February 1998

Micrograviity investigations of foundation conditions

GEOPHYSICS, VOL. 63, NO. 1 (JANUARY-FEBRUARY 1998); P. 95–103, 6 FIGS.

Microgravity investigations of foundation conditions

Donald E. Yule*, Michael K. Sharp*, and Dwain K. Butler*

ABSTRACT

A microgravity investigation was conducted in the upstream and downstream switchyards of the Wilson Dam powerplant, Florence, Alabama. The objective of the survey was the detection in the switchyard foundations of subsurface cavities or other anomalous conditions that could threaten the stability of the switchyard structures. The survey consisted of 288 gravity stations in the downstream switchyard and 347 stations in the upstream switchyard. Significant anomalous areas in the switchyards were selected on the basis of residual gravity anomaly maps. These results were prioritized and used to guide an exploratory drilling program to investigate the cause of the anomalies. Highest-priority boring location recommendations were in negative gravity anomaly areas, since negative anomalies could be caused by actual cavities or low-density zones that might represent incipient cavity formation. Remaining boring locations were in positive anomaly areas for verification purposes. The results of the borings confirm the presence of cavities and soft zones indicative of cavity formation.

BACKGROUND

A cavity was discovered in foundation fill material beneath the upstream switchyard of Wilson Dam powerplant, Florence, Alabama (Figure 1). The cavity was approximately 3 m (10 ft) in diameter, extended to within 0.6 m (2 ft) of the surface, and was manifested by a small surface depression resulting from settlement caused by piping of soils into the cavity. After the cavity was filled with concrete, subsequent exploratory drilling encountered no further cavities beneath the original cavity and above the top of rock. Rock (limestone) was encountered at depths of 11.6–17.4 m (38–57 ft), and within the formation, cavities up to 0.4 m (1.5 ft) in vertical extent were encountered. Concern about the possible existence of other cavities beneath the upstream switchyard as well as the downstream switchyard dictated a thorough foundation investigation (Yule et al., 1990). An extensive exploratory drilling program in these switchyards would be very hazardous and expensive because of the confined working space and close proximity of high-voltage structures. Therefore, it was necessary to find a way to rationally focus the drilling program while ensuring complete coverage of the site. All engineering geophysical methods were considered, and several were selected for field testing (microgravity, resistivity, and seismic methods). Because of the need for a high-resolution survey to detect small targets while covering as much of the site as possible, noise effects and method survey footprints were important considerations. The seismic methods were hindered by noise from the powerhouse activities and limited site access for source and receivers and the small target features. The electrical methods were negated by a near-surface buried copper mesh grounding mat. Ground-penetrating radar and electromagnetic methods were not tried because of the dense assemblage of buried, surface, and overhead conductors and electromagnetic fields in the switchyards. Microgravimetry emerged as the only viable geophysical method of measurement for application under the severe constraints in the switchyards.

Microgravimetry indicates the accuracy and also generally the scale of gravity surveys. A gravity measurement accuracy of 2–5 μGal is required to ensure anomaly significance in the range of 5–10 μGal. Station spacings for small-site microgravity surveys are typically 1.5–6 m (5–20 ft). Gravity meters with inherent sensitivities of 1–2 μGal are required. Detection and delineation of subsurface cavities are frequent applications for microgravity surveys, although the technique also is used to detect bedrock channels, covered mine shafts, underground tanks, and landfill cells (Camacho et al., 1994; Hinze, 1990; Wenjin and Jiajian, 1990). Results of a microgravity survey generally allow the most definitive assessment of the presence or absence of shallow cavities (depth, $\lesssim$6–8 effective cavity diameters) at a site (Butler, 1980, 1984a, 1984b).

SITE GEOLOGY

The project site is located on a river bluff with an approximate elevation of 150 m (500 ft), national geodetic vertical datum (NGVD) along the Tennessee River, in the Black Warrior

Manuscript received by the Editor June 5, 1995; revised manuscript received March 5, 1997.
*Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180. E-mail: yuled@ex1.wes.army.mil; sharpm@ex1.wes.army.mil; butled@ex1.wes.army.mil.

