophysical techniques has been simplified, enabling engineers to take full advantage of data integration. Recognition of the increasing importance of integrating geophysical methods in subsurface exploration for transportation projects can be seen in preparation of the United States National Cooperative Highway Research Program Synthesis “Use of Geophysics for Transportation Projects” [1]. The synthesis identified the following top three greatest values of including geophysical methods: (1) speed of data acquisition, (2) cost benefits, and (3) better characterization of the subsurface. The synthesis also identified that improved utilization of geophysical methods is dependent of familiarizing the designing engineers with available methods and their most suitable applications. The following text presents a brief overview of selected ground- and aerial-based geophysical methods and presents several examples of their integrated implementation for transportation and other linear infrastructure projects.

## 2 Subsurface investigation methods

A simple subdivision of subsurface investigation tools could be made between the point based investigation tools physically penetrating the ground (such as borings and CPTs) and those characterizing subsurface continuously by measuring geophysical properties (wave response, electromagnetic response, etc.) over a larger area of interest.

### 2.1 Point based investigation methods (borings and CPTs)

Data gathered advancing geotechnical borings are still major source of directly characterizing the soils. However, only a limited number of borings is advanced within a specific project due to time and cost constraints. The introduction of CPT methods has already provided a great supplement to the borings-only approach. Although not directly sampling soil, CPT combined with soil boring correlations can provide higher density of site-specific subsurface data at lesser cost. Based on typical investigation cost and schedule in the USA, the CPT type investigation can provide four times more coverage compared to borings but typically requires at least some geotechnical borings for calibration purposes.

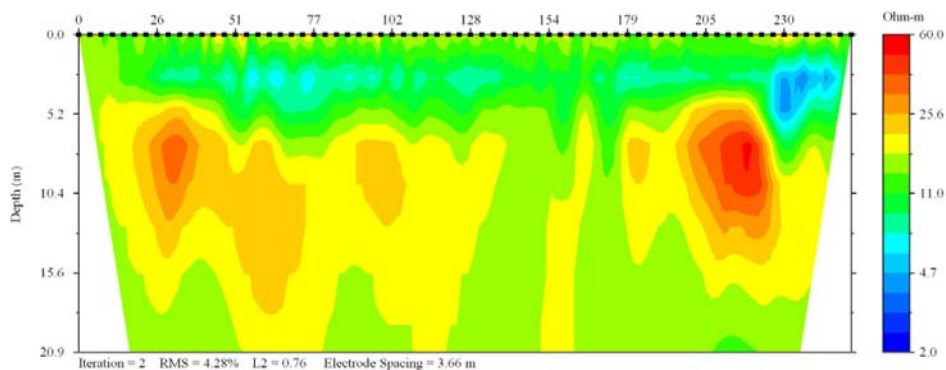
### 2.2 Continuous characterization methods (geophysical methods)

A significant increase in information coverage can be achieved by using geophysical methods. Geophysical methods provide continuous coverage over larger areas and provide a cost effective manner of collecting data that covers a linear corridor. There are numerous geophysical methods employing various physical principles in data collection including: magnetic, electrical, electromagnetic, seismic, and gravity. The data can be collected on instrumentation positioned on the ground surface, using airborne-based methods, or using boats for water-based surveys. On land, the use of airborne-based methods has been steadily gaining popularity as it can provide a cost-effective data collection solution for larger projects. Airborne-based geophysical investigation is performed using equipment mounted on either a helicopter or fixed-wing platform. Use of airplanes can provide large coverage quickly and relatively cheaply. Helicopter-based surveys can provide more small-scale detail and operate in areas that may have limited accessibility such as rugged and steeper terrain or heavily forested areas. Selected geophysical methods are described below with their applicability for subsurface investigations.

**Seismic survey.** Seismic surveys are one of the most commonly used geophysical methods in site investigations. Data is collected using a series of geophones measuring the seismic wave propagation from an artificially created seismic source. Seismic reflection and refraction data

can be collected on land or in water where geophones are towed behind the boat. These techniques are used very successfully in mapping horizons between different soil layers (seismic reflection) and characterization of likely subgrade properties such as potential rippability (seismic refraction) that can later be sampled directly using point-based investigation methods. In addition, seismic surveys can achieve significant penetration depth, allowing for accurate characterization of depth to bedrock and potential subsurface structures such as faults.

**Resistivity survey.** Surface electric resistivity surveys measure resistivity variations in vertical and horizontal directions. Collected data can be used to assess depth to water table, map subsurface voids, identify faults and fractures, characterize depths of key geologic layers, and provide information on potential external corrosion hazard. The data can usually be collected to depths of about 60 meters. An example vertical resistivity profile is shown in Fig. 1. Sandy materials have higher resistivity and show as yellow and reddish zones while fine grained silts and clays have lower resistivity and show as greenish and blue zones. The horizontal extend of the presented profile is about 1000 meters with depth penetration of about 20 meters.



