MICROGRAVITY AND ITS APPLICATIONS TO CIVIL ENGINEERING

Gildas Omnes, Geoterrex, Ltd.

Microgravity surveys may be defined as surveys in which the accuracy of measurements is better than 0.05 mgal (0.5 $\mu m/s^2$) and the spacing between stations is less than 100 m. The development of microgravity as a tool for detecting cavities was favored because of local European conditions, particularly the numerous old underground quarries in and near the cities. A method was needed that could be used on roads still open to traffic, among or within buildings, and in gardens without causing any damage. Moreover, gravity measurements are not affected by the buried metal pipes that disturb resistivity measurements considerably. The productivity of microgravity crews was greatly increased by the introduction in 1968 of the Microgal gravity meter. Before the end of 1968, good standard gravity meters were used but stations had to be surveyed up to 3 times to obtain required accuracy. Significant anomalies of 0.020 mgal (0.2 $\mu m/s^2$) or a little less with an accuracy better than 0.004 mgal (0.04 $\mu m/s^2$) can now be studied. Microgravity has been successfully applied to the detection of several types of cavities. The amplitude of the anomaly due to a cavity frequently has been observed to be more than twice the size of the anomaly calculated on the basis of the dimensions of the cavity. A microgravity survey gives significant results only if the behavior of the gravimeter is observed continuously, the leveling of stations is carried out with an accuracy of better than 1 cm, and all calculations and corrections are adapted to the type of problem. A microgravity test carried out at Golden Hill near Boulder, Colorado, on an adit dug in a granite hill showed that the 6 by 8-ft (1.8 by 2.4-m) adit was detected at a depth greater than 20 ft (6.1 m).

•MANY European cities have been built with stone mined from underground quarries located under the cities themselves or on their outskirts. A large proportion of these quarries are centuries old and their exact location or even their existence is unknown. This also is true for old coal mines and natural cavities in limestone.

A phase of expansion for European cities began during the 1950s as larger buildings were erected, freeways were built, and the activities of the building industries were no longer restricted to the repair of damages caused by World War II. The need for a tool capable of detecting and mapping these cavities became evident. Drilling was certainly the first reconnaissance method used for that purpose. However, builders soon found out that drilling is a costly reconnaissance method. A high density of holes is necessary because the information given by a drill hole is strictly exact. A drill hole in a narrow natural dissolution joint and a drill hole intersecting a wide cavity may look the same. Working with even the lightest rigs where the land is still being cultivated or among old buildings or on roads still in use is often a problem. The advantages of a geophysical method sensitive to the volume of the cavities and based on the use of light instruments are evident.

As a consequence, the activity of Compagnie Générale de Géophysique (CGG) in the domain of cavity detection has been continual since 1958. Between 1958 and 1963, the main geophysical tool was direct-current resistivity, although some research and some tests were carried out on the application of seismic methods. Resistivity was successful enough to give rise to continual activity even though there are important drawbacks to the method. Cavities may be filled with air, mud, and rubble and give rise to resis-

tive or conductive anomalies or to no anomalies at all. Buried metal pipes disturb resistivity measurements in built-up areas. Use of even a short quadrupole array among buildings is sometimes difficult. Velocity contrasts due to cavities are generally more constant than resistivity contrasts, but the complexity of seismic sections near the surface makes the interpretation of seismic results very difficult. Electromagnetic methods are applicable where cavities are situated in very resistive rocks and where there is no clayey conductive overburden; these conditions rarely exist, at least in most temperate and tropical countries.

As early as 1940, gravimeters existed that had a sensitivity of 0.01 mgal (0.1 $\mu m/s^2$) but this sensitivity was never called on in structural studies. When the interval between stations is about 1,000 ft (304.8 m) or more, an accuracy better than 0.05 mgal (0.5 $\mu m/s^2$) is certainly not required, and gravimeters and theodolites are not used to the limits of their capabilities. Microgravity surveys may be defined as surveys where the Bouguer anomaly is defined with an accuracy better than 0.05 mgal (0.5 $\mu m/s^2$) and where the spacing between stations is less than 300 ft (91.4 m).

