AN OVERVIEW OF METHODS AND STRATEGIES ASSESSING SUBSURFACE GEOLOGIC CONDITIONS AND STRUCTURAL TESTING OF ROADS AND BRIDGES

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ABSTRACT

A variety of non-invasive and minimally invasive methods such as remote sensing, surface geophysics, borehole geophysics and various push technology can be used to determine subsurface geologic conditions of roads, bridges and their associated structures. Some of these methods can be utilized to determine subsurface geologic conditions prior to construction. Some can be applied to QC measurements during construction and many can be applied after construction to determine as-built conditions, as well as degradation.

The benefits of such measurements include: non-destructive sampling, in-situ measurements of a wide range of physical properties, sampling larger areas or volumes and providing continuous measurements in some cases. These benefits result in a greater sample density, which can more readily identify uniform conditions as well as locate anomalous conditions. Once anomalies conditions are identified, those areas requiring further tests, borings or repairs can be accurately and quickly located. These methods can also provide temporal measurements (detecting changes in conditions with time). Such data can be used in a database to guide management decisions for maintenance and repairs. Maintenance and repairs on roads, bridge decks and bridge scour is becoming ever important as our infrastructure ages. A variety of methods can be used to increase the efficiency and technical effectiveness of such inspections.

This three-part paper provides an overview of a wide range of methods that can and have been applied to characterizing conditions of roads and bridges. Part I discusses some of the problems associated with site characterization and provides an introduction to the methods and other applications. Part II provides a tabulation of the non-intrusive and minimally intrusive methods of measurement. Part III discusses the selection and use of appropriate methods.

PART I

THE GEOLOGIC SITE CHARACTERIZATION PROBLEM

Geology is the most critical and the most unforgiving issue in any geotechnical or environmental site investigation. If all sites were simple (horizontally stratified geology with uniform properties) site characterization would be easy. Data from just one boring would be sufficient to characterize the site. However, in most geologic settings, this will not be the case. Even at sites where the geology appears to be uniform, one must be alert to sometimes subtle variations which can cause significant changes in structural or hydrological properties and therefore, affect site characterization.

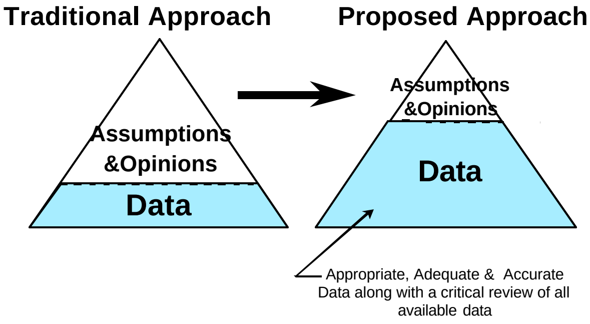
The primary factor affecting the accuracy and completeness of any site characterization is the limited number of data points available to spatially and or temporally describe site conditions. Achieving a reasonable spatial sampling of hydrogeologic conditions for geotechnical investigations requires borings and/or sampling in a close-order grid, which would reduce the site to "Swiss cheese" (Benson, 1993). Yet we commonly accept data from a limited number of data points to characterize large areas and complex geologic settings.

In order to obtain a sufficiently complete picture of site conditions, measurements must be taken over denser spacings than direct sampling can feasibly provide. Remote sensing, geophysical methods and non-destructive testing (NDT) methods can economically provide this denser spacing.

The emphasis should be upon obtaining appropriate data for the task, adequate data, and accurate data. A solid base of data (Figure 1) enables us to carry out subsequent efforts such as modeling, risk assessment, remediation, engineering design and maintenance with much greater confidence and accuracy, while minimizing uncertainties, assumptions, and opinions.

Many of these same issues apply to non-destructive testing (NDT) which may be done:

- Along a roadway, runway or bridge to assess conditions of asphalt, concrete or sub-base; or
- At specific locations to determine pile length, integrity, or bridge scour.



Appropriate, Adequate & Accurate Data along with a critical review of all available data

Figure 1. Increasing the data and minimizing assumptions and opinions forms a solid basis for understanding site conditions.

WHY USE NON-INVASIVE AND MINIMALLY INVASIVE METHODS

A geophysical or non-destructive testing survey consists of a set of measurements made from the air, at the ground surface or in a borehole. A geophysical measurement or non-destructive test responds to some change in a physical electrical or chemical property, such as seismic velocity, density, magnetic, electrical, dielectric, radioactive or thermal. These measurements are used to identify lateral or vertical changes in subsurface conditions or structures. Unlike direct sampling, such as obtaining a soil sample and sending it to a laboratory, each non-destructive, non-invasive or minimally invasive method responds to a different parameter in a different way. Each method sees the subsurface conditions in a different way and often different than a driller's log might.

Some geophysical methods are active i.e., they provide their own "field"(radar, EM, resistivity, seismic). Other geophysical methods are passive, i.e. they utilize a natural field of the earth (magnetics, microgravity).

Characterization of Geologic Conditions

Because soil and rock vary widely in their physical properties, (some by many orders of magnitude), one or more of these properties will usually correspond to a geologic discontinuity, such as a stratigraphic contact (i.e. soil and rock) or a structural contact (i.e., a fault). Boundaries determined by geophysical methods will usually coincide with geological boundaries, and a cross-section produced from the geophysical data may resemble the geological cross-section, although the two are not necessarily identical.

Geophysical data itself simply represents lateral and or vertical changes in the measured parameter. The geophysical data can only be interpreted by using some knowledge of the likely geologic conditions.

