QA/QC and Geophysical Projects

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ABSTRACT
This paper will examine quality assurance (QA) and quality control (QC) for geophysical projects. Model methods for QA and QC will be examined, and ways to adapt the model methods to geophysical projects will be addressed.

Familiarity with the application of geophysical methods to environmental and geotechnical projects is increasing. However, the selection of methods and acquisition parameters is highly variable. Even among geophysical service provider companies, there is variability with respect to the application of geophysics to similar projects. Confounding both the casual and experienced users is the underlying question about the probable usability of the acquired geophysical data. Therefore, fundamental QA and QC roles and some example procedures will be presented and discussed herein in an effort to illustrate these issues.

Introduction
As often noted, QA and QC are key aspects of many projects. However, few of us have stopped to contemplate just what these aspects are or how they can be used or misused on a project. A Google™ search for "Quality Control" yields 606 million citations. A similar search for "Quality Assurance" yields 155 million citations. If we add "geophysics" to the search, we find 325,000 and 469,000 citations, respectively. Yet, an examination of many referenced citations yields few useful pieces of information about what QA and QC are for geophysics projects. The internet information suggests that while a lot of people talk about QA and QC, there is really very little written about it in a fashion that provides specific guidance to potential users of geophysics. This paper will explore some of the common "philosophical" approaches, as well as provide examples of QA and QC considerations that can lay the foundation for the development of a useful and implementable geophysical QA/QC program.

Being responsible for a diverse program of geophysical services for a national company provides many challenges in terms of ensuring useful geophysical data are collected in a usable fashion. QA and QC are important aspects of this work because no degree of data processing or interpretative insight can compensate for poor quality data or for poor data management. Therefore, the objective of QA and QC is establishing a means for consistently acquiring good data. For geophysics, good data are necessary for good interpretations.

Part of the services provided by our diverse geophysical staff includes detection of unexploded ordnance (UXO). In the spring of 1999, Jeff Gamey of the Oak Ridge National Laboratory and Bob Selfridge of the U.S. Army Corps of Engineers in Huntsville served as Government observers for a field demonstration of geophysical capabilities. Although approximately 50 companies entered a competition for a contract, the selection committee was now considering only four teams. The team that could demonstrate the best ability to detect ordnance and minimize the amount of misidentified clutter items (noise) selected for excavation would go home with a $50M contract. As later reported, Gamey and Selfridge were amazed by the number of misidentifications introduced by operator error. If this group of four finalists represented the best of the best, imagine the challenges faced by new companies entering the emerging geophysical UXO marketplace. That day, Gamey and Selfridge decided to record all of the painful lessons learned throughout their careers and to document them. "Additional Errors Observed" became the backbone of the Ordnance and Explosives Digital Geophysical Mapping Guidance-Operational Procedures and Quality Control Manual (DGM QC Manual) prepared for the U.S. Army Engineering and Support Center, Huntsville (NAEVA, 2003). While focused on UXO and the limited geophysical methods used for this application, the lessons put forward are equally applicable to other geophysical applications.

The DGM QC Manual went a step further than most. This manual provides concrete steps in defining geophysical QA and QC. Specific steps in these processes are described for several geophysical methods as applied to UXO. However, the overall lessons for QC, as well as some of the specificity in terms of QC steps, go well beyond just the methods commonly utilized in the arena of UXO or even geophysics.

It is the purpose of this paper to lay some groundwork for the development of geophysical QA and QC steps that will be useful and adaptable for any geophysical program.

Definitions

A good reference for the definition of QA and QC comes from a United States Environmental Protection Agency (USEPA) document "Quality Assurance Guidance for Conducting Brownfields Site Assessments" (USEPA, 1998). **Quality Assurance is** an integrated system of management activities involving planning, implementation, assessment, reporting and quality improvement to ensure that a process, system, or service is of the type and quality needed and expected. **Quality Control is** the overall system of technical activities (including checks on sampling and analysis) that measure the performance of a process against defined standards to verify that they meet predefined requirements.

