CONTRACTING FOR GEOPHYSICAL SERVICES

Gregory L. Hempen*, PhD, PE, RG, and David L. Butler^, DSc, RGp

*U.S. Army, Corps of Engineers, St. Louis District,
St. Louis, MO; hempen@mvs02.usace.army.mil
^MicroGeophysics Corporation,
Wheat Ridge, CO; microgeo@aol.com

OVERVIEW

Geophysical exploration is an art that may be applied to site investigations for the benefit of engineers' or geologists' understanding of the site. Geophysics is a specialized field that requires an interpreter with some skill and adequate capabilities. The goal of geophysical contracting should be to obtain the desired objective(s) with an experienced contractor during an early exploration cycle. The type and details of the geophysical contract will have an important impact upon the study's quality. A project team best accomplishes the integration of geologic hypotheses, available geophysical methods, and budgetary constraints early in the exploration cycle. The correlation of myriad geophysical methods and innumerable geologic problems requires site knowledge, interdisciplinary cooperation, contract resolution, and geophysical experience. Geophysics is a cost-effective tool for evaluating large areas and/or complex sites.

INTRODUCTION

Geophysical input can occur at various times in a project cycle. Contracting for geophysical services requires effective management based on decisions by a project team and a phased investigation to achieve cost-effective results. The team requires a clear engineering objective, current site knowledge, and cost motivation to use geophysics to determine geological hypotheses.

This paper is a reformating and revision of two other documents. Reference is not made to the particular document citation. Large direct excerpts may have been used unmodified. The first document from which large excerpts are taken is Chapter 2, Geophysical Exploration for Engineering and Environmental Investigations, EM 1110-2-1806 (USACE, 1995). The second document is Geophysical Methods for Hazardous Waste Site Characterization, Course Notes (Hempen & Hatheway, 1992). Both documents are valuable in their entirety and may be obtained from the references.

USES OF GEOPHYSICAL SURVEYS

Objectives addressed by geophysical surveys include: the verification of geologic features, the in situ determination of engineering properties, the detection of hidden cultural features, and regulatory compliance. Geologic features may include bedrock properties (topography, discontinuities, and voids), soil stratigraphy, and ground water. 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 detected by geophysics comprise buried underground tanks and pipes, contaminant plumes, and landfill boundaries. In the regulatory arena, "best available technology" or "best effort" arguments may resolve severe geologic conditions or environmental problems.

Often geophysical techniques do not directly measure the parameter needed to solve the problem under consideration. Geophysical procedures measure <u>contrasts in physical properties</u>. Some engineering problems may be answered directly from the measurements, i.e. finding the resistivity for design of a grounding mat of an electrical power grid. However the vast majority of objectives are inferred from the measured geophysical contrast and the known geologic data. Some example contrasts that provide geologic answers are:

- Top of rock determined from a contrast in seismic velocities between formations;
- Permeable zones in a dam abutment determined by a change in streaming potentials measured by the self-potential technique;

- Inorganic plume location determined by high conductivities measured with a terrain conductivity meter;
- Buried drums or other metallic objects determined by the high apparent conductivity or change in magnetic field assessed with a metal detector or magnetometer; and,
- Voids due to karst or abandoned shallow coal mines determined by gravity measurements.

General observations

The application of geophysical methods should consider resolution, ambiguity and geologic inference.

Resolution is the ability of the geophysical measurements to differentiate between two similar geologic situations and varies widely between geophysical methods. Resolution is a function of effort expended and is capable of being improved far in excess of the resources available. Ambiguity is a property of the mathematical physics of geophysical method wherein even "quality" geophysical measurements can be accounted by several physical models. Additional geologic information is required to choose between the two (or more) calculated models. Geologic interference is the geologic variability to the extent that it is either difficult to measure the contrast in detail or unlikely to be defined by the assessment.

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 under special conditions. The correlation of geophysical contrasts with geologic inferences most often is empirical and is dependent on the quality of both the geophysical results and the geologic hypotheses.

Usually an "inverse" solution is determined in geophysical interpretation. Inversion implies that a cause was inferred from an effect. The physical, property contrast (the cause) is inferred from the field measurements (the effect). Inverse solutions are not unique conclusions, and provide only a most likely solution selected from numerous possibilities.

Forward solutions proceed from cause to effect and are unique determinations. Forward analyses are done as preliminary evaluations to predict the amplitude of the field measurements from a possible set of geologic conditions and physical contrasts. Forward solutions may be used subsequent to field surveys to assess hypothesis variants among geologic alternatives or where an inverse solution is not possible using current algorithms.

The interpretation of geophysical contrasts is based on geologic assumptions. Ambiguity is a prime consideration in geophysical interpretation. Preparation of geophysical models usually assumes the following.