While some geotechnical and environmental data may extend to depths of 1,000 feet or more, most environmental and geologic investigations are limited to the upper 100 feet or so, and often less. While NDT often utilizes special hardware and procedures, many surface and borehole geophysical methods can also be applied to NDT.

NDT measurements are usually applied to relatively shallow man-made structures (piles and foundations), and are often applied to very shallow measurements within the upper foot or so (i.e., pavements, concrete and sub-base).

While hydrogeologic measurements are often made over large areas of a site to identify anomalous conditions before making more detailed measurements, NDT measurements are most often focused upon structures whose locations are known (i.e., piles and foundations).

A Wide Range of Methods are Available

Remote sensing, geophysical, minimally invasive, and NDT methods encompass a wide range of airborne, surface and downhole measurement techniques, which provide a means of investigating subsurface geologic and hydrologic conditions, and obtaining engineering properties. In the broad sense, remote sensing, geophysics, and NDT are similar since they all make in-situ measurements.

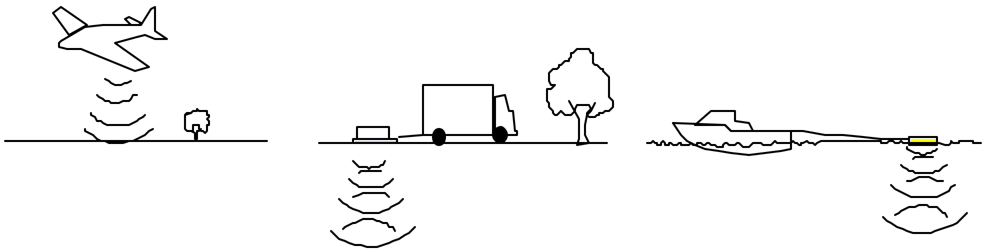


Figure 2. Measurements can be made from the air, surface, and over water.

Satellite data, aerial photography and other airborne geophysical measurements (Figure 2) are used to provide reconnaissance level data over large areas and can provide some site specific data. These methods clearly have merits in terms of spatial coverage per unit time and cost. The *imaging* methods (photographic, infrared, and thermal imagery) provide a "picture" of the site and the surrounding area and can quickly establish the regional setting.

Surface geophysical methods (Figure 2) yield much less spatial coverage per unit time than the airborne methods; however, they significantly improve resolution (the ability to detect smaller features) while providing subsurface information typically up to a few 100 feet or more. With some methods, continuous data acquisition can be obtained at speeds up to several miles per hour (and in some cases at highway speeds). In certain situations, total site coverage is technically and economically feasible. Because of the greater sample density, anomalous conditions (problem areas) are more likely to be detected. An inherent limitation of all surface geophysical methods is that their resolution decreases with depth. Most of the surface geophysical methods can be used on water (rivers, lakes, estuaries, and coastal) or over frozen bodies of water as well as on land. ASTM D6429 provides a brief description of the surface geophysical methods and their applications.

Downhole geophysical methods are used to provide very localized details down a borehole, monitoring well or a core hole in a concrete footing or pile (Figure 3a). The volume sampled by downhole methods is usually limited to the area immediately around the boring (a cubic foot to a cubic yard). Unlike surface geophysical methods where resolution decreases with depth, the resolution of downhole logging is independent of depth. If holes are already in place or if they are to be drilled for other purposes, the overall cost of downhole logging is relatively low. There are a variety of tools available to measure properties of the borehole fluids, imaging of the borehole wall, and measurement of properties a few inches to a few feet beyond the borehole wall. Some of the borehole logs must be used in an open borehole, some can be run in a PVC-cased borehole and some can be run in a steel-cased borehole. Some logs can be run in dry or wet holes and some must be run in wet holes. ASTM D5753 provides a brief description of the downhole geophysical methods and their applications.

Surface to borehole measurements (Figure 3b) are typically seismic measurements made to provide P and S wave velocities to calculate bulk modulus. Resistivity and radar measurement may also be made between the surface and borehole, but are less common.

Measurements between two or more boreholes (Figure 3c) provide a means of increasing the volume of measurements to be more representative of large volumes, locating changes in strata and measurement of the properties. Hole to hole measurements are commonly made to make P and S wave measurements to calculate bulk modulus (ASTM D4428M-91). However, resistivity and radar measurements can also be made hole to hole.

Tomographic imaging can also be done between boreholes (Figure 3d). Tomographic measurements can be made with seismic (sonic), resistivity or radar. These measurements provide a means of imaging the location, size and character of features, such as fractures, cavities, tunnels between two or more boreholes. A detailed series of measurements are made between each pair of boreholes (Figure 3d), the data are then processed by a computer algorithm to provide the 2D image of the space between boreholes. Three-dimensional tomographic measurements may also be made between arrays of boreholes. These are analogous to the C.A.T. scans used in the medical profession.

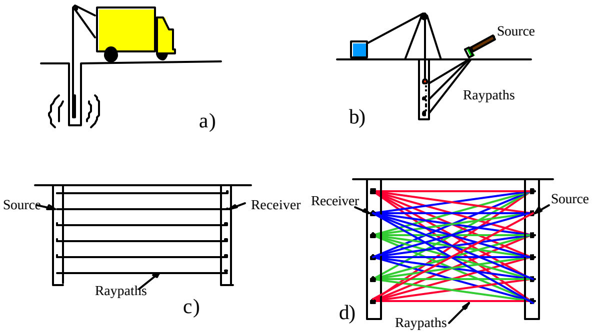


Figure 3. Borehole logging, surface to borehole, hole-to-hole and tomography

Minimally invasive tools such as cone penetrometers, hammer-driven tools (push technology), along with some simple hand tools (Figure 4) provide a minimally-invasive means of characterizing subsurface conditions in areas of unconsolidated materials. These methods do not create the soil and water waste that borings do. A number of parameter may be measured by these tools.

