SOME CONSIDERATIONS FOR SELECTION AND SUCCESSFUL APPLICATION OF SURFACE GEOPHYSICAL METHODS

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Abstract

A complete and accurate site characterization for geotechnical and environmental purposes is a difficult task. In many cases, the approach is superficial and incomplete leading to costly repetitive efforts and surprises as the project proceeds. Geophysical methods can be an effective component of many site characterization investigations. One of the primary benefits of geophysical measurements is to increase spatial sampling density so that background and anomalous conditions can be accurately identified early in the investigation.

There are numerous geophysical application guidelines that have been developed by ASTM, as well as federal and state agencies. These guidelines are intended for initial planning purposes by personnel not experienced with geophysical methods. However, all to often, the guidelines are used as a means of final selection of methods without the benefit of experience. Each geophysical method is dependent upon physical property contrasts between the desired target and the surrounding soil and rock. It is important to understand which physical properties are associated with, and effective for, a particular target and geophysical method.

Understanding the purpose of the investigation and the site-specific conditions is a critical aspect in selecting geophysical methods. Site-specific conditions include the expected geologic conditions and the expected cultural conditions, both of which can limit the usefulness of geophysical measurements. In addition, expected results may exceed what is reasonable. Geophysics, or any other measurement technique, should not be used as stand-alone solution to a problem. Any successful site characterization is based upon an integrated approach, whether it includes geophysics or not.

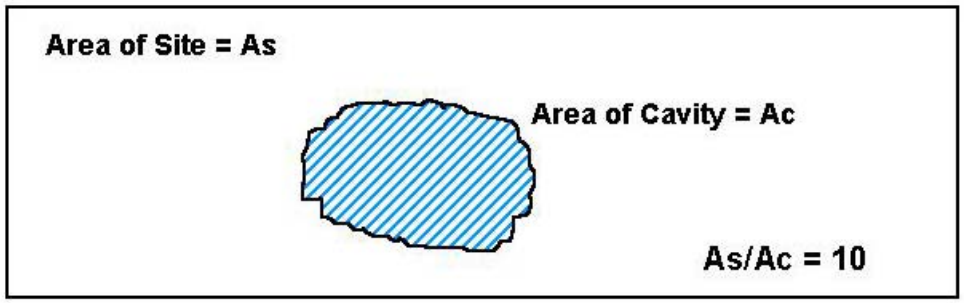
This paper reviews some of the considerations in selecting geophysical methods for the site characterization process, focusing upon the impact of the scale and resolution of the measurements.

The Role of Geophysical Measurements in Site Characterization

Geophysical methods can be an effective component of many site characterization investigations. One of the primary benefits of geophysical measurements is to increase spatial sampling density so that background and anomalous conditions can be identified early in the investigation; thereby accurately positioning detailed measurements (e.g. borings, trenches and sampling) to critical areas of concern.

The Probability of Detection

Benson and Yuhr (2002) has shown that borehole densities are commonly inadequate to detect geologic anomalies. For example, ten regularly spaced borings will be required to provide a detection probability of 90% to detect the presence of a target 75-foot diameter within an area of an acre (Figure 1). The target could be a cavity or sinkhole, a burial site, or a contaminant plume. For smaller targets, such as widely spaced joints, 100 to 1,000 borings per acre may be required to achieve a 90% probability of detection. Such detection probabilities make a subsurface investigation for localized isolated targets, such as sinkholes, fractures, or buried channels by a limited number of borings alone, like "looking for a needle in a haystack" and almost assures failure.



Probability of Detection	As/Ac = 10	As/Ac = 100	As/Ac = 1000
100	16	160	1600
98	13	130	1300
90	10	100	1000
75	8	80	800
50	5	50	500
40	4	40	400

Figure 1: Probability of detecting a target within a site area

Geophysical measurements can be used to greatly improve the odds of detecting and delineating such features. Many of the geophysical measurements provide continuous or nearly continuous measurements or allow station measurements to be made effectively so that spatial sampling is increased. Even so, we must still pass over (or nearly so) the target to detect it. Therefore, we need to have sufficient spatial sampling (data density) to detect such targets.

The technology is in place to solve just about any earth science problem and includes a wide array of geophysical techniques. However, all geophysical measurements have advantages and limitations. Successful selection, application and interpretation of geophysical data within an integrated program of site investigation requires consideration of many factors of which the selection and there application are but a few.

Geophysical measurements are often made as a separate entity, often isolated from the overall site characterization program and sometimes as a last ditch effort to solve a problem when all else has failed and the budget is nearly expended. Here we will consider the use of geophysical methods within an integrated site characterization program, where the geophysical data and other data are integrated into a coherent site characterization program. While the geophysical methods can be applied from the air (or sometimes space), on the ground, on the water and down boreholes, the focus of this paper is upon measurements made from the ground surface and from boreholes.

Selection of Methods

There are a variety of surface geophysical methods available for site characterization. The commonly used ones are listed in Table 1 along with the parameter they measure or respond to.

