Standard Guide for
Using the Gravity Method for Subsurface Investigation[1]

This standard is issued under the fixed designation D6430; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose and Application:*

1.1.1 This guide summarizes the equipment, field procedures, and interpretation methods for the assessment of subsurface conditions using the gravity method.

1.1.2 The gravity method described in this guide is applicable to investigation of a wide range of subsurface conditions.

1.1.3 Gravity measurements indicate variations in the earth's gravitational field caused by lateral differences in the density of the subsurface soil or rock or the presence of natural voids or man-made structures. By measuring spatial changes in the gravitational field, variations in subsurface conditions can be determined.

1.1.4 Detailed gravity surveys (commonly called microgravity surveys) are used for near-surface geologic investigations and geotechnical, environmental, and archaeological studies. Geologic and geotechnical applications include location of buried channels, bedrock structural features, voids, and caves, and low-density zones in foundations. Environmental applications include site characterization, groundwater studies, landfill characterization, and location of underground storage tanks (**1**)[2].

1.2 *Limitations:*

1.2.1 This guide provides an overview of the gravity method. It does not address the details of the gravity theory, field procedures, or interpretation of the data. Numerous references are included for that purpose and are considered an essential part of this guide. It is recommended that the user of the gravity method be familiar with the references cited and with the Guides D420, D5753, D6235, and D6429, and Practices D5088, and D5608.

1.2.2 This guide is limited to gravity measurements made on land. The gravity method can be adapted for a number of special uses: on land, in a borehole, on water, and from aircraft and space. A discussion of these other gravity methods, including vertical gravity gradient measurements, is not included in this guide.

1.2.3 The approaches suggested in this guide for the gravity method are the most commonly used, widely accepted, and proven. However, other approaches or modifications to the gravity method that are technically sound may be substituted.

1.2.4 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education, experience, and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM document is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

1.3 *Precautions:*

1.3.1 *It is the responsibility of the user of this guide to follow any precautions in the equipment manufacturer's recommendations and to establish appropriate health and safety practices.*

1.3.2 *If this guide is used at sites with hazardous materials, operations, or equipment, it is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of any regulations prior to use.*

1.3.3 *This guide does not purport to address all of the safety concerns that may be associated with the use of the gravity method. It is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of regulations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D420 Guide to Site Characterization for Engineering Design

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[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

and Construction Purposes (Withdrawn 2011)[4]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D5088 Practice for Decontamination of Field Equipment Used at Waste Sites

D5608 Practices for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites

D5753 Guide for Planning and Conducting Borehole Geophysical Logging

D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites

D6429 Guide for Selecting Surface Geophysical Methods

3. Terminology

3.1 *Definitions*—Definitions shall be in accordance with the terms and symbols in Terminology D653.

3.2 Additional technical terms used in this guide are defined in Sheriff (**2**) and Bates and Jackson (**3**).

4. Summary of Guide

4.1 *Summary of the Method*—The gravity method makes measurements of gravity variations at stations along a profile line or grid relative to an arbitrary selected local base station gravity value. The gravity measurements are then corrected for other effects that cause variations in gravity. Lateral variations or anomalies in the resulting residual gravity data can then be attributed to lateral variations in the densities of subsurface materials, for example, buried channels, structures, or caves. The data are interpreted by creating geologically consistent density models that produce similar gravity values to those observed in the field data.

4.1.1 Measurements of variations in the subsurface density of soil and rock are made from the land surface using a gravimeter (Fig. 1). The lateral variations in density are used to interpret subsurface conditions along a profile line or grid of gravity measurements.

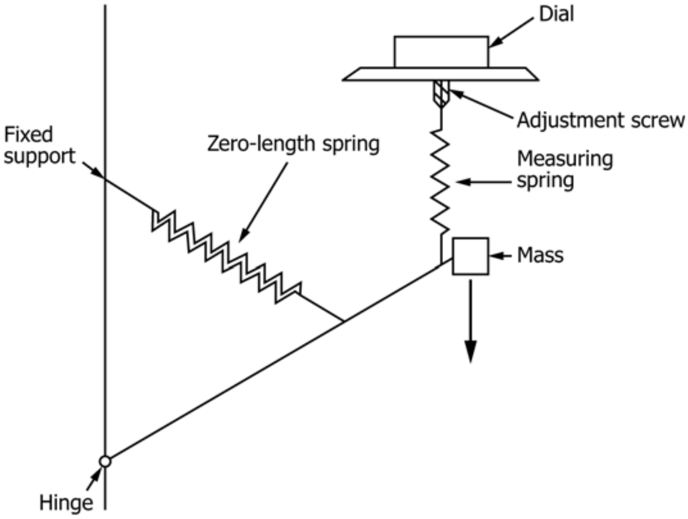

FIG. 1 Gravimeter (from Milsom (**4**))

4.1.2 Gravity measurements can be interpreted to yield the depth to rock, the location of a buried valley or fault, or the presence of a cave or cavity. The results obtained from modeling can often be used to characterize the densities of natural or man-made subsurface materials.

