AN OVERVIEW OF GEOPHYSICAL AND NON-DESTRUCTIVE METHODS FOR CHARACTERIZATION OF ROADS AND BRIDGES

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Abstract

A variety of remote sensing, surface geophysical, borehole geophysical and other non-destructive methods can be used to determine conditions of roads and bridges. 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.

The benefit of such measurements are that they are: non-destructive, provide in-situ measurements of a wide range of physical properties, sample larger areas or volumes, provide continuous measurements in some cases, and provide faster measurements. All of this results 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 paper provides an overview of those methods that can and have been applied to characterizing conditions of roads and bridges.

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THE GEOLOGIC SITE CHARACTERIZATION PROCESS

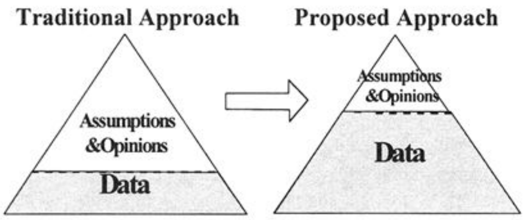

Figure 1. Increasing the data and minimizing assumptions and opinions forms a solid basis for understanding site conditions.

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).

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.

A solid base of appropriate types of data, adequate data and accurate 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.

This paper provides an overview of remote sensing, geophysical, and NDT methods that can and have been applied to characterizing conditions of roads and bridges. While a variety of methods have been listed which can be applied to a wide range of applications, this list of methods is by no means a complete listing.

A Wide Range of Remote Sensing, Geophysical and NDT Methods are Available

Remote sensing, geophysical 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.

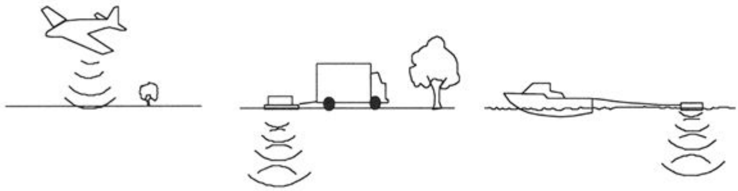

Figure 2. Measurements can be made from the air, surface, and over water.

Satellite data, aerial photography and other airborne geophysical measurements 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.

While surface geophysical methods yield much less spatial coverage per unit time than the airborne methods, they significantly improve resolution (the ability to detect smaller features) while providing subsurface information up to a few 100 feet. 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, core hole in a concrete footing or pile or a well (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. Measurements between boreholes (Figure 3b) provide a means of measuring conditions between two or more boreholes and increasing the volume being measured. Tomographic imaging can also be done between boreholes (Figure

3c). ASTM D5753 provides a brief description of the downhole geophysical methods and their applications.

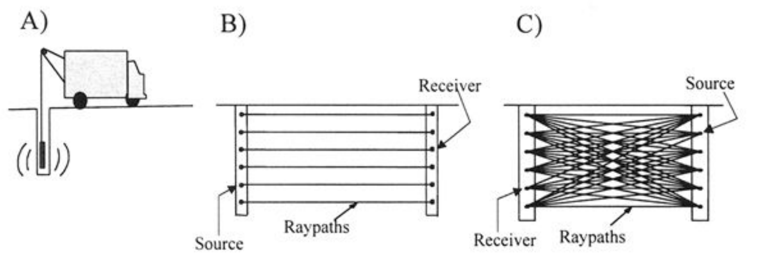

Figure 3. Borehole logging, surface to borehole, hole-to-hole and tomography

Unlike direct sampling, such as obtaining a soil sample and sending it to a laboratory, these methods provide in-situ measurements of some physical, electrical, or chemical property of the soil, rock and pore space fluids or some property of the subbase, asphalt or concrete. Benson (1993) describes the application of geophysical measurements to a number of geologic, hydrologic and environmental problems. Olson (1998) discusses some of the many seismic and sonic tests used in NDT. O'Connor (1999) presents applications for the TDR methods to monitor site stability.