The first microgravity surveys were carried out on mining projects. The first paper published on the subject was by Hammer (1) in 1953 where a 0.36-mgal (3.6-$\mu m/s^2$) anomaly due to a chromite body was presented. The accuracy was estimated at 0.016 mgal (0.16 $\mu m/s^2$); the grid was 20 by 20 m. Approximately 20 years later, some surveys are carried out on a 2 by 2-m grid, and significant anomalies of 0.020 mgal (0.2 $\mu m/s^2$) or a little less are studied with an accuracy better than 0.004 mgal (0.04 $\mu m/s^2$), or 4 μgal. In 1963, Colley (2) published the first paper on the detection of caves by gravity measurements, but the topic was restricted to the detection of very large caves with a station interval of 100 m. CGG carried out its first microgravity survey for the detection of cavities in 1963 near Paris on a freeway route. Between 1963 and 1969, both resistivity and microgravity were used but the share of microgravity increased continually. Neumann (3), who supervised the development of microgravity as a tool for the detection of cavities, presented the first paper on the subject at a meeting of the European Association of Exploration Geophysicists in 1966.

There are 3 main advantages of microgravity for the detection of cavities.

1. Whether filled with air, fresh water, salt water, mud, or rubble, a cavity corresponds to a negative density contrast.
2. A gravimeter can be operated almost everywhere—on roads, on building sites, in gardens, even in basements—without disturbing the environment.
3. Gravity measurements are not affected by buried metal pipes or stray currents. Vibrations due to traffic or activity on building sites can be a problem, but operation during periods when these activities are stopped or greatly reduced is generally possible.

Until 1969, good standard gravimeters were used. An accuracy of 0.02 mgal (0.2 $\mu m/s^2$) could be obtained only by repeating measurements. Having to survey each station up to 3 times was a serious drawback. After several contacts with different manufacturers, one manufacturer came up with realistic and satisfying specifications. At the end of 1968, CGG started carrying out field work with the Microgal gravimeter. The "reading accuracy" of this gravimeter is about 2 μgal (0.02 $\mu m/s^2$), but the influence of instrumental drift is relatively stronger than for standard instruments, and the "measuring accuracy" is about 5 μgal (0.02 $\mu m/s^2$). When operated in the same conditions, the Microgal gives results affected by an error that is one-fifth of the error affecting the results obtained with a good standard gravimeter.

The introduction of the Microgal gravimeter increased the production of microgravity crews drastically. The last CGG resistivity surveys for the detection of cavities were carried out in 1971. Since 1958, 82 resistivity surveys for the detection of cavities had been carried out by CGG in Europe; among them, 8 were on freeway construction sites. Between 1963 and 1971, 55 microgravity surveys had been carried out; among them, 6 were on highways of freeway construction sites. After 1971, microgravity became the sole method used by CGG for the detection of cavities. Since the beginning of 1972, 63 microgravity surveys have been carried out for the detection of

cavities; among them, 5 took place on freeway construction sites. These figures prove that the application of microgravity to detection of cavities has been successful.

GRAVITY ANOMALIES DUE TO CAVITIES

Figures 1 and 2 show examples of theoretical anomalies corresponding to possible types of cavities. Amplitudes generally do not exceed 0.3 mgal (3 $\mu m/s^2$), and anomaly widths slightly exceed cavity widths.

After 10 years of experience with microgravity surveys over cavities, Neumann (4) said:

> The fact that measured anomalies are always larger than the anomalies calculated on the basis of the geometrical dimensions should be considered as established experimentally. Observed anomalies are frequently more than twice the size of the corresponding calculated anomalies. This is certainly a most important fact in favor of microgravity. It authorizes the application of microgravity to problems which were considered as beyond the reach of all geophysical methods a few years ago.

This phenomenon is attributed to stress relief, jointing, and dissolutions induced by the creation of the cavity. The density contrasts created by decompression, jointing, and dissolution are weak, but they affect volumes much larger and closer to the surface than the cavity itself. Figure 3 shows a weak anomaly barely larger than 0.05 mgal (0.5 $\mu m/s^2$) associated with an underground quarry. Actually this amplitude is more than twice the theoretical influence of the voids. The height of the chambers ranges between 1 and 2 m. They are 16 m deep, and the total volume of the pillars is larger than the total volume of the voids. Secondary efforts of this nature are naturally stronger above older cavities and in rocks subject to jointing and dissolution such as limestone, gypsum, and schist. They are weaker in the case of recent cavities dug in compact homogeneous rocks such as some granites or sandstones. In the case of Figure 3, it is interesting to note that the first drill holes intersected pillars. Drilling additional holes was decided on only because of the microgravity results. Contour interval in Figure 3 is 0.01 mgal (0.1 $\mu m/s^2$).