Numerous geophysical application guidelines that have been developed by ASTM, as well as federal and state agencies. For example, ASTM D6429 covers the applications of surface geophysical methods and ASTM D5753-95 covers the borehole methods. Geophysicists have presented a number of papers on selecting appropriate geophysical methods (Anderson and Ismail, 2003; Benson and Yuhr, 2002; Ward, 1990). These papers provide an excellent overview of the state-of-practice geophysical methods available for geologic site characterizations. These guidelines and papers are intended for initial planning purposes by personnel not experienced with geophysical methods. However, all to often, they are used as a means of final selection of methods without the benefit of experienced counsel.

Table 1: Surface Geophysical Methods

Method	Parameter/Condition Measured
Ground Penetrating Radar	Dielectric constant
Electromagnetic Frequency and Time Domain	Electrical conductivity
VLF (Very Low Frequency)	Electrical resistivity
Resistivity	Electrical resistivity
SP (spontaneous potential)	Electrochemical and streaming potential
Seismic Refraction	Seismic velocity
Seismic Reflection	Seismic velocity
Seismic Surface Wave Analysis	Seismic velocity/dispersion
Microgravity	Density
Magnetics	Magnetic susceptibility
Metal Detector	Electrical conductivity of metal
Thermal Imagery	Temperature of surface
Radiation	Natural gamma radiation

All guidelines are inherently generalized and cannot possibly consider all of the variables involved in planning a site specific site investigation program. As a result, unique conditions are not considered and may tend to eliminate a method from consideration.

> For example, ground penetrating radar is well known for its poor performance (limited penetration) into a clayey environment and would be cited in guidelines as a factor for not using radar. Yet it was the method of choice for successfully detecting fractures in the earthen runways of the dry clay covered lakebed of Edwards Air Force Base in California (Kratochvil, et al, 1972). The presence of these shallow voids just under the runway surface could rip off the landing gear of both military aircraft and the space shuttle landing on these natural earthen runways.

Anderson and Ismail (2003); Benson and Yuhr (2002); and Olhoeft (2003) have outlined some of the key steps and considerations for proper selection of the geophysical methods. The following is a composite list from these papers:

- The first step is to define the problem or project objective.
- What is the area of interest?
- What are the physical properties of interest and which geophysical methods will respond to the physical properties of interest?
- What is the geometry of the target? What is the required site coverage, spatial sampling and resolution to detect the target and which techniques can provide the desired results?
- What is the depth or range of depths of interest of the target?
- What are the site specific constraints and which geophysical tools can perform well under these conditions?
- Which techniques can provide complementary data?
- What other data (geophysical or non-geophysical) is required to interpret and or constrain the interpretation of acquired geophysical data and when will it be obtained?
- What are the expected results?
- What are the likely limitations?
- Who will make the decision of the methods to be used, plan the survey, make the measurements, analyze the data, integrate the geophysical data with other data to arrive at a realistic conceptual geologic model and write the report?
- Will the overall program likely be technically successful and cost-effective?

Note that approximately half of these issues deal with non-geophysical aspects which are as critical to the overall success of the program as are the selection and proper application of the method(s).

Since no guideline or paper can cover all of the many interwoven issues involved in properly selecting and applying geophysical methods we will focus attention on the first six issues, with emphasis on the issues of the scale and resolution of the measurements.

The First Six Issues

1) Define the Problem or Project Objective

Olhoeft (2003) suggests that the problem as defined by the client may not be the actual issue to be resolved. It is important at this stage to resolve the basic issue or issues of concern to arrive at the best possible definition of the problem to be resolved. The problem will commonly be described covering a wide range of issues including a wide range of depths (i.e. from the surface to 100 and more) detailed site coverage (approaching 100%) along with maximum resolution (to within a foot or less) and a high level of accuracy and success. Such requirements for a wide range of depths with high resolution will inherently require multiple methods of measurement (both geophysical and non-geophysical measurements). Coverage approaching 100% may be limited by site access and or interference from cultural features. In all cases, cost and schedule will impact the final approach. Reality must set in prior to planning the survey.

In addition, the problem or project objective may be focused on an end product and be missing the steps to get there. For example, a client wants to map an organic contaminant plume at an industrial facility. An organic contaminant does not generally provide a contrast that can be mapped with any geophysical method. So the question should be asked “can geophysics map the geologic conditions controlling the contaminants?” Very often the answer will be yes and it can be done cost-effectively.

2) What is the Area of Interest

Are we interested in a local area (a few acres) or regional area (extending over tens to hundreds of acres), or along a proposed roadway of 10’s of miles long.

An investigation can be carried out at a reconnaissance level (wide spacing of data Figure 2A) or at a detailed level (Figure 2C). Evaluation of large areas will usually be managed by an initial reconnaissance (Figure 2A) to evaluate overall conditions. The results of this effort identifies regional geologic trends or large scale features. From this, a more detailed survey to better define conditions in a selected area may be carried out (Figure 2B). Then a final detailed survey can provide necessary detailed data (Figure 2C). Since we have narrowed down the area of interest, it is in this phase of the investigation that we can carry out trenching, borings and sampling within the final area of interest.