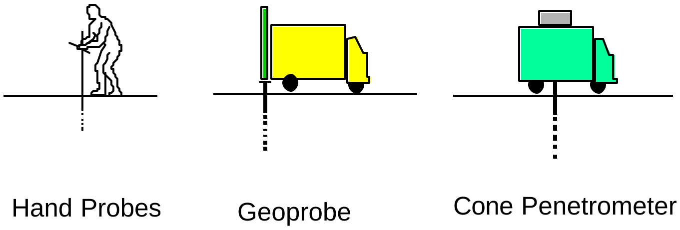


Figure 4. Minimally invasive methods

There is a surprising similarity between many medical techniques and the geophysical methods. The wide range of tools available to a medical professional measure different physical, chemical or electrical parameters of the body, such as x-ray, ultrasound, EKG or CAT scan. Doctors use these tools to collect a sufficient amount of data and insight on the patients internal conditions. These data along with blood tests, personal observations and discussion with the patient are used to provide a diagnosis of the patient's condition prior to prescribing a medication or surgery. A similar approach should also be used in the engineering field to minimize assumptions and opinions (Figure 1).

PART II
NON-INTRUSIVE AND MINIMALLY INTRUSIVE METHODS OF MEASUREMENTS

Tables 1 through 9 identify a wide range of methods that can be applied to various aspects of geologic site characterization and NDT of roads and bridges. These lists are not intended to be complete, but cite the more commonly used methods.

Some of these methods can be utilized to determine subsurface conditions prior to construction. Some can be applied to QC measurements during construction and many can be applied after construction to determine as-built conditions, as well as degradation of conditions.

Table 1 - Airborne or Satellite Measurements

Method	**Parameter/Condition Measured**
Satellite Imagery Multispectral and radar	Surface image documentation and terrain interpretation
Aerial Photo and Video Imagery	Surface image documentation and terrain interpretation
Thermal Imagery	Temperature of surface (moisture/seeps/karst)
Airborne geophysical measurements	Subsurface characterization (e.g., magnetic data, electromagnetic, conductivity or resistivity data and radiometric measurements of natural radiation)

Table 2 - Non-Invasive Surface Methods

Method	**Parameter/Condition Measured**
Ground Penetrating Radar	Dielectric constant (stratigraphy/top of rock/karst)
Electromagnetic Frequency and Time Domain	Electrical conductivity (lateral variation in soil and rock/ inorganic contaminants)
VLF	Electrical resistivity (lateral variations in soil and rock, fractures, contacts)
Resistivity	Electrical resistivity (spatial variation in soil and rock/ inorganic contaminants)
SP (spontaneous potential)	Electrochemical and streaming potential (seepage/karst)
Seismic Refraction	Seismic velocity (top of rock/rippability)
Seismic Reflection	Seismic velocity (stratigraphy)
Seismic Surface Wave Analysis	Seismic velocity/dispersion (S-wave/stratigraphy)
Microgravity	Density (bedrock channels/karst)
Magnetics	Magnetic susceptibility (location of ferrous minerals, utilities/tanks/ drums/metal debris)
Metal Detector	Electrical conductivity of metal (location of utilities/tanks/metallic debris)
Thermal Imagery	Temperature of surface (moisture/seeps/karst), location of pipelines
Radiation	Natural gamma radiation (exploration for ores, fracture patterns)

Table 3 - Non-Invasive methods Used on rivers, lakes, and coastal waters

Method	**Parameter/Condition Measured**
Fathometer	Travel time of acoustic wave/Depth to bottom
Side scan sonar	Travel time of acoustic wave/Acoustic image of bottom
Subbottom Seismic Reflection Profiling	Travel time of acoustic wave/Profile of sediment strata and depth to rock
Scanning sonar	Travel time of acoustic wave/Acoustic image of bottom
Photo/Video	Documentation of bottom conditions and structures
Remote Operated Vehicle with photo or video	Used as a vehicle for various sensors, typically video and cameras/visual inspection and documentation
Thermal Imagery	Water temperature/Seeps, springs, contaminants

Note that many of the surface geophysical measurements can also be applied on water.

Table 4 - Borehole Logging/Measurements (Single Hole)

TYPE OF LOG	PARAMETER/CONDITION MEASURED
Nuclear	
Gamma	Natural gamma radiation/stratigraphic correlation, relative clay content.
Gamma Spectrometry	Natural gamma radiation/characterize mineralogy based upon radio-isotopes
Gamma-Gamma (Density)	Relative density/Bulk density of strata sometimes used as a cement bond log.
Neutron-neutron	Relative moisture/moisture content above the water table, porosity below the water table.
Electrical/Electromagnetic	
Induction	Electrical conductivity of soil, rock, and pore fluids
Resistivity	Electrical resistivity of soil, rock and pore fluids
Single Point Resistance	Resistance/Stratigraphy/voids/fracture/flow
Spontaneous Potential (SP)	Electrochemical effects at wall streaming potential due to movement of pore fluids/Stratigraphy/voids/fracture/flow
Magnetic susceptibility	Magnetic susceptibility of soil and rock for stratigraphic purposes, also responds to presence of ferrous metals for location of steel casing, drilling hazards, or other well problems
Radar	Travel time of the electromagnetic wave/Identification of anomalous conditions, far-field from the borehole, such as fractures, cavities, tunnels and mines
Fluid	
Water level	Water level of fluids in borehole
Conductivity	Electrical conductivity of borehole fluids/Provides a measure of borehole fluid, specific conductance (or total dissolved solids). Assess movement of water into or out of borehole locating permeable or fracture zones. Determine salt water interface.
Temperature	Borehole fluid temperature (groundwater flow)
Flow Meter (Fluid Movement) Impeller Heat Pulse	Fluid flow within borehole (groundwater flow)
In-Situ Chemical Sensors (Minimum diameter borehole 2 to 6 inches)	Borehole fluid electrical conductivity (flow/contaminants)/conductivity, pH, oxygen, Eh, specific ion electrodes, tracers.
Mechanical	
Caliper	Borehole diameter (voids/cavities)
Deviation (inclinometer)	Borehole deviation from vertical
Acoustic/Sonic/Seismic	
Sonic or Full Wave Sonic	P and S wave velocity (near borehole)
Borehole Imagery	
Television	TV image of borehole wall/geologic strata, voids and fractures
Acoustic Televiewer (ATV)	Acoustic image of borehole wall/geologic strata, voids and fractures
Borehole Image processing Systems (BIPS)	Electrical image of borehole wall/geologic strata, voids and fractures
Scanning Sonar	Acoustic travel time/measurements of large voids and cavities intersecting the borehole

