GRAVITY METHOD

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OVERVIEW

The gravity method is a geophysical technique that measures differences in the earth's gravitational field at different locations. This nondestructive technique has found numerous applications in engineering and environmental studies, including the location of voids, near-surface faults and the determination of soil layer thickness. The gravity method works because different earth materials have different densities (mass) and hence produce different gravitational fields. Gravitational field variations can be interpreted to determine a source's depth, geometry and density.

Gravity data in engineering and environmental applications must be collected in a grid or along a profile with stations spacing less than 5 meters. In addition, gravity station elevations must be determined at least within 0.2 meters. The data are then processed to remove all predictable components of the earth's gravitational field. The processed data are known as Bouguer gravity anomalies, measured in mGal.

The interpretation of Bouguer gravity anomalies usually involves separating a residual gravity anomaly due to an object of interest from some sort of regional gravity field. There are many manual and computer techniques to perform this separation including graphical smoothing and polynomial surface fitting. The interpretation of residual gravity anomalies involves creating a model of the subsurface density variations to infer a geological cross-section. These models can be determined using a variety of methods ranging from analytical solutions due to simple geometries to complex three-dimensional computer models.

INTRODUCTION

The gravity method involves measuring the earth's gravitational field at specific locations on the earth's surface to determine the location of subsurface density variations. The gravity method works when buried objects have different masses, which are caused by the object having a greater or lesser density than the surrounding material. However, the earth's gravitational field measured at the earth's surface is affected also by topographic changes, and the earth's shape and rotation. These factors must be removed before interpreting gravity data for subsurface features. The final form of the processed gravity data can be used in many types of engineering and environmental problems, including determining the thickness of the soil layer, and the detection of buried tunnels, caves, sinkholes and near-surface faults. Table 1 lists the main uses of the gravity method in engineering and environmental studies.

The gravity method is a relatively easy geophysical technique to perform and interpret. It requires only simple data processing, and for detailed studies the determination of a station's elevation is the most difficult and time-consuming aspect. The technique has good depth penetration when compared to ground penetrating radar, high frequency electromagnetics and DC-resistivity techniques. The main drawback is the ambiguity of the interpretation of the anomalies. This means that a given gravity anomaly can be caused by numerous source bodies. The determination of the source usually requires outside geophysical or geological information.

The use of the gravity data is relatively straightforward as can be seen in the following summary of the fundamentals of the gravity method as applied to engineering and environmental studies including overviews of the theory, data collection, processing, and interpretation. For more detailed information on the gravity technique, numerous papers covering all aspects of applied gravity are available in the following journals: Geophysics, Geophysical Prospecting, Exploration Geophysics, and Journal of Applied Geophysics (formerly Geoexploration) (see the general reference list for a partial list of papers related for engineering-type gravity investigations). For more detailed investigation on the theoretical background of the applied gravity method, the reader is referred to books by Grant and West (1965) and Blakely (1995). For overviews of the applied gravity method, the reader is referred to the books by Telford *et al.* (1990) and Robinson and Caruh (1988). Recent books by Burger (1992), Sharma (1997) and Reynolds (1998) contain a chapter on the gravity method with an emphasis on shallow applications, while an overview paper by Hinze (1990) specifically focuses on shallow gravity applications.

Table 1. Engineering and environmental applications of the gravity method.

Detection of subsurface voids including caves, adits, mine shafts
Determination of soil and glacier sediment thickness (bedrock topography)
Location of buried sediment valleys
Determination of groundwater volume in alluvial basins
Mapping landfills
Mapping steeply dipping contacts including faults

THEORY

To appreciate the gravity method, one must understand Newton's law of gravity, which describes the force between two masses separated by a specific distance. In the gravity method, we are concerned with acceleration at the earth's surface. To obtain the gravitational acceleration, **g,** we can use Newton's law, **F**=m**g**, where m is mass, to obtain **g** on the earth's surface:

$$g = G\frac{Me}{Re^2}r', \qquad (1)$$

where M_e is the mass of the earth, G is the universal gravitational constant and R_e is the radius of the earth. The units for **g** are cm/s^2 in the c.g.s system and are commonly known as Gals, where the average acceleration of gravity at the earth's surface is 980 Gals. Most applied gravity studies are involved with variations in the acceleration of gravity ranging from 10^{-1} to 10^{-3} Gals, so most workers use the term milliGal (mGal). In some detailed work involving engineering and environmental applications, workers are dealing with microGal variations.