Figure 4 shows a stong anomaly due to a karstic cavity; its amplitude reaches 0.26 mgal (2.6 $\mu m/s^2$). A drill hole located at its center did not intersect any void, but refraction results showed that the limestone is replaced by loose material in locations. Subsequent geological studies showed that several karstic cavities in the area had been filled with coarse detrited material from a nearby creek. Contour interval in Figure 4 is 0.02 mgal (0.2 $\mu m/s^2$). Figure 5 shows a 0.03-mgal (0.3-$\mu m/s^2$) anomaly due to a much smaller shallow karstic cavity on a freeway building site. The small sink hole appeared after the completion of the survey when a light post was being set up. Contour interval in Figure 5 is 0.01 mgal (0.1 $\mu m/s^2$).

Figure 6 shows a fortunately rare occurrence. Anomalies A and B have almost the same amplitude. Anomaly A corresponds to a known quarry. Several drill holes on anomaly B failed to intersect any cavity. Anomaly B is now considered to be due to geological causes. Contour interval in Figure 6 is 0.02 mgal (0.2 $\mu m/s^2$).

REQUIREMENTS AND FIELD PROCEDURES

We emphasize that substituting a Microgal for a standard gravimeter is not enough. All procedures should be adapted to the conditions particular to microgravity. The gravimeter operator must not be misled by the apparent simplicity of measurements. He or she must continually study the behavior of the gravimeter, temperature, and light shocks and note drift in detail. Results may be disappointing if the operator is not permanently conscious of the fact that the best possible performances are asked for. Figure 7 shows a comparison on a 2 by 2-m grid of results obtained by an operator who did not know more than taking readings (Figure 7a) with results obtained by an

Figure 1. Theoretical anomalies and detection of cavities, example 1.

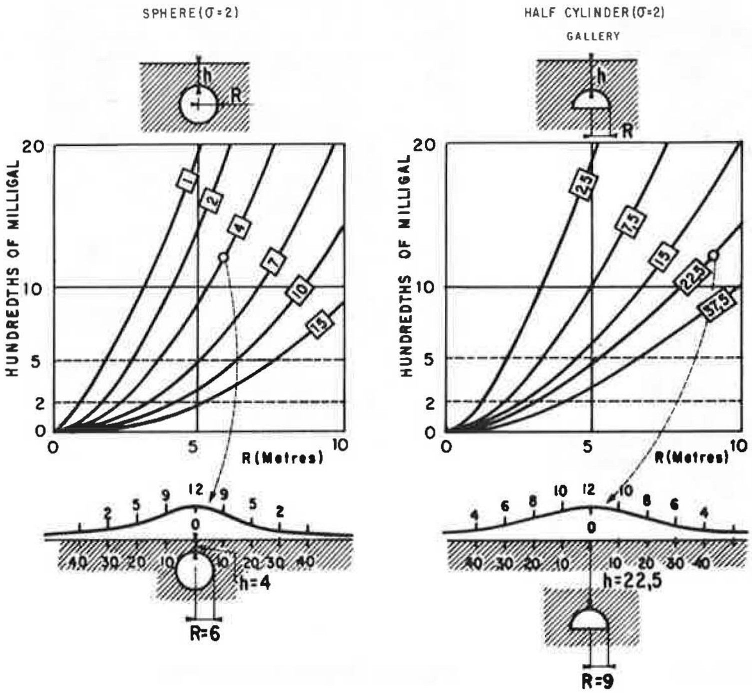


Figure 2. Theoretical anomalies and detection of cavities, example 2.

