Chapter 1
Introduction

1-1. Purpose

This manual provides an introduction to geophysical exploration for engineering, geological, and environmental (to include Hazardous, Toxic and Radioactive Waste) investigations. Descriptions and guidance are provided for geophysical methods typically used in these investigations. The manual furnishes a broad overview of geophysical applications to common engineering, environmental and geological problems. Descriptions of the most commonly conducted geophysical procedures are given. These contents are not proposed to explicitly develop field procedures and data reduction techniques for geophysical surveys. Chapter 2 develops the procedural evaluation, use, and deployment of the generalized geophysical approach. Subsequent chapters address particular geophysical methodologies.

1-2. Applicability

This manual applies to Headquarters, U.S. Army Corps of Engineers elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for civil works and/or military programs.

1-3. References

References are listed in Appendix A.

1-4. Worker and Environmental Safety

This manual does not purport to address the safety risks associated with geophysical exploration. Geophysical surveys have their own associated hazards, particularly with active energy sources. Some active sources are: shallow explosions for seismic methods; applied electrical current with resistivity methods; and, pulsed electromagnetic fields for ground-penetrating radar. These hazards are addressed regularly by the geophysical survey crew during planning and field deployment. The addition of environmental site hazards (such as unexploded ordnance) may compound the risks of geophysical exploration. Every instance of compounded hazard cannot be uniquely addressed in this manual. Geophysical personnel and the survey customer must have a continuous dialogue and flexible plan to consider and accommodate the aspects of environmental hazards. In addition, that plan should incorporate health and safety practices in accordance with applicable regulations and expert guidance.

1-5. Glossary

Appendix B is a list of terms used in seismic processing and well-logging.

1-6. Proponent

The U.S. Army Corps of Engineers' proponent for this manual is the Geotechnical and Materials Branch, Engineering Division, Directorate of Civil Works (CECW-EG). Any comments or questions regarding the content of this Engineer Manual should be directed to the proponent at the following address.

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Chapter 2
Geophysical Methodology

2-1. Uses of Geophysical Surveys

a. Objectives.

(1) Three classes of objectives are addressed by geophysical surveys: the measurement of geologic features, the in situ determination of engineering properties, and the detection of hidden cultural features. Geologic features may include faults, bedrock lows, discontinuities and voids, and groundwater. Engineering properties that can be determined in situ include elastic moduli, electrical resistivity and, to a lesser degree, magnetic and density properties. Hidden cultural features available for geophysical detection and characterization include buried underground tanks and pipes, contaminant plumes, and landfill boundaries.

(2) Applied geophysics can contribute to the solution of most geotechnical engineering and environmental problems. The geophysical technique does not often directly measure the parameter needed to solve the problem under consideration. Each geophysical procedure measures a contrast. A few problems of interest in engineering may be developed directly from the measured contrast, i.e. finding the resistivity for design of a grounding mat of an electrical power grid. The vast majority of objectives are inferred from the known geologic data and the measured geophysical contrast. Some surveyed contrasts that provide indirect hypotheses are:

(a) Media velocities from seismic methods to determine the top of rock.

(b) Streaming potentials from the self-potential technique to locate a flowing reservoir conduit in a dam abutment.

(c) High conductivities measured with a terrain conductivity meter to locate an inorganic plume on the groundwater surface.

(d) High apparent conductivity assessed with a metal detector which infers a large metallic cache of possibly buried drums.

(e) Low density contrast measured with a gravimeter due to a suspected abandoned shallow coal mine.

b. General observations. Several general observations should be kept in mind when considering applications of geophysical methods.

(1) Resolution, that is the ability of the geophysical measurements to differentiate between two similar geologic situations, varies widely between geophysical methods. Resolution is a function of time and effort expended and may be improved up to a limit, usually far in excess of the resources available to conduct the study. Ambiguity usually indicates a practical limit on geophysical results before the lack of resolution becomes a factor.

(2) Most geophysical methods do not directly measure the parameter desired by the project manager, geologist or engineer. Resistivity and acoustic bursts (for acoustic emissions) are exceptions. The correlation of measured geophysical contrasts with geologic inferences most often is empirical and certainly is dependent on the quality of both the results and the hypotheses. Usually an inverse solution is determined in geophysical exploration. Inversion implies that a cause was inferred from an effect. The physical property, the cause, is inferred from the field survey readings, the effects. Inverse resolutions are not unique conclusions, and provide a most likely solution selected from numerous possibilities. Forward solutions proceed from cause to effect and are unique determinations. Forward analyses are often preliminary evaluations to predict amplitudes and relations from possible physical conditions. Forward solutions may be used subsequent to field surveys to assess hypothesis variants among geologic alternatives.

(3) The interpretation of geophysical contrasts is based on geologic assumptions. Ambiguity is inherent in the geophysical interpretation process. Preparation of geophysical models almost always assumes the following:

(a) Earth materials have distinct subsurface boundaries.