Since the gravity method is concerned with determining subsurface variations in mass distributions, most interpretation techniques involve the solution of (1) due to some mass distribution. This can be accomplished by solving for the gravity field due to a generalized mass distribution using an integral equation. In most gravity work, gravity meters only measure the vertical (z) component of **g**, Using mass=?*volume (V), where ? is density, the vertical component of **g** becomes

$$g_z = G\int\int\int ? \frac{zdxdydz}{r^3}. \qquad (2)$$

Equation 2 is the basic equation used for solving for the gravitational field due to bodies of uniform density.

DATA COLLECTION

Gravity data acquisition is a relatively simple task that can be performed by one person. However, two people are usually necessary to determine the location of the gravity stations. The first consideration is a gravity meter. The most commonly used meters do not measure an absolute gravitational acceleration but differences in relative acceleration. There are several gravity meter manufacturers (Telford *et al.*, 1990). However, the accuracies of these meters vary greatly. Two manufacturers that provide the accuracy required for engineering and environmental work are: LaCoste and Romberg (models G, D and E) and Scintrex (CG-3M Autograv). These meters are temperature controlled to stabilize meter readings, however, recent repetition studies (Carlos Aiken, personal communication, 1997) showed that the Scintrex gravity meter has higher stability and experienced less tares (a sudden jump in a gravity reading) over long periods of time. Since these meters are temperature controlled and contain small pen lights to read the meters, they are connected to rechargeable batteries. The meter usually has two batteries, which allows for over 16 hours of readings. Figure 1 shows a typical gravimeter.

After deciding on a gravity meter, the user must lie out a grid or profile over the feature(s) of interest. This involves determining the spacing between observation points (gravity stations), and then surveying the location and elevation of each station. The gravity station spacing for engineering and environmental studies varies between 0.5 to 5 meters depending on the size of the object of interest. After deciding on a station spacing, a local base station must be located, where one repeats a gravity reading every 0.5 to 1 hour. These repeated readings are performed because even the most stable gravity meter will have their readings drift with time due to creep in the meter's springs and to remove earth tide gravitational effects. The instrument drift is usually less than 0.01 mGal/hour under normal operating conditions (Figure 2 shows a typical drift curve). From a drift curve, a base reading corresponding to the time a particular gravity station was measured is obtained by subtracting the base reading from the station reading. This gravity reading is not in mGal but in gravity meter units. One must multiply the gravity meter reading by the manufacturer supplied meter constants (calibration constants) to obtain mGal.

Figure 1. A Lacoste and Romberg model E gravity meter that can be used for all types of gravity surveys. Adapted from Lacoste and Romberg Inc.

An engineering and environmental gravity survey is usually done on foot with the user carrying the gravity meter in a backpack. The user will first level the meter using the leveling bulbs on top of the meter. Additionally, the user should check the meter temperature every few stations. The temperature for each meter is preset (usually between 50° and 53° C) and if the temperature drops, a new battery must be attached. The user then should wait at least one hour before taking readings to allow the meter to stabilize. Readings not taken at the correct

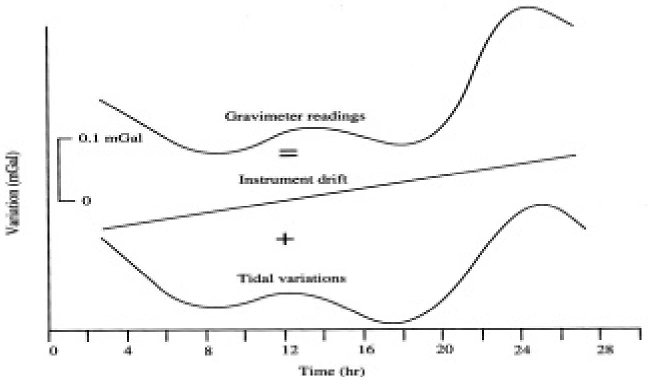

Figure 2. Typical drift curve (top curve) which is a combination of instrument drift and earth tidal variations (adapted from Burger, 1992).

temperature will result in useless gravity values. At each station, the user will take at least two readings or take enough readings so that the differences between readings are less than 0.01 mGal.

