GEOPHYSICAL CHOICES FOR KARST AND MINE INVESTIGATIONS

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ABSTRACT

It is not unusual for a geologist or engineer to be called upon to investigate and address problems related to sinkholes in karst environment or subsidence features related to mines. Most professionals know that geophysics can help, but the geophysical method and parameters that may be best suited for the problem at hand are a less certain choice. Geophysical technology and standards have evolved tremendously over the last 10-years. This paper briefly examines geophysical standards that have been developed. A discussion of the methods that are commonly applied to karst investigations, the advantages and disadvantages of the methods, acquisition parameters, and the kinds of results to be expected will be presented. Common geophysical methods to be examined in detail include electromagnetic terrain conductivity, gravity, electrical imaging and seismic.

INTRODUCTION

It is not unusual for a geologist of engineer to be called upon to evaluate, investigate or address existing or perceived problems related to a sinkhole in a karst environment or a subsidence feature related to mining. Most professionals recognize that geophysics can help quantify the problem so appropriate actions may be developed, and expand the information known about a site beyond the limited information available from traditional borings. However, the geophysical method and parameters represent a less certain choice for many professionals due to the lack of familiarity with many geophysical methods. Methods for selecting surface geophysical methods are discussed in the context of existing consensus standards. The method, advantages and limitations, interferences, common acquisition parameters means of geophysical information presentation are discussed for a number of geophysical methods. When these are recognized, the right geophysical method can be applied to the right kind of problem. This can lead to a more successful application of geophysical methods, and a more successful karst investigation project.

SPATIAL SAMPLING ESTIMATE

In assessing a karst feature or mine subsidence issue, most professionals are familiar with soil boring techniques and the resulting data. For karst or subsidence features the challenge with soil borings alone is the probability of detection. Given the ratio of the area of the site of interest (As) to the area of the target (At) the probability of detection can be derived from standard mathematical methods (Benson et. al 1982). If, for example, there is interest in an area 100-foot wide, and 400-foot long (As=40,000 ft^2), and a karst or mine feature 20-foot by 20-foot (At-400 ft^2), then the ratio is 100. In order to have a certain detection of the feature, 160 soil borings would be required in the approximately 1-acre area as shown on Table 1. This requires a boring program to be undertaken on a 15-foot grid.

Table 1 Probability of Detection

Detection Probab	As/At=100	Example Boring Gr Size
100	160	15' Grid
90	100	20' Grid
75	80	25' Grid
50	50	30' Grid

The number of borings could be cut in half to 80 (on a 25-foot grid pattern), but the probability of detecting the feature of concern decreases to 75%. On all projects there is a balance between the cost of information and the probability of detecting the features of importance. Clearly the level of drilling provided in this example, when extended across any significant sized area will lead to significant costs for any scale project.

The use of geophysical information can identify anomalous zones within which a boring program can be targeted. Similarly, geophysics can be used to interpolate conditions between borings to ensure that a boring program has not overlooked features of potential concern. By using geophysical methods, the probability of detecting the features of interest can be increased while the cost of borings can remain the same or in some cases significantly reduced. Therefore the integration of geophysics into any program can help reduce costs.

CHOOSING A GEOPHYSICAL METHOD

For those who are not geophysicists, ten years ago, the choice of a geophysical method for application to a particular engineering or geologic problem frequently depended on experience or guesswork. Today, standards have evolved in the engineering community that assists non-geophysical professionals in understanding the method theories and how to select and apply each one. The American Society of Testing and Materials (ASTM) have published a guide to selecting surface geophysical methods (ASTM-6429). The guide represents a consensus standard for the selection and use of geophysical methods for a variety of subsurface problems. The guide also provides a standard for selecting surface geophysical methods in addition to an overview of the methods. The guide established a simple index table for the selection of geophysical methods with either an A or B ranking. The meaning of A- or B- indicates a primary (A) or secondary (B) consensus geophysical method for a particular application. For the investigation, of sinkholes and voids, the consensus standard includes five methods with either an A or B ranking. These recommendations are shown on Table 2.