(b) A material is homogeneous (having the same properties throughout).

(c) The unit is isotropic (properties are independent of direction).

These assumptions are, in many cases, at variance with the reality of geologic occurrences. Units may grade from one material type to another with no distinct surface between two materials. At some scale, inhomogeneities exist in practically all units. Properties may occasionally vary greatly in magnitude with direction, such as in shales. Ambiguity, however, can be summarized as an equivalence of geometry/size and a material's properties. Structure may be reevaluated by changing physical parameters. Ambiguity applies to all geophysical methods, and is most conveniently resolved by understanding geologic reality in the interpretation. The extent to which these presumptions are valid or the magnitude that the assumptions are in error will have a direct bearing on the conclusions.

(4) It is important to differentiate between accuracy and precision in geophysical results. Geophysical measurements are very precise. The measurements can be repeated to a remarkable degree on another day, even by another field crew. If accuracy is evaluated as the convergence of the geophysical interpretation with measured geologic data, then geophysical results are not particularly accurate by themselves. However, when appropriate subsurface investigations are integrated with geophysical measurements, large volumes of material can be explored both accurately and cost-effectively.

(5) There is no substitute for specific geologic or engineering observations (such as borings, test pits, trenches, geophysical well logging, and cross-hole tests), because of the empirical correlation between results and the inferred objective solution. These borings or other tests are used to validate and calibrate the geophysical results, and ultimately to improve the accuracy of the integrated conclusions. Except where accuracy considerations are not important, some form of external calibration of the empirical geophysical assumptions is required.

(6) Interpretation is a continuous process throughout geophysical investigations. The adequacy of the field data to achieve the project objectives is interpreted on the spot by the field geophysicists. Data processing, the steps of preparing the field data for geophysical interpretation, often includes judgements and observations based on the experience of the processor. Implementation of a geophysical model, which satisfactorily accounts for the geophysical observations, fits only the narrowest definition of interpretation. Correlation of the geophysical model with available ground truth can be a laborious interpretative process, especially since iterations of both the geophysical models and the geologic model are usually required. Production of the final product in a form useful to the customer (engineer or geologist) is the most necessary interpretative step.

(7) Applied geophysics is only one step in a phased, sequential approach in performing a geologically based task. Any goal requires basic data, a problem statement, investigation of the problem and solution development. Problems in geological, geotechnical or environmental projects require some basic geological information prior to use of geophysical techniques. The determined geophysical contrasts are evaluated and a solution inferred for the likely environment. This hypothesis itself may require geologic assessment with borings or other field exploration. The planning of the phased, sequential solution will provide the best solution at the lowest cost.

c. Geophysical methods. Geophysical methods can be classified as active or passive techniques. Active techniques impart some energy or effect into the earth and measure the earth materials' response. Passive measurements record the strengths of various natural fields which are continuous in existence. Active techniques generally produce more accurate results or more detailed solutions due to the ability to control the size and location of the active source.

(1) There are scores of geophysical techniques which have demonstrated commercial success. In addition, innumerable variations of well-known techniques have been applied in special cases. This manual cites many surface, subsurface, and airborne geophysical methods. The included procedures have been utilized most often or have significant applicability to engineering, environmental, and geologic problems.

(a) Classified by physical effect measured, the following surficial techniques are considered herein:

- Seismic (sonic) methods, Chapter 3.

- Electrical and electromagnetic procedures, Chapter 4, with natural electrical fields (self-potential), resistivity (AC and DC fields), and dielectric constant (radar) theory.

- Gravitational field techniques, Chapter 5.

- Magnetic field methods, Chapter 6.

(b) Geophysical measures can also be applied in the subsurface (Chapter 7) and above the earth's surface (Chapters 8 and 9). Down-hole application of geophysics provides in situ measurements adjacent to the borehole or across the medium to the surface. Subsurface applied geophysics gains detailed insight into the adjoining earth materials. Airborne geophysics is usually not as detailed as surface procedures but offers the distinct advantages of rapid coverage without surface contact.

(c) Vibration theory is considered in Chapter 10. Consideration of earthquake problems, blasting and machine foundations, acoustic emission theory, and non-destructive testing are sections of Chapter 10. These topics are unified under vibration theory, but are accomplished by differing program approaches.

(2) The number of geologic issues considered are limited to the problems most commonly encountered in an engineering or environmental context, since the number of geologic problems is vastly larger than the number of geophysical methods. The accompanying matrix of Table 2-1 displays the cited methods versus the problem types, and evaluates the applicability of the method. One cannot rely blindly on the applicability of this table, because geology is the most important ingredient of the selection of method. This matrix will suggest potential geophysical techniques for particular needs. Geologic input, rock property estimates, modeling, interference effects, and budgetary constraints are co-determining factors of method selection. In an attempt to reduce the impact of geology, the evaluation assumes that a moderate degree of geologic knowledge is known before the matrix is consulted.

d. Contracting considerations. Most geophysical work is done by geophysical contractors. Even in-house work is usually done by specialists and the following discussion applies to internal, as well as external, contracting.