In addition to obtaining a gravity reading, a horizontal position and the elevation of the gravity station must be obtained. The horizontal position could be either latitude and longitude or the x and y distances (meters or feet) from a predetermined origin. The required elevation accuracy for detailed surveys is between 0.004 and 0.2 m and to obtain such accuracy requires performing either an electronic distance meter (theodolite) survey or a total-field global positioning survey (GPS).

The last task of most fieldwork is to determine the topographic changes surrounding a gravity station. These topography changes will be used later in processing the gravity data. There are a number of techniques to determine the elevation changes (Hammer, 1939; Cogbill, 1990; Aiken *et al.*, 1998) and these usually involve a combination of recording elevation changes in the field and computer computations using digital elevation models (DEM). The most common technique is by Hammer (1939) where one records an elevation change in quadrants at set distances (commonly from 0 to 1000 meters) from the gravity station. A newly developed technique (Aiken *et al.*, 1998) uses a laser positioning gun to obtain more accurate elevation changes within 100 meters of a gravity station.

DATA PROCESSING

The observed gravity readings obtained from the gravity survey reflect the gravitational field due to all masses in the earth and the effect of the earth's rotation. To interpret gravity data, one must remove all known gravitational effects not related to the subsurface density changes. These include latitudinal variations, elevation changes, topographic changes and earth tides (LaFehr, 1991). The field survey usually removes the earth tidal effect during the drift curve determination.

Engineering and environmental gravity surveys usually involve north-south distance changes of only a few hundred meters, so a latitudinal correction using the following equation may be used:

$$C_\phi = 0.812 \sin \phi \quad \text{mGal/km}, \tag{3}$$

where ϕ is the latitude of the southernmost gravity station. For the accuracy desired in most engineering problems, the horizontal distance must be known to within 1.2 meters (Sharma, 1997).

To take into account the vertical decrease of gravity with the increase of elevation from a predetermined datum plane (usually sea level) and the gravitational field of the mass between the datum plane and a gravity station, a free-air and Bouguer corrections are applied to the observed gravity data. The Bouguer correction requires an average density value (Bouguer reduction density) of the mass, which is usually assumed to be 2.67 gm/cm^3. The problem in engineering and environmental work is that average density of the rocks may not be 2.67 gm/cm^3 (usually it is less). Numerous authors have dealt with these problems by making variable density corrections (Grant and Elsaharty, 1965) or by trying to determine an average density for the survey region (Nettleton, 1939). Nettleton's technique involves correcting gravity data along a profile with different Bouguer reduction densities and the corrected data is compared to a topographic profile. The Bouguer corrected gravity profile that reflects the topographic profile the least is the one with the best reduction density.

The last correction is the terrain correction, which takes into account topographic changes surrounding a gravity station. In engineering and environmental gravity surveys with topographic changes greater than 5 meters within 100 meters of a gravity station, the commonly used Hammer technique (Hammer, 1939) can introduce errors of up to 1 mGal (Aiken *et al.*, 1998). Tests have shown that the laser positioning gun technique developed by Aiken *et al.* (1998) will obtain more accurate models of local elevation changes. The final form of the processed gravity data is called a complete Bouguer gravity anomaly.

DENSITY

The interpreter of gravity data is interested in determining the subsurface variations of mass and this process requires that the density of the material of interest or the density contrast between the material of interest and the surrounding material is known. The density can be determined in many ways, with the best technique being acquiring rock samples within the study area and determine their average density. One can also use density logs obtained from drill holes but these are not always available. Density can also be estimated from experimental relationships relating compressional seismic velocities (obtained from seismic refraction surveys) and density (Nafe and Drake, 1957; Birch, 1961). Also, the interpreter can use average density values from tables obtained from measurements of numerous rock, soil and mineral samples (Johnson, and Olhoeft, 1984; Telford *et al.*, 1990). Table 2 shows the density range for common rock types.

Table 2. Density range of common rock types.

Rock Type	Density (gm/cm^3)
Sedimentary	
Soil	1.20-2.40
Gravel	1.70-2.40
Sand	1.70-2.30
Sandstone	1.60-2.75
Shale	1.75-3.20
Limestone	1.93-2.90
Igneous	
Granite	2.50-2.81
Basalt	2.70-3.30
Andesite	2.40-2.80
Rhyolite	2.35-2.70
Metamorphic	
Marble	2.60-2.90
Slate	2.70-2.90
Schists	2.40-2.90

DATA ANALYSIS AND INTERPRETATION

Basically, the object of the gravity method is to determine information about the earth's subsurface. To determine this information, it is necessary to separate the anomaly of interest (residual) from the remaining background anomaly (regional) (Figure 3). Then the residual gravity anomaly is modeled to determine the depth, density and geometry of the anomaly's source. Below, I will describe some of the most commonly used methods in interpreting gravity data in engineering and environmental applications.

