Overview

The latest environmental concerns related to contamination from landfills and other disposal sites, along with the need for improved evaluation of the mechanical properties of soils and other geological substrates in civil engineering, have greatly increased the interest in the application of geophysics in geotechnical investigations. Geophysics provides the means to probe the properties of soils, sediments, and rock outcrops without costly excavation. The nonintrusive sampling of geological formations is important because extensive disturbance of these deposits could compromise the integrity of a natural geological migration barrier or foundation site. Moreover, many physical properties of importance in engineering such as density, porosity, permeability, and shear modulus are highly sensitive to in-situ conditions. Relief of overburden stress, shearing, and desiccation associated with sample retrieval can significantly alter the measured properties of sediments. On the other hand, most geophysical methods involve the measurement of physical properties such as acoustic velocity or electrical conductivity that are different from those needed for engineering studies. In the ideal situation, laboratory analysis of a finite number of carefully extracted samples can be used in conjunction with continuous geophysical surveys to produce a two- or three-dimensional map of the area of interest.

More than 25 years ago, ASTM Committee D-18 on Soil and Rock indicated an interest in geophysical methods by including several papers on both borehole and surface geophysical applications in a symposium on Soil Exploration [*1*]. Even earlier (1951), ASTM Committee D-18 sponsored a symposium on Surface and Subsurface Reconnaissance [*2*] in which the subsequent STP contained 8 papers and a panel discussion related to surface geophysics techniques and applications in engineering site investigations.

This present volume presents a series of papers originally given at the ASTM Symposium on Geophysical Methods for Geotechnical Investigations held on 29 June 1989 in St. Louis, Missouri. The papers were selected to provide a broad overview of the latest geophysical techniques being applied to environmental and geotechnical engineering problems. Such geophysical methods have traditionally been divided into those applied at the land surface to generate two-dimensional maps of geophysical properties and those applied in boreholes to generate one-dimensional maps, or "logs," of geophysical properties along the length of the borehole. The two approaches yield complementary results because the geophysical well logs provide much greater spatial resolution (usually on the order of a metre) in comparison with the surface soundings (where resolution is on the order of 10 to 100 m). When surface methods result in soundings plotted as a vertical cross section of the formation, geophysical logs can be used to calibrate the depth scale in the surface-generated data section.

In the latest geophysical technology, the distinction between surface and borehole methods has become somewhat blurred. Borehole-to-borehole and surface-to-borehole soundings are now being used to generate three-dimensional images of the rock volume between boreholes on spatial scales intermediate between those traditionally assigned to either surface geophysics or well logging. We can expect the scale disparities between surface and borehole geophysics to become even more indistinct in the near future. The papers included in this volume are but a sample of the many different kinds of investigations that may soon be used to probe the properties of geological formations on scales ranging all the way from small volumes immediately adjacent to individual boreholes to the entire rock mass containing a potential repository site or building foundation.

Surface Geophysics

Surface geophysical methods provide valuable information in geotechnical studies in the form of horizontal maps of subsurface properties or vertical profiles or "soundings" along sections of interest. The paper by Cummings in this volume gives a broad overview of the various geophysical techniques applicable in studies at hazardous waste sites, but it also serves as a useful sampling of the many techniques available for other applications. Saito et al.'s paper gives an excellent example of the state of the art in application of both seismic and electromagnetic (resistivity) methods to three-dimensional mapping (known in the literature as "tomography") of the properties of a volume of rock and sediment located beneath a proposed bridge foundation.

Both of these papers demonstrate the importance of using different methods for the investigation in that the seismic and electromagnetic methods respond to different properties of geological formations. The seismic methods are closely tied to the compressional and shear velocities, related in turn to rock bulk and shear moduli, whereas the electrical methods are related to the degree of saturation, presence of clay minerals, and quality of saturating fluids. The non-uniqueness associated with the interpretation of any given geophysical investigation is one of the most important issues in geophysical applications. The planning of such investigation almost always prescribes the use of more than one technique or makes provisions for other investigations such as drilling and sampling to calibrate the geophysical interpretation or to verify the assumptions required to implement the interpretation.

Borehole Geophysics

Borehole geophysics or "well logging" was originally developed as a way to apply the techniques of surface sounding to the volume of rock adjacent to the borehold. The log consists of the continuous recording of a specific geophysical measurement such as electrical resistivity or natural radioactivity along the length of the borehole. Although the measurement is almost always related to a physical property of the formation other than those of direct interest to the hydrologist or civil engineer, the log has the advantage of providing a single continuous measurement associated with a uniform depth scale. The advantages of such a reliable depth scale become apparent when compared to a limited set of laboratory tests performed on a few samples recovered during drilling, each a "part" measurement associated with a certain finite depth error. In the ideal situation, the core sample analyses can be used to calibrate the continuous logs in terms of parameters of interest, so that the log is used to generate a vertical profile of the geological formation or the contaminated ground water within the formation. This approach is evidently best suited for locating the edges of plumes, geologic boundaries, or the local maxima or minima of specific properties of interest.