Other geophysical methods may work at a given site however these methods identify the consensus methods that are most likely to succeed in most geologic settings. Similarly, these methods may fail given the proper setting, however they form the basic methods that geophysicists will consider when assessing sinkholes and voids.

Table 2. ASTM Consensus Standard Methods for assessing sinkholes and voids

Method	Consensus Standard
Seismic Refraction	B
Electrical (DC)	B (A)
Frequency Domain Electromagnetic	A
Ground Penetrating Radar	A
Gravity	A

All geophysical methods apply physical measurements to answering geologic questions. With geophysical applications, a volume of the subsurface is measured. It is necessary to recognize the physical properties of the feature being measured as well as the effective volume of measurement in order to define survey objectives. The investigation of a small sink feature causing soil piping adversely affecting a residential building footer will require a different scale of geophysical information than the design needs for a proposed shopping mall in a karst setting. The need to scale the geophysical method to the size of the problem becomes an important consideration (Benson, 1992).

Preparing for a geophysical survey, it is necessary to identify the volume of the subsurface of interest and be able to contrast the size of the features of interest with the resolution of the geophysical methods considered. Geophysical limitations related to resolution relative to the target, and site constraints from interferences can dictate the method of investigation. The scale of the project will determine the cost effectiveness of the geophysical methods employed

SEISMIC

Seismic refraction methods measure the velocity of energy transmitted through the soil and rock. Typical seismic velocities range from 500 to 6,000 feet per second for soils, and 6,500 to 18,000 feet per second for bedrock (Haeni, 1984). Lower soil velocities can be expected when unconsolidated soils are present near sinkhole features.

Seismic surveys provide a mechanical measurement of energy movement. Therefore the method has an advantage of less interference common with other methods. The seismic method can be applied to investigations near power lines, areas with saturated clay soils, or significant topographic irregularities. Nearby heavy equipment, causing vibrations can cause a noise source in developed areas. When frozen ground, is present, creating a faster velocity layer the seismic refraction method may not be viable.

A typical karst investigation involves placing 12 to 24 sensors called geophones along a line on the ground surface (Figure 1). Geophone separation commonly ranges from five to twenty feet. The geophone spacing is a critical factor in determining the resolution to be attained by the seismic methods. Very small fractures or narrow bedrock pinnacles cannot be resolved with widely spaced geophones. Common energy sources include sledge hammer, mechanically assisted weight dropping devices, or shot-gun shells. The number of energy source locations along a line of geophones determines data redundancy necessary for more sophisticated data interpretation methods. Three or five source locations are common in a karst survey, while two and seven source locations are used at some sites. The number of source locations has a significant bearing on cost, due to the time required to both acquire and interpret the data.