Regional and residual gravity anomalies

There are many techniques that can be used to accomplish the regional-residual anomaly separation (Telford *et al.*, 1990). In engineering and environmental gravity studies, the most common techniques are manual and polynomial surface fitting (Hinze, 1990). This is due to the small scale of the gravity survey and the regional gravity field over such a small area usually has small lateral changes. The simplest methods are manual techniques such as graphical smoothing where a simple smooth regional anomaly is subtracted from the observed gravity anomaly to obtain a residual anomaly (Figure 3). An advantage of the manual techniques is that the interpreter may have information on the lateral location of the source bodies and this information can be used to select a "correct" regional anomaly.

Most other regional-residual anomaly separation techniques involve mathematical operations using a computer. One problem with the mathematical techniques is that they do not accurately represent the "true" residual gravity anomaly due to a specific body. Thus, they should not be used for quantitative interpretation of the subsurface but only for qualitative interpretation (Ulyrch, 1968). The most common mathematical techniques are surface fitting and weighted averaging. Surface fitting involves a least-square fitting of a 2-D polynomial (Beltrao *et al.*, 1991) or 2-D Fourier series (James, 1966) of different orders to the original gridded Bouguer gravity data to represent a regional gravity anomaly map. The higher the surface order, the greater the fit to the original data however, high-order surfaces are usually not desired, as they will contain part of the anomaly that is desired. Figure 4 shows a third-order polynomial surface that was removed from the original Bouguer gravity data to produce a third-order residual anomaly map over a landfill (Hinze, 1990).

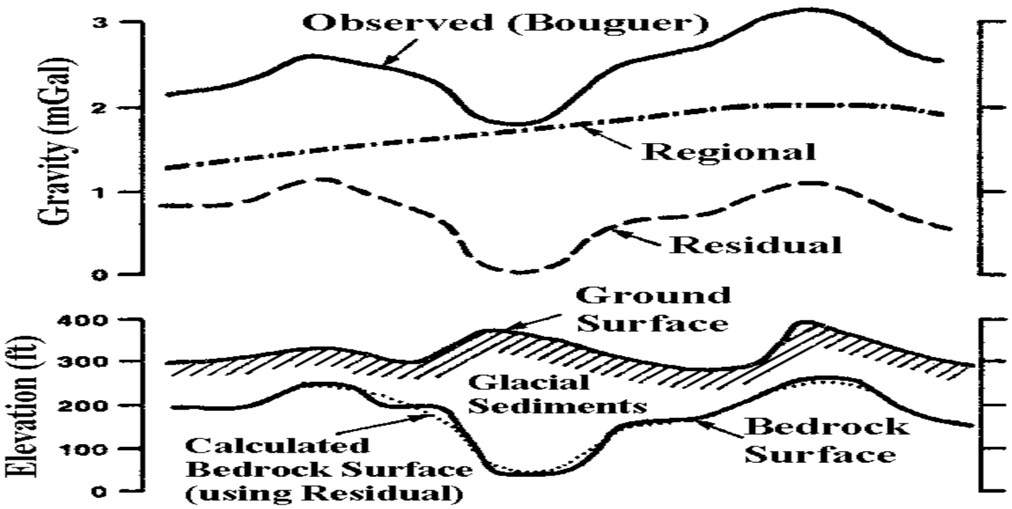

Figure 3. Example of a regional-residual gravity anomaly separation using graphical smoothing to determine the thickness of surficial glacial sediments (adapted from Adams and Hinze, 1990).