**Figure 1** Example of resistivity profile collected by surface based method.

**Electromagnetic survey.** Electromagnetic surveys can be performed using ground or airborne means. Airborne collected electromagnetic data is frequently used to map the resistivity / conductivity of the subsurface for larger infrastructure projects. Frequency domain systems are most suitable for near surface mapping, offering highest resolution in the top 20 to 50 metres and maximum depths of penetration of up to 150 metres in resistive regimes. Because access is not required, airborne surveys are an ideal way to collect information on the subsurface over large areas quickly and effectively. The success of an airborne electromagnetic survey depends on sufficient geo-electrical contrast between the material of interest and underlying rock. Airborne electromagnetic surveys are ideally flown at a preliminary stage of any site assessment. The electromagnetic data collected can then be used in conjunction with ground data to help constrain the parameters used for modelling and analysis.

**Microgravity survey.** The microgravity technique is a relatively new technique ideal for identification of voids or fractures in the subsurface, or density variations that may be associated with subsidence or other construction hazards. Microgravity technique measures with high accuracy minute variations within the Earth's gravitational field due to changes in density in near surface materials. Changes can be caused by fractures or rock voids, buried chambers or karst solution features. The technique can be applied in a range of terrains and is particularly useful at detecting the presence of less dense materials. Fig. 2 presents microgravity measurements used to identify subsurface cavities in limestone material.

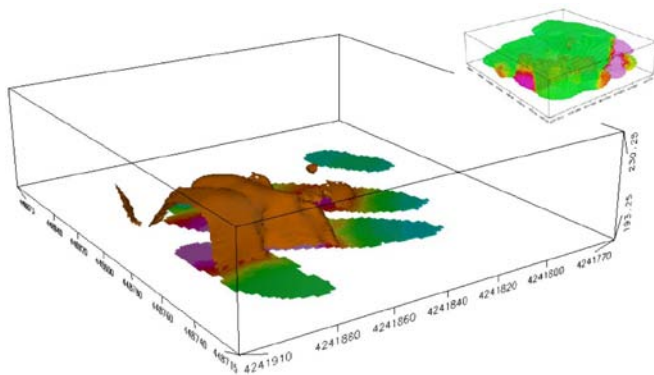


Figure 2 Cavity detection using microgravity survey (courtesy of Fugro Aperio Ltd.)

### 3 Example studies

The following section describes selected examples of the authors' experience with use of an integrated approach in subsurface characterization on linear infrastructure projects.

#### 3.1 California levee study

Fugro was involved in several on-going studies of the flood-control levees in the Sacramento Valley in California. The surveys included helicopter borne electromagnetic (HEM) and magnetic surveys, geomorphologic studies, DC resistivity surveys, cone penetrometer testing and borings. The HEM data was interpreted to map highly sandy resistive areas and conductive clay regions beneath the levee. The locations and depths of sandy layers are critical to the evaluation of levee stability since they can cause localized seepage problems. Differential resistivity profiles were calculated from the frequency and resistivity data obtained by the RESOLVE system and then correlated with the data collected using borings and CPTs. The HEM differential resistivity profile flown over one of the levees is shown in Fig. 3.

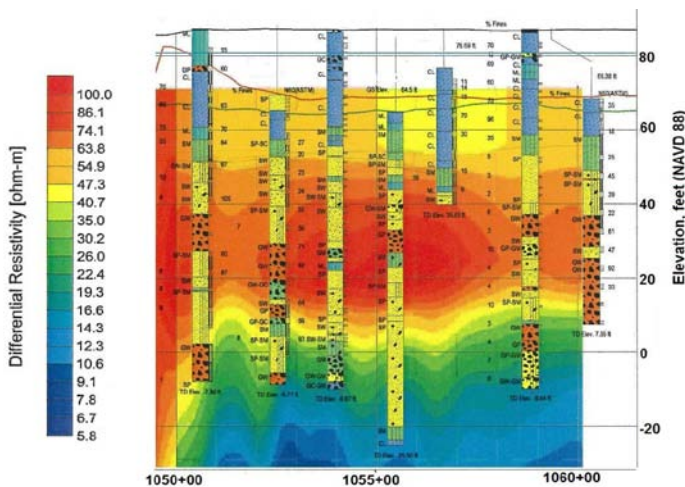


Figure 3 HEM Differential Resistivity Profile.

The geotechnical borings were superimposed on the differential resistivity data. The ground-based subsurface data corresponds well with the HEM, and the HEM data proved useful successful resolving the thickness of the top later. The continuous coverage of airborne data also helped distinguish sandy regions which were targeted for further ground-based geotechnical investigation, primarily borings and CPTs.

### 3.2 Dallas Trinity Parkway highway project

The Trinity Parkway (TRP) is a proposed 6-lane highway in Dallas, Texas, USA. The unique feature of the TRP is that about 8.6km of its 14.4km length will be within an existing flood plain. The TRP will be on the river side of a 7.5 to 9 meter tall levee that currently protects much of Dallas' central business district and adjacent areas from flooding of the Trinity River. The geotechnical field investigation consisted of geotechnical drilling and sampling, CPTs and geophysical surveys. The geophysical investigation performed for the TRP project was land-based, using electromagnetic surveys and electrical resistivity imaging techniques.