Basin of the Interior Low Plateaus Province. The site geologic cross-section is engineered fill on overburden extending to bedrock at depths of 11.5–17.4 m (38–57 ft). The overburden sediments are sands, gravels, and clays. The bedrock is the Fort Payne Formation, a member of the Osage group, of Mississippian age. This formation is a gray, crystalline, hard limestone with chert beds. Site borings show solution features, open cavities, voids, vugs, and weathering along bedding planes throughout the rock cores, which extend to depths of 30 m (100 ft).

SURVEY DETAILS AND FIELD PROCEDURES

The downstream and upstream switchyard gravity station grids consisted of 288 and 347 measurement stations, respectively. Each station on soil consisted of a 2 × 2 inch stake driven flush with the ground surface, while stations on concrete were marked with paint. The elevation of each station was determined with a total-station surveying instrument to within an accuracy of 0.3 cm (0.01 ft). A basic grid dimension of 3 m (10 ft) was used in the interior of the areas and modified as required by locations of switchyard structures. In remote areas of the switchyard, the grid dimension was increased to 6.1 m (20 ft). A detailed explanation of microgravity survey field procedures is given in Butler (1980). Data were collected with a Lacoste & Romberg model D gravity meter. This meter has electronic levels, a sensitivity of approximately 1 μGal, and an accuracy of 3–5 μGal for relative gravity measurements. Data collection consisted of loops of 6 to 10 "reasonably" random selected gravity station measurements between two successive occupations of the base station. A time limit of 30–45 minutes was imposed between base station measurements. The base station reoccupations were used to correct the survey data for time-varying gravity values caused by earth tides and instrument drift. Theoretical tide curves and/or tables were compared with the site base station data and with recorded tidal data acquired during periods when grid stations were not being measured (Butler, 1980).

Each loop or set of readings included one or more stations that were occupied during a previous loop. During the upstream microgravity survey, 33% of the stations were reoccupied (two or more measurements), and during the downstream survey, 27% were reoccupied. Comparison of the repeat values, after correction for the factors described in the following section, allowed the quality and accuracy of the data to be monitored during the course of the survey.

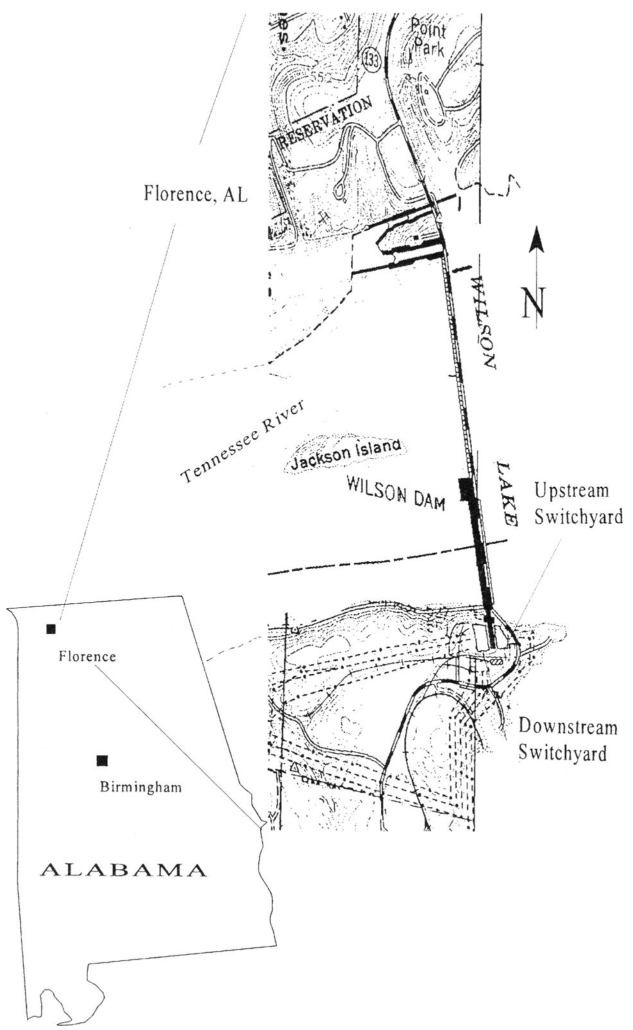

FIG. 1. Site map showing location of Wilson Dam in Florence, Alabama.

GRAVITY CORRECTION CONSIDERATIONS

Corrections to microgravity data are required to compensate for normal gravity variations at the site over the time span required for the survey. Measured values are corrected for effects caused by variations in latitude, elevation, topography, earth tides, and instrument drift. These normal gravity variations and compensating corrections applied to microgravity data are discussed in brief below. For a more in-depth discussion of gravity data corrections, see Butler (1980) or Telford et al. (1990).