Almost all of the earliest applications of well logging were developed for the petroleum industry. After 1960, there were a number of programs designed to apply the petroleumorientated logging technology to environmental and hydrological studies. A decade later the accelerating interest in environmental issues and radioactive waste disposal prompted interest in designing logging equipment for various specific environmental and engineering applications. The recent proliferation of microprocessors and solid state electronics has further increased the flexibility available in logging for geotechnical applications. Today, geotechnical logging equipment includes sources and transducers designed to measure properties of interest in engineering and hydrology, compensated probe configurations equivalent to the most sophisticated used in the petroleum industry, downhole digitization of geophysical measurements, and uphole processing of log data. All of these trends indicate that in the future geophysical logging will become an important tool in many kinds of geotechnical studies in which logging has not usually been considered relevant in the past.

The papers included in this volume were selected to give a representative cross section of the latest equipment designs and data analysis techniques being made available to the hydrologist and civil engineer. The overview of logging logistics and economics by Crowder provides an instructive introduction into the role of borehole geophysics in environmental studies. One of the most important issues is related to time and efficiency. Complete coring provides a direct sampling of formations, but simple drilling and logging provides most of the information in a fraction of the time and at substantially reduced costs. A carefully thought-out combination of sampling, drilling, and logging clearly has an important role in such studies and may sometimes be the only way in which a study can be completed to meet schedules imposed by legal and operational constraints.

The papers by Jorgensen and Burns describe some of the most recent developments in relating geophysical measurements in boreholes to the specific sediments properties of interest in engineering and hydrology. Burns describes the information that can be derived from the most advanced acoustic logging techniques. Not only are the seismic velocities of sediments directly related to the mechanical properties (dynamic rather than static), but acoustic measurements can sometimes be related to formation permeability. The latest acoustic studies show that new transducer designs may greatly improve the ability to make mechanical property and permeability measurements in situ. The paper by Jorgensen presents a review of the methods which may be used to infer the quality of water present in the formation. In many situations, these methods can be used to produce a qualitative or semi-quantitative profile of contaminant distribution adjacent to the borehole. If additional information is available under the proper circumstances, these qualitative measurements can be turned into estimates of solute content. The interested reader can consult the references listed by these papers, especially the earlier review by Alger [*3*], the case study by Dyck et al. [*4*], or the recent review by Alger and Harrison [*5*].

The papers by Kaneko et al. and Hess and Paillet each present a specific logging tool developed to address geotechnical applications. Hess and Paillet describe a recently developed flowmeter logging system capable of measuring vertical flows in boreholes with much greater resolution than available by means of conventional spinner flowmeters. This device has important applications in identifying the location of inflows and exit flows in boreholes under stressed and unstressed conditions, providing useful information on the source of waters sampled from test wells and on the distribution of permeability in tight or fractured formations. The significance of high-resolution flowmeter data in identifying the movement of water in fractured crystalline rocks is indicated by such studies as Hess [*6*], Paillet et al. [*7*], and Paillet [*8*].

The paper by Kaneko et al. emphasizes the interpretation of the shear modulus of soils in situ by what appears to be standard geophysical logging methods. However, the approach is based on a relatively new transducer design [*9*] developed especially for such engineering applications. This source configuration was but the first of many such applications of acoustic logging with nonaxisymmetric sources [*10,11*]. The paper in this volume indicates the use of these low-frequency shear measurements in boreholes; some of the future applications for this developing method are also mentioned by Burns.

The five papers on borehole geophysics applications in geotechnical studies included in this volume are but a small sample of the proliferating technologies becoming available to modern geoscientists and engineers. Additional information on geotechnical applications of logging can be found in the two recent monographs by Keys [*12*] and Hearst and Nelson [*13*] and in the paper by Keys [*14*]. We hope that these four papers in this volume serve as examples indicating a number of important ways in which borehole geophysics can contribute to geotechnical studies, and that they stimulate the reader to investigate the broader possibilities of geophysical logging in the future.

Contributions made by the authors and technical reviewers are gratefully acknowledged. The editors also express appreciation to the ASTM staff and officers of ASTM Committee D-18 for their assistance and support in organizing and publishing these papers resulting from the symposium.

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