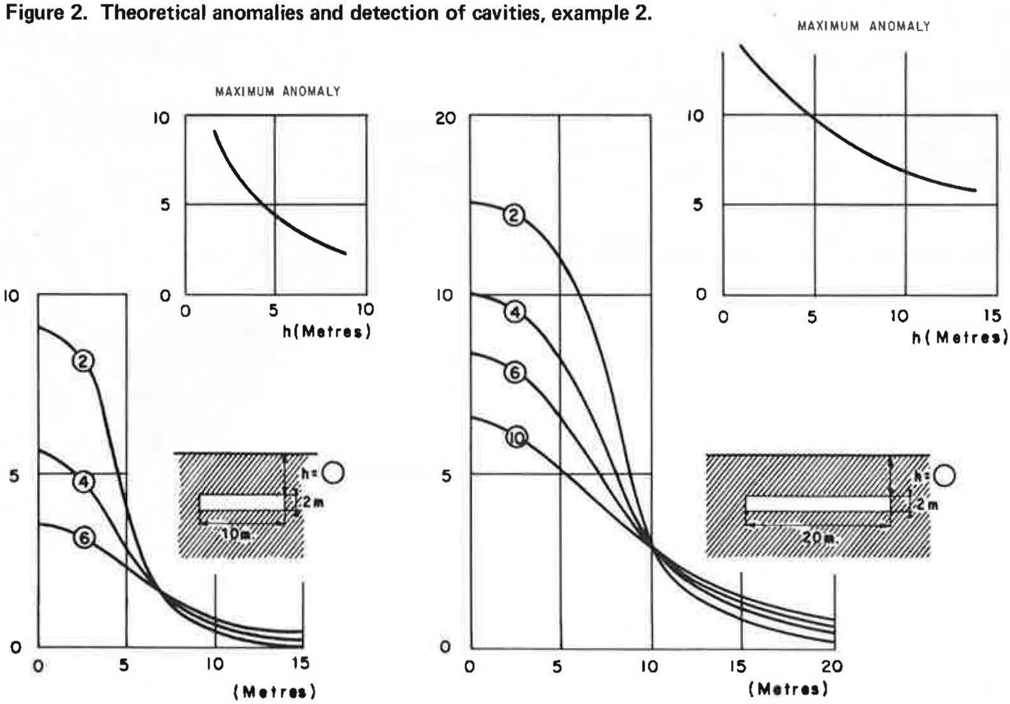


Figure 3. Residual anomaly for gravimetry and drill holes.

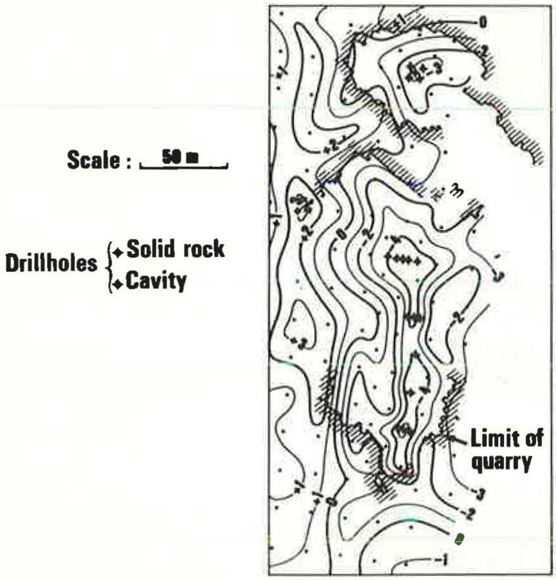


Figure 4. Detection of karstic cavities.

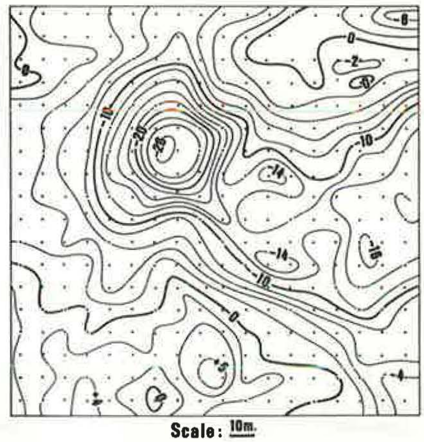


Figure 5. Detection of cavities under freeway.

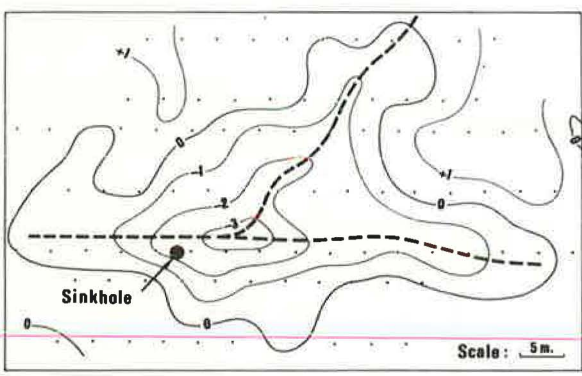
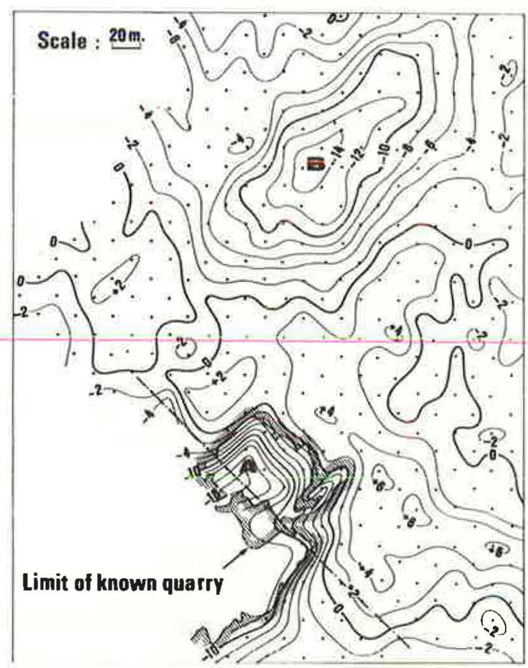


Figure 6. Detection of quarries.



operator aware of the intricacies of the behavior of a highly sensitive gravimeter (Figure 7b).

