



Designation: **D6430–99 (Reapproved 2010) D6430–18**

Standard Guide for Using the Gravity Method for Subsurface Investigation Site Characterization¹

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 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. However, this standard does not address the use of marine, airborne, or satellite gravity measurements.

1.1.2 The gravity method described in this guide is applicable to investigation site characterization 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 investigation site characterizations 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 Units—The values stated in SI units are regarded as standard. No other units of measurement are included in this standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.4 Precautions:

1.4.1 *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 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.

*A Summary of Changes section appears at the end of this standard

1.4.2 *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.~~

1.5 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.

1.6 This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 ASTM Standards:³

[D420 Guide to Site Characterization for Engineering Design and Construction Purposes](#) (Withdrawn 2011)

[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 Sampling and Non Sample Contacting Equipment Used at Low Level Radioactive Waste Sites](#)

[D5753 Guide for Planning and Conducting Geotechnical 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](#).

3.1.1 For common definitions of terms used in this standard, see 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.

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.

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.

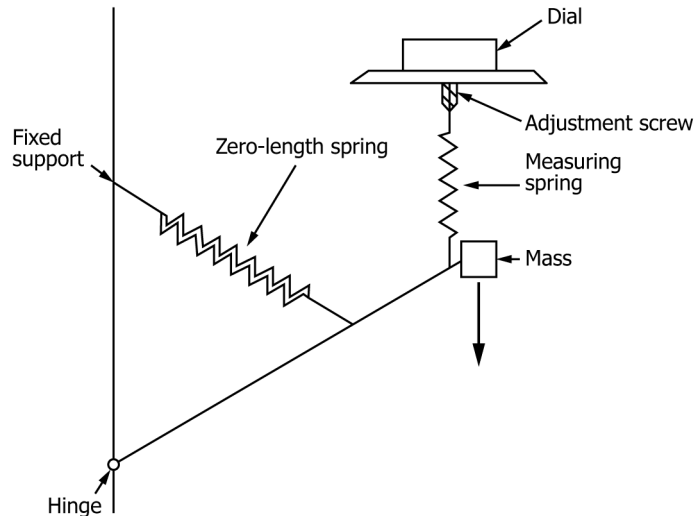


FIG. 1 Gravimeter (from Milsom (4))

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, Gal (in honor of Galileo), based on the gravitational force at the Earth's surface. The average gravity at the Earth's surface is approximately 980 gal. Gal. The unit commonly used in regional gravity surveys is the milligal mGal (10^{-3} gal). Gal). Typical gravity surveys for environmental and engineering applications require measurements with an accuracy of a few µgals µGals (10^{-6} gal). Gal), 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) meters to approximately 100 meters) and is carried out with a gravimeter capable of reading to a few µgals 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 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:

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.

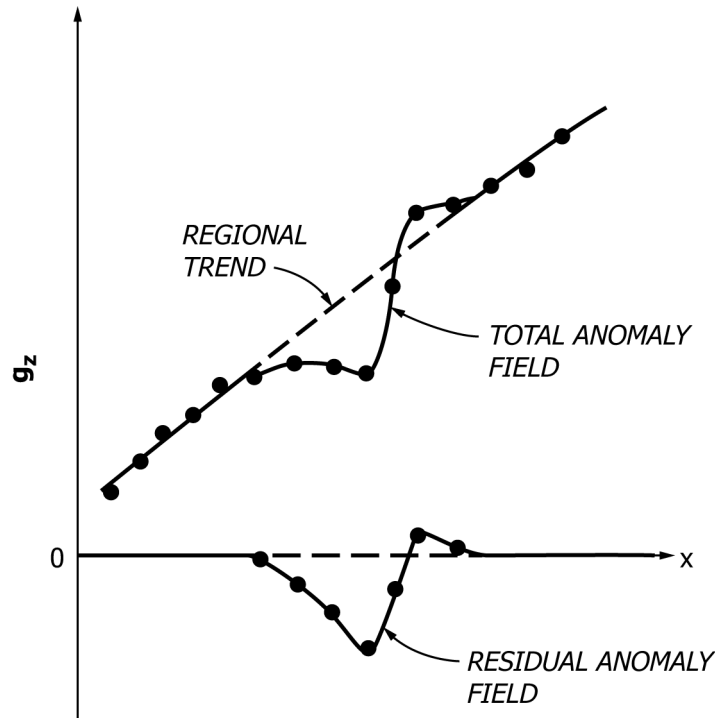


FIG. 2 Graphical Method of Regional-Residual Separation (from Butler (5))

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
Gabbro	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

5.3.2 *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 $1 \mu\text{Gal/m}$ 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* — *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 μgal 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 μgal .

(c) *Earth Tides*—Solar and lunar tides affect the force of gravity at the Earth's surface by as much as 300 μgal with a rate of change as large as 1 $\mu\text{gal}/\text{min}$. 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 non-geophysical 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*—*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, ~~the site characterization,~~ 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~~meters 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~~meters). 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.