In general, regardless of the area of interest, work should progress from the regional to the local setting and then the site specific details. The philosophy of working from the regional to the local and then to the site specific should be followed in any comprehensive site investigation (Figure 3). This sequence provides a solid base on which to build an understanding of site conditions each step of the way. This approach should be used whether carrying out field work or assembling existing data. This same philosophy should also be used in the application of geophysical techniques to the site investigation. Using the geophysical techniques to provide surface reconnaissance information (including background conditions) before pursuing detailed logging information or hole to hole measurements.

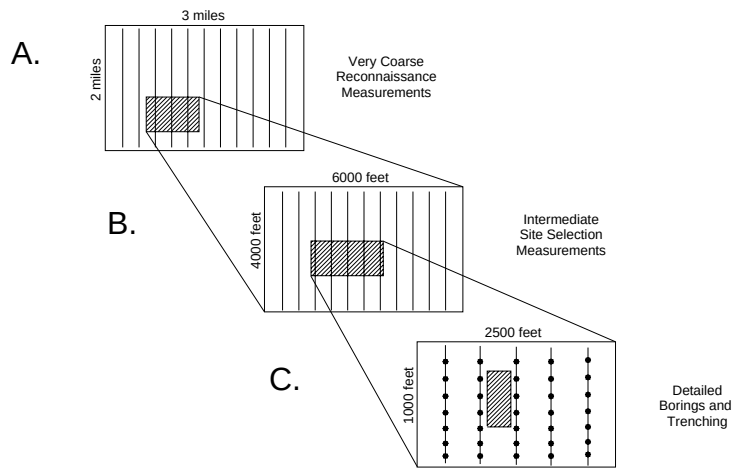


Figure 2: Scale of the investigation

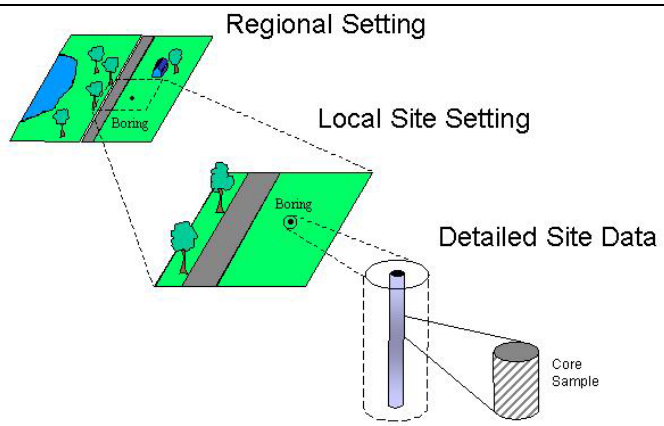


Figure 3: Sequential approach to site characterization

There are exceptions, for example, if there is a concern of settlement of bridge piles due to the geologic conditions, we need to know something about the regional geologic setting as well as the site specific conditions to properly understand the problem. On the other hand if the problem is with the failure of the piles then we can focus upon direct non-destructive measurements of the piles themselves and may not need to concern ourselves with the geology.

3) What Physical Properties will be Measured

Each geophysical method is dependent upon a physical property contrast existing between the desired target and the surrounding soil and rock (Table 1). It is important to understand which physical properties are associated with, and effective for, a particular geophysical method. Therefore, for a geophysical method to detect a change in geologic conditions, man-made structures or contaminants there must be a sufficient physical contrast between the various geologic materials, structures and contaminants for the geophysical method to be effective. In addition, is it a distinct uniform contact (a clear contact with distinct physical property contrast) or a gradational boundary (a highly eroded weathered contact) with gradual changes over some depth?

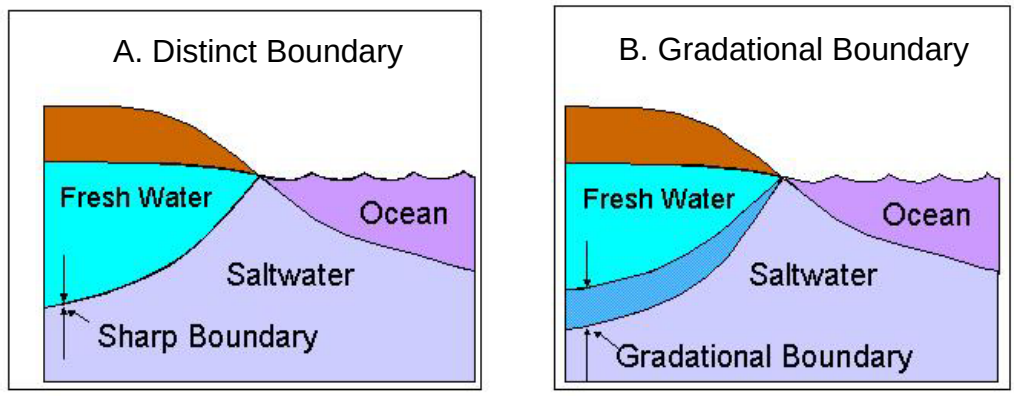


Figure 4: Example of different boundary conditions as illustrated by saltwater intrusion

For example, the contact between freshwater and salt water (typically a threshold of 1000 mg/liter chloride; Figure 4A) can easily be detected by various electrical methods because fresh water has high electrical resistivity usually in the hundreds of ohm-meters while saltwater has substantially lower resistivity value of around 1 ohm-meter. Similarly, the contact between surface soil and underlying massive unweathered rock (Figure 5A) can easily be determined by the seismic refraction method because soils typically exhibit a compression wave velocity of 250 - 1000 meters/second while massive unweathered limestone is typically in the range 8000 - 12000 meters/second.