Corrections for time variations

Gravity values over a survey area change with time because of earth tides and instrument drift. Instrument drift is caused by creep of the metal components in the meter as a result of thermal expansion or excessive movement. Over short time periods (less than 60 minutes), tidal gravity variation is approximately linear with time. The procedure used for correcting time variations is frequent reoccupation of a base station and assumption that the gravity values at all stations in the survey area vary in the same manner as at the base station. The drift correction Δg_{zD} for each station is determined directly from the base station data.

Latitude correction

Both the rotation of the earth and its nonspherical shape produce an increase in gravity values with latitude. For the relatively small areas of microgravity surveys, it is sufficient to assign a reference latitude to the base station and use equation (1) to compute latitude corrections Δg_{zL} for all other stations,

$$\Delta g_{zL} = \pm 0.811 \times \sin(2\phi) \times \Delta s, \qquad (1)$$

where Δg_{zL} is given in μGals, Δs is the north-south distance (in meters) between the measurement and the base station, and ϕ is the reference latitude of the base station (34.5° for this site). The correction term is added (subtracted) to the measured

gravity value if the station is positioned south (north) of the base station.

Free-air correction

The free-air correction Δg_{zFA} compensates for variations in gravitational attraction caused by the changing distances of the measurement stations from the center of the earth and is written as

$$\Delta g_{zFA} = \pm 308.55 \times \Delta h, \quad (2)$$

where Δg_{zFA} is given in μGals and Δh is the difference between the elevation (in meters) of the measurement station and the reference elevation of the base station. The correction term is added (subtracted) to the measured gravity value if the elevation of the station is higher (lower) than the reference elevation.

Bouguer correction

The Bouguer correction Δg_{zB} compensates for gravity values affected by different masses of material beneath the measurement stations solely as a result of elevation variations and is written as

$$\Delta g_{zB} = \pm 41.91 \times \rho \times \Delta h, \quad (3)$$

where Δg_{zB} is given in μGals, ρ is the material density (in grams per cubic centimeter; 1.8 g/cm^3 for this site), and Δh is the elevation difference (in meters) between the measurement station and the base station. The quantity Δg_{zB} is subtracted (added) from the measured gravity if the elevation of the station is above (below) the reference elevation.

Bouguer gravity values

When all of the preceding corrections have been applied to the observed gravity data, the result is the Bouguer gravity value g_B, which is written as

$$g_B = g_{\text{obs}} \pm \Delta g_{zL} \pm \Delta g_{zFA} \pm \Delta g_{zB} \pm \Delta g_{zD}, \quad (4)$$

where g_{obs} is the observed gravity reading and the remaining terms are the gravity corrections discussed above. Subtracting the gravity readings recorded at the base station g_{base} from the Bouguer gravity values at each station with the equation

$$\Delta g_B = g_B - g_{\text{base}} \quad (5)$$

results in the Bouguer gravity anomaly.

Terrain correction and regional-residual field separation

Terrain correction compensates station gravity values for the attraction of terrain features. Within the upstream and downstream switchyard gravity grid areas, the only corrections were for the switchyard structures, including the transfer track trenches, each approximately 0.8×1.2 m (2.5×4 ft) in cross-section, since the areas were otherwise flat. Outside the downstream survey grid area there are small dropoffs (approximately 2 m, or 6.5 ft) to the south and the east and a significant dropoff (>30 m, or >100 ft) resulting from the Tennessee River bluff to the north. Outside the upstream survey grid area, however, there are significant topographic variations that must be addressed: large dropoffs on the north and east boundaries of the survey area, resulting from the location of the switchyard on the high bluffs above the Tennessee River and the impounded reservoir.

Careful consideration was given to the terrain of effects on the switchyard structures. The terrain corrections for the transfer track trenches were accomplished by modeling each trench as a horizontal, rectangular cross-section prism of infinite extent. Because of the impracticality of directly modeling the complex assemblage of the above-ground transformers and switchbanks, other approaches were followed. Gravity measurements were made around one of the transformers in an effort to detect its gravity effect. Also, the gravity anomaly for a simple model of a transformer was calculated. These efforts indicated that the effect of a transformer on gravity measurements was less than 5 μGal for distances of greater than 3 m (10 ft) from the base. Next, an overlay of the non–terrain-corrected gravity anomaly map and a switchyard structure location map was examined for correlations. There was no apparent correlation between structure locations and gravity anomalies. Therefore, it was concluded that the net effect of the dense assemblage of structures was approximately constant over the interior of the survey grid.