Table 5 - Surface to Hole Measurements

Method	Parameter/Condition Measured
Seismic P and S wave measurements	Spatial variation in travel time of seismic waves to identify spatial anomalies P and S wave velocities used to calculate elastic moduli
Ground Penetrating radar	Spatial variation in travel time (dielectric constant) to identify spatial anomalies
Resistivity	Spatial variation in resistivity to identify anomalies

Table 6 - Hole-to-Hole Measurements

Method	Parameter/Condition Measured
Seismic P and S wave measurements	Spatial variation in travel time of seismic waves to identify anomalies, P and S wave velocities used to calculate elastic moduli between holes
Ground Penetrating radar	Spatial variation in travel time (dielectric constant) to identify anomalies
Resistivity	Spatial variation in resistivity to identify anomalies

Table 7 - Tomography Hole to Hole Measurements

Method	Parameter/Condition Measured
Seismic (Sonic) P wave	Image of conditions between holes
Ground Penetrating Radar	Image of conditions between holes
Resistivity	Image of conditions between boreholes

Table 8 - Hand Probes/In-Situ Sensors

Method	Parameter/Condition Measured
Nuclear density gauges	Density (attenuation of gamma rays) (shallow in situ density measurements)
Time Domain Reflectometry (TDR)	Displacement and/or changes in fluids levels (monitor change in conditions or stability)
Acoustic Emission	Sonic noise due to fluid flow or structural movement (monitor site stability)
Temperature	Subsurface temperature (monitor changes in conditions, water recharge/heat flow)
Elevation Monuments	Changes in elevation to monitor subsidence stability, compaction

Table 9 - Minimally Invasive Push Technology

"Geoprobe" percussion tools	Blows/ft or speed of penetration (stratigraphic data) Electrical conductivity or resistivity (stratigraphic data and contacts), soil sampling, various chemical sampling and sensing
Cone Penetrometer	Tip, sleeve, pore pressure (stratigraphic data) specialty sensors including resistivity, seismic velocity, and various indirect chemical sensors (stratigraphic data and contacts)

Variations

Within a single method listed in these tables, there are often many variations in the specific hardware, its application in the field, software, and methods of interpretation for each method. For each of the methods listed in Tables 1 through 9, the hardware, software, data acquisition parameters, and data processing must be tailored to fit the needs of the project.

For example, when using the seismic refraction method, a survey can be made with a single-channel instrument and sledgehammer source to map a simple, shallow bedrock profile, or a 48-channel seismograph with high-energy sources to map deeper, more complex stratigraphy. The software to support such measurements can range from simple hand calculations to sophisticated computer inversion programs (ASTM D5777-00).

Many of the surface methods can be used on land or over water. For example, a seismic refraction survey can also be carried out on land or in the water. Radar and frequency domain electromagnetic measurements can be made in fresh water, but not saltwater.

Two or more methods can be combined to make measurements simultaneously. For example, when carrying out marine surveys bathymetry data may use multiple sensors to map a wide swath of lake, river or ocean bottom in a single pass. A side scan and subbottom survey may be combined or a magnetometer and side scan survey may be combined in a single pass.

All methods of measurements have advantages and limitations, and there is no single, universally applicable method or group of methods that can be used to meet all project needs. While a given method may be successful in one situation it may not be in another. Although there are many method selection guidelines available (see ASTM D6429 and D5753), the selection of the appropriate combination of methods can only be arrived at by experienced hands on professionals.

Applications

Remote sensing, geophysical and NDT methods are routinely applied to four areas:

- Mapping natural hydrogeologic conditions such as depth to rock or potential sinkhole areas;
- Detection and mapping of buried utilities, debris and contaminant plumes associated with roadway development;
- Evaluation of soil and rock properties, along with assessment and non-destructive testing of man-made structures;
- Temporal measurements for monitoring conditions such as bridge scour, subsidence, and to support remediation management

Probably the most important task of any site investigation is characterizing the natural hydrogeologic conditions. Understanding the hydrogeologic conditions can make the difference between success and failure for site investigations. Mapping natural hydrogeologic conditions includes a wide variety of objectives such as:

- determining thickness of unconsolidated materials, top of rock or structural features;
- mapping lateral variations in sand/clay deposits; and
- locating geologic anomalies (e.g. sinkholes, bedrock channels, fractures, and faults).