In some cases the contact between boundaries will be less clearly defined. In the example of saltwater intrusion (Figure 4) if there is vertical mixing of the fresh and saltwater over a substantial distance, then a gradation boundary exists (Figure 4B). The presence of saltwater determined by surface electrical resistivity measurements alone will be deeper than the 1000 mg/liter chloride level. In the example of mapping the top of rock (Figure 5) if the geological setting involves a soil layer overlying a highly weathered bedrock (Figure 5B) the vertical change in compression wave seismic velocity may be gradational between the soil and weathered rock and no clear contact of the top of weathered rock can be defined. In this case, the refraction measurements will indicate the presence of a higher velocity rock below the weathered section where the physical property contrast is more distinct.

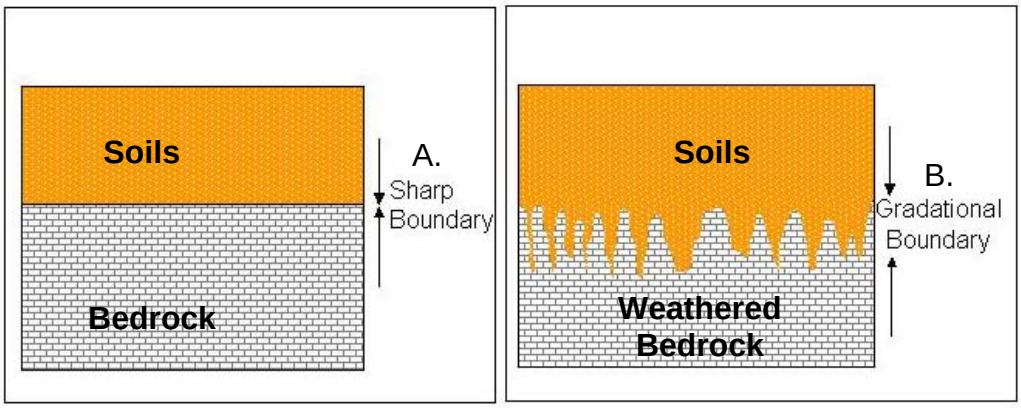


Figure 5: Example of different boundary conditions as illustrated by variations in the soil/rock interface

Once it is determined what physical property contrast will be used for detection of a target, some initial data should be obtained. This data may be from site specific reports, regional studies or even from standard tables of physical properties for different geologic materials. Based upon this initial data a preliminary conceptual geologic model of site conditions can be constructed along with possible forward modeling to determine the possible level of success.

4) Nature of the Target and its Geometry

What is the nature and geometry of the target? As an example the target could be mapping top of rock (a planar target Figure 6A), locating a buried channel or fracture in the top of rock (long linear feature Figure6B), determining the presence and extent of structure, or evaluating if any local karst collapse features are present (distinct and localized; Figure 6C). Does the target have a preferred orientation and, if so, is it known or can it be reasonably estimated? The nature of the target and its geometry will impact the issues of site coverage, spatial sampling and the resolution needed. Sufficient site coverage and spatial sampling are necessary to detect the target and sufficient resolution is needed to define the target.

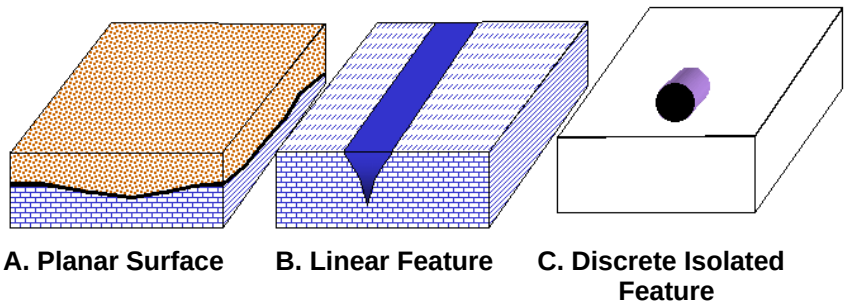


Figure 6: Example of different target geometries

Figure 1 illustrates the detection probability for a discrete isolated target such as in Figure 6C by discrete borings, samples or measurements. Figure 1 is concerned with the detection of a discrete target and is not concerned with defining its shape in detail.

Figure 7 considers survey geometries necessary for detecting other types of targets. For example if the target is a planar feature as in Figure 6A widely spaced station measurements on a grid pattern (Figure 7A) would be effective. For mapping a linear feature such as a fault, fracture, buried channel, disposal trench, or utilities the survey lines should be oriented approximately at 90 degrees to the feature so as to cross the feature a number of times as illustrated in Figure 7B. Often the target geometry is unknown or may be a combination of shapes and orientations. Therefore, a higher density of station measurements or continuous measurements may be needed by acquiring data along closely spaced profile lines (Figure 7C). Regardless of project objectives or target geometry, site access may limit where measurements can be made (Figure 7D).