Because of the small target size, 3 m in diameter or less, and the shallow depths of interest, less than 30 m, the gravity effects of topographic features outside the survey areas generally will have spatial wavelengths larger than that of the target anomalies. Therefore, the topographic features outside the survey area can be treated as components of the local regional field variation and corrected in a single regional-residual field separation step (Butler, 1980, 1985). The local regional field can be estimated by row and column averaging of the gravity data, polynomial surface fitting to the gravity data, or analytical forward modeling (Balch and Thompson, 1989; Butler and Yule, 1984; Butler, 1985). The procedures used to correct the data for topographic variations are discussed in the following sections.

DATA PROCESSING

Initial processing

The initial field processing consisted of applying the drift, latitude, free-air, and Bouguer corrections to the gravity readings. The readings were inspected for agreement of repeat measurements and for anomalous high or low readings with respect to readings for surrounding stations. The repeat station measurement differences (mean $\pm$ standard deviation) were 5 ± 3 μGal for the downstream switchyard and 10 ± 6 μGal for the upstream switchyard. This procedure was instituted daily to allow modifications to the data acquisition to investigate possible inconsistencies in the data.

Regional-residual field separation

A final grid file was used to generate the Bouguer gravity map, which was inspected to identify general regional field characteristics so that an appropriate regional-residual field separation method could be selected. Postsurvey data processing consisted of application of terrain corrections and regional field removal, producing the final residual gravity map. The residual gravity map was used for anomaly selection and

interpretation. The final processing step involved removing the effects of the regional gravity field component and surrounding terrain features. A direct approach is to calculate analytically the gravity effects of surrounding terrain and shallow geologic structures for each measurement station. Although these methods are the most direct and rigorous, they require additional elevation data to define the surrounding terrain and much detail about the geologic structures below and around the survey area. Another approach, which relies only on the gravity data set, is possible if there is a heavily populated, well-distributed data set for the survey area: "Best-fitting" surfaces can be generated for the Bouguer gravity map. Correcting the gravity data by removing a best-fitting surface through the data accomplishes local regional-residual field separation and corrects for the effects of terrain outside the survey area. The degree of the surface removed from the data determines the spatial wavelengths of the anomalies that will be removed and those that will be passed over. It is desirable to remove spatial wavelengths on the order of and greater than the survey grid dimensions from the gravity map. Since the spatial wavelength is proportional to the maximum possible depth of the causative subsurface feature, these procedures result in a residual map that contains gravity anomalies caused predominantly by subsurface features shallower than the mean survey area dimension in depth.

A simple, direct approach to define and remove the site regional field and correct for nearby terrain is to use a row and column average removal technique. This approach works well if the regional field has components that are broad and well defined in one direction, especially if the direction coincides with a grid axis. Removal of row and column averages was successfully implemented in the removal of the river bluff effect in the survey of the downstream switchyard. Later reprocessing of the downstream switchyard data with polynomial surface removal verified the appropriateness of the earlier approach. However, this simple approach is too crude for the regional field that exists in the data from the upstream switchyard. The upstream switchyard survey requires a more versatile approach to appropriately model the gravity data surface trends. A general polynomial surface removal can account for more complicated regional fields and terrain geometries with no preference for features aligned with the grid axes.

After the regional field separation step was accomplished, the resulting residual gravity map was examined to identify anomalies. This is a judgement phase in which relative high- and low-gravity areas are selected for subsequent investigation. The residual anomalies, particularly their magnitudes, are a function of the selected regional surface. The regional surface defines the local reference level over the site from which depart relative high- and low-gravity areas. However, if an anomaly is detectable, a possible error caused by selecting an arbitrary reference surface would incorrectly estimate the size and depth of the subsurface feature causing the anomaly. The grid location of the feature would be relatively unaffected.

RESIDUAL ANOMALY MAPS

The Bouguer gravity map for the upstream switchyard is shown in Figure 2, and that for the downstream switchyard is shown in Figure 3. The local regional field and terrain effects are evident as the broad surface trends, and the scattered, relatively small surface deviations are gravity anomalies caused by shallow, subsurface density anomalies. The purpose of the subsequent processing is to remove these broad trends and enhance and reveal localized deviations from the overall trend.