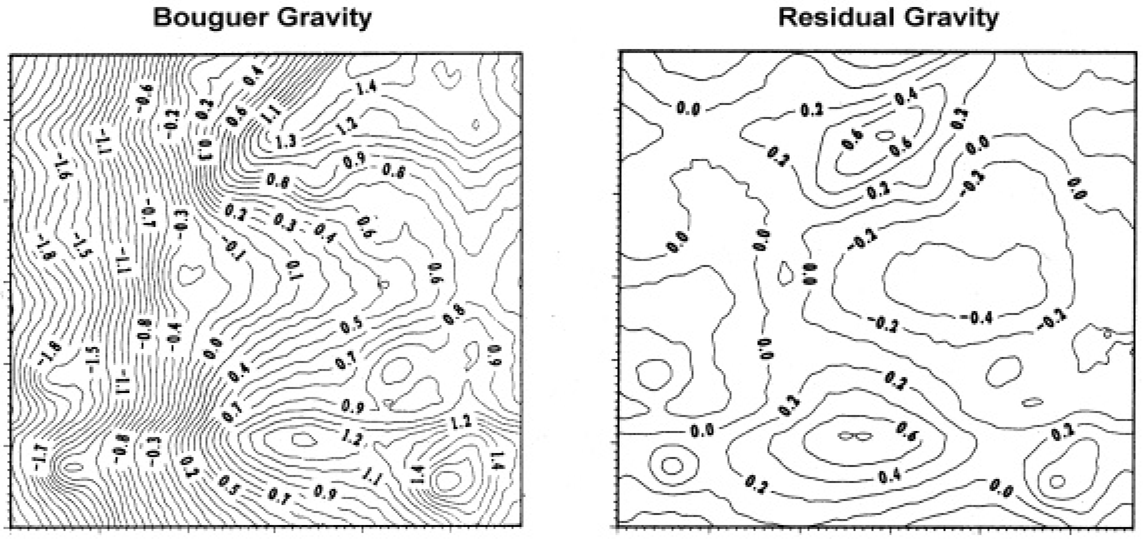

Figure 4. Bouguer gravity map and a third-order residual gravity map constructed by removing a third-order polynomial surface from the Bouguer gravity data (adapted from Hinze, 1990).

Data Enhancement

Data enhancement techniques are used to increase the perceptibility of the gravity anomalies that might be related to bodies of interest. This is important in engineering and environmental gravity work as most of the anomalies have small amplitudes and are easily obscured by the regional gravity field. The most important techniques are derivative methods. The most commonly used derivatives are the first (gradient) (Fajklewicz, 1976; Butler, 1984a,b) and second (curvature) (Elkins, 1951) which are analytically calculated from a Bouguer gravity anomaly grid. The first and second derivative methods both enhance near-surface anomalies at the expense of deeper anomalies and are good at locating the edges of a body. Traditionally, the second vertical derivative has been the most commonly used derivative as the amplitude and width of a second vertical derivative is higher and narrower than the first vertical gradient and thus, supposedly easier to interpret. However, the second vertical derivative is more susceptible to data noise and errors, and topographic irregularities and should only be used for large-scale interpretations. Given the problems with second vertical derivatives, numerous authors (e.g., Butler, 1984a,b) developed methods of determining the vertical and horizontal gradients for shallow gravity applications. Numerous case studies by Butler (1984b) show that the horizontal gravity gradients do not contain topographic effects and located shallow objects better than the vertical gravity gradients. Figure 5 shows observed gravity, horizontal gradient and second vertical derivative profiles over a cavern and limestone pinnacle.

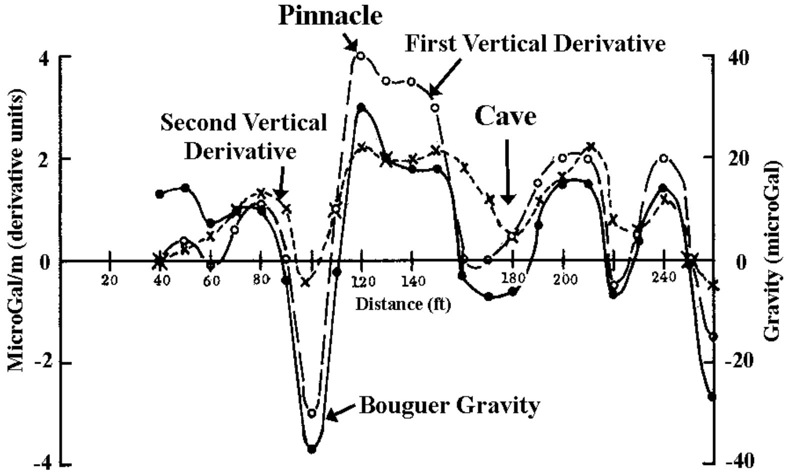

Figure 5. Bouguer gravity (solid circles), horizontal gradient (nonsolid circles) and second derivative (x's) measurements over a cave and a limestone pinnacle (adapted from Butler, 1984b).