Establishing new roadways or expanding existing ones, often involves traversing previously developed properties with few records or documentation. Prior to roadway development, environmental issues such as waste disposal areas and underground storage tanks may also need to be addressed. Surface geophysical methods can significantly aid in the detection and mapping of landfills, construction debris, pipelines/utilities, underground storage tanks, old building foundations and contaminant plumes. These methods provide a high degree of spatial sampling to ensure that buried objects and environmental concerns are adequately characterized before construction.

Providing an assessment of problem areas in road beds or structures allows maintenance and repairs to be more effectively carried out. A wide variety of applications fall into this category including rock stability, soil properties, pile length and integrity, bridge scour assessment and roadbed evaluations. While geologic and hydrologic studies often require investigations over many acres or over many line miles, NDT investigations are usually very localized measurements.

Many of these methods can be used to monitor changes in conditions with time to identify frequency and distribution of potential problems. Such data can be incorporated into a database to guide management decisions for maintenance priority and repairs as well as to avoid high risk failures. Monitoring can be accomplished in two ways: by measurements which are repeated at suitable intervals in time or by in-situ measurements (made by implanting sensors, such as TDR) to provide semi-continuous monitoring of any change in conditions.

Benson (1993, 2000a) describes the application of geophysical measurements to a number of highway applications, including geologic, hydrologic, environmental problems, and NDT. Olson (1998) discusses some of the many seismic and sonic tests used in NDT.

PART III
SELECTING AND USE OF APPROPRIATE METHODS

Because of the range of investigation, the type of potential problem, the need for reconnaissance or detailed data, and cost considerations; the strategies and selection of methodology become critical factors in such investigations. This section reviews the strategy used in selecting the methods of investigation.

Many remote sensing, non and minimally invasive methods, as well as invasive methods of investigation can be applied to provide an understanding of geologic conditions to resolve geotechnical and environmental problems. A suitable combination of methods must be selected to provide the appropriate and adequate data to reach a reasonably accurate and complete interpretation of subsurface conditions for specific project needs. All methods of measurements have advantages and limitations, and there is no single, universally applicable method or group of methods that can be used to meet all project needs. While a given method may be successful in one situation it may not be in another.

There are many guidelines available for the selection of both surface and borehole geophysical methods such as ASTM D6429 and ASTM D5753-95. There is even an expert system to aid in the selection of geophysical methods (Olhoeft 1988). ASTM has also published guidelines for the use of commonly used surface and borehole geophysical methods. Yet the correct combination of methods can only be arrived at by experienced hands on professionals.

- First we must select methods that will have a reasonable chance of success based upon the parameter measured by the method.
- The issue of scale must be considered, including: the area of investigation, the expected size of anomalies, and the volume or resolution of our measurements.
- The spatial density of our measurements must be adequate to detect and define anomalous conditions. If we are monitoring changes of conditions over time, our temporal sampling must be adequate.
- The sequence of work; usually starting with the regional setting, and working toward the local setting, and then to the very local boring, sampling, and testing program.
- In addition we must remain focused upon obtaining basic hydrogeologic data working from the simple basics to the more complex.
- Multiple sources of data must be integrated into our conceptual model to confirm site specific conditions.

A CONTRAST IN PROPERTIES MUST EXIST FOR GEOPHYSICAL MEASUREMENTS TO SUCCEED

Geophysical methods measure the physical, electrical, or chemical property of the soil, rock, and pore fluids. To detect an anomaly, a soil to rock contact, the presence of inorganic contaminants, or a buried drum, there must be a contrast in the property being measured (i.e., the target to be detected or geologic feature to be defined must have properties significantly different from “background” conditions). In some cases, the differences in properties may be too small for detection by geophysical methods. Two examples will illustrate the point:

The interface between fresh water (<25 to 50 mg/l chloride) and saltwater (19,000 mg/l chloride) can easily be detected by the differences in electrical properties using surface geophysical measurements. However, the 250 mg/l chloride level used by many regulatory agencies to define the salt water interface (in contrast to fresh water 0 to 100 mg/l) can only be reliably identified by using geophysical logging within a monitor well (Yuhr and Benson, 1997).

The contact between soil and unweathered bedrock can be detected by differences in the travel time of seismic waves measured by the seismic refraction method. If, however, the rock is highly weathered, with a thick layer of material having a lower velocity or gradually increasing velocity with depth, the rock layer may not be detected. If detected, the interface will be below that determined by boring logs since the driller will often pick top of rock much shallower (within the weathered zone) than the top of massive unweathered rock determined by seismic refraction measurements.

In selecting methods of measurement, we must make some assumptions about site conditions and then match our methods of measurement to them.

THE ISSUE OF SCALE

The scale of the problem refers to three issues. First is the size of the area to be surveyed. Second is the size of the expected anomalous conditions. Third is the depth and volume (resolution) of our measurements.

The size of the area to be surveyed will ultimately limit the coverage or density of our measurements. For example a high density of measurements (including 100% site coverage) can be economically obtained over smaller areas of a few acres or a few line miles, while less dense measurements (or reconnaissance coverage) can be economically obtained over hundreds of acres and hundreds of miles.

The size of the expected anomalous conditions will determine the density of data needed to detect the anomaly as well as the method used to make the measurements. Definition of a thin fracture will require greater density of measurements and higher resolution measurements than will a wide buried channel.

The depth of measurements must be somewhat deeper than the depth of interest. The resolution of all surface geophysical methods decreases with depth while the resolution of geophysical logging measurements are independent of depth. A small sample volume can provide greater detail while a large sample volume yields less detail (less resolution) but greater coverage. For example, a hand-held rock core sample is less than a cubic foot, while a surface geophysical measurement may integrate data over a thousand cubic feet or more. The rock core can be used to identify fractures less than an inch, while the surface geophysical measurements are limited to locating fracture zones one to tens of feet in width. On the other hand borehole geophysical logging can identify small fractures of an inch or so and borehole imaging methods can define fractures on the borehole wall much less than an inch and can do it in-situ without sampling and the potential for loss or damage to the sample.