Downstream switchyard

The row and column average removal technique, which involves finding the grid row and column averages and then subtracting these quantities from the Bouguer gravity, was used successfully for the data set from the downstream switchyard (Yule and Butler, 1984). As shown in Figure 4, a plot of row averages clearly defined the decreasing gravity values from south to north (toward the river bluff); this plot was closely predicted by the gravity response of the 2-D model shown below the data in the figure. It is clear from a comparison of measured and modeled gravity response data that the decrease in gravity observed in the row averages was caused predominantly by the river bluff. Calculations such as those shown in Figure 4 were made for various rock densities and bluff slopes (since the bluff slope is not well characterized). The best fit to the data in Figure 4 was for a rock density of $\rho_R = 2.5\ \text{g/cm}^3$ and a bluff slope of 45°. Including the small dropoff to the south of the survey area in the model provided a nearly exact fit to the measured data.

In later reprocessing of the downstream data set, polynomial surface modeling was used for the regional-residual field separation (Camacho et al., 1994). In this method, a mathematical surface was generated to fit the non–terrain-corrected Bouguer gravity data with a polynomial equation of various orders. For this data set, second-, third-, and fourth-order polynomial surfaces were fit to the data with the calculated degrees of fit, a measure of how well they approximated the original surface, 91.3%, 91.4%, and 91.9%, respectively. These results led to the conclusion that the second-order fit was appropriate, supporting the earlier row and column averaging approach in this case. The procedure described here accomplishes the external terrain correction and local regional-residual field separation in a single step. The results from both regional-residual field separation techniques were very similar. Figure 5 is a plot of the downstream switchyard residual gravity anomaly derived from the polynomial surface fitting method.

Upstream switchyard

Because of the complexity of the upstream switchyard regional trend, the local regional field was removed by use of polynomial surface fitting. The nature of the Bouguer gravity surface indicated a third-order polynomial surface as a minimum. Higher-order (fourth and fifth) surfaces also were generated to model the regional field to help select the appropriate fit. The calculated degrees of fit for third-, fourth-, and fifth-order polynomial surfaces to the Bouguer gravity, 86.5%, 90.3%, and 90.9%, respectively, led to the conclusion that the fourth-order fit was appropriate and fit all the long-wavelength features of the surface. The residual gravity anomaly map (obtained by subtracting the fourth-order best-fit surface from the Bouguer anomaly map; Figure 3) is shown in Figure 6.

ANOMALY SELECTION AND ASSESSMENT

Anomalous zones were identified on the residual gravity maps and ranked. The zones were identified on the basis of

whether they exceeded a threshold level (±10 μGal), possessed areal coherence, and were unexplained.

The ranking was based on considerations of location (near critical structures or the known past sinkhole) and anomaly sense. Negative anomalies are of critical interest for this survey, whereas verifying the positive anomalies is useful in determining the correctness of the data processing and to help in explaining general subsurface conditions. In the downstream switchyard, anomalous areas, such as those indicated by A to H in Figure 5, were selected and prioritized as possible targets for the verification drilling program. Anomalies A, B, C (C′ and C″), F, and G are closed negative features that could indicate shallow (<10-m), compact cavities or low-density zones. Anomaly D is distinctive because of its large negative magnitude (≈−60 μGal) and relatively small spatial extent (<10 m); this anomaly could be caused by a near-vertical, cylindrical, low-density feature that lies very close to the surface. Anomaly E was identified as an artifact of the terrain correction process and assigned allow priority. Anomaly H is a positive-anomaly area arbitrarily selected for validation and is embedded in a