Modeling

Gravity modeling is usually the final step in gravity interpretation and involves trying to determine the density, depth and geometry of one or more subsurface bodies. The modeling procedure involves using a residual gravity anomaly. When modeling a residual gravity anomaly, the interpreter must use a density contrast between the body of interest and the surrounding material, while modeling Bouguer gravity anomalies, the density of the body is used. There are many different techniques available to perform the modeling procedure and they can be broken down into three main categories: 1) analytical solutions due to simple geometries, 2) forward modeling using 2-(two-dimensional), 2.5- (two and one-half dimensional) and 3-D (three-dimensional) irregularly shaped bodies, and 3) inverse modeling using 2-, 2.5- and 3-D irregularly shaped bodies. Most of these techniques

$z = 1.3 x_{1/2}$. (4)

involve iterative modeling, where the gravitational field due to the model is calculated and compared to the observed or residual gravity anomalies. If the calculated values do not match the observed anomalies, the model is changed and the procedure is performed again until the match between the calculated values and the observed anomalies is deemed close enough. Before the advent of computers, solutions to simple geometries (e.g., spheres, cylinders, prisms, thin sheets) were used to approximate subsurface mass distributions using residual gravity anomalies (Grant and West, 1965; Telford *et al.*, 1990). What are more commonly used are simplifications of the analytical solutions to obtain an approximation of a body's depth. These simplifications are termed depth or half-width rules because they are based on the horizontal distance ($x_{1/2}$) from the maximum anomaly value to one-half of that anomaly value. The half-width formula for a sphere, which is used to determine the depth to the center of the sphere is:
The half-width rules are used in the field to determine a "quick" approximation to the depth of a given source.

The most common technique in gravity modeling is computer forward modeling of polygonally-shaped, multiple 2- and 2.5-D bodies (Cady, 1980) along profiles of data. The difference between 2- and 2.5-D is that for 2.5-D bodies, the cross-sectional shape extends out a finite distance (called strike lengths) in both directions perpendicular to the profile. 2- and 2.5-D models can be used in engineering and environmental studies to determine the lateral position and offsets of shallow faults, the thickness of the soil layer and the bedrock topography (Adams and Hinze, 1990), and the size of and depth to subsurface voids (Cornwell and Carruthers, 1985). Figure 6 shows a 2.5-D gravity model of a typical landfill using a residual gravity anomaly determined using graphical smoothing (Roberts *et al.*, 1990).

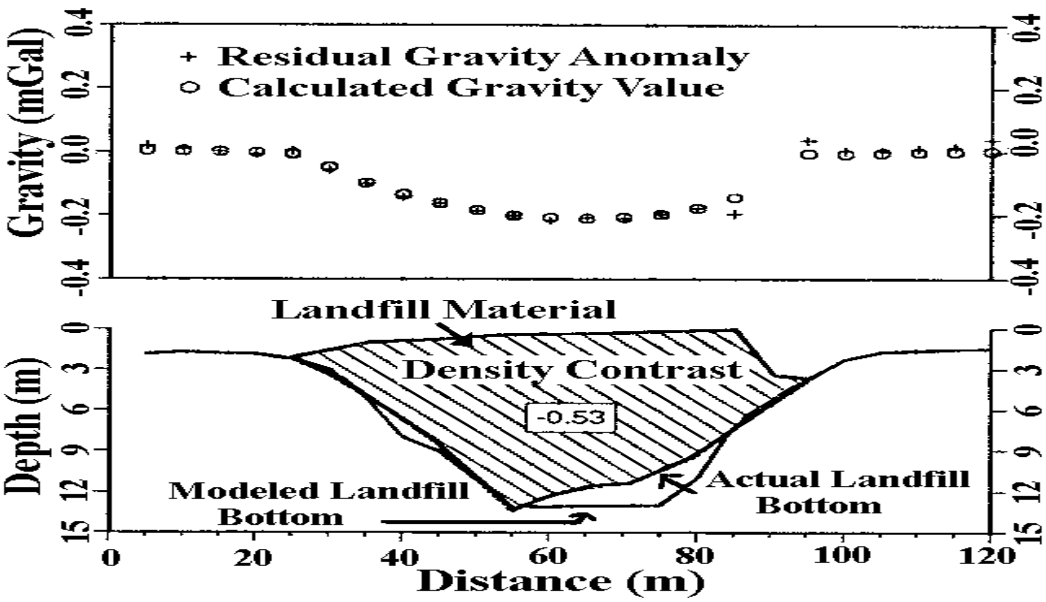

Figure 6. Two and one-half dimensional gravity model (adapted from Roberts et al., 1990). The density contrast between the landfill and surrounding material is measured in gm/cm^3.