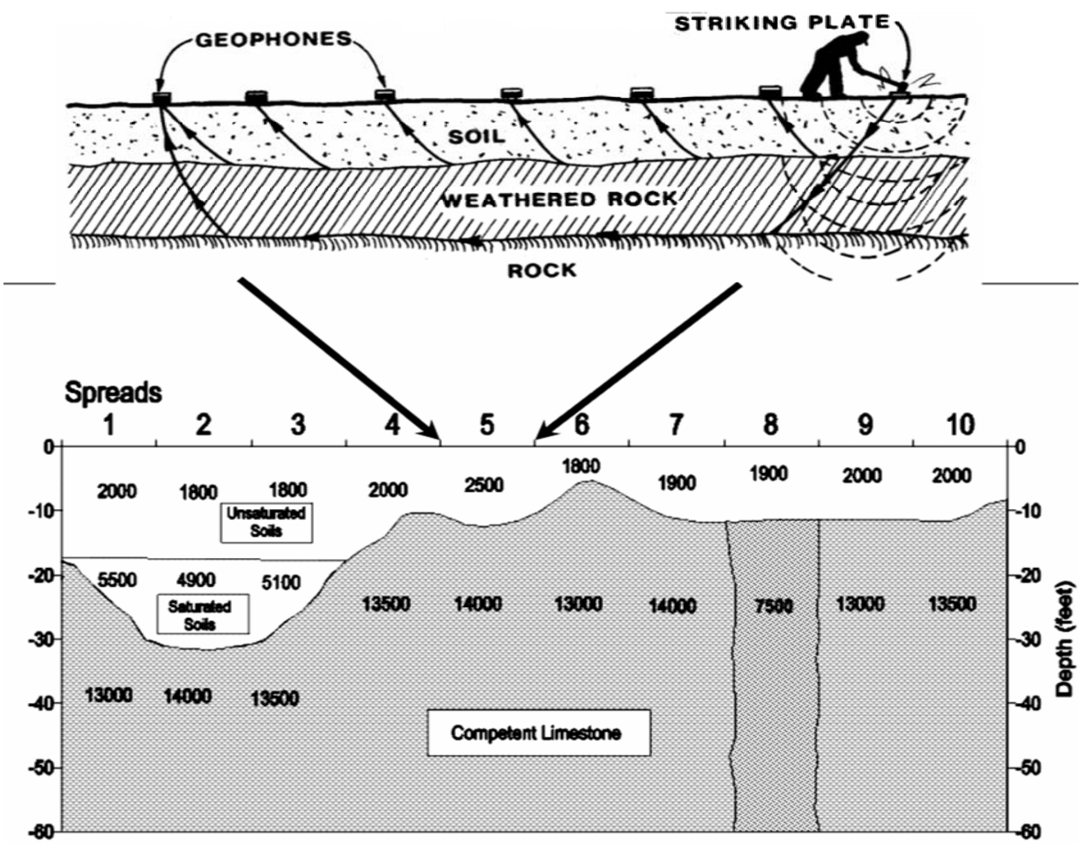


Figure 1. Seismic refraction spread and resulting cross section developed from ten spreads, each with 24 geophones spaced 20-feet apart.

The depth of penetration of a seismic refraction survey is typically 1/3 the length of the geophone spread. Other seismic methods can provide a deeper investigation with a more limited surface area. With reasonable site access, a small refraction survey team of two persons can collect 4 to 6 lines of data during an 8 or 10 hour field day.

Seismic survey results are commonly presented as a profile along the line being surveyed. If several seismic lines are acquired in the same area, the information can be provided in map form, however normal software limitations preclude this as a normal presentation of the data.

ELECTRICAL

Electrical resistivity surveys, sometimes called electrical imaging, measure the ability to pass an electric current through the earth. Soil resistivities range from 5 to 8,000 ohm meters while bedrock resistivities range from 200 to 4,000 ohm meters (Ward, 1990). The presence of a void in the subsurface represents an infinite resistivity, and will increase the apparent bedrock resistivity; while mud filled voids will lower the apparent bedrock resistivity. Therefore, changes or anomalous apparent resistivity values are usually the feature of interest.

Electrical methods, work well in areas with vibration noise and irregular topography. The presence of underground utilities, particularly metallic pipelines and electric lines will provide a significant interference in the data. Dry soils can make electrical contact between the electrode and soil the greatest variable in planning the time necessary to collect good quality data at a site.

Twenty eight to fifty six electrodes are commonly placed into the ground at 1, 2, 3 or 4 meter electrode spacing. A commonly accepted rule of thumb is the depth of investigation is ¼ the distance between the two end electrodes used for measurements. Electrode spacing has a direct effect on the horizontal and vertical resolution of an electrical survey. An electrical survey crew of two people can collect two or three electrical profiles during a 10-hour field day.

Electrical survey results are commonly presented in profile fashion (Figure 2). Maps are seldom produced from this kind of survey. Data processing methods and the manner of presentation for electrical methods permit a clearer insight into weathering features within the bedrock than available with many other geophysical methods. Interpretation of electrical profiles requires a good understanding of the electrical variations related to subsurface materials as well as the limitations of the inversion algorithms.