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. The 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).

These Methods can be Applied to a Wide Range of Applications for Roads and Bridges

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 objects and contaminant plumes associated with new right of ways;

- Evaluation of soil and rock properties, and non-destructive testing of man-made structures, and
- Temporal measurements for monitoring conditions and remediation management

The following tables identify a wide range of methods that can be applied to various aspects of site characterization and NDT of roads and bridges. This listing is not intended to be complete, but cites 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.

Mapping Natural Hydrogeologic Conditions

The mapping of natural hydrogeologic conditions is applicable to right of way selection and more specifically to roadway and bridge design and construction. Identifying problems ahead of time we can avoid costly surprises during construction.

Satellite imagery, remote sensing or aerial photo interpretation can establish the regional setting and aid in route selection, identifying direct routes and minimizing cut and fill. Once a route selection has been made, incorporating surface geophysical techniques with geotechnical borings, borehole logging, and hole-to-hole methods along the right of way can effectively provide reliable subsurface information for design and construction (Tables 1, 2 and 3). Whether it is as simple as mapping the top of rock or as complicated as determining the presence of karst features, surface and borehole geophysics can greatly improve spatial sampling and the accuracy of an assessment.

Table 1
Summary of Methods Applied to Right-of-Way Selection

Method	Parameter/Condition Measured
Satellite Imagery	Surface image documentation and terrain interpretation
Aerial Photo Imagery	Surface image documentation and terrain interpretation
Thermal Imagery	Temperature of surface (moisture/seeps/karst)
Video and photos	Surface image documentation

Table 2
Summary of Surface Geophysical Methods Applied to Hydrogeologic Characterization

Method	Parameter/Condition Measured
Ground Penetrating Radar	Dielectric constant (stratigraphy/top of rock/karst)
Electromagnetic	Electrical conductivity (lateral variation in soil and rock/ inorganic contaminants)
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)
Gravity	Density (bedrock channels/karst)
Thermal Imagery	Temperature of surface (moisture/seeps/karst)

Table 3
Summary of Borehole Methods Applied to Hydrogeologic Characterization

Method	Parameter/Condition Measured
Single Hole	
Natural Gamma Logging	Natural gamma radiation (stratigraphy – clays/shales)
Gamma Gamma Logging	Density (stratigraphy/voids/fractures)
Neutron Neutron Logging	Porosity (stratigraphy/permeable zones)
Induction/resistivity Logging	Electrical conductivity /resistivity (stratigraphy/contaminants)
Spontaneous Potential (SP) Logging	Electrochemical and streaming potential (stratigraphy/voids/fractures/flow)
Resistance Logging	Resistance (stratigraphy/voids/fractures/flow)
Caliper Logging	Borehole diameter (voids/cavities)
Temperature Logging	Borehole fluid temperature (groundwater flow)
Conductivity Logging	Borehole fluid electrical conductivity (flow/contaminants)
Flow Logging	Fluid flow within borehole (groundwater flow)
Sonic Logging	P and S shear wave velocity (near borehole)
Borehole Imagery (TV/ATV/BIPS)	Voids and fractures in core holes
Hole-to-Hole	
P-S Wave Measurements	P and S wave velocity (elastic moduli between holes)
Sonic Tomography	Image of conditions between holes
Radar Tomography	Image of conditions between holes

Examples of surface geophysical methods for site characterization include:

- A new 4 lane bridge is being planned to connect South Florida with Key Largo in the Upper Florida Keys. The issue of possible sinkholes affecting the bridge foundation was of concern. Technos carried out a three-phase investigation which defined geologic conditions. Phase I was a reconnaissance investigation intended to see if a problem existed. The work included both surface geophysics as well as aerial photo interpretation included a microgravity survey along 8,000 feet of the project roadway, and a reconnaissance subbottom profiling (seismic reflection on water) over an area of about 200 acres. The results of this work identified an area of concern within the foundation foot print of the high portion of the four lane bridge. Once a problem was identified, a Phase II effort was undertaken to verify and define the limits of the problem. Phase II work included additional microgravity data, along with detailed subbottom profile to develop a contour of dipping strata. In addition, a deep seismic reflection program determined that the depth of the large cave system which had caused the paleo-collapse was about 700 feet. Phase III work included both drilling and core sampling along with geophysical logging. Four 200-foot boreholes were drilled and geophysical logged to confirm findings and assess the stability of deeper conditions. Based upon the seismic reflection data, these borings were located in the worse case active throat of the paleokarst collapse to assess possible karst activity. They showed that open water filled cavities were present below 100 feet. (Benson, et al., 1995a; Benson, et al., 1995b). This work resulted in recommendations for the depth and locations for bridge piers and recommended procedures for detailed geotechnical testing prior to placing each poured bridge piers in the immediate area of concern.

- A site characterization was carried out on a section of I-70 south of Frederick, Maryland to locate and characterized sinkhole prone areas. EM conductivity measurements and microgravity measurements were made along 7,000 feet of I-70. EM measurements were very effective for identifying areas of thicker soil (cutter pinnacle profiles). Microgravity data revealed two areas of substantial (100 to 200 μGals) gravity anomalies. These anomalies are interpreted as cavity zones due to dissolution-enlarged joints and bedding planes within the limestone bedrock resulting in the identification of two high risk zones of subsidence. A few months after completion of the site assessment, a major sinkhole collapse (100 feet in diameter and 60 feet deep) occurred 100 yards south of I-70 within the western zone identified as being highly susceptible to sinkholes (Benson, et al., 1998a; Benson, et al., 1998b).

- A reconnaissance site characterization of karst conditions was carried out over 4.3 miles of Highway 340 in northwest Virginia, within the Shenandoah Valley. Four new bridges and adjacent road ways are to be replaced. The road lies within an area underlain by limestone susceptible to karst development. To provide an initial reconnaissance assessment of karst conditions and their impact on construction, Technos carried out a Phase I reconnaissance survey of the entire 4.3

mile long route. Continuous electromagnetic data were obtained to depths of up to 20 and 50 feet respectively. In addition, resistivity imagery measurements were used to assess subsurface conditions at four new bridge sites. Areas of massive unweathered rock were identified which would provide an excellent base for bridge foundations and roadways. However, 41% of the 4.3 miles were found to have extensive weathering and fractures, which can significantly impact bridge design and road construction. These areas will require further subsurface investigation prior to construction.

Detection and Mapping of Buried Objects and Contaminant Plumes

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 (Table 4). These methods provide a high degree of spatial sampling to ensure that buried objects and environmental concerns are adequately characterized before construction.

Table 4
Summary of Methods Applied to Location of Buried Materials and Contaminants

Method	Parameter/Condition Measured
Ground Penetrating Radar	Dielectric constant (utilities/tanks/debris)
Electromagnetic	Electrical conductivity (utilities/tanks/debris/contaminants)
Resistivity	Electrical resistivity (utilities/tanks/debris/contaminants)
Magnetics	Magnetic susceptibility (ferrous utilities/tanks/drums/metal debris)
Metal Detector	Electrical conductivity of metal (utilities/tanks/metallic debris)

Examples of surface geophysical methods include:

- Phases I and II environmental site assessments had been carried out at a Brownfield site. Extensive review of historical documents, analysis of aerial photographs from the 1940's to the present, and surface observations did not indicate the presence of any subsurface structures (although septic tanks were suspected). Initial soil and groundwater assessment conducted as part of the Phase II investigation did not reveal any significant amounts of contamination. A geophysical survey using EM31 measurements along with ground penetrating radar revealed a number of underground storage tanks, septic tanks, a contaminant plume and other buried debris that were not evident during the Phase I and Phase II investigations. Most of these features would have gone undetected if historical searches and conventional random sampling procedures were the only methods used to assess the property (Kaufmann and Benson, 1999).