Three-dimensional modeling is not commonly used in engineering and environmental studies because of the difficulty in setting up the model, the time involved in determining a model and because a grid of data must be used as the observed data. Complicated models involving multiple bodies with varying densities are usually not attempted. More commonly, the modeling of a few bodies (commonly one) using a residual gravity anomaly is attempted. Three-dimensional models are sometimes used to determine the total volume of subsurface voids (Hinze, 1990).

The final method of gravity interpretation is inverse modeling where given a set of observed data and a general starting model, a computer algorithm will determine a set of parameters (body geometry and density) that best fit the observed data (Mickus and Peeples, 1992). Along with determining a model, the algorithm will determine how well that model fits the data and a range of models that equally fit the given observed anomalies. These so-called automated techniques seem attractive, however, there are problems in determining the inversion parameters, which has limited their use in engineering and environmental studies. However, studies by Butler (1995) have shown that using gravity gradient inversion may be useful in shallow geophysical investigations.

COSTS FOR A GRAVITY SURVEY

The typical costs for a gravity survey depends on if the client wants to perform the survey themselves, contract out the survey to a consulting company, the amount of interpretation and data processing, the number of stations, and the object of interest. A gravity survey is not as complicated as a seismic refraction/reflection survey but not as easy as a magnetic survey. If the client has experience collecting and processing gravity data, they may just want to rent a gravity meter. Typical rental costs are shown in Table 3 for the most commonly used gravity meters.

If the client wishes to contract out the survey to a consulting firm, of course, the costs jumped dramatically (Table 3). The per day costs include equipment rental and one person performing the survey. Surveying the station locations will add additional costs, which costs more than magnetic surveys because of the accuracy needed in the elevations. Most engineering and environmental surveys will collect between 40 and 80 stations per day with the number of stations depending on the target.

The amount of data processing and interpretation (map making and estimates of the depth to density contrasts) depends on the source target. If only gravity anomaly maps are required, costs are less but still more time consuming than for the magnetic method because time-consuming terrain corrections are usually required. If geologic mapping is the objective, more detailed modeling and data enhancement techniques are required which are more time consuming to perform. Estimates on these costs are shown in Table 3.

Table 3. Typical costs for gravity surveys.

Service	Costs
Gravity meter rental	
Lacoste and Romberg model G	\$50-60/day plus \$240-270 mobilization
Lacoste and Romberg model D	\$70-100/day plus \$240-270 mobilization
Scintrex CG-3M autograv	\$100-130/day plus \$240-270 mobilization
Portable GPS receivers	\$45-55/day plus \$90-110 mobilization
Consulting services	
Gravity survey (data collection only)	\$900-1100/day
Station surveying	\$300-350/day
Data processing (Bouguer gravity anomalies)	\$200-300/day
Data processing and interpretation	\$300-400/day

SUMMARY

The gravity method is a straightforward geophysical technique that can be applied to a variety of engineering and environmental problems including the location of shallow subsurface voids and faults, and the thickness of the soil layer. Gravity data collection is performed by one or two persons on a grid or along a profile with the gravity stations spaced between 0.5 and 5 meters. The observed gravity data are then processed into complete

Bouguer gravity anomalies that represent all lateral subsurface density changes in the earth. To interpret the subsurface sources of the Bouguer gravity field, a residual gravity anomaly due to an object of interest is separated from a regional gravity field. This separation is accomplished either by manual or computer methods. The residual gravity anomaly can then be modeled by computer methods to determine the depth, geometry and density of the source of the anomaly. These models then provide a basis of a geological interpretation of the subsurface.

REFERENCES

Adams, J.M., and Hinze, W. J., 1990, The gravity-geologic technique of mapping varied bedrock topography, *in* Ward, S.H., Ed., Geotechnical and environmental geophysics: **2,** Society Exploration Geophysicists, 99-105.