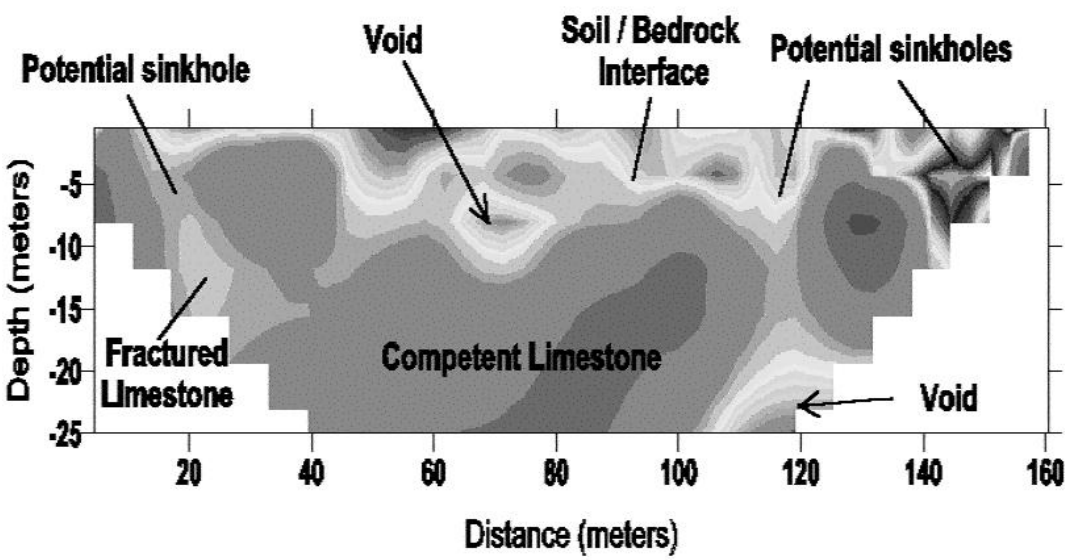


Figure 2. Electrical imaging profile developed from 56-electrodes spaced 1-meter apart.

EI surveys have undergone tremendous change over the last 10-years. The use of multiple electrode cables, data inversion algorithms, the personal computer, and electronic innovation have affected a renaissance in the cost effectiveness use of electrical surveys.

FREQUENCY DOMAIN ELECTROMAGNETIC

First introduced in 1976, electromagnetic terrain conductivity (EM) instruments created a reconnaissance renaissance during the 1980's. During this period EM applications and methods were refined and expanded. Today, the EM method is being closely integrated with global positioning systems (GPS) to provide a high quality tool that is highly cost effectively.

EM surveys measure the subsurface conductivity as opposed to resistivity, measured by electrical methods. Subsurface conductivities typically range from 3 to 40 milliSiemen per meter (mS/m). Generally, soils have higher conductivities than bedrock (McNeill, 1980).

The EM method does not require sensors to be placed on the ground. Measurements are made as the operator walks along the ground surface carrying the instrument. The instrument has a fixed distance between an electromagnetic field transmitter and a receiver. The separation of the transmitter as well as the orientation (horizontal verses vertical) determines the depth of investigation. For a common instrument (the EM31) the depth of investigation is approximately 18-feet. Integrated with GPS for use in environmental applications the location of measurements, variations and the interpreted origins can be established with great accuracy.

The results of an EM survey are typically presented in map form, with a qualitative interpretation (Figure 3). High conductivities are interpreted as thick soils and low conductivities are interpreted as thin soils or shallow bedrock. The interpretation can be calibrated to permit an estimate of depth if adequate information is available on the top-of-bedrock. Variations in measured conductivity due to soil type or moisture content can make the depth conversion somewhat suspect.

EM has the advantage of speed and a crew size of one. EM data is typically collected at one second intervals as an operator walks across the ground surface. This permits several miles of data collection per day. The principal limitation of the method is the qualitative result, and depth estimates are normally limited to shallow or deep. The presence of utilities, fences cars or buildings poses interference for EM surveys, limiting the use of this method at developed properties.