4.2 *Complementary Data*—Geologic and water table data obtained from borehole logs, geologic maps, and data from outcrops or other complementary surface geophysical methods (D6429) and borehole geophysical methods (Guide D5753) are usually necessary to properly interpret subsurface conditions from gravity data.

5. Significance and Use

5.1 *Concepts*—This guide summarizes the equipment, field procedures, and interpretation methods used for the determination of subsurface conditions due to density variations using the gravity method. Gravity measurements can be used to map major geologic features over hundreds of square miles and to detect shallow smaller features in soil or rock. In some areas, the gravity method can detect subsurface cavities.

5.1.1 Another benefit of the gravity method is that measurements can be made in many culturally developed areas, where other geophysical methods may not work. For example, gravity measurements can be made inside buildings; in urban areas; and in areas of cultural, electrical, and electromagnetic noise.

5.1.2 Measurement of subsurface conditions by the gravity method requires a gravimeter (Fig. 1) and a means of determining location and very accurate relative elevations of gravity stations.

5.1.2.1 The unit of measurement used in the gravity method is the gal, based on the gravitational force at the Earth's surface. The average gravity at the Earth's surface is approximately 980 gal. The unit commonly used in regional gravity surveys is the milligal (10^{-3} gal). Typical gravity surveys for environmental and engineering applications require measurements with an accuracy of a few µgals (10^{-6} gals), they are often referred to as microgravity surveys.

5.1.2.2 A detailed gravity survey typically uses closely spaced measurement stations (a few feet to a few hundred feet) and is carried out with a gravimeter capable of reading to a few µgals. Detailed surveys are used to assess local geologic or structural conditions.

5.1.2.3 A gravity survey consists of making gravity measurements at stations along a profile line or grid. Measurements are taken periodically at a base station (a stable noise-free reference location) to correct for instrument drift.

5.1.3 Gravity data contain anomalies that are made up of deep regional and shallow local effects. It is the shallow local effects that are of interest in microgravity work. Numerous corrections are applied to the raw field data. These corrections include latitude, free air elevation, Bouguer correction (mass effect), Earth tides, and terrain. After the subtraction of regional trends, the remainder or residual Bouguer gravity anomaly data may be presented as a profile line (Fig. 2) or on a contour map. The residual gravity anomaly map may be used for both qualitative and quantitative interpretations. Additional

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[4] The last approved version of this historical standard is referenced on www.astm.org.

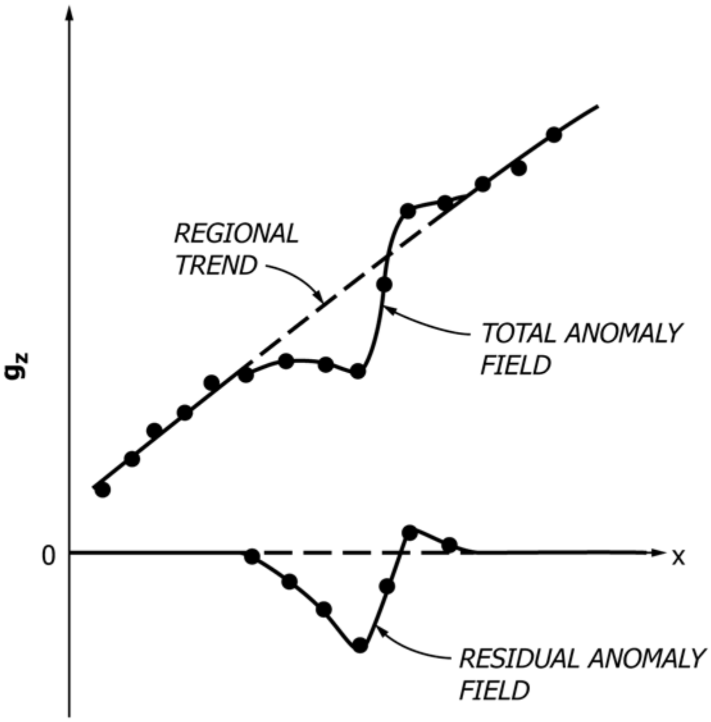

FIG. 2 Graphical Method of Regional-Residual Separation (from Butler (5))

details of the gravity method are given in Telford et al (**5**); Butler (**6**); Nettleton (**7**); and Hinze (**8**).

5.2 *Parameter Being Measured and Representative Values:*

5.2.1 The gravity method depends on lateral and depth variations in density of subsurface materials. The density of a soil or rock is a function of the density of the rock-forming minerals, the porosity of the medium, and the density of the fluids filling the pore space. Rock densities vary from less than 1.0 g/cm^3 for some vesicular volcanic rocks to more than 3.5 g/cm^3 for some ultrabasic igneous rocks. As shown in Table 1, the normal range is less than this and, within a particular site, the realistic lateral contrasts are often much less.