Once the target is detected, we need to consider how much definition of the target is needed in either 2D or 3D. This is a function of lateral resolution which is an inherent function of the method used, the volume sampled by the specific measurement, the spacing between measurements and their orientation with respect to the target. The lateral resolution is very high for continuous measurements such as EM and radar and is limited by station spacing for measurements such as seismic, resistivity and gravity measurements.

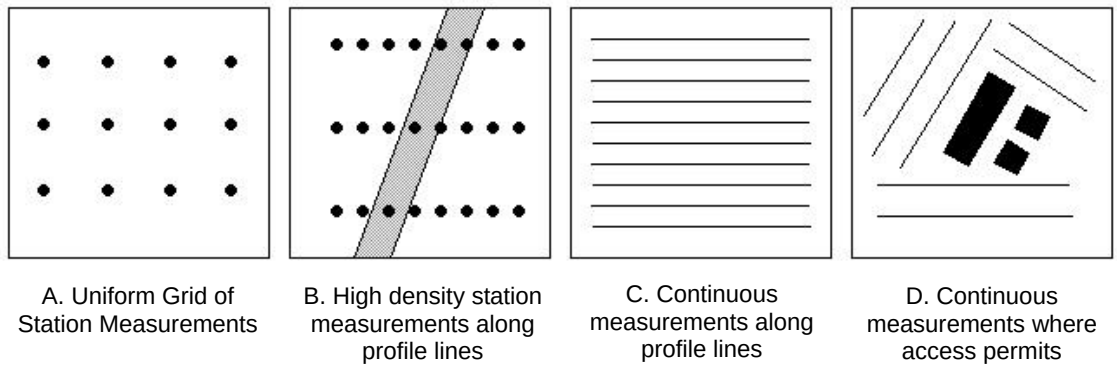


Figure 7: Various survey geometries

Figure 8 illustrates the impact of spatial sampling by comparing continuous measurements to station measurements made along the same profile line. This profile line was oriented perpendicular to expected fractures (long linear features). The data in Figure 8A were obtained by discrete station measurements. The data in Figure 8B show the results of continuous measurements along the same survey line. Continuous measurements imply data that is obtained at a short sample interval, typically less than 0.5 second (one measurement every few feet at a slow walking pace). The fractures in gypsum (Figure 8B) were about 6 inches wide and buried under 6 to 8 feet of alluvium allowing water to migrate under a storm water retention dam.

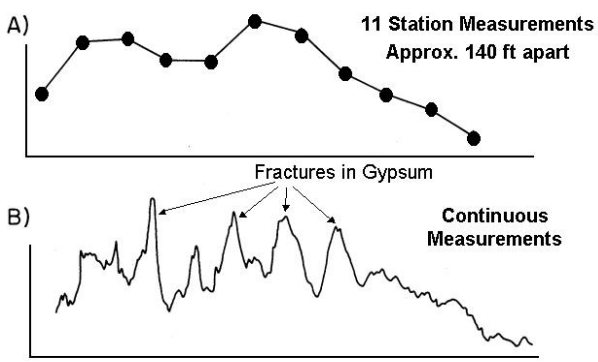


Figure 8: Comparison of point (station) and continuous geophysical measurements. Continuous measurements provide greater resolution than station measurements.

While the benefits of continuous data Figure 8B are clear, geophysical measurements made on a closely spaced station basis, can be just as effective. The key is having the station measurements spacing smaller (closer) than the dimension of the target to be detected. This is also the case when collecting data on a grid, the measurement spacing needs to be closer than the target to be detected.

5) Depth or Range of Target Depths

The expected depth of a target or range of depths must be known or estimated when selecting geophysical methods and planning a survey. Is the target in the upper 10's of feet, upper 100 feet, or upper 1000 feet? Some geophysical methods are limited in depth of penetration. As the target becomes deeper, the resolution of surface geophysical measurements decrease (Figure 9). This is fundamentally due to the large volume of the subsurface material being measured as the depth increases. Because a

larger volume is sampled, the contrast between the target and surrounding materials needs to be even greater. At some point, a discrete localized target, such as a cavity, may be more difficult or impossible to detect at depth. Figure 9 illustrates the reduction in response at the surface as the target depth is increased. This is true for those methods providing a bulk measurement such as electromagnetics, VLF, magnetics, metal detection and microgravity.

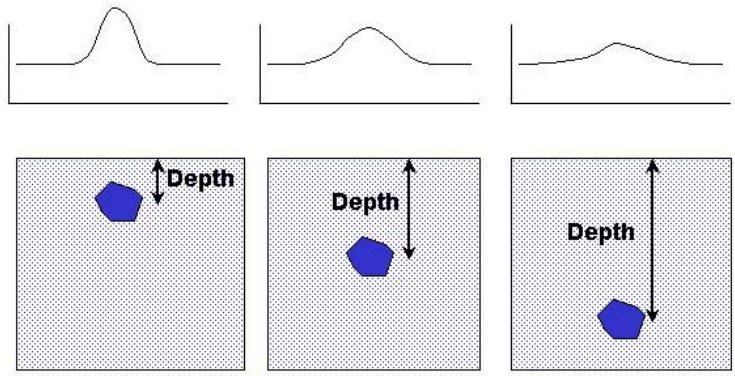
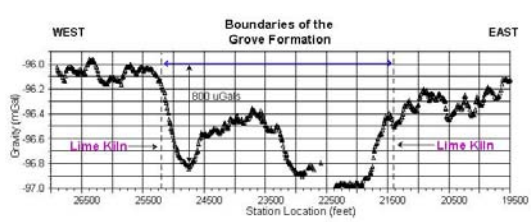