(1) The most important part of the contracting process is the preparation of a set of written objectives. The primary pitfall is the tendency of geophysicists to focus on what can be measured, and not on the needs of the customer. If siting monitoring wells on bedrock lows is the objective, detailed bedrock lithology is probably unimportant. The action of writing down the explicit desired final results will often radically change the approach to the problem.

(2) The scope of work also requires a common understanding between contractor and purchaser. However, undue restrictions in the scope of work may prevent an alteration of parameters, quantities, techniques, or methods. Such alterations are common on geophysical projects. Because of the close cooperation required between the customer and the producer, daily reports (including preliminary results) are almost always required.

(3) Less important, but critical factors subject to negotiation, are: standby time, inclement weather payments, contents of field reports, liability, terms of payment, rights-of entry, responsibility for locating underground utilities, deadlines, and rates. Geophysical daily rates are usually straightforward. The productivity of field crews, however, is dependent on some or all of the following factors: terrain, vegetation, hazardous waste, insects and other biohazards, weather (particularly season), logistics, commute time or access to the field location, third-party observers, experience and resourcefulness of field crew, and interference with geophysical measurements (noise, often related to industrial or urban location).

(4) The geophysicist(s) must have access to all relevant information concerning the site. This data includes: site geology, site maps, boring logs, sources and contaminant types that are known or presumed, hazards and safety conditions impacting field work, etc. The development of field work and the hypotheses from the processed geophysical material depend upon validation of the known conditions. Field safety and hazard avoidance may only occur when the field crew has knowledge of all field conditions. Significant liability reverts to the government when all known information is not shared with the geophysical crew.

(5) A site visit is recommended and should be undertaken by an experienced estimator of geophysical costs. Many geophysical contracts are let on a line-mile, per-station, or lump-sum basis. However, if the common objective is neither the bankruptcy of the contractor nor the overcharging of the customer, usually a method can be found to “share the misery” on difficult projects. There is no substitute for experience and trust to supplement written documents purporting to cover all eventualities.

(6) A field-release clause may be a useful vehicle for both the customer and the geophysical contractor. This clause allows contract termination, if the contractor’s ability to assess the objective after a short field evaluation is unlikely. Careful scrutiny of the field results near a ground truth area allows the contract to be site-justified, the objective revised, or the contract to be ended. The contract is modified by the consequences of the field-release evaluation.

Table 2-1
Decision Matrix of Surficial Geophysical Methods for Specific Investigations

	Lithology	Top of Bedrock	Rippability	Detection of Water Surface	Fault Detection	Suspected Voids or Cavity Detection	In Situ Elastic Moduli (Velocities)	Material Boundaries, Dip, ...	Linear Subsurface Water Conduits	Landfill Boundaries	Large Ferrous Bodies-Tanks	Conductive Bodies, Ores, Plumes, ...
Seismic Refraction	S	W	W	S	S		W	S				
Seismic Reflection	S	S	S		S	S		W				
SP									W			S
DC Resistivity	S	S		S	S	S		S		W	S	S
Electro-Magnetics					S			S	W	S	S	W
Ground Penetrating Radar		S		S	S	S		S	S	S	S	
Gravity					S	S		S				
Magnetics					S					W	W	

W - works well in most materials and natural configurations.
S - works under special circumstances of favorable materials or configurations.
Blank - not recommended.

(7) Effectively written contracts provide the clear objective of the geophysical work and the minimum reporting requirements.

2-2. Responsibilities of the Project Team

The objective of any investigation is maintained by exchange of information between the customer and the geophysical contractor. The customer directs the inquiry, but is rarely a specialist in the application of particular procedures.

a. Interdisciplinary team. Geophysical exploration is a highly specialized field. Few geophysicists are equally adept at all facets of geophysics. The project manager, the technical specialist (usually an engineer or geologist), and the geophysicist(s) form an interdisciplinary team to meet the objective.

b. Stated objective. The project manager is required to have a known and written objective. The technical specialist correlates the site information and identifies tasks to be completed to reach project goals. Engineering and geologic requirements are evaluated by the specialist and the role of geophysics in satisfying those requirements in detail. A phased approach including preliminary geologic investigations, geophysical contracting, and final engineering evaluation is developed. The geophysical contractor accomplishes the objective established by the manager, as developed from phased site information directed by the specialist.

c. Geophysical sequence. The geophysical exploration should be considered early in the development of site characterization. Monetary and time efficiency will be greatest when the geophysical surveys are part of a phased program, especially at large and/or geologically complex sites. Early geophysical exploration allows some subsequent geologic, engineering, or environmental verification. Problems studied late in the field assessment may have little funding for their resolution remaining in budgets to perform necessary work. Further, there will be little advantage from geophysics performed late in exploration programs, as compared to early geophysical application where subsequent investigations may be revised in location and detail.