At shallow depths the anomaly is not much wider than the anomalous body itself. Therefore, the grid should not be larger than the horizontal projection of the cavity. Figure 8 shows the result of a test over a known cavity by using 2 different grids. In Figure 8b, the exact location of the cavity cannot be deduced from the gravity anomaly.

The Bouguer anomaly may be written

$$B = g - g_0 + cz + T \qquad (1)$$

where

g = measurement in milligals (micrometers per second^2),
g_0 = value of g on the international ellipsoid in milligals (micrometers per second^2),
c = 0.3086 - (0.0419 × d) in milligals per meter (micrometers per second^2 per meter),
d = density of formations affected by elevation variations,
z = elevation in meters, and
T = terrain correction in milligals (micrometers per second^2).

The surveying should be accurate enough to render negligible the errors due to the corresponding corrections; obtaining an accuracy of 1 cm in elevation and 10 cm in position is not difficult. Terrain corrections are a more difficult problem when they are necessary. Special charts have been calculated that make use of the elevations of the surrounding stations and not of the contours. Because the extent of microgravity surveys is generally small, the effect of remote large reliefs may be considered as part of the regional anomaly. The determination of d is carried out by various methods, all of which are based on the cancellation of correlations between the variations of the Bouguer anomaly and elevation variations. Computers currently are used for this operation because the solution is sometimes complex and d varies horizontally as well as vertically.

MICROGRAVITY TEST AT GOLDEN HILL

In June 1974, a test was carried out by Geoterrex, Ltd., for the U.S. Bureau of Mines on an old adit driven in a granite hill near Boulder, Colorado. The adit is driven horizontally from the surface under a 15-deg slope. The width of the adit is approximately 6 ft (1.8 m), and its height is 8 ft (2.4 m). The adit is not located in homogeneous granite but follows shattered quartz veins.

The contoured Bouguer anomaly is presented in Figure 9. A density of 2.5 was taken for the superficial formations after other values were tested. In this case, the number of stations is too small for the application of statistical methods and the determination of variations of d.

In Figure 10, the Bouguer anomaly and a section of the ground on line 1 are plotted. A plane regional anomaly was assumed on all lines because it appears to correspond to an actual phenomenon and because the total number of stations is too small for the application of more refined calculations or a regional anomaly. Terrain corrections were not carried out because of the small size of the surveyed area located on the flank of a large hill. Terrain effects are considered as included in the regional anomaly. Figure 11 shows the resulting residual anomaly. In lines 2 and 3, a negative axis coincides with the projection of the main adit; moreover, isogals are parallel to the secondary adit.

To verify the validity of the residual anomaly, one may compare it to a map obtained through a more "objective" method. Figure 12 shows a map of an approximation of a calculated vertical gradient. This vertical gradient was calculated separately on the 3 lines by using an approximative formula reduced to the sum of 3 terms instead of the

Figure 7. Comparison of results obtained by (a) operator who did not know more than taking readings and (b) operator aware of the intricacies of gravimeter.

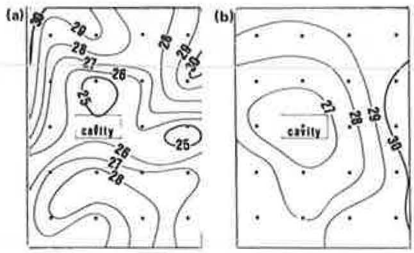


Figure 8. Importance of density of stations for (a) 2 x 2-m grid and (b) 4 by 4-m grid.