Figure 9: Response of a bulk measurement with respect to depth of target

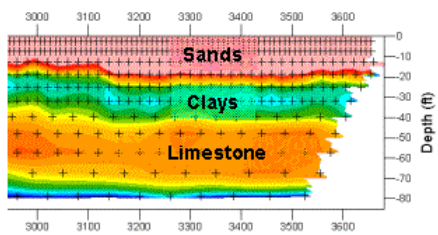
If the project objective is to map targets at various depths, then multiple surveys may be required. For example, mapping voids just beneath a concrete foundation as well as voids at depths of 20 to 30 feet would require two different surveys, if not two different methods.

The depth of the target or range of depth and the vertical resolution of a given geophysical measurement will impact the selection of techniques.

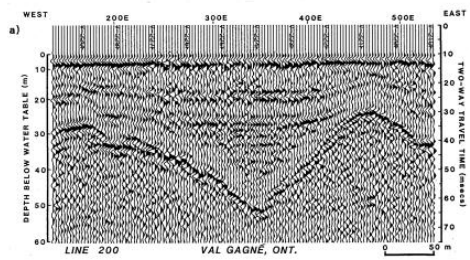
For example, some surface geophysical measurements provide only a single value representative of bulk subsurface conditions, such as gravity measurements (Figure 10A). Some measurements can provide local station measurements or continuous measurements (Figure 8). Other methods like 2D resistivity imaging can provide multiple measurements with depth to provide greater detail (Figure 10B). Yet other methods such as seismic reflection (Figure 10C) and ground penetrating radar (Figure 10D) provide an even greater level of detail with depth, so that the data is a cross section of the subsurface along a given profile line.



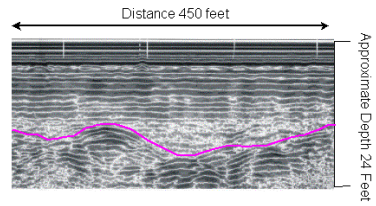
A. Microgravity Data



B. 2D Resistivity Imaging Data



C. Seismic Reflection Data



D. Ground Penetrating Radar Data

Figure 10: Data illustrating variation in vertical data resolution

6) Site Specific Constraints

A number of natural and cultural constraints may limit what can be done at a site in terms of surface geophysical measurements. These constraints may be more logistical in nature rather than technical, yet can render a preferred geophysical method useless under certain conditions.

Natural Conditions

All geophysical measurements have limitations in certain natural conditions. Natural conditions at the surface that may impact a survey include dense vegetation, variable topography, and surface water. These conditions may not prohibit a particular method, but will often dictate how the data will be acquired. Near-surface geologic conditions can also greatly impact a survey. Ground penetrating radar, for example, will have limited penetration in areas with clayey soils. Resistivity, on the other hand, will be limited in areas with dry, resistive soils and may be more beneficial in areas with clayey soils.

Cultural Features

Man-made features, both surface and subsurface, can cause interference and render geophysical data unusable in some situations. Data acquisition can be slowed or even prohibited by the surface conditions of the site. Man-made obstacles such as canals, roads, and buildings should be considered when planning the data coverage for the site. Fences, pipelines, construction debris, reinforced concrete, and other metallic objects will often mask the electromagnetic response from subsurface targets of interest. Vibrations from traffic, industrial equipment and operations may affect seismic or microgravity data and require nighttime surveys. Even nearby radio transmission towers can affect the quality of some data.

A simplistic example may include a property needing to detect the presence of a potential underground storage tank. If the site is clear and accessible, the presence of a relatively large metallic target can be detected quickly and easily using electromagnetics, magnetometer or metal detection. However, if the site has cars parked on it, or dumpsters present, or extensive reinforce concrete, then the first choice of methods would not be appropriate. In this case, the site conditions would require the use of ground penetrating radar, that is not effected by the surface features (cars and dumpsters) and can provide data below reinforced concrete.

Summary of the Issues

Figure 11 illustrates a possible sequence for selection of geophysical methods. This sequence is not to be considered inclusive of all considerations when selecting geophysical methods. In addition, each factor for consideration is not necessarily independent of other considerations. A balance should be met based upon technical issues. The reality of it is that your initial conceptual model may have limited or incomplete data or site specific conditions and changes in project objectives may lead to changes in selection of methods. In some cases, limited geologic data and other unknowns may impact the results unexpectedly. A test phase may be in order before a final selection and optimum choice can be made.