When one looks at the definitions, the answers at first seem obvious. However, when one sits down and begins to write that these are for implementation on a geophysical project or geophysical program, the answers and choices become daunting.

Geophysical QA

A written plan is often a cornerstone for technical projects. The plan identifies how one will get to the answers desired. For geophysics, a quality assurance plan identifies the framework of steps that will result in quality deliverables. The QA plan is a "management tool" based on the premise that the presentation of quality geophysical data is an important aspect of doing business. To be most effective, a QA plan is written and agreed to by managers responsible for quality geophysical data.

One of the most basic QA procedures is highlighted in a number of American Society for Testing and Materials (ASTM) geophysical standards. When referencing QA, there is a common notation "to provide quality assurance of the ... work, it is generally a good practice to have the entire work, including the report, reviewed by a person who is knowledgeable with the method and the site geology, but not directly involved with the project."

Geophysical customers must decide if they want to employ a rigorous QA process. There is a cost for developing the management tool for QA; there is a cost for peer reviewing draft reports, etc. Therefore, geophysical customers need to decide if they are willing to pay the cost of a QA program, or if they would prefer to accept the inherent risks of proceeding without rigorous QA.

An example of the costs can be demonstrated by considering the papers presented at this conference. The steering committee chose to have all papers for this conference peer reviewed. The decision to employ a peer review process is a QA step designed to ensure that a reasonable level of information is provided within each paper and that information provided is based on sound science. The "cost" is that the authors had to prepare their papers earlier to permit time for the peer review process. Blessed with contributions from our peer reviewers, we were able to provide a QA service for the conference. However, in the commercial world, the peer reviewer is often expecting a paycheck for his or her services, and that is a cost that is directly related to the project.

Consistent with the USEPA definition provided above, geophysical data and information acquired through the auspices of a QA program must come from an organization which is willing to assess the geophysical information and make quality improvements to the approaches used on an "as-needed" basis. This means not just having a second set of eyes scan the incoming data or draft report, but a commitment to look at, and look for, ways to improve the geophysical process. This requires a commitment to learn lessons and continuously improve the process. There is an additional commitment of time and effort to ensure employees are working with the improved procedures.

The QA process includes commitments to equipment maintenance and upgrades, as well as commitment to software, computers, and process improvements. It can include a commitment to employee training and education. QA can be a commitment to look for changes and improvements that will provide not only a cost-competitive advantage, but also a more technically sound and reliable product. For a company providing geophysical services, company management and client commitment to QA begin with these commitments. However, for geophysics, implementation is in QC.

Assessment of Existing Approaches

Within the Federal Highway Administration (FHWA), there is limited guidance regarding QA and QC. Within the Geotechnical Engineering Circular No. 5, "Evaluation of Soil and Rock Properties" (Sabatini et al, 2002), subsurface investigation is intermixed with laboratory testing programs. This is a reasonable place to begin, since most geophysical services provided to highway and transportation projects relate to geotechnical engineering. For planning subsurface investigation and laboratory testing programs, this document guides the engineer to be aware of parameters and properties needed for design and construction, as well as to understand the geologic conditions and site access restrictions. Specific steps include the following: (1) identify data needs; (2) gather and analyze existing information; (3) develop a preliminary site model; (4) develop and conduct a site investigation; and (5) develop and conduct a laboratory testing program.

As one considers the five steps, the rationale seems appropriate. However, implementation becomes challenging from the geophysical perspective. The first step of an investigation and testing program requires that the engineer develop the data needs by understanding the project requirements and the site conditions and/or restrictions. The ultimate goal of this phase is to identify geotechnical data needs for the project and potential methods available to assess these needs. During this first step, it is necessary for the engineer to:

1. Identify design and constructability requirements (e.g., provide a grade separation, transfer loads from bridge superstructure, provide for a dry excavation);
2. Identify performance criteria (e.g., limiting settlements, right-of-way restrictions, proximity of adjacent structures) and schedule constraints;
3. Identify areas of concern on-site and potential variability of local geology;
4. Develop likely sequence and phases of construction;
5. Identify engineering analyses to be performed (e.g., bearing capacity, settlement);
6. Identify engineering properties and parameters required for these analyses;
7. Evaluate methods to obtain parameters and assess the validity of such methods for the material type and construction methods; and
8. Evaluate number of tests/samples needed and appropriate locations for them.