5.2.2 Table 1 shows that densities of sedimentary rocks are generally lower than those of igneous and metamorphic rocks. Densities roughly increase with increasing geologic age because older rocks are usually less porous and have been subject to greater compaction. The densities of soils and rocks are controlled, to a very large extent, by the primary and secondary porosity of the unconsolidated materials or rock.

5.2.3 A sufficient density contrast between the background conditions and the feature being mapped must exist for the feature to be detected. Some significant geologic or hydrogeologic boundaries may have no field-measurable density contrast across them, and consequently cannot be detected with this technique.

5.2.4 While the gravity method measures variations in density in earth materials, it is the interpreter who, based on knowledge of the local conditions or other data, or both, must interpret the gravity data and arrive at a geologically reasonable solution.

5.3 *Equipment:*

TABLE 1 Approximate Density Ranges (Mg/m^{-3}) of Some Common Rock Types and Ores (Keary and Books (9))

Alluvium (wet)	1.96–2.00
Clay	1.63–2.60
Shale	2.06–2.66
Sandstone	
Cretaceous	2.05–2.35
Triassic	2.25–2.30
Carboniferous	2.35–2.55
Limestone	2.60–2.80
Chalk	1.94–2.23
Dolomite	2.28–2.90
Halite	2.10–2.40
Granite	2.52–2.75
Granodiorite	2.67–2.79
Anorthosite	2.61–2.75
Basalt	2.70–3.20
Gabbo	2.85–3.12
Gneiss	2.61–2.99
Quartzite	2.60–2.70
Amphibolite	2.79–3.14
Chromite	4.30–4.60
Pyrrhotite	4.50–4.80
Magnetite	4.90–5.20
Pyrite	4.90–5.20
Cassiterite	6.80–7.10
Galena	7.40–7.60

5.3.1 Geophysical equipment used for surface gravity measurement includes a gravimeter, a means of obtaining position and a means of very accurately determining relative changes in elevation. Gravimeters are designed to measure extremely small differences in the gravitational field and as a result are very delicate instruments. The gravimeter is susceptible to mechanical shock during transport and handling.

5.3.2 *Gravimeter*—The gravimeter must be selected to have the range, stability, sensitivity, and accuracy to make the intended measurements. Many gravimeters record digital data.

These instruments have the capability to average a sequence of readings, to reject noisy data, and to display the sequence of gravity measurements at a particular station. Electronically controlled gravimeters can correct in real time for minor tilt errors, for the temperature of the instrument, and for long-term drift and earth tides. These gravimeters communicate with computers, printers, and modems for data transfer. Kaufmann (**10**) describes instruments suitable for microgravity surveys. A comprehensive review of gravimeters can be found in Chapin (**11**).

5.3.3 *Positioning*—Position control for microgravity surveys should have a relative accuracy of 1 m or better. The possible gravity error for horizontal north-south (latitude) position is about 1 µgal/m at mid-latitudes. Positioning can be obtained by tape measure and compass, conventional land survey techniques, or a differential global positioning system (DGPS).

5.3.4 *Elevations*—Accurate relative elevation measurements are critical for a microgravity survey. A nominal gravity error of 1 µgal can result from an elevation change of 3 mm. Therefore, elevation control for a microgravity survey requires a relative elevation accuracy of about 3 mm. Elevations are generally determined relative to an arbitrary reference on site but can also be tied to an elevation benchmark. Elevations are obtained by careful optical leveling or by automatic digital levels.

5.4 *Limitations and Interferences :*

5.4.1 *General Limitations Inherent to Geophysical Methods:*

5.4.1.1 A fundamental limitation of all geophysical methods is that a given set of data cannot be associated with a unique set of subsurface conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and some additional information, such as borehole data, is required. Because of this inherent limitation in the geophysical methods, a gravity survey alone can never be considered a complete assessment of subsurface conditions. Properly integrated with other geologic information, gravity surveying is a highly effective, accurate, and cost-effective method of obtaining subsurface information.

5.4.1.2 In addition, all surface geophysical methods are inherently limited by decreasing resolution with depth.

5.4.2 *Limitations Specific to the Gravity Method:*

5.4.2.1 A sufficient density contrast between the background conditions and the feature being mapped must exist for the feature to be detected. Some significant geologic or hydrogeologic boundaries may have no field-measurable density contrast across them, and consequently cannot be detected with this technique. An interpretation of gravity data alone does not yield a unique correlation between possible geologic models and a single set of field data. This ambiguity can only be resolved through the use of sufficient supporting geologic data and by an experienced interpreter.

5.4.2.2 *Interferences Caused by Ambient, Geologic, and Cultural Conditions:*

(1) The gravity method is sensitive to noise (vibrations) from a variety of natural ambient and cultural sources. Spatial variations in density caused by geologic factors may also produce unwanted noise.

(2) Ambient Sources of Noise—Ambient sources of noise include earthquakes, microseisms, tides, winds, rain, and extreme temperatures.