Aiken, C.L.V., Balde, M., Ferguson, J., Lyman, G., Xu, X., and Cogbill, A., 1998, Recent developments in digital gravity data acquistion on land: The Leading Edge, **17,** 93-97.

Beltrao, J. F., Silva, J. B. C., and Costa, J. C., 1991, Robust polynomial fitting method for regional gravity estimation: Geophysics, **56**, 80-89.

Birch, F.S., 1961, The velocity of compressional waves in rocks to 10 kilobars: Journal Geophysical Research, **66**, 2199-2224.

Blakely, R.J., 1995, Potential theory in gravity and magnetic applications: Cambridge Univ. Press.

Burger, H.P., 1992, Exploration geophysics of the shallow subsurface: Prentice-Hall Inc.

Butler, D.K., 1984a, Gravity gradient determination concepts: Geophysics, **49**, 828-832.

Butler, D.K., 1984b, Microgravimetric and gravity gradient techniques for detection of subsurface cavities: Geophysics, **49**, 1084-1096.

Cady, J. W., 1980, Calculation of gravity and magnetic anomalies of finite-length right polygonal prisms: Geophysics, **45**, 1507-1512.

Cogbill, A., 1990, Gravity terrain corrections using digital elevation models: Geophysics, **55**, 102-106.

Cordell, L. and Henderson, R.G., 1968, Iterative three-dimensional solution of gravity anomaly data using a digital computer: Geophysics, **33**, 596-601.

Cornwell, J.D., and Carruthers, R.M., 1985, Geophysical studies of a tunnel-valley system near Ixworth, Suffolk: Geophysical Journal Royal Astronomical Society, v. 81, 312.

Elkins, T.A., 1951, The second derivative method of gravity interpretation: Geophysics, **16**, 29-50.

Fajklewicz, Z.J., 1976, Gravity vertical gradient measurements for the detection of small geologic and anthropomorphic forms: Geophysics, **41**, 1016-1030.

Grant, F. S. and Elsaharty, A. F., 1962, Bouguer gravity corrections using a variable density: Geophysics, **27**, 616-626.

Grant, F.S., and West, G.F., 1965, Interpretation theory in applied geophysics: McGraw-Hill Book Co.

Hammer, S., 1939, Terrain corrections for gravimeter stations: Geophysics, **4**, 184-194.

Hinze, W. J., 1990, The role of gravity and magnetic methods in engineering and environmental studies, *in* Ward, S.H., Ed., Geotechnical and environmental geophysics: **1,** Society Exploration Geophysicists, 75-126.

James, W.R., 1966, Fortran IV program using double Fourier series for surface fitting of irregularly spaced data: Kansas Geological Survey Computer Contribution 5.

Johnson, G.R., and Olhoeft, G.R., 1984, Density of rocks and minerals: *in* Carmicheal, R.S., Ed., Handbook of physical properties of rocks, CRC Press, **3**, 1-38.

LaFehr, T. R., 1991, Standardization in gravity reduction: Geophysics, **56**, 1170-1178.

Mickus, K. L., and Peeples, W. J., 1992, Inversion of gravity and magnetic data for the lower surface of a 2.5 dimensional sedimentary basin: Geophysical Prospecting, **40**, 171-194.

Nafe, J., and Drake, C., 1957, Variation with depth in shallow and deep water marine sediments of porosity, density and the velocities of compressional and shear waves: Geophysics, **22**, p. 523-552.

Nettleton, L.L., 1939, Determination of density for reduction of gravimeter observations: Geophysics, **4**, 176 -183.

Reynolds, J.M., 1998, An introduction to applied and environmental geophysics: Wiley and Sons.

Roberts, R. L., Hinze, W. J., and Leap, D. I., 1990, Application of the gravity method to the investigation of a landfill in glaciated midcontinent, U.S.A.: a case history, *in* Ward, S.H., Ed., Geotechnical and environmental geophysics:, **2**, Society Exploration Geophysicists, 253-259.

Robinson, E., and Caruh, C., 1988, Basic exploration geophysics: Wiley and Sons.
Sharma, P.V., 1997, Environmental and engineering geophysics: Cambridge Univerisity Press.
Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1990, Applied Geophysics, Cambridge Univ. Press.
Ulrych, T.J., 1968, Effect of wavelength filtering on the shape of the residual anomaly: Geophysics, **33**, 1015-1018.