Associating these recommended steps with geophysics could be a challenge. Working through these eight considerations and similar points for the additional four steps results in an unnecessarily complex sequence to develop what should be a straightforward solution. On the surface, the approach outlined becomes more challenging than the resulting quality improvements. The description is a process, with few concrete examples, steps, or activities that lend themselves to geophysical surveys. Therefore, an easier approach may be appropriate.

Following the USEPA a bit and going beyond definitions, one finds an advocacy of the data quality objectives (DQO) process, which has the following seven “common sense” steps. The seven steps include:

1. Statement of the problem: What is the purpose of the project?
2. Identify the decision(s): What are the available options under consideration?
3. Identify inputs in the decision(s): What information is needed to make informed, defensible decisions?
4. Define the boundaries of the study: What are the geographical extent, time, and budget constraints for the project?
5. Develop a Decision Rule: Formulate “if..then” statements that relate the data to the decision they support.

6 Specify Limits on Decision Errors: Estimate how much uncertainty will be tolerated in the site decision(s).
7 Optimize the Design: Identify the most cost-effective means to gather the data needed. If obstacles exist, reassess all the steps of the DQO process to refine decisions and goals until a workable roadmap or decision tree is produced.

Outfall of the DQO process is a quality assurance project plan (QAPP), which documents the planning process and describes necessary QA and QC steps for the project. A QAPP represents a very formalized process for what many professionals do while implementing their trade. The development of the DQO process is a QA procedure developed by the USEPA for use on projects with which they are involved.

DQO process is intended to define number and types of samples to be collected and to assess the detection limits and certainty. This is done to establish methods and instruments that can be selected to develop the most cost-effective sampling design that will meet the project objectives. This is also the area where most people fail to perform effectively and efficiently. This is generally due to a lack of familiarity with the variety of methods, detection limits, and uncertainty available today. Trying to adjust the DQO steps for geophysics becomes the challenge.

Step 1-Statement of the problem. The statement can be quite simple. What do you want to know from the geophysical investigation? If the presence of pinnacled bedrock and potential sinkhole areas is of concern, this needs to be identified. If the presence of caves or mines is a concern, identify them as the problem. If the road base is suspect, then this needs identification.

Step 2-What are the available options? For a geophysical investigation, the choices are typically the choice of geophysical methods. The ASTM guide to selecting surface geophysical methods and the individual geophysical standards (Hoover, 2005) provide an overview of geophysical methods from which to choose. A USEPA expert advisor (Olhoeft, 1992) provides another means of identifying geophysical methods for those who are not geophysicists. This step is not intended to focus on acquisition parameters for a geophysical method, but rather provide an assessment of various geophysical methods that can or should be considered for a particular project.

Step 3-What information is needed to make an informed defensible decision? This becomes a two-part step. Site features become important at this stage as site features can impede some geophysical methods. The presence of a high-voltage transmission line will impede electromagnetic methods. Reinforced concrete and metal guide rails will eliminate magnetometer use as a consideration.

The second consideration involves the methods being evaluated and the resolution that can be provided by that method. Building upon Step 1, the size and depth of features of concern become relevant. A 3-foot-high void (or cave) is potentially more critical at 5 feet below grade than that same void at 50 feet. Likewise, the methods that can resolve the three-foot void at these two depths likely require radically different geophysical approaches.

Step 4-Define the boundaries of the study. Several things are important geophysically. Three critical pieces of information must be present for selection of geophysical methods. These include the following: (1) size of the area to be assessed; (2) geologic and soil conditions to be considered; and (3) interferences to be mitigated.