(a) Earthquakes—Local earthquakes seldom are a problem during gravity observations. They occur and are gone before they are any inconvenience. Distant earthquakes however, can lead to gravity changes of 100 µgals or more with periods of tens of minutes or more. These effects can delay gravity observations for several hours or even days.

(b) Microseisms—Microseisms are defined as feeble earth tremors due to natural causes such as wind, water, or waves (Sheriff (**1**)). They are believed to be related to wave action on shorelines and to the passage of rapidly moving pressure fronts whose effects are seen as sinusoidal variations in the gravity data. Their amplitude can readily exceed several tens of µgals.

(c) Earth Tides—Solar and lunar tides affect the force of gravity at the Earth's surface by as much as 300 µgals with a rate of change as large as 1 µgal/min. These solid earth tides are predictable and can be corrected for as a part of gravity data correction procedures.

(d) Wind and Rain— Wind and heavy rain can cause movement of the gravimeter. The gravimeter should be shielded from the wind and rain.

(e) Extreme Temperatures— Extreme temperature changes over short periods of time can cause instrument drift. In order to minimize this effect, the gravimeter should be insulated from extreme heating or cooling. Slow gradual changes in temperature are normally accommodated by repeat base station measurements and drift corrections made as a normal part of the gravity survey.

(f) Geologic Sources of Noise—Geologic sources of noise may include unknown variations in the natural spatial distribution of soil and rock and their densities.

(g) Topography—Hills, mountains, and valleys affect gravity measurements. Depending on the objectives of the survey, topographic corrections may be needed (Hinze (**8**)).

(h) Cultural Sources of Noise—Cultural sources of noise include vibration from vehicles, heavy equipment, trains, and even persons walking near the gravimeter.

5.4.3 *Summary*—During the course of designing and carrying out a gravity survey, the sources of ambient, geologic, and cultural noise must be considered and time of occurrence and location noted. The exact form of the interference is not always predictable because it depends upon the type and magnitude of noise and distance from the source of noise.

5.5 *Alternate Methods*—In some cases, the factors previously discussed may prevent the effective use of the gravity method, and other geophysical (Guide D6429) or nongeophysical methods may be required to investigate subsurface conditions.

6. Procedure

6.1 This section includes a discussion of personnel qualification, considerations for planning and implementing the gravity survey, and interpretation of gravity data.

6.1.1 *Qualification of Personnel* —The success of a gravity survey, as with most geophysical techniques, is dependent upon many factors. One of the most important factors is the competency of the person(s) responsible for planning, carrying out the survey, and interpreting the data. An understanding of the theory, field procedures, and methods for interpretation of gravity data along with an understanding of the site geology is necessary to successfully complete a gravity survey. Personnel not having specialized training or experience should be cautious about using this technique and solicit assistance from qualified practitioners.

6.2 *Planning the Survey*—Successful use of the surface gravity method depends to a great extent on careful and detailed planning as discussed in this section.

6.2.1 *Objectives of the Gravity Survey*—Planning and design of a gravity survey is done with due consideration to the objectives of the survey and the characteristics of the site. These factors will determine the survey design, the equipment used, the level of effort, the interpretation method selected, and budget necessary to achieve the desired results. Important considerations include site geology, desired depth of investigation, topography, and access. The presence of noise-generating activities and operational constraints (which may restrict survey activities) must also be considered. It is good practice to obtain as much of the relevant information as possible about the site prior to designing a survey and mobilization to the field. For example, data from any previous gravity work, other surface geophysical methods, boreholes, and geologic and geophysical logs in the study area and topographic maps or aerial photos should be used to plan the survey.

6.2.2 A simple geologic/hydrologic model of the subsurface conditions at the site is developed early in the design phase and should include the thickness and type of soil cover, depth and type of rock, depth to water table, stratigraphy and structure, and targets to be mapped with the gravity method.

6.2.3 *Assess Density Contrast:*

6.2.3.1 One of the most critical elements in planning a gravity survey is the determination of whether there is an adequate density contrast to produce a measurable gravity anomaly.

6.2.3.2 Assuming that no previous gravity surveys have been made in the area, knowledge of the geology from published references containing the geologic character or densities of earth materials and from published reports of gravity studies performed under similar conditions is required. From this information, the feasibility of using the gravity method at the site can be assessed.

6.2.3.3 Forward modeling using analytical equations or numerical modeling methods can be used to calculate gravity data for a given set of subsurface conditions. Given the depth and the shape of the subsurface feature and the difference in density, such models can be used to assess the feasibility of conducting a gravity survey and to determine the geometry of the field-survey. However, all too often, sufficient information about the depth, shape, and density contrast will not be available to accurately model a site before fieldwork is carried out.

6.3 *Survey Design:*

6.3.1 There must be a clear technical objective to the gravity survey. The target's size, depth, orientation, number and distribution, and density should be estimated. A forward model of the gravity anomaly caused by a specific geologic condition can be used to determine its shape and size. This will determine the required measurement station spacing. The length of a profile line or area of survey should be larger than the area of interest so that measurements are taken in background conditions to establish a regional gravity gradient. For example, in mapping a buried channel, the gravity survey line should cross over the channel so that its boundaries can be determined.