Integration of Data

No method available for site characterization should be used as independent information on which to base conclusions. This is particularly true for geophysical techniques. Geophysical data acquired independent of other information provide non-unique interpretations, meaning that a given measurement can be due to more than one set of geologic conditions. Because of this, geophysical data must be integrated with other site specific information. The following two examples illustrate the need and benefits of data integration.

Figure 12 shows the results of mapping the top of rock by the seismic refraction method. Geophones were spaced at 10-foot intervals which provided a fare bit of detail of the top of rock. The data identified local low areas which can provide traps for DNAPLS. Armed with this data we can accurately select

specific locations for drilling and sampling. Since there are site specific geologic and cultural conditions which can impact data quality at most sites (at this site thick asphalt and concrete foundations, large buried utilities, and unknown locations of fill) we elected to also use microgravity measurements as a means of providing complimentary data. Gravity measurements were made 40-foot station intervals. Note that the refraction data (Figure 14) provides more detail of the top of rock profile than do the gravity measurements. However the general trend of the gravity measurements agree quite well with the refraction measurements and existing boring data. In areas where seismic refraction data was impacted by site conditions and not useable, microgravity could be used to map the trends in the top of rock. The general agreement of the refraction and gravity data provide an increased level of confidence in the resulting data sets and their interpretation. Note the correlation between the seismic refraction, gravity and boring data in Figure 14. When measurements by different methods measuring different physical parameters tend to correlate we can have an increased confidence in our interpretation of the data.

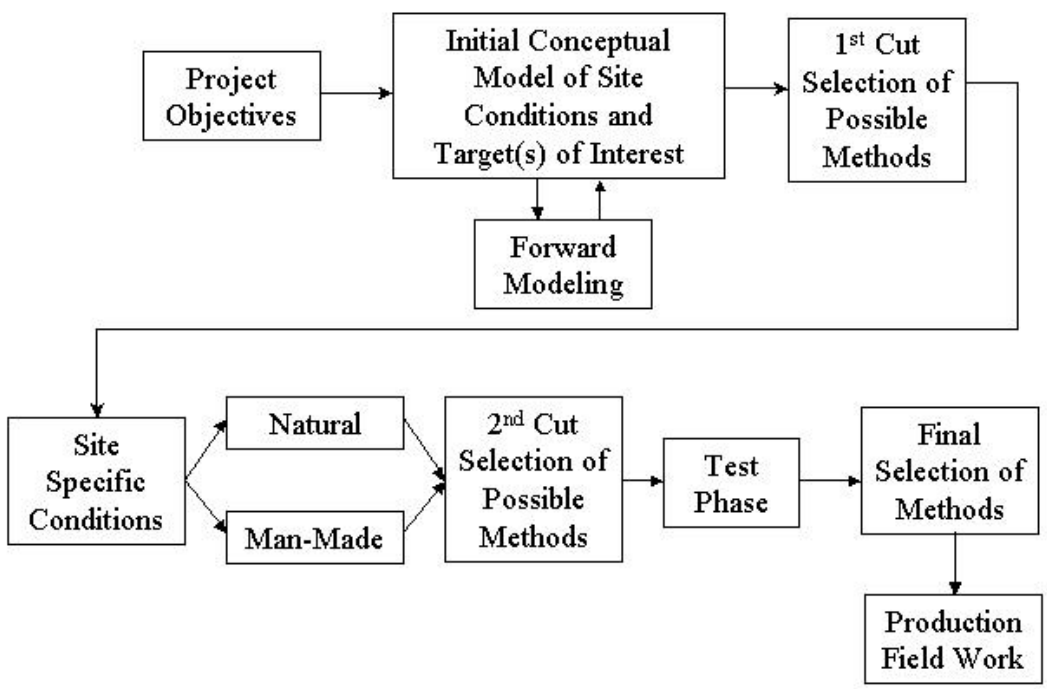


Figure 11: One possible sequence for selection and optimization of geophysical methods

A 130-acre facility on the west coast of Florida was being investigated for the presence of karst (cavities, sinkholes, etc.). A microgravity survey was completed over the entire facility using survey lines spaced 100 feet apart and station measurements that varied from 40 to 20-foot spacing. A total of 1826 microgravity measurements were made and identified localized areas of low gravity values. Rotosonic test borings were completed within these anomalies. Geophysically logging of these test borings indicated zones of very low density. The soil cores showed the presence of organic materials where there should have been limestone. These organic materials were dated using C-14 analysis and found to be 40,000 years before present. The integration of these different data types all indicated a paleo-collapse karst feature (Figure 13). Each method, on its own, provided limited information about the feature; however, when combined, the paleo-collapse feature is well defined with confidence.