Step 5-Develop "if…then" rules. This represents a challenge but should be doable for many sites where there are unknown aspects of the project.

Step 6-Specification of error limits is an assessment of uncertainty. Uncertainty, the chance of drawing an incorrect conclusion, is a challenge for many geophysical methods. A single value may represent a number of geological conditions. Intertwined with this issue is the resolution of individual geophysical methods. If one were to consider ground-penetrating radar (GPR), then challenges related to resolution and penetration depth become more obvious. Using a 1,500 megahertz (MHz) antenna, we can see a feature that is inches in size; however, the penetration of this radar antenna is 12 to 18 inches. On the other hand, if we use a 100 MHz antenna, we can only see a feature whose thickness is several feet thick at depths of 20 to 50 feet.

This aspect can be taken one step further, beyond evaluating the variety of tools available, to assessing how a tool is used. If a frequency domain electromagnetic survey is undertaken using an EM61, a common tool for locating buried metallic objects such as utilities, noise can be an issue. The noise is frequently related to the antenna's bounding when a rough ground surface is encountered. If the project was competitively bid, then the faster data can be collected, the lower the cost. However, the faster the antenna is moved across the ground, the higher the noise level. There reaches a point when the noise level can exceed the threshold of detecting the buried metallic material. A QA step may require the identification of this limit; the QC step is to slow down to keep the noise level below the threshold of detection for the feature that is being investigated.

In practice, the USEPA approach begins to be cumbersome for geophysical projects, and other approaches are necessary. A similar assessment can be made for the U.S. Army Corps of Engineers, which uses the Technical Project Planning (TPP) process to develop similar information. Unfortunately (with the exception of the USACE/DGM QC manual), limitations in applicability exist in most common reference documents. There are very few references with good or adequate guidance for geophysical QC. Therefore, a new approach focused on geophysics projects requires consideration.

Recommended Approach for Consideration

All QC procedures reviewed and assessed in preparing this paper include three common themes. Themes require that a) reasonable guidelines be developed, b) guidelines be written and c) guidelines be followed. Given the nature of geophysical projects, there are four broad components of geophysical work that should be considered as specific QC steps are developed. Specific QC steps include (1) planning, (2) field collection of data, (3) data processing, and (4) interpretation. General QC procedures in essence require the QC steps to be written and followed and appropriate documentation of the work be made.

A geophysical quality control program should ensure data are optimally acquired in the field; artifacts are not introduced during processing; and the information prepared for interpretation correlates with geologic, hydrogeologic, or man-made features related to the survey objective. For the good geophysicist, the steps described below may seem simple, trivial, or just plain common sense. In reality, not every practitioner is a good geophysicist. Therefore, a good QC plan reflects the procedures that a good geophysicist, using common sense, would apply given the same level of experience, project, and objectives.

Planning QC

QC planning is a documentation of the field procedures, data processing, and interpretation methods that will be used for a survey. The method of processing and interpretation will often dictate the field procedures. Conversely, the site conditions and field procedures may limit the planned processing and method of interpretation. These can be established based upon a piece of equipment or a common application. Standard operating procedures can establish the basis of this approach for equipment, but all standards must be prepared to conform to project-specific conditions and objectives. Therefore, any standards developed must permit adequate flexibility to be modified, provided the reason for the modification can be justified.

An approach that can effectively be done on small projects, with focused objectives, is to include information about the equipment, acquisition parameters, data processing, and presentation in the project proposal. Supplementing the proposal, and frequently unseen by a client, are written organizational standard operating procedures or published standards (such as ASTM International) that provide some of the details which are necessary components of a QC program. Some companies have established written procedures that define how a particular survey is performed in general terms, leaving site- and project-specific information for definition within the proposal.