6.3.2 The distance between station measurements should be close enough to define the expected anomaly. An anomaly must be defined by a minimum of 3 points and preferably by more points.

6.3.3 Preliminary location of survey lines is usually done with the aid of topographic maps and aerial photos if an on-site visit is not possible. Consideration should be given to:

6.3.3.1 The need for data at a given location,

6.3.3.2 The accessibility of the area with adequate space for the gravity line or grid,

6.3.3.3 The proximity of wells or test holes for control data, and

6.3.3.4 The need for topographic corrections.

6.3.4 The extent and location of any buried structures and other cultural features that may introduce noise into the data or noise that will prevent measurements from being made should be considered when locating survey lines.

6.4 *Type of Survey*—In reconnaissance surveys over large areas, measurement station spacing may be large (hundreds of metres or more). Under these conditions, the cost of obtaining gravity data may be relatively low, but the resulting subsurface data are not very detailed. In detailed surveys, measurement station spacing is relatively small (a few metres). Under these conditions, the effort for obtaining gravity data is higher, but resulting subsurface data is more detailed.

6.5 *Survey Geometry*—Gravity data may be obtained along a single profile line, widely spaced profile lines, or over a uniform grid. The station spacing will be determined by the resolution required.

6.6 *Survey Implementation:*

6.6.1 *On-Site Check of Survey Plan*—A systematic visual inspection of the site should be made upon arrival to determine if the initial survey plan is reasonable. At this point, modifications to the survey plan may be required.

6.6.1.1 The results of initial measurements can be used to confirm the existence of an adequate density contrast and can also be used to assess noise at the site. Results of these initial measurements may require that changes be made to the original survey plan.

6.6.2 *Lay Out the Survey Lines*—Locate the best position for the gravity survey lines based on the survey design described in 6.3 and the on-site visit. Designing the survey grid to avoid proximity to features such as ditches, rivers, or ravines can minimize the need for terrain corrections. The gravity station should be at least 3 to 4 times the distance from the feature as the feature's height.

6.6.3 *Establish a Base Station or Stations*—Establish a base station at any stable, accessible location near or within the survey area (a concrete surface that is reasonably level is ideal). The base station is used as a reference point with repeated measurements throughout the day. This provides a means to detect and correct any offsets in the gravimeter measurements caused by jarring, vibration, or extreme temperature shifts.

6.6.3.1 The base station gravity reading should be obtained at the beginning and end of each workday, and at least once each hour during the course of the survey.

6.6.4 *Obtain the Location and Elevation of the Measurement Stations*—The local (*x, y*) coordinates of the measurement station can be obtained by tape measure and compass to the nearest 0.5 m (2.0 ft). For a microgravity survey, relative elevations with an elevation accuracy of 50 cm (2.0 ft) is necessary.

6.7 *Survey Methods:*

6.7.1 *Measurements at a Single Gravity Station*—Consistency is extremely important in a gravity survey. A clear and concise field procedure should be established and followed methodically at every station. The general sequence for obtaining a measurement at a station is as follows:

6.7.1.1 Place the baseplate over gravity station and level it,

6.7.1.2 Place the gravimeter on the baseplate and level it,

6.7.1.3 Measure the height of the gravimeter,

6.7.1.4 Take an initial measurement,

6.7.1.5 Recheck level bubbles or electronic levels, and

6.7.1.6 Monitor the reading over a period of time for consistency.

6.7.2 The station location, station elevation, instrument height above survey point, meter reading, time of reading, and general comments are recorded at each station. Even if the measurements are digitally recorded, a careful set of notes with comments is recommended.

6.8 *Gravity Program*—Measurements made between two successive base station measurements make up a program. Programs should be planned to minimize the distance between the last measurement station and the base station. Each program should include at least 20 % remeasurement (overlap) of stations from previous programs. After correction for drift, remeasurement station measurements should agree with each other to within 5 to 20 µgal (depending on survey objectives and noise conditions), or a third measurement should be made during a subsequent program (Butler (**6**)). Periodic base station measurements and repeated station measurements are essential quality control procedures for gravity surveys.

6.9 *Quality Control (QC)*—No amount of computer processing can remedy a low-accuracy field survey. It is imperative that the quality of data be monitored as the survey proceeds. It is critical to have sufficient record keeping so that the entire time sequence of events, along with the gravity data and any anomalous conditions that may affect the data, can be easily reconstructed and checked for errors.

6.9.1 *Calibration and Standardization* —In general, the manufacturer's recommendations should be followed for calibration and standardization of equipment. If no such recommendations are provided, a periodic check of equipment should be made. A check should also be made after each equipment problem and repair. An operational check of equipment are carried out before each project and before starting fieldwork each day.

6.10 *Data Processing*—Procedures for correcting gravity field data are discussed thoroughly in standard references, such as Grant and West (**12**) and Telford et al (**5**).