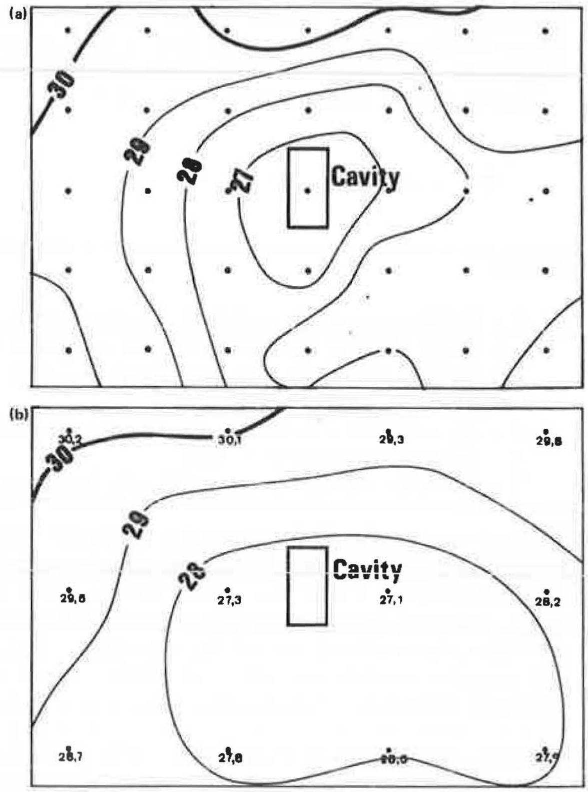


Figure 9. Golden Hill Bouguer anomaly.

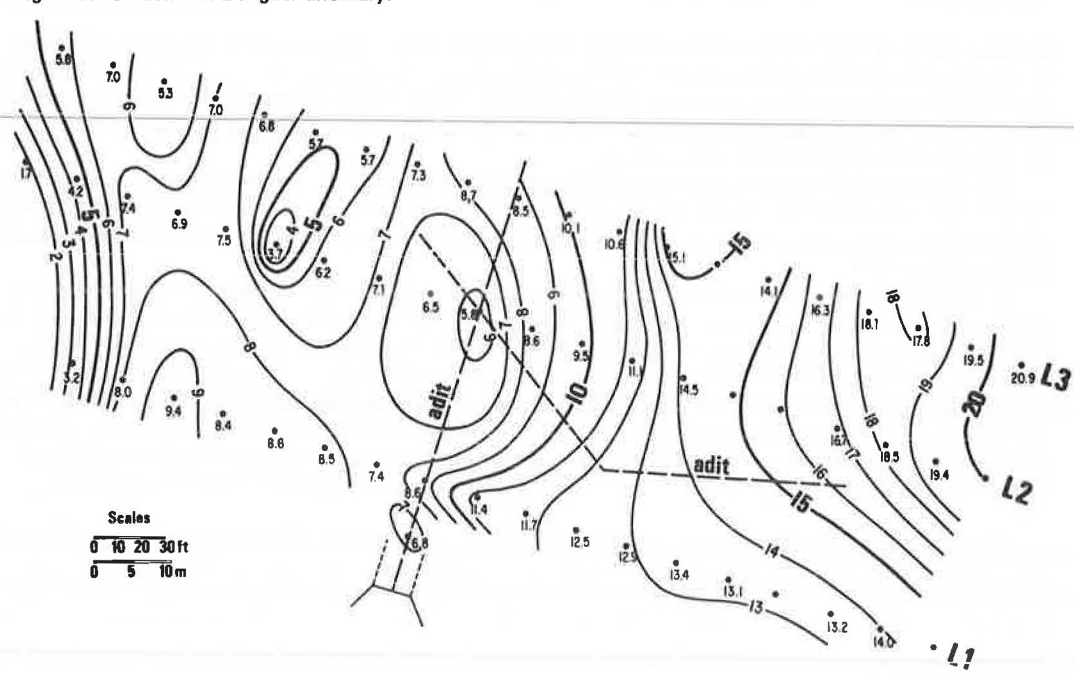


Figure 10. Golden Hill line 1.

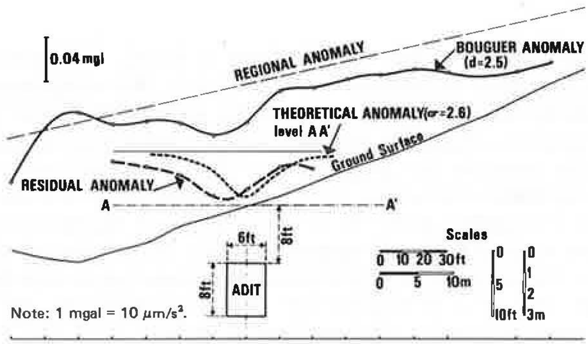


Figure 11. Golden Hill residual anomaly.