While most organizations have checks and balances in place to assess the cost of a geophysical survey when it is budgeted or proposed, a QC plan can have influence on the technical approach that is applied to a survey. A QC question sometimes posed by a client “How will the survey be done, and how does it fulfill the project objectives?” forms a project focus which is resolved within the QC plan. Frequently, with engineering-driven projects, geophysical input into the questions is limited. Unfortunately, this leads to a disparity between what is requested, what is offered, and what is finally delivered. The question of data quality is seldom raised at this critical time of a project. If data quality issues are raised, they are frequently not included due to the cost-competitive approach used and the lack of specifications or requirements in this area. These are technical issues that are often addressed by technical people. But with all things human, there is a need to have a check and a balance.

General Geophysical Field QC Procedures

In preparing for QC in the field, no amount of computer processing can remedy low accuracy, poor quality data collected in the field. It is critical for the fieldwork to create sufficient record to support the data so the sequence of events, field conditions, and anomalous conditions that may affect the data can be reconstructed and checked for errors if necessary. There are a number of rudimentary steps that can be used to ensure this occurs.

Field QC requirements and documentation of all fieldwork are critical to provide an historical record for future reviews and analysis of the usability of the data produced. Field logbooks, data collection sheets, and good field notes form the basis for this record (USEPA, 1998). In a detailed QC plan, the field logbook can also be required to contain the equipment settings and field operational procedures used for the project. However, many modern geophysical instruments automatically record data digitally, and a large amount of information is contained within the digital record. The instrumentation being used and the level of data captured must be considered to keep the level of manual field record-keeping reasonable. The classic field logbook may only require notation of the instrument being used and the name of the operator.

Recognition of the importance of equipment calibration and standardization should be made in the written QC plan. In general, the manufacturer recommendations should be followed. If no such recommendations are provided, a routine check of equipment should be made on a periodic basis and after each problem and repair. An operational check of equipment, along with a test measurement made in a background or test area, should be carried out before each project, before the start of a new project, and before starting fieldwork each day.

The field-record QC plan needs to recognize that changes to planned field procedures due to previously unknown site conditions should be documented. It is helpful if the QC plan requests (or requires) that the rationale for the changes, as well as the compromises that the changes may represent, are documented in the field logbook or records for the project.

Conditions that affect the survey and measurements should be a required component of the field record. These can range from topography, ground cover, obstacles, and weather. Concentrations of metal (buildings, reinforced concrete sidewalks and roads, etc.), radio transmission towers or electric transmission lines, pipelines, fences, etc., are all interferences that should be noted. Sometimes, the sources of these contributing factors may not be obvious and can go unnoticed by less experienced people, but the effects of geophysical noise sources are critically important. When recognized, they require documentation. The QC plan provides the guidance for less experienced people to note these important conditions.

The QC plan should require that equipment problems and steps taken to correct those problems be recorded. It may be appropriate to encourage documentation of how these corrections may affect the data. When the corrections are implemented and documented, the solution may have an effect on subsequent processing or interpretation. Therefore, it is important that this QC step be included in any QC plan or program.

For data that are electronically recorded, a QC step would include periodic review of the digital data. At a minimum, a field personal computer should be available to ensure the ability to read the digital file that has been recorded. Slightly more complex is having the operator recognize that the data are variable, and assess if the digital record contains usable data or noise. The more complex QC steps for the more experienced geophysicist will include data review to ensure the kind of data and recorded values are consistent with the setting. Any QC plan should be careful that any plots or initial field assessments of the data should be marked as "draft" or "preliminary" as the data have not been through a complete and thorough interpretation. While subtle, this distinction can be extremely important on some projects.

Method-Specific Field QC Procedures

Different geophysical methods require different pieces of information. A good QC program will have a QC plan (or plans) containing specific requirements for recording information that is method-dependent. For example, there should be documentation requirements for the survey grid or station layout for an electromagnetic or magnetometer survey. The location of base stations or calibration locations are not typically required for seismic or resistivity surveys but important for other geophysical methods. The level of detail and the items that may be required in a QC plan can be varied and as complex as the method and site require. For some sites, the procedures can be quite simple as highlighted in some of the following paragraphs. For other sites or methods, the QC will be quite exhaustive and rigorous. This is why the QC planning step referenced above is so important. It is necessary to find the appropriate level of effort to assure valid data necessary to meet the survey objectives.