- Earth materials have distinct subsurface boundaries.
- Each material or formation is homogeneous (having the same properties throughout).
- Each 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 boundary 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 conclusions will be impact by either the extent to which these assumptions are valid or the assessed condition’s error is sizeable varying from the expected contrast.

It is important to differentiate between accuracy and precision in geophysical results. Geophysical measurements are very precise. Even another field crew can repeat the measurements to a remarkable degree on different day. If accuracy is evaluated as the convergence of the geophysical interpretation with known 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.

There is no substitute for specific geologic or engineering observations (such as borings, test pits, trenches, geophysical well logging, and cross-hole tests). Empirical correlation between results and the inferred objective solution are required. 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 minimal, some form of external calibration of the empirical geophysical assumptions is required.

Production of the final product in a form useful to the customer (engineer or geologist) is the most essential interpretative step. 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. Inversion of geophysical data to produce 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 because iterations of both the geophysical models and the understood geology are usually required.

Applied geophysics is only one step in a phased, sequential approach to completing 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 the proper use of geophysical techniques. The presumed 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 a phased, sequential program will provide the best solution at the lowest cost.

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 that exist continuously. 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.

There are scores of geophysical techniques that have demonstrated commercial success. In addition, innumerable variations of well-known techniques have been applied in special cases. Procedures that have been utilized most often or have significant applicability to engineering, environmental, and geologic problems are:

- Seismic (sonic) methods,
- Electrical and electromagnetic procedures, with natural electrical fields (self-potential), resistivity (AC and DC fields), and dielectric constant (radar) measurements,
- Gravitational field techniques, and
- Magnetic field methods.

Geophysical measures can also be applied in the subsurface, on the surface (including marine), and above the earth's surface. Down-hole application of geophysics provides in situ measurements adjacent to the borehole or between holes or from the borehole to the surface. Subsurface geophysics yields detailed insight into the nearby earth materials. Airborne geophysics is usually not as detailed as surface procedures, but offers the distinct advantages of rapid coverage without surface contact.

The number of geologic problems is vastly larger than the number of geophysical methods. Geologic input, rock property estimates, modeling, interference effects, and budgetary constraints are co-determining factors of method selection. To reduce the impact of unexpected variations in geology, a moderate degree of geologic knowledge is necessary to determine the appropriate geophysical method. The field operator should be allowed to revise the method or incorporate other geophysical methods for cause.

CONTRACTING ISSUES

Geophysical contractors conduct most geophysical work. Geophysical specialists may provide in-house work. The following discussion applies to internal, as well as external, contracting.

The most important part of the contracting process is the preparation of a set of written objectives. The primary pitfall may be focusing on what can be directly measured, and not on the needs of the customer. [If determination of gross cuts and fills for differing alignments are the objective, detailed bedrock velocities may not be of interest to the customer.] The action of writing down the explicit, final requirements may radically change the approach to the problem.

The scope of work also requires a common understanding between the geophysical contractor and the customer. Undue restrictions in the scope of work may prevent an alteration of parameters, quantities, techniques, or methods. Such alterations are common on geophysical projects. Daily field reports (including preliminary results) should be required to encourage close cooperation between the customer and the interpreter.

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, et cetera. Fieldwork progress and assumptions' validation are based on the geophysical material developed daily. Field safety and hazard avoidance may only occur when the field crew has knowledge of all field conditions. Significant liability, both for field safety and reaching the objective, reverts to the customer, when all known information is not shared with the geophysical crew.

Contract development

Effectively written contracts provide the clear objective of the geophysical work and the minimum reporting requirements. The contract should not allow changing the originally proposed geophysical firm by a main (or intermediary) contractor without the expressed consent of both the customer and the original company. Likewise, bid costs should not be revised without the expressed consent of both the customer and the original geophysical firm.

Contracting for geophysical work may be a two-step process. Evaluation of the objective and possible geophysical method(s) to meet the objective (first step) should proceed the contracting for the work (second step).

Low-bid specifications will normally be difficult to create a uniform presentation for bid comparison. There is no difficulty in conducting low-bid contracting when both the geophysical duties (i.e., one-half mile of seismic reflection survey with specified minimum survey requirements) may be established, and the geophysical contractor's interpretation experience is not pertinent (only acquiring field data for processing by the customer). The bid proposals will be difficult to appraise by cost alone. The skill and capacity of a geophysical contractor to meet the objective may be left unresolved. [Engineers should consider whether they would allow an analogous situation of a complex design-build by a low-bid contract.] Some bidding submissions will be only for the exact work specified with a predetermined evaluation of fieldwork and interpretation. Either the customer or contractor will not receive the full benefit of the bid cost. The customer will likely receive a less complete objective than could be resolved with better coordination, or fuller appraisal of anomalies or reassessment of the interpretation following added site investigations. On the other hand, the geophysical contractor may provide added services without assurance of compensation.