Table 19 is a partial list of generic methods that may be applied to different scales of a site characterization problem. The methods are listed in descending order from those which are mostly applicable to the assessment of larger regional areas to those which are applicable to hand-held samples.

Table 19 - Some Methods of Subsurface Characterization and Their Practical Range of Spatial Sampling

METHOD	Regional	Local Setting	The Site Itself	Localized	Hand and Core
	>1,000 acres	<1,000 acres	1 to 100 acres	<0.01 acre (20 sq. ft	<1/1000 acre (1-2 sq ft
Airborne/Satellite Measurements	X	X	X		
Geologic Mapping	X	X	X	X	X
Dye Tracing	X	X	X		
Surface Geophysics	X	X	X		
Hydrologic Measurements from a Group of Wells			X	X	
Downhole Geophysics Between a Group of Boreholes			X	X	
Hydrologic Measurements in a Single Well			X	X	
Downhole Geophysical Logs in a Single Borehole				X	X
Geologic /Driller's Logs/Cone Penetrometer					X
Laboratory Measurements on Core Samples					X

The methods of measurement must be selected to fit the scale of measurements and the scale of the expected geologic uncertainties. The scale or volume of our measurements will affect the resulting data. For example, measurements of hydrologic and engineering properties of rock can vary by many orders of magnitude, depending upon the size of the sample tested with respect to the spacing between joints. If we increase the volume of rock that we test, we will find that at some point the test results will become independent of a further increase in volume of the rock. The smallest volume that can be considered representative, for the property being measured, or the behavior of the rock mass, is called the Representative Elementary Volume (REV). The concept of REV can be applied to measurements of hydrologic or engineering properties.

- Based upon data from 39 geological media, Schulze-Makuch, et al., concluded that the relationship of hydraulic conductivity (K) to scale of measurement is a function of (1) the type of fluid flow present in a medium, and (2) the degree of heterogeneity in the medium. In heterogeneous porous media, K increases by half an order of magnitude with each order of magnitude increase in scale of measurement (using volume of tested material as the scale measure). In fracture and conduit flow media, K increases by about one order of magnitude with each order of magnitude increase in scale of measurement.

- Da Cunha (1990) shows a variation of seven orders of magnitude variation in hydraulic conductivity as the scale of tests range from laboratory to basin scale;
- Quinlan, et al., 1992 have compared flow velocity determined by a variety of methods with different scales of sampling. The methods range from analysis of core samples to dye tracing. The velocity obtained from these different methods of measurement range over 8 to 9 orders of magnitude;
- Nelson (1986) has suggested that to obtain representative hydraulic conductivity values from fractured rock requires that measurements be made on a volume of rock whose dimensions are 10 times the fracture spacing.

To illustrate the concept, we can compare hydraulic conductivity values which are commonly needed for most site characterizations. Hydraulic conductivity values can be obtained from estimates of grain size, lab measurements on small soil or rock samples, or in-situ measurements such as percolation tests, packer tests, or pump tests. The appropriateness of the hydraulic conductivity data will depend upon its intended use which will dictate which method should be used to acquire the data. Quinlan (1992) has shown that up to 9 orders of magnitude in flow velocities can be obtained depending upon the scale of the measurement technique used.

DATA DENSITY

Data density must be sufficient to adequately define conditions. Insufficient spatial or temporal data density can miss anomalous conditions leading to an incomplete and erroneous interpretations of subsurface conditions. All too often, adequate data density is decreased to save cost. This is a false sense of savings since it often ends up costing orders of magnitude more in corrective action and legal fees.

In some cases, a reconnaissance survey with limited coverage may be used to provide a statistical sampling over large areas. If so, the limitations of such a survey must be recognized.

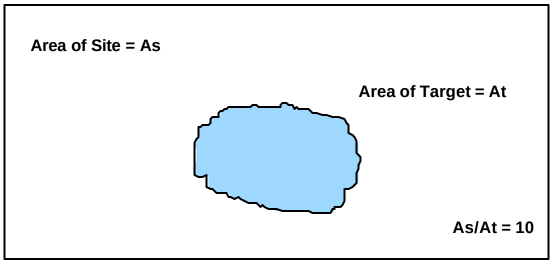


Figure 5. Illustrates site to target area ratio As/At = 10

Table 20 - Approximate Number of Station Measurements to Detect the Target

Probability of Detection	As/At = 10	As/At = 100	As/At = 1,000
100	16	160	1600
98	13	130	1300
90	10	100	1000
75	8	80	800
50	5	50	500
40	4	40	400

Benson, et al., (1982) has shown that borehole and monitoring well densities are commonly inadequate to detect geologic anomalies. For example, ten regularly spaced borings will be required to provide a detection probability of 90% to detect the presence of a target 75-foot diameter within an area of an acre (Figure 5 and Table 20). The target could be a cavity or sinkhole, a burial site, or a contaminant plume. For smaller targets, such as widely spaced joints, 100 to 1,000 borings per acre may be required to achieve a 90% probability of detection. Such detection probabilities make a subsurface investigation for such geologic features, by a limited number of borings alone, like “looking for a needle in a haystack” and almost assures failure.

If the expected anomaly is large, it may be detected by certain methods using low density coverage. On the other hand, if it is small, we will need a method with higher resolution and a greater density of measurements to identify it. Three examples of spatial density are shown below.