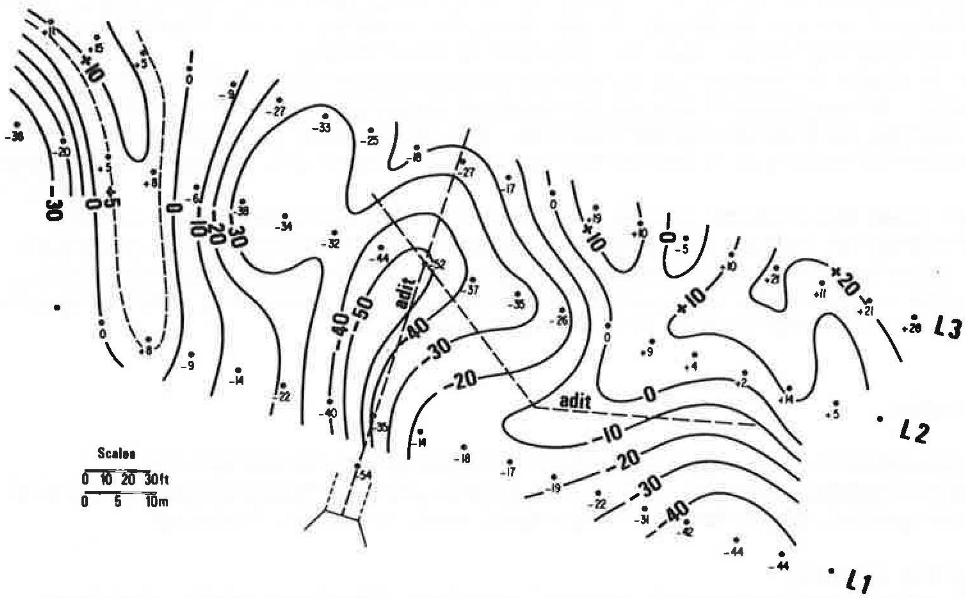
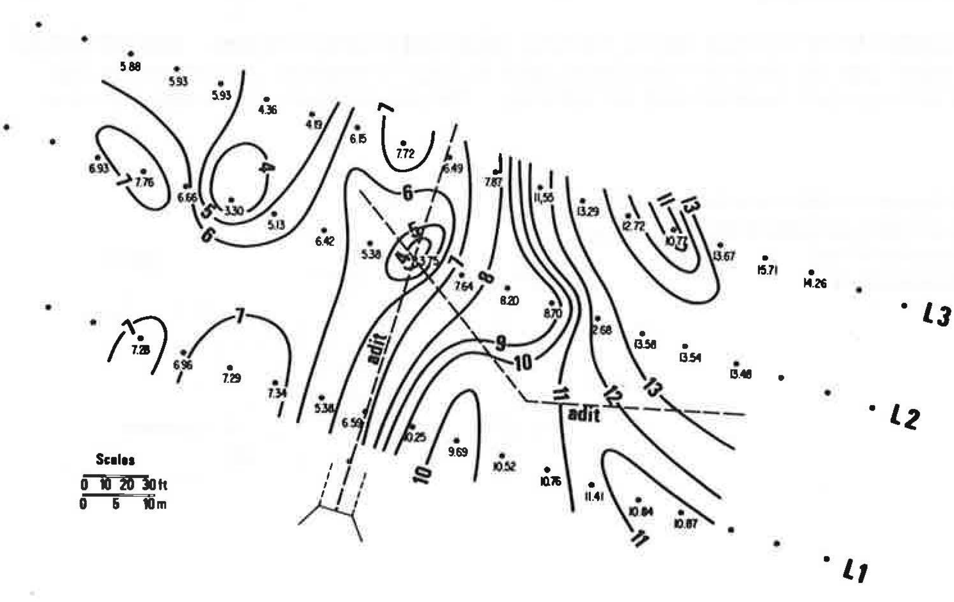


Figure 12. Golden Hill approximate calculation of vertical gradient.



minimum of 5 generally used for calculations by hand. The result is in good agreement with the residual anomaly of Figure 11. On line 1, the minimum of the residual anomaly does not coincide with the projection of the axis of the adit (Figure 10). This could be thought to be due to a residual terrain effect similar to the effect shown in Figure 13. This effect results because the Bouguer anomaly is the difference between a measurement of the gravity field corrected for instrumental drift and lunisolar variations and a theoretical value associated with the station (5). The theoretical value is $g_0 - cz - T$. Consequently, the values of the Bouguer anomaly calculated at stations located at different elevations are affected by elevation variations as shown by Figure 13.