6.10.1 *Corrections*—Butler (**6**) summarizes the corrections needed for a microgravity survey, which include:

6.10.1.1 *Meter Factor*—The meter factor is the value that converts the gravimeter readings to values in µgal. Each meter has its own table of conversion factors for the various ranges of meter readings.

6.10.1.2 *Instrument Drift*—Drift is assumed to be linear between the hourly observations at the base stations, and a linear drift correction is applied to all measurements between base station observations.

6.10.1.3 *Earth Tides*—Earth tidal corrections are made using a theoretical computation of tides at the site (Longman (**13**)).

6.10.1.4 *Latitude Correction*—A latitude correction must be made to take into account the gravity increase with increasing latitude. The correction is more than 0.5 milligal/km for all latitudes between 25 and 65°. For microgravity surveys, it is usually sufficient to assign a reference latitude to the base station and then to compute latitude corrections for all other stations (Butler (**6**)). Determination of relative positioning to within 1 m or better will keep errors in the latitude correction well below 1 µgal.

6.10.1.5 *Elevation Corrections*—Two corrections are necessary to account for elevation differences between stations in a microgravity survey.

(1) Free-Air Correction—A free-air correction is made to compensate for the change in gravity due to the elevation of a station above an arbitrary datum above sea level. An increase in elevation, above datum, causes a decrease in gravity because the station is further from the center of the earth. The normal free-air vertical gravity gradient (0.30855 milligal/m) is essentially constant and can be used for all stations in a microgravity survey (Butler **5**). The gravity values should also be corrected for variable meter height above ground level (the height from the base plate to the ground surface).

(2) Bouguer Correction—A Bouguer correction is made to compensate for the mass of near-surface soil or rock between the gravity station and the datum. A bulk average density is often assumed for the site. When the observed gravity value at a station is corrected as previously described, the result is called the Bouguer anomaly for the station (Butler (**6**)).

6.10.1.6 *Terrain Correction*—A terrain correction compensates for gravity values due to nearby "hills" or "valleys." These terrain corrections must be added to the station gravity values. The effects caused by more distant terrain features (caused by large mountains or valleys approximately 1 km or more distant), while possibly quite large in magnitude, will influence each station value in a small area microgravity survey to an equal extent. These more distant terrain feature corrections need not be considered for a microgravity survey (Butler, (6)). For a microgravity survey, the correction for terrain effects within 50 m of a station can be significant and must be carefully considered.

(1) Terrain corrections can be estimated using analytical equations or hand calculations of the terrain effect at a few points along the survey line. For a detailed terrain correction to be made to a set of gravity data, a detailed topographic map and computer calculations are required. After the terrain correction, the resulting gravity data set is called the Terrain Corrected or Complete Bouguer Anomaly.

6.10.2 *Removal of Regional Gravity Gradient*—For the common case where the regional gravity gradient is approximately a simple inclined plane over the survey area, the regional component can be determined by visual inspection of the gravity data. The concepts of this regional-residual separation process by the inspection or graphical method are illustrated in Fig. 2.

6.11 *Interpretation of Gravity Data:*

6.11.1 In some cases, quantitative interpretation of the data is not required and a simple qualitative interpretation is sufficient. Examples of qualitative and semiquantitative interpretation include identifying the location of a buried channel (Fig. 3) or a cavity. In some cases, however, a quantitative interpretation, such as an assessment of mass deficit to estimate the volume of grout needed to fill a void will be necessary. The level of effort involved in the interpretation depends upon the objectives of the survey and the detail desired.

6.11.2 While the processing of gravity data can be carried out manually, the process can be tedious and labor intensive. A variety of computer programs are available from the manufacturers of gravimeters and software vendors to aid in processing of gravity data and modeling of the results.

6.11.3 A problem inherent in all geophysical studies is the nonunique correlation between possible geologic models and a single set of field data. This ambiguity may be resolved only through the use of other data and by an experienced interpreter. Fig. 4 illustrates that the identical gravity anomaly can be caused by a number of subsurface conditions. A gravity anomaly with a small lateral extent is due to a small shallow feature; however, an anomaly with a large lateral extent may be due to a variety of shallow or deep features.

6.11.4 *Anomaly Depth*—For any well-defined gravity anomaly, it is possible to estimate the maximum depth at which the cause of the anomaly is located. An estimate for the maximum anomaly depth can be made by measuring the width of the anomaly (Butler, 6). This maximum depth estimation