Figure 6 shows how a buried contaminated area at Love Canal was missed by six borings.

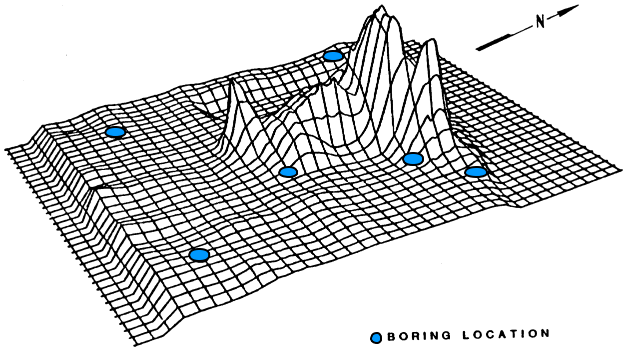


Figure 6 shows EM31 measurements responding to buried fly ash.

Figure 7A shows the results of electromagnetic measurements made by station measurements at a low spatial density. These measurements fail to define any fractures in the underlying gypsum. Figure 7B shows the detail that can be obtained in defining narrow fractures in gypsum (less than 1 foot wide) using continuous electromagnetic measurements. These fractures had not been detected by four major geotechnical drilling investigations at a dam (Carlsbad, New Mexico). A highly weathered (wide and deep) fracture zone will easily be detected by less dense surface geophysical measurements while small joints in rock will require densely spaced downhole geophysical measurements. Continuous coverage can be economically obtained over smaller areas of a few acres or a few miles while only reconnaissance coverage can be made over hundreds of acres and hundreds of miles.

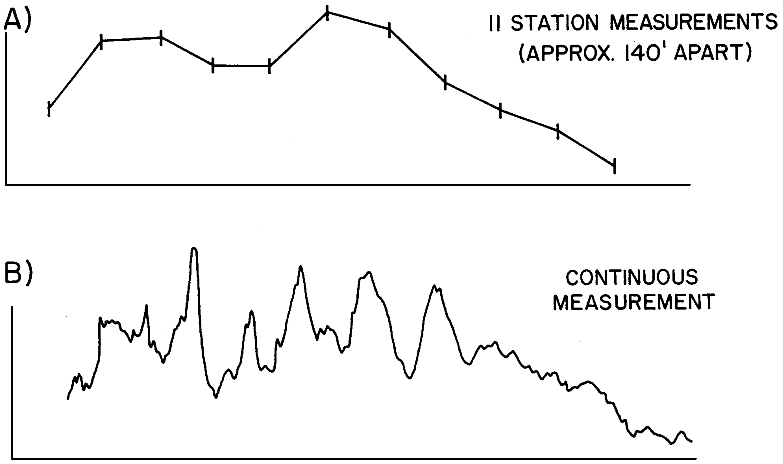


Figure 7. Continuous measurements provides greater resolution than station measurements.
Data are EM measurements of fractures in gypsum.

A groundwater model was based on the assumption that well data were uniformly distributed both laterally and vertically. Figure 8 shows the actual vertical density of wells. The impact of insufficient vertical density of wells to define deeper groundwater conditions invalidates the groundwater model.

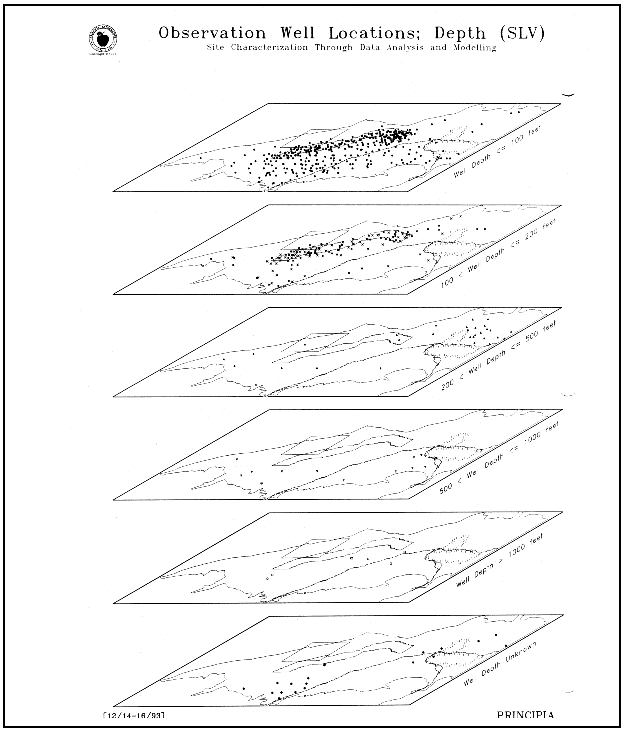


Figure 8. Spatial distribution of wells (lateral and with depth)

Temporal data density is concerned with sufficient data points over time as well as gaps in the data.

THE SEQUENCE OF WORK

Work From Regional To Local

In general, the process of site characterization should be approached in sequence, starting with regional site characterization and reconnaissance (the big picture) and then proceed to the site setting and finally focus attention upon the detailed site specific data (Figure 9). In this manner, the regional setting data forms the basis for the site setting and the site setting data forms the basis for the detailed site specific data including a boring, sampling, and testing program. In this way each step toward more localized and detailed data are based upon previous data from a larger area. Then, as the site characterization proceeds, piezometers, monitoring wells, sampling and detailed tests can then be accurately located so they are truly representative of site conditions. This sequencing of data aids in identifying anomalous areas as well as background conditions and assures that subsequent detailed data and samples are obtained in representative areas.