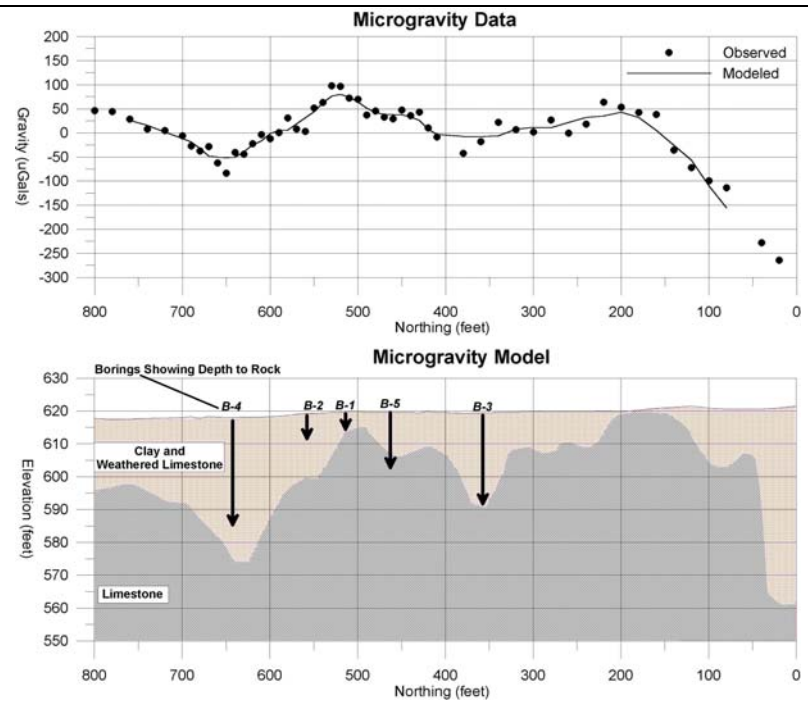


Figure 12

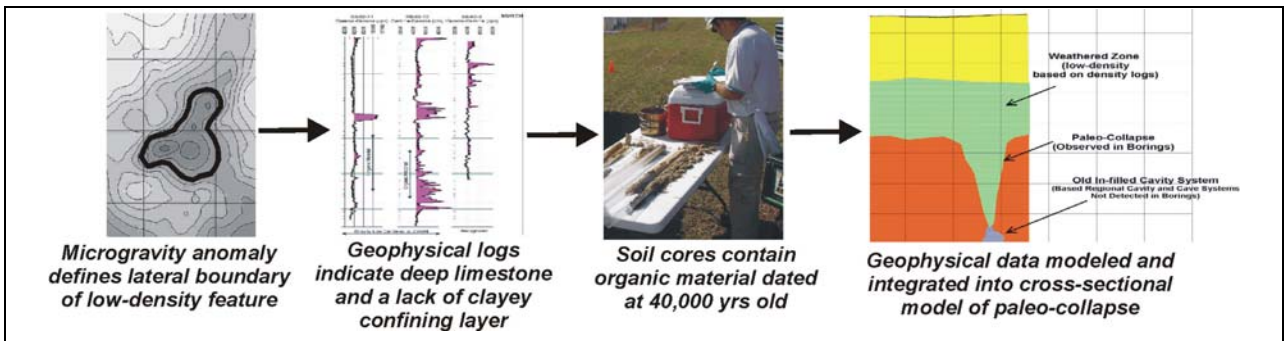


Figure 13: Defining a Paleo-Collapse Feature

Conclusions

We have now seen examples of detection probability, site coverage, spatial sampling and resolution of some of the surface geophysical methods and how they are interrelated to project objectives and acquisition of useful data. Prior to selecting geophysical methods for a project, the project objectives should be clearly defined. The expected benefits and limitations should be fully understood for each geophysical method planned for a site characterization. The field plan can then be modified to optimize the acquisition of each dataset. Rarely will one geophysical method satisfy all objectives. Multiple methods of measurement (geophysical and non-geophysical) are commonly needed to provide supporting data for interpretation, to characterize features at different scales of resolution and depths, and to correlate with other geologic data and observations. There are always compromises made when planning for every project. Project objectives, desired site coverage, resolution of measurements and spatial sampling will always be balanced with time, budget, logistical and political constraints.

Clearly many surface geophysical methods can be used to obtain appropriate and adequate site coverage to significantly enhance our hydrogeologic site cauterization. The obvious benefit of incorporating surface geophysics into a site characterization project is to spatially define the background

and anomalous conditions of the site. We can then proceed to make detailed measurements since we now know where to locate these detailed measurements. Detailed data can be obtained with borings, sampling, geophysical logging, hole to hole measurements, tomography and possibly 3D measurements. While the resolution of all surface geophysical measurements decrease with depth, the resolution of geophysical logging in a single borehole or by hole to hole measurements are independent of depth.

The knowledge, tools, and experience to solve the problem of locating, mapping and characterizing geologic and man-made anomalies are presently available. Many remote sensing, non and minimally invasive methods, as well as traditional boring methods of investigation can be applied to resolve such geotechnical problems. Unfortunately, there are no technologies, procedures, guidelines, software or graphics that will, by themselves, minimize geologic uncertainties and improve upon inappropriate data, insufficient data, inaccurate data or poor critical thinking skills. What is needed is a simple back to basics multidisciplinary approach using good science to reduce the uncertainty to an acceptable level.

The selection and successful application of geophysical methods for geologic site characterization depends on many factors including the experience of the professionals carrying out the survey and a well-designed program of appropriate geophysical methods. As important as selecting appropriate methods are the people who will do the work. Ideally, the professionals involved with planning the work, should also make the measurements in the field, analyze and interpret the data and write the report. This approach provides an integrated approach with continuity from beginning to end of the site characterization effort.

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