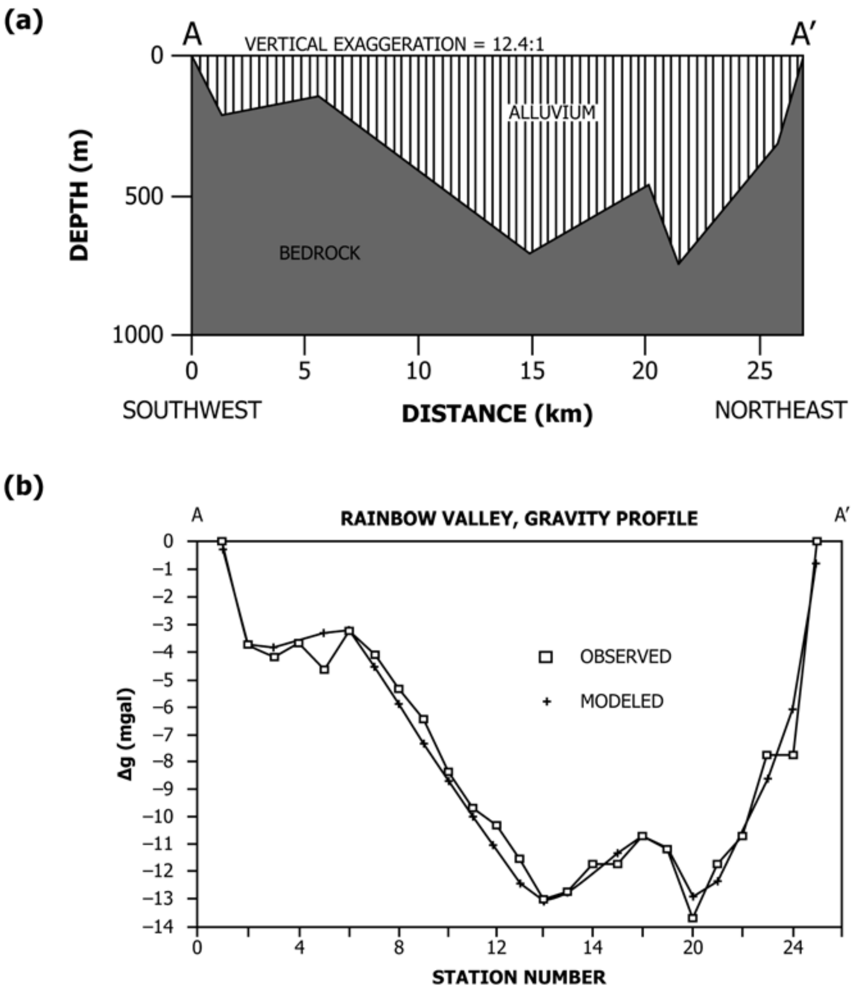

FIG. 3 Buried Channel (from Sharma (14)) ((a) is the Gravity Model and (b) is the Gravity Profile.)

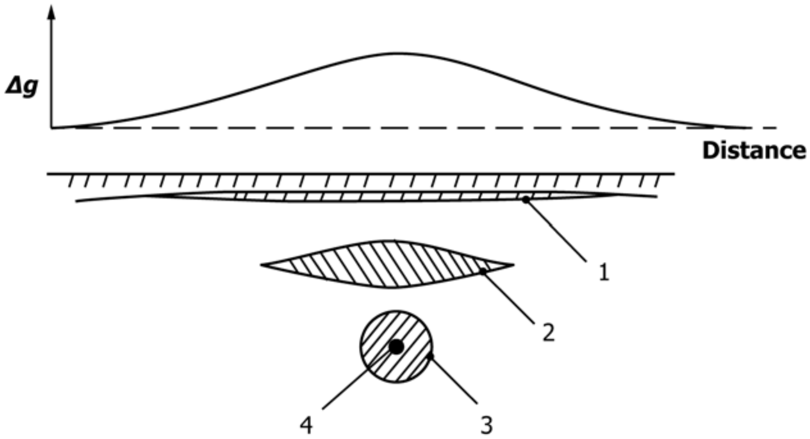

FIG. 4 Ambiguity in Gravity Interpretation (from Sharma (14))

assumes a single isolated target is responsible for the gravity anomaly. However, the same gravity response can be due to the combined effects of a variety of smaller features at various depths (Fig. 4).

6.11.5 *Detectability Threshold*—Measurement error plus background noise for microgravity surveys can be kept below 5 µgal (Butler (6)). This background noise does not include the “lithological noise” component, which is site-dependent. Lithological noise is here defined as gravity variations due to shallow, erratic density variations usually caused by variations in soil thickness. If measurement error and background noise are held to 5 µgal, then assigning a detectability threshold of 10 µgal allows conservative anomaly detection (Butler (6)). A gravity anomaly should be defined by at least 3 points.

6.11.6 *Preliminary Interpretation* —Preliminary interpretation should be labelled as draft and be treated with caution because it is easy to make errors in an initial field interpretation and a preliminary analysis is never a complete and thorough interpretation. Analysis in the field is done mostly a means of quality control.

6.12 *Modeling*—Gravity data may be modeled in 2, 2.5, and 3 dimensions (D). In many cases, profile line data are modeled in 2D. 2.5D modeling is used where the modeled structures are assumed to extend perpendicular to the profile line to infinity. When other data are available (including parallel gravity profiles), a full 3D model may be needed.