Requests for proposal (RFP) may be a proper vehicle when the project team has the talent to evaluate the proposals. RFP offerings may lead to more problems than choosing a skillful, geophysical contractor. Ineffective RFPs include those that: specify payment and more than objective; require a particular geophysical method with no latitude for a complementary or alternative method; provide insufficient requirements to compare proposals; and/or, do not allow for modification to the advantage of both the customer and contractor. RFP payment is usually not offered for bid preparation, site visits, and survey design. As none of these processes are free, the customer should consider some reimbursement after the negotiation for those proposals not accepted.

An alternative to the bid and RFP approaches would be for the project team to develop the contract with a preselected geophysical contractor. This team approach allows the assumption of risk and cost by the team. The risk and cost are not solely borne by the customer nor the main contractor nor the geophysical contractor. The team approach quickly moves to resolving the true objective and its presentation, and does not usually dwell on the geophysical method(s) and their interpretation. The method and interpretation are important in negotiating contract cost.

Considerations for contract inclusion

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. Better contracts may provide compensation for several tasks, including iterative interpretation after added geologic information (at or near anamolies) is obtained. There is no substitute for experience and trust to supplement written documents purporting to cover all eventualities. 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.

Less important, but critical, factors subject to negotiation, are: standby time, likely interpretation requirements, contents of field reports, liability, terms of payment, rights of entry, responsibility for locating underground utilities, deadlines, inclement weather stand-by costs, 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), personal protective equipment, logistics, commute time or access to the field location, third-party observers, experience and resourcefulness of the field crew, and interference with geophysical measurements (noise often related to industrial or urban location).

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 assessment of actual field conditions and validity of geological hypotheses does not justify continuation after a short field evaluation. 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.

The geophysical contractor's report should be required specifically to contain:

- An executive summary with the contract's objective(s) and generalized interpretation,
- Purpose and scope of the investigation,
- Dates and location (index map) of the investigation,
- Personnel and organizations involved,
- Amount and type of data collected,
- Quality (reliability) of data collected,
- Methods of investigation/equipment employed,
- Methods of analyses and interpretations,
- Geologic calibration analyses – verification of, or departure from, site conditions,
- Interpretation in a form useful to the customer,
- Summary and recommendations, and
- Appendix of field data and notes with either originals or usable copy.

RESPONSIBILITIES OF THE PROJECT TEAM

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

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

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 is specified in detail. A phased approach should develop preliminary geologic investigations, geophysical contracting, and final engineering evaluation. The geophysical contractor accomplishes the objective established by the manager, as developed from phased site information directed by the specialist.

Geophysical sequence with other work

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 not have the resources available for solution. Further, the advantage of geophysical information developed late in an exploration program, as compared to data obtained earlier, will be smaller than when subsequent investigations may be revised in location and detail. Often subsequent field investigations will be necessary after the geophysical deployment. Additional geophysical interpretation may be warranted based on the added geologic investigations without more field geophysical exploration.

SUMMARY

The goal of geophysical contracting should be to obtain the desired objective(s) with an experienced contractor during an early exploration cycle. Contracting recommendations have been provided to achieve a quality product. A project team best accomplishes the integration of geologic hypotheses, available geophysical methods, and budgetary constraints early in the exploration cycle. The correlation of myriad geophysical methods and innumerable geologic problems requires site knowledge, interdisciplinary cooperation, contract resolution, and geophysical experience. Geophysics is a cost-effective tool for evaluating large areas and/or complex sites.

ACKNOWLEDGEMENTS

This paper is a reformating and revision of two other documents. The authors appreciate the publication of both documents by the Association of Engineering Geologists and USACE. Neither organization is responsible for the views contained in this paper. Individual reference has not been made to the particular document citation. Large direct excerpts may have been used without quotation. The referencing and excerpts were judged to have made readability difficult. The revisions and modifications are no reflection on the documents (Hempen & Hatheway, 1992, nor USACE, 1995) nor on the organizations.

Revisions to the two texts were made for the reader. There is no implication that either Hempen & Hatheway (1992) or USACE (1995) requires revision to be complete. Hempen was the author of both documents' excerpts (Hempen & Hatheway, 1992, and USACE, 1995). As the author, the source may be used in other documents with appropriate citation. Hempen was the author of Chapter 2 (USACE, 1995) and edited the document for the Corps of Engineers. Butler reviewed Chapter 2 (USACE, 1995) and wrote other sections. The second document is Geophysical Methods for Hazardous Waste Site Characterization, Course Notes (Hempen & Hatheway, 1992).

REFERENCES

Hempen, G.L. and Hatheway, A.W., 1992, Geophysical Methods for Hazardous Waste Site Characterization, Course Notes, Special Publication No. 3, Association of Engineering Geologists, 54 p.

U.S. Army, Corps of Engineers (USACE), 1995, Geophysical Exploration for Engineering and Environmental Investigations, EM 1110-2-1806, Chapter 2.