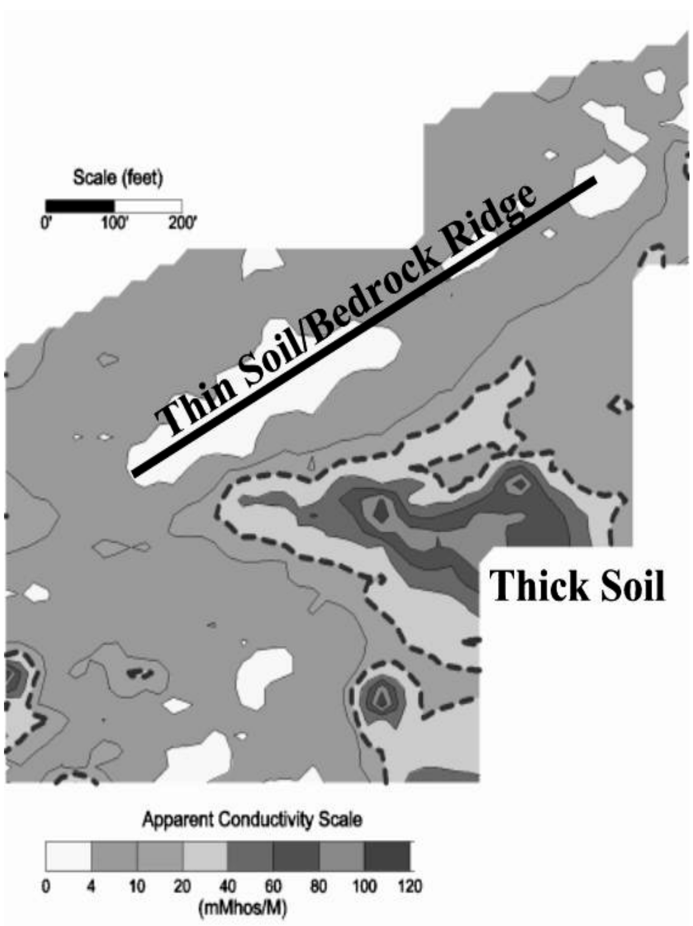


Figure 3. EM Survey map with traverses 20-feet apart

GROUND PENETRATING RADAR

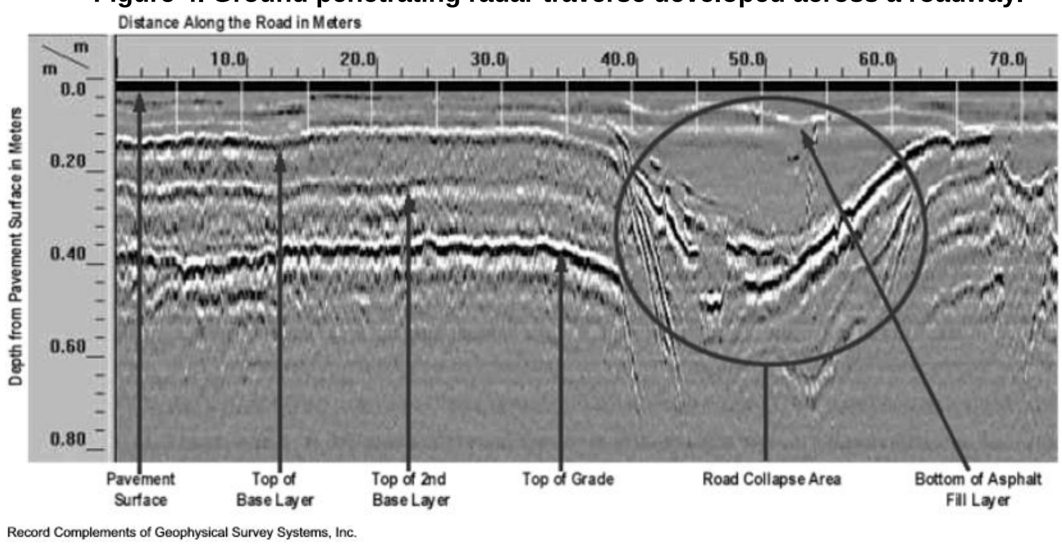
Ground penetrating radar (GPR) represents both a qualitative and quantitative tool. GPR surveys are conducted by moving an antenna across the ground surface. An electromagnetic pulse is transmitted into the ground where it reflects at changes in dielectric constants in the subsurface (Annan 1997). The dielectric constants are dependent on the ability of a material to store a charge when an electric field is applied. In practice this becomes dependent on the presence of water and the presence of free ions. Fortunately, soil and rock changes frequently exhibit changes in dielectric properties so a contrast is present leading to the presence of reflectors which can frequently be readily identified within a GPR record.