6.12.1 For simple geometries, analytical equations are used to provide approximate models of subsurface features. Simple geometries include spheres, infinite long horizontal polygons, finite length horizontal polygons, and vertical polygons. Numerical modeling provides a more detailed level of analysis for more complicated geometries.

7. Report

7.1 The following is a list of the key items that should be contained in most reports. In some cases, there is no need for an extensive formal report.

7.2 Report the following information:
7.2.1 Purpose and scope of the gravity survey,
7.2.2 Geologic setting,
7.2.3 Limitations of the gravity survey,
7.2.4 Assumptions made,
7.2.5 Field approach, including a description of the equipment and the data acquisition parameters used,
7.2.6 Location of the gravity survey line(s) or grid on a site map, base station location descriptions, and gravity values,
7.2.7 Corrections applied to field data, and justification for their use,
7.2.8 Results of field measurements,
7.2.9 Copies of typical raw data,
7.2.10 Copies of the processed gravity profiles and or contours,
7.2.11 Method of interpretation used and specifically what analytical method(s), or software program(s) were used,
7.2.12 Interpreted results along with any qualifications and alternate interpretations,
7.2.13 Format of recording data,
7.2.14 Appropriate supporting data or references used in the interpretation, and
7.2.15 Person responsible for the gravity survey and data interpretation.

7.3 *Quality Assurance*—It is generally good practice to have the entire survey results, including the report, reviewed by a person knowledgeable with the gravity method and the site geology but not directly involved with the project.

8. Precision and Bias

8.1 *Bias*—For the purposes of this guide, bias is defined as a measure of the closeness to the truth.
8.1.1 Some of the factors that affect bias are:
8.1.1.1 Errors in field procedures, record keeping, corrections to data, processing, and interpretation,
8.1.1.2 Instrument errors in measuring or recording,
8.1.1.3 Geometry limitations, relating to line location and topography,
8.1.1.4 Variation of the earth from simplifying assumptions used in the field and interpretation procedure,
8.1.1.5 Site-specific geologic limitations, such as dip, joints, fractures, and highly weathered rock with gradual changes in density with depth, and
8.1.1.6 Ability and experience of the field crew, data processor, and interpreter.

8.2 *Differences Between Depths Determined Using Gravity and Those Determined by Boreholes:*

8.2.1 The bias of a gravity survey is commonly thought of as how well the gravity results agree with borehole data. In many cases, the depth to the feature obtained by gravity data may agree with the borehole data. In other cases, there will be disagreement between the gravity results and borehole data. While a gravity measurement itself may be accurate, the interpreted results may disagree with a depth obtained from drilling for the following reasons. It is important that the user of gravity results be aware of these concepts and understand that the results of gravity survey will not always agree with drilling data.

8.2.2 *Fundamental Differences Between Gravity and Drilling Measurements*—A gravity measurement integrates density over a large volume of the subsurface. In contrast, a borehole examines an extremely small volume of the subsurface. Therefore, it is unreasonable to expect a one-to-one correlation between these two measurements. However, the depth profile along a gravity line should correlate with the depth profile obtained by drilling. Furthermore, a gravity anomaly can be caused by a number of different features (sizes and shapes) at different depths and at different positions (Fig. 4). Unless the features have been resolved, it is not reasonable to depend upon borehole data as a means of confirming the cause of the gravity anomaly(ies). The confirmatory borehole program must be carefully designed to yield data to support (or modify) the conceptual model of subsurface conditions.

8.2.3 *Lateral Geologic Variability* —Agreement between gravity and borehole measurements will vary along the gravity survey line depending upon lateral geologic changes, such as, structural dip, degree of weathering, fracturing, or dissolution of rock. Gravity measurements may not account for lateral geologic changes. Therefore, it is not always possible to have agreement between gravity and borehole data along a survey line.

8.2.4 *Positioning Differences*—The drilling location and the gravity measurement may not be made at exactly the same point. It is common to find that the boreholes are located based on drill-rig access and may not be located along the line of the gravity measurements. Differences in position can easily account for anywhere from a few metres to tens of metres of difference in depth where the top of rock is highly variable, for example karst.

8.3 *Precision*—Precision is the repeatability between measurements. If a gravity measurement is repeated under identical conditions, with low noise levels, the measurements would be expected to be within 5 µgals. Different data quality objectives may be set depending on the purposes of the survey and on site conditions.

8.4 *Resolution:*

8.4.1 *Lateral Resolution*—Lateral resolution of a gravity survey is determined by the spacing between measurement stations. Gravity measurements are not able to resolve small individual features that are spaced less than the spacing between stations.

8.4.1.1 For certain combinations of depths and separations of the features, separate gravity anomalies are not observed. Instead, the individual gravity anomalies will not be observed. The individual gravity anomalies will be superimposed as a single anomaly.

8.4.2 *Vertical Resolution*—Vertical resolution with the gravity method is a complex function of the target(s), size(s), depth(s), relative position(s), and densities.

9. Keywords

9.1 geophysics; gravity; microgravity; surface geophysics

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