EM survey QC plans should consider requiring the operator to log the initial instrument responses and verify equipment functionality. An assessment of coil orientation and the effects of a level coil may be appropriate on some projects. A base station location may be established for a number of measurements before and after performing the survey to assess system drift. During processing, examination of these two files for drift and the correction of drift should be addressed.

Seismograph timing is important for some reflection and refraction surveys. Delays associated with the source trigger should be identified and incorporated into field procedures for seismic surveys. A good plan will have the seismograph operator note that a "toe-tap" assessment was performed to verify geophones were functioning before data were recorded. Most near-surface seismographs have the ability to record acquisition parameters along with the seismic data. Therefore, the notation of this information may not be required. However, there is value to including in the field notes the frequency of geophones used for a survey and the type of seismic energy source utilized, and this information is sometimes not well recorded in the digital record that comes out of the field.

Most **GPR** systems record instrument settings along with the data. However, GPR can be site-specific. Therefore, a QC plan may require the operator to collect data using a number of different settings in order to demonstrate the ones used for the project are appropriate. A GPR QC plan may require the resurvey of one or more lines to confirm the system is working properly and without drift. If a survey wheel is used, the QC plan may establish parameters to verify the wheel calibration at the survey site.

Resistivity surveys are dependent on good earth contact. Therefore, a resistivity QC plan should require a record of electrode contact resistances at each electrode location prior to conducting a resistivity survey. Establishing what is a good contact and a poor contact should be identified in the QC plan, along with steps that are taken to mitigate contact problems should they be present. Identification of locations that may provide contact challenges may be important to understanding site conditions that will influence both processing and interpretation of the data. Therefore, this simple step can have significant ramifications to a project. Similarly, conducting relay tests and receiver tests on a regular basis can ensure quality data are recorded and also document that the data collected are reliable and representative of site conditions.

A wise geophysicist once noted "The largest errors in geophysics come from inadequate knowledge of the position and orientation of the measurement sensor" (Olhoeft , 2005). The choice of using tape measure, GPS, DGPS, or RTK system can influence the approach and cost to a given project or site. Any geophysical QC program should include information on positioning. Like the geophysical methods above, it is important that QC for different positioning methods be integrated into their use. However, the focus of this paper is on geophysics, and the positioning QC issue is noted, but not addressed within this paper. However, as integrated into a geophysical QC program, consideration of lag between position and the geophysical sensor must be considered, measured, and adjusted if necessary.

Data Management

QC of data management takes two distinct forms. First, there is a degree of data review that occurs in the field and was described earlier. Field assessment of geophysical data is normally not intended for interpretation, but to verify that the data is of adequate quality and quantity to meet the project objectives. Following field activities, however, the office aspect of geophysical QC becomes as important as the field aspects. The office aspect of QC in data management is somewhat unique to geophysics because data management is often as important as data collection on most geophysical projects.

Like the field aspect of geophysical work, it is important to appropriately document the activities that occur in processing the geophysical data. If data editing occurs, the criterion for editing should be established and written. Establishing the criteria can be included as part of the project QC plan (before doing the editing) or documented as part of the data management activities as and after the editing the data is performed. As part of a plan, acceptable data limits or boundaries may be established based upon familiarity with the method. Velocities, apparent resistivities, or measured conductivity above or below a threshold can be identified in a QC plan and managed appropriately. However, refinement of the thresholds may not be possible until the data are examined more closely and site-specific thresholds are established. While both establish acceptable limits, one is part of a plan which occurs before the work begins, while the other is a documentation of the refinement.

Many geophysical methods present data in map view. Many geophysicists are familiar with Surfer® used to contour and present the data. Surfer® has some specific components which can facilitate some of the data QC work. As part of some QC programs, data validation can and should be performed on data sets. Depending on the application, data density, and quality, an assessment of girding algorithms may be an appropriate aspect of a geophysical QC program. Is inverse distance a more appropriate girding method than kriging?