In some cases, the axis of an anomaly may be displaced. This effect can be compensated for by carrying out a continuation of the gravity field. A horizontal datum plane is selected, and the gravity field at the projection of each station on the datum plane is calculated. These calculations generally are carried out by computers, but an approximation can be obtained by hand. Calculation by hand is an extrapolation based on the calculated vertical gradient. In this case, the residual terrain effect was verified to be not large enough to shift the minimum of the anomaly.

Figure 10 shows the theoretical anomaly corresponding to the adit for a density contrast of -2.6. Its amplitude is almost the same as the amplitude of the experimental anomaly, and the right flanks almost coincide. The discrepancy between the left flanks can be considered to be due to low-density near-surface material, perhaps a small landslide.

Further quantitative interpretation work does not seem warranted in this case because the number of stations is relatively small and because the bedrock is not homogeneous. Also the compensation for terrain effects cannot be carried out accurately. However, the results of the test appear to be positive, and a small 6 by 8-ft (1.8 by 2.4-m) adit at a depth greater than 20 ft (6.1 m) can be detected.

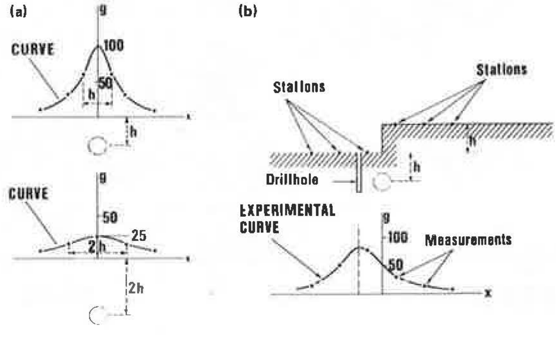
CONCLUSIONS

The examples given in this paper show that microgravity is undoubtedly a well-established geophysical method. It has been particularly successful in the detection of all types of cavities, empty or filled with water, mud, or rubble, including

1. Karstic cavities;
2. Old underground quarries in various formations (limestone, chalk, sandstone, schist, and granite);
3. Old open quarries filled with rubble, soil, and the like; and
4. Old mine workings.

Most surveys were carried out on building sites and freeway routes. For historical reasons, microgravity until now has been used mainly in western Europe where the number of surveys per year is still increasing. The advantages of microgravity are

Figure 13. Influence of residual terrain effect for (a) anomalies at constant levels (upper and lower levels) and (b) experimental anomaly.



such that it can be expected to be used widely in karstic countries and in old mining areas outside western Europe.

ACKNOWLEDGMENT

I wish to thank Robert Neumann for all the documents taken from his previous papers and presented here. Figures 1 through 8 and Figure 13 are based on his work.

REFERENCES

1. S. Hammer. Usefulness of High Quality Gravity Surveys. Oil and Gas Journal, Sept. 1953.
2. G. C. Colley. The Detection of Caves by Gravity Measurements. Geophysical Prospecting, Vol. 11, No. 1, 1963.
3. R. Neumann. La gravimetrie de haute precision—Application aux recherches de cavites. Geophysical Prospecting, Vol. 15, No. 1, 1967.
4. R. Neumann. Prospection gravimetrique appliquee a la localisation des cavites souterraines. Hanover, 1973.
5. H. Naudy and R. Neumann. Sur la definition de l'Anomalie Bouguer et ses consequences pratiques. Geophysical Prospecting, Vol. 13, No. 1, 1965.
6. R. Neumann. High Accuracy Gravity—Recent Progress. Compagnie Générale de Géophysique, Paris, June 1972.

SPONSORSHIP OF THIS RECORD

GROUP 2—DESIGN AND CONSTRUCTION OF TRANSPORTATION FACILITIES
W. B. Drake, Kentucky Department of Transportation, chairman

SOIL AND ROCK PROPERTIES AND GEOLOGY SECTION
L. F. Erickson, Idaho Department of Highways, chairman

Committee on Exploration and Classification of Earth Materials
Robert L. Schuster, U.S. Geological Survey, Denver, chairman
Robert C. Deen, Edward A. Fernau, Albin D. Hirsch, William P. Hofmann, Frank L. Jagodits, Robert B. Johnson, Ralph W. Kiefer, Robert D. Krebs, Clyde N. Laughter, R. M. Mattox, Donald E. McCormack, Olin W. Mintzer, R. Woodward Moore, Arnold C. Orvedal, David L. Royster, A. Rutka, Robert B. Sennett, William W. Shisler, Preston C. Smith, Ernest G. Stoeckeler, J. Allan Tice, Walter H. Zimpfer

John W. Guinnee, Transportation Research Board staff

The organizational units and the chairmen and members are as of December 31, 1974.