The survey method results in the presentation of a profile across the area where the antenna was moved. The depth axis is initially recorded as time, however this may be converted to feet or meters if an estimated subsurface dielectric constant is used, or a measurement is performed over a feature of known depth and a velocity can be established.

Typical GPR systems scan (pulse and sense) at a rate of 8 to 100 times per second. A slowly moved antenna can measure features that are centimeters or less apart. This high later sampling rate results in the greatest lateral resolution available with common geophysical instruments. The unfortunate limitation to GPR with karst investigations is the depth of penetration. Karst bedrock commonly weathers into a clayey soil, which is conductive. The addition of moisture increases the conductivity of the soils. In the presence of conductive materials, the electromagnetic radar pulse is conducted at the near-surface rather than transmitted deeper into the subsurface. This variation makes survey depth prediction difficult under all but the best conditions.

In karst environments, the interpretation of GPR records is dependant on the geometrical changes in reflector patterns (Figure 4). Soil facies as well as the soil/rock interface provide GPR reflectors that are commonly present across measurable areas. The presence of detached rock fragments can be observed. The magnitude of contrast is mostly used in a qualitative sense, but with subsurface control can be used in a quantitative sense. Therefore, good interpretation of GPR data requires an understanding of the local geology and soil morphology.

Figure 4. Ground penetrating radar traverse developed across a roadway.



GPR surveys typically have little interference that prohibits data collection. Most interference tends to degrade data quality or reduce the depth of penetration. Interferences include external electromagnetic fields of similar frequencies or irregular ground surfaces. A relatively smooth ground surface improves the coupling between the radar antenna and ground, maintaining data quality. Recent limitations on GPR use by the Federal communications commission (FCC) in favor of telecommunication applications will create increased interference from external sources in the future.

GRAVITY

Microgravity surveying is based on the principles of mass and density. Isaac Newton established that all objects in the universe attract each other with a force which is proportional to their masses, and inversely proportional to the square of the distance between their masses. By carefully and accurately measuring the mass of an object at different locations, changes in the measured mass can be attributed to changes in the earths' mass at the measurement location. The measured mass is a function a number of things including elevation, solar and lunar tidal effects and the vertical distribution of mass beneath the measurement station. The measured gravity will be greater at a measurement station directly underlain by dense bedrock, than at a station underlain by thick soils and then bedrock. Similarly, a smaller gravity measurement will be present if there is a subsurface void present within the bedrock or soil at the measurement station. Typically, limestone and dolomite bedrock has a density of 2.6 grams per cubic centimeter (g/cc) while soils have densities of 1.6 to 2.0 g/cc. (Johnson and Olhoeft, 1984).

Gravity measurements can be made at select stations along a traverse, or in a grid pattern. One person is required to perform the gravity measurements; however a two person crew is necessary to perform a necessary elevation survey. The measured value represents an average value which is dependant upon many things including:

1. The elevation of the station since higher stations are farther from the center of mass of the earth,
2. The latitude and longitude of the station (since the earth is not truly spherical),
3. The positions of the sun and the moon, which cause the readily observed ocean tides as well as small deformations of the entire earth called earth tides,
4. Minute changes in the calibration of the gravity meter called instrument drift,
5. The attraction of massive landforms near, or obliquely above, the station (i.e. the mass of a nearby mountain actually produces a gravitational attraction which can have a significant effect on a precise gravity reading), and
6. The density of materials immediately beneath a station.