Data management is more commonly done using a variety of software packages. Most geophysical equipment manufacturers have data transfer or download software that is provided for their instruments. Some of the software permits data editing and limited manipulation. Unless there are provisions within the software to track what is done, it is incumbent upon the geophysicist to keep track of editing and manipulation steps that are performed on the data.

There are a number of complex, manipulative software packages that are used by the geophysical community. These permit geophysicists to organize and enhance the data along with noise mitigation, which may be present. The outfall of the data processing or modeling is the data that everyone desires. However, one of the challenges with some common geophysical software is keeping track of the parameters that were used. Few geophysicists will pass up an opportunity to adjust a filter or modify a constraint parameter to examine the effects on the data. This can be an iterative process. Sometimes, it is judged to be as much of an art as a science, yet few software packages keep track of every parameter that is selected and assessed. A geophysical QC program needs to have a minimum requirement to track parameters that are used in the preparation of the data. A good QC program will include specific parameters for assessment and consideration during data processing. These provide the geophysicist with insight into parameter sensitivity, data variability, and reliability.

A geophysical QC plan should require a comparison of the measured information to geologic expectations. Seismic velocities should be compared to expected velocities for the geologic setting. Modeled resistivities should be assessed for reasonableness. Geometric patterns established with GPR should be assessed against the expectations for a site and the target. For all geophysical surveys, the measured values are to a degree predictable. Measurements beyond the expected are often edited, called anomalous, or otherwise have their meaning sidestepped. Yet, in each case, if the data were recorded in a reliable fashion, and the results of the survey were reasonably predictable, important information can be overlooked, ignored, or thrown away. A limited amount of time and effort must be permitted for understanding the origin of these unusual data values.

Interpretation Criteria
While difficult to include in a QC plan, the objective of geophysical surveys is the interpretation of geologic conditions represented by the physical measurements. A reasonable expectation of how the geophysical data will be interpreted is ideally a partnership between the geophysicist and the geotechnical engineer or environmental scientist. However, the engineer or scientist frequently has more information available in greater detail than the geophysicist. Therefore, the geophysicist can establish the framework for interpretation beyond their control.

QA will define the need to state the interpretation criteria. QC for interpretation must frame the geophysical data within the geologic context where the measurement is made. Within data management, QC deals with realistic values and patterns within the data. With interpretation, the assessment must determine whether the geologic interpretation makes sense. The challenge is to integrate the geology and physical measurements in meaningful ways that can be used by the engineer or environmental scientist.

Summary
This paper has defined and examined both quality assurance (QA) and quality control (QC) for geophysical projects. Several models of QA/QC approaches were examined, and none was found to provide adequate guidance for geophysical projects. Tips and suggestions for developing components of QA and QC protocols have been presented. The ideas are not all encompassing, but provide a framework of information that permit the development of reasonable QA and QC programs.

Some of the biggest problems in geophysics come from human error. These can be as simple as forgetting to charge a battery, incorrectly assembling cables, failing to note sensor orientation, falling asleep, typing in a wrong number, or erasing a file. A good QC program recognizes these issues and provides for adequate information to be captured to reconstruct and resolve issues related to these errors.

A good QA program will require geophysical companies and managers to make a commitment to quality. It will also require geophysical service consumers to be willing to recognize and reward quality data. An examination of QA and QC issues over a number of years indicates that there is very little concrete or specific information available regarding geophysical QA and QC. To mitigate this, geophysical service companies will have to improve the level of their QC programs. Quality, written QA/QC programs can be a marketing tool, as well as a competitions discriminator. QA/QC programs should be written and should include four distinct components: (1) planning; (2) field collection of data; (3) processing; and (4) interpretation. There are some generic components from model QC programs that can be loosely applied to geophysical projects; in general, many other components are method- or application-specific. For the methods and applications, there is a remarkably limited amount of specific guidance available. Hopefully, this paper can be a starting place to begin the development and implementation of more effective QA and QC for geophysical projects.

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