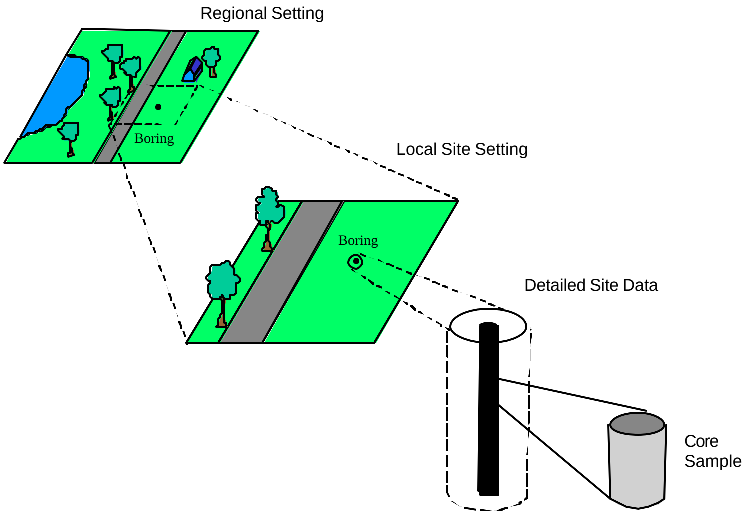


Figure 9. Regional to local to site specific approach to site

Each step along the way we should be able to predict (or at least provide a reasonable guess) as to the results of subsequent measurements or observations. For example, when we get to the stage in our investigation where we will be locating borings, we should be able to predict with some reasonable degree of certainty where and why the borings should be located and in general predict the expected results to be obtained from the boring data. If we are correct in our predictions, our conceptual model is reinforced. If we are wrong, we clearly need to rethink our interpretation.

Work From The Simple To The Complex

The simplest measurements and basic data should be acquired prior to making more sophisticated measurements and seeking complex data. Since the basic hydrologic and geologic conditions are the foundation upon which our understanding of site conditions are based, we must have the basics in place before attempting to acquire more complicated data. Complex measurements, statistical methods, or sophisticated computer imaging cannot substitute for missing basic data. First things first and keep it simple are the rules for success.

Consider the other obvious characteristics of the methods before making a selection. For example, consider ease of use, continuous versus station measurements and the amount of processing required. Cost is always of concern and the continuous easy to use methods requiring little processing are lowest cost. Do not make difficult measurements (e.g. refraction, reflection, gravity) if simple measurements (radar frequency domain electromagnetics, etc.) will solve the problem.

For example, if one is faced with the problem of finding a cavity system in limestone, one generally starts with the regional setting using aerial photos to look for lineaments and existing paleo-sinkholes, then surface geophysical methods are used to provide more detail, and finally borings and various geophysical logs, along with TV or acoustic television log or hole to hole tomography. In this way, we tie the obvious regional fracture trends to the intermediate site trends and finally to the very detail data within a borehole. The data from each step will lead us to an understanding of the site and help us focus on the locations of boreholes for more detailed data.

If we start with just borings and borehole geophysical measurements, we can easily come up with the wrong interpretation. If our boreholes are in the wrong location, our measurements will fail to detect the cavity. Before tomographic measurements can identify and characterize a cavity, the boreholes must be placed on either side of the cavity. This is not a failure of the tomographic method, but a failure in our approach to the problem.

Integration of Multiple Independent Sets of Data

Some combination of appropriate, adequate, and sufficiently accurate data based upon observations and measurements are necessary to reach a reasonable level of understanding of site conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and additional information, such as geologic, hydrologic or contaminant data, or combination thereof is required.

The conversion of raw data to useful information is a value-added process which is achieved by careful analysis of experienced professionals. Each set of data is first interpreted on its own, using appropriate existing data. Then, the interpretation is refined by combining individual data sets. When measurements by different methods agree, our interpretations will have a higher level of confidence. This process of correlation also provides a secondary form of quality assurance for individual sets of data and provides a reliable, defensible means of testing the hypothesis embedded in the conceptual model of site conditions.

CONCLUSIONS

There are a variety of roadway and bridge problems that can be resolved by integrating remote sensing, non-invasive geophysical and minimally invasive measurements, and non-destructive testing techniques, along with invasive methods of trenching, drilling, sampling, and making observations. In each case, remote sensing and geophysical measurements play an important roll in reaching an accurate and complete interpretation of subsurface conditions.

All methods of measurements have advantages and limitations, and there is no single, universally applicable method or group of methods that can be used to meet all project needs. While a given method may be successful in one situation it may not be in another. Although there are many method selection guidelines available, the selection of the appropriate combination of methods can only be arrived at by experienced hands on professionals.

Key issues which impact the selection and use of methods are the scale of the problem and measurements and data density. Other factors include the sequence of work and the use of multiple methods. Each step of the way should be focused upon obtaining basic hydrogeologic data with multiple sources of data are used to confirm site specific conditions. When measurements by different methods agree, our interpretations will have a higher level of confidence and the impact of the non-uniqueness of each set of geophysical data is reduced.

The major portion of the site characterization effort (including budget) should be focused upon gathering data. While interpretative conclusions and opinions are a necessary and important part of any site characterization, they must be supported in a logical and obvious way by sufficient data which has been tested and proven to be correct. A solid base of data (Figure 1) enables us to carry out subsequent efforts such as modeling, risk assessment and remediation with much greater confidence and accuracy while minimizing uncertainties. The more data we have, the less we rely on assumptions and opinions. In addition, observations by experienced professionals are essential to resolving complex geotechnical problems.

When we finally arrive at a reasonably accurate site characterization, we may look at the result as trivial and obvious. However, the path and effort to reach this point will never be easy or straight forward.

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