The variations in gravity due to the first four factors typically have magnitudes measured in milligals (where 1,000 milligals equal one cm/s^2). The fifth and sixth factors are typically measured in microgals (where 1,000 microgals equal one milligal or 1,000,000 microgals equals one cm/s^2). Since the purpose of a microgravity survey is generally to determine factor six, the density or mass distribution in the subsurface, the raw gridded or profile gravity measurements that comprise a gravity survey must be corrected for the first five factors. This produces a set of numbers (which are generally several parts per billion of the earth's adopted average gravity) that can be interpreted to determine subsurface density of mass distribution (see e.g. Telford et al., 1990).

Gravity surveys are commonly presented as contoured maps. For the lay person, the key concept is recognizing those areas where there is a mass deficiency (gravity low) or a mass excess (gravity high). With this approach an understanding of the geophysically mapped information can be assessed without too much problem.

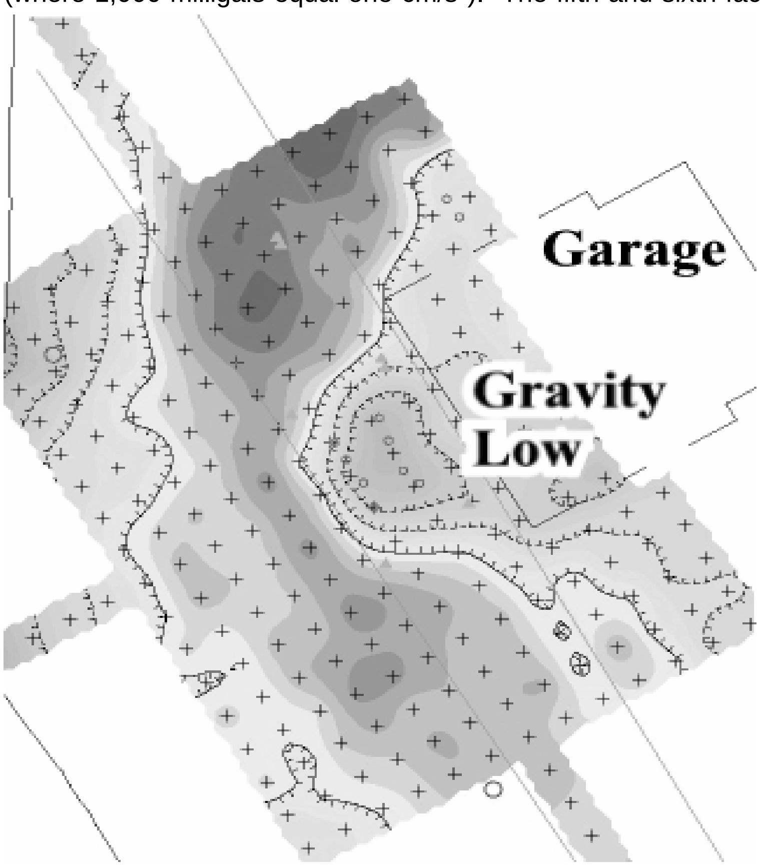


Figure 5. Gravity survey results with a 10-foot survey station grid

Microgravity surveys are excellent when an assessment is required near or within a building that would cause interference or limitations to other methods. A gravity survey is able to survey effectively within and outside the building footprint to provide a comprehensive assessment of site conditions. Gravity surveys can be limited in their effectiveness in areas of significant topographic relief. Gravity surveys are also of limited value when extreme resolution of small "crack-like" features is required.

CONCLUSION

When a spatial sampling estimate is performed to identify the number of borings necessary to develop a reasonable probability of finding a subsidence feature of concern, the results can be eye-opening. Geophysical methods can supplement a boring program. Consensus standards for selecting surface geophysical methods to be applied to karst or mine investigation are available and have been published as ASTM-6429. These standards identify three primary and two secondary geophysical methods as acceptable for evaluating sinkholes and voids in karst settings. Common acquisition methods and interferences have been described for each geophysical method. Each method has benefits when applied to the right scale problem in the correct setting. Each geophysical method also has limitations relative to the detail of information that can be provided by the method. When the correct geophysical method is applied in the correct setting, significant cost benefits can be realized with any karst investigation.

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