Evaluation of Soil and Rock Properties, and Non-Destructive Testing of Structures

Providing an assessment of problem areas in road beds or structures allows the 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 (Tables 5, 6, 7, 8 and 9). While geologic and hydrologic studies often require investigations over many acres or over many line miles, in contrast NDT investigations are usually very localized measurements where the point of measurement is known.

Correlation between a non-destructive method and other engineering measurements are often used to enable the more rapid non-destructive method to be used. For example, seismic P-wave velocity can be measured and used to determine rock rippability and shear wave velocity measurements can be correlated to N (blow counts).

Table 5
Summary of Methods Applied to Monitoring During and After Construction

Method	Parameter/Condition Measured
Nuclear density gauges	Density (attenuation of gamma rays) (shallow in situ density)
TDR	Displacement and/or changes in fluids levels (monitor stability)
Acoustic Emission	Sonic noise due to fluid flow or structural movement (monitor stability)
Thermal Infrared Imagery	Temperature of surface (moisture/seeps)
Ground Penetrating Radar	Dielectric constant (thickness of roadbed)
Seismic Surface Wave Analysis	Seismic velocity/dispersion (S-wave/stratigraphy)
Laser Rugosity	Reflection (Surface roughness of roadbed)
Video	Surface image (documentation of road bed conditions)
Via Boreholes in Drilled Shafts and Slurry Walls	See borehole logging methods in a single hole or between holes (monitor stability)

Examples include:

- The use of a radar survey to identify changes in road construction;
- The use of a nuclear density probe used to measure changes in density of materials to shallow depths.

Table 6
Summary of Methods Applied to Pile Length Determination and Integrity Assessment

Method	Parameter/Condition Measured
Pile Length Determination	
Sonic Impulse (reflection)	P wave Velocity (Length of pile and or discontinuity within the pile)
Magnetometer/Induction Log	Presence of rebar (length of pile)
Sonic (refraction)	P wave velocity (length of pile)
Pile Integrity Assessment	
Sonic Impulse (reflection)	P wave reflection (Discontinuities within the pile)
Cross-hole Sonic Logging	P Wave velocity – (quality and uniformity of concrete)
Sonic Tomography	P wave velocity (tomographic image of quality and uniformity of concrete)
Gamma-gamma (density log)	Density (quality and uniformity of concrete)
Neutron-neutron (porosity log)	Porosity (quality and uniformity of concrete)
Corrosion Potential	Voltage due to galvanic action (areas of rebar corrosion)
Caliper	Diameter of core holes (Voids/fractures)
Borehole Imagery Methods TV/ATV/BIPS	Image of core hole (Voids and fractures)

Examples of pile length determination include:

- A sonic impulse (reflection) measurements to determine the length of a concrete pile;
- The use of a magnetic or induction log run adjacent to the pile in a drilled hole.

An example of pile integrity assessment include:

- A density log run within one or more boreholes within a concrete pile.

Table 7
Summary of Methods Applied to Concrete Structure Integrity Assessment

Method	Parameter/Condition Measured
Rebar Corrosion Potential	Voltage due to galvanic action (areas of rebar corrosion)
Ground Penetrating Radar	Dielectric constant (slab thickness/rebar)
Seismic Surface Wave Analysis	Seismic velocity/dispersion (S-wave velocity/thickness)
Slab impulse respond	Vibration frequency of concrete slab (voids/thickness)
Ultrasonic Velocity	P wave velocity (concrete strength)
P-S Wave Measurements (hole-to-hole)	P and S wave velocity (elastic moduli/integrity))
Borehole Logging with a Density Log	
Borehole Imagery Methods TV/ATV/BIPS	Image of core hole (Voids and fractures intersecting the borehole)
Sonic Tomography	P wave velocity (Image of conditions between boreholes based upon sonic measurements)
Radar Tomography	Radar velocity (Image of conditions between boreholes based upon radar measurements)