Due to a short project schedule, all three types of investigation (drilling/sampling, CPTs and geophysical surveys) were conducted concurrently. However, the spacing of adjacent CPT was adjusted (to as close as 7.5 meters) to further investigate identified areas of significantly variable soil conditions. Obtaining geophysical information from areas of known soil variations is helpful in identifying similar variations, and associated potential construction issues, at locations where drilling and CPT data are not available. The geophysical data, while providing no site-specific samples for testing in the laboratory, provide subsurface information for a relatively large area at a fraction of the cost of either drilling/sampling or CPT investigations. Also, the collection and analyses of geophysical data was much quicker than boring or CPT investigations. For future projects the best-case scenario for an investigation would include geophysical work performed first, followed by the CPT investigation in areas of interest, and finally by geotechnical borings in areas justified by the geophysical work and/or CPT data. The staged deployment mode of different investigation methods is most likely to results in a cost-effective and confident subsurface interpretation effort.

The benefits of using standard geotechnical investigation techniques such as borings and CPTs, as well as geophysical investigative techniques can reach beyond the initial project for which these methods were used. In this case, the work completed for the TRP may result in an expanded use of geophysical techniques in future levee-assessment work in the Dallas area. Furthermore, although only land based geophysical survey was performed for TRP, airborne-based geophysical survey could have also been used, which would be beneficial in areas that are difficult to access. The continuous coverage of an airborne survey makes it a cost effective way of covering large areas. Covering the same area with ground work could cost up to 10 times the amount of an airborne survey.

### 3.3 Bay Tunnel project

Bay Tunnel Project involves a new 8km water pipeline proposed as part of the larger upgrade of the pipelines in the San Francisco bay area. The Bay Tunnel portion crosses the bay in an east-west direction. Geotechnical site investigation for the project involved extensive geotechnical and geophysical exploration programs in an effort to characterize variable soil conditions along the pipeline alignment and develop an understanding of soil and rock horizons within the proposed tunnel corridor.

The site investigation involved the following methods: aerial based topography and bathymetry survey, land geophysical survey, marine geophysical survey, land geotechnical drilling and CPT program, and marine geotechnical drilling program. Site characterization involved integrating collected data into a coherent subsurface profile. Soil layer horizons were developed from interpretation of geophysical land and marine survey data as shown on the example in Fig. 4.

Such developed horizons were compared and confirmed with the layer breaks observed in geotechnical borings. All available data was integrated using the computer software ArcMap to develop integrated subsurface cross sections as shown in Fig. 5. Subsurface cross-sections developed by integrating the geophysical data and geotechnical exploration provides a higher confidence in the understanding of the subsurface variations. Additionally, including geophysical investigations as part of subsurface investigation is cost effective approach compared to an increased number of geotechnical explorations that would be required if no geophysical data was available.

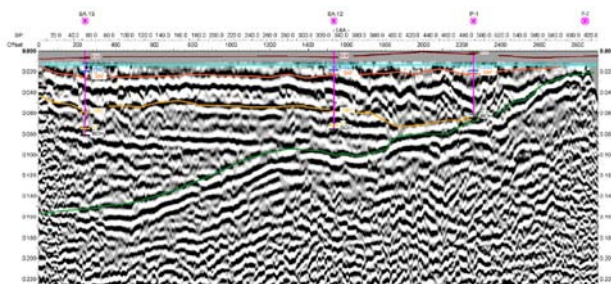


Figure 4 Seismic reflection data interpretation.

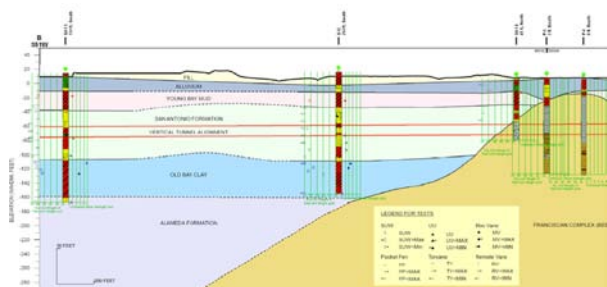


Figure 5 Integration of geophysical and geotechnical data into a single interpretative subsurface cross section.

## 4 Conclusion

Integrating data collected using direct subsurface sampling and testing methods and geophysical surveys enables a better understanding of subsurface conditions along the proposed project alignment. Advantages of large area airborne surveys can be especially beneficial for the subsurface evaluation of proposed new transportation corridors. Accurate and rapid determination of ground conditions along a proposed project corridor can reduce the need for expensive ground-based exploration. However, characterization of subsurface conditions requires careful implementation and interpretation of various geophysical survey options. Proper combination of geotechnical and geophysical methods during subsurface characterization can considerably reduce the construction risks including the likelihood of costly changes during the construction process.

## References

- [1] National Cooperative Highway Research Program, Use of Geophysics for Transportation Projects, Synthesis 357, 2006.