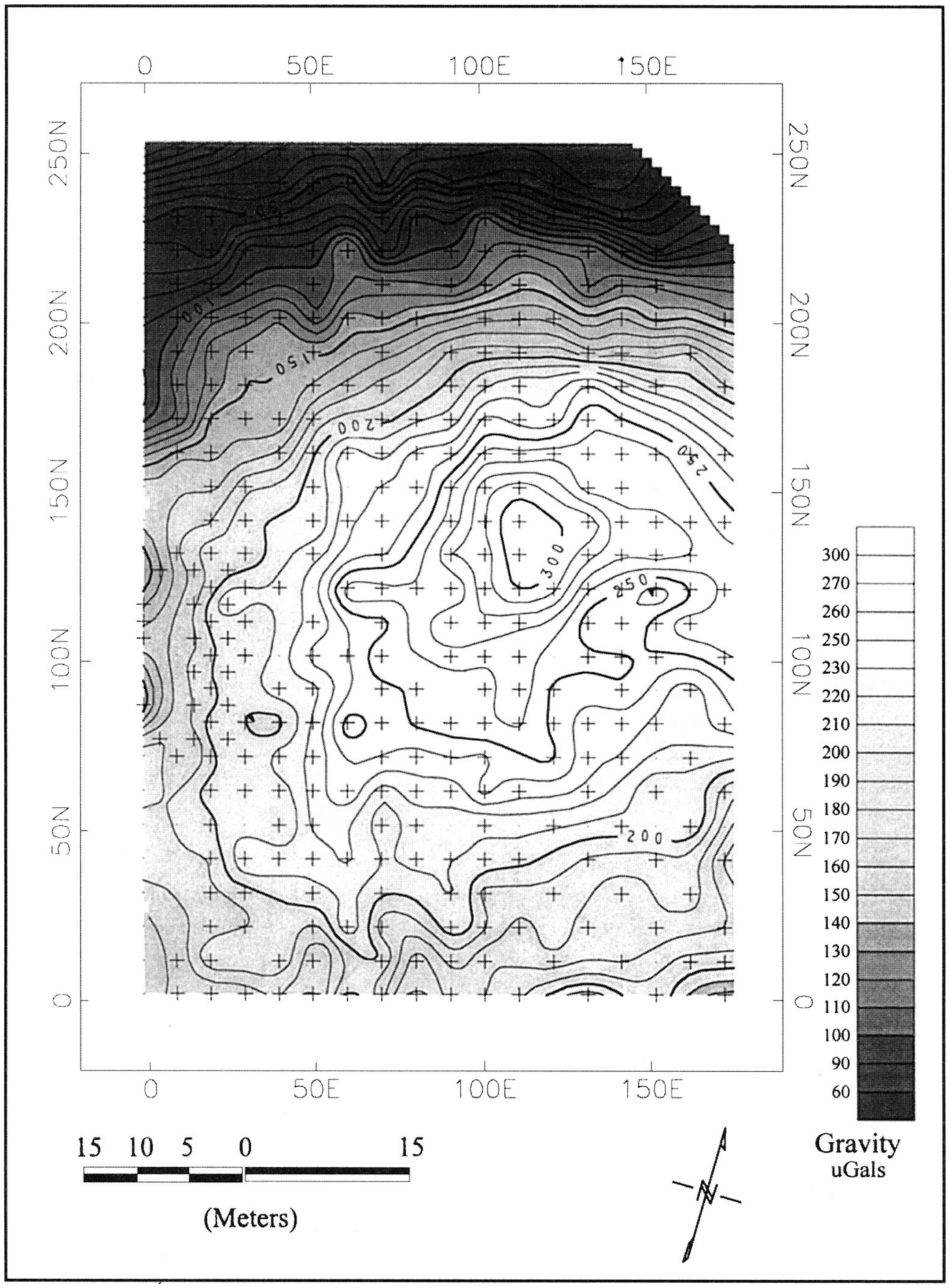

FIG. 2. Bouguer gravity map for the upstream switchyard.

larger, "meandering" positive-anomaly area. With the 10-μGal significance threshold, it is important to foundation assessment that approximately 75% of the survey area has a residual gravity anomaly of $>-10\,\mu$Gal (i.e., more positive than $-10\,\mu$Gal). The majority of the switchyard structures lay within this area free from significant negative anomalies.

In the upstream switchyard, anomalous areas were selected for investigation as indicated in Figure 6. Some anomalous areas were not recommended or were given lower priority for further investigation because of their noncritical nature or because they apparently could be explained by surface features. Areas A1 and A2 are in the vicinity of the original cavity that led to the foundation investigations; if the localized anomalies are caused by cavities, these cavities are small and shallow (<3 m). Areas A3 and A4 are caused by larger and/or deeper (<10-m) anomalous features. Areas B1 to B3 were assigned a lower priority for verification: B1, a corner of the survey area, is away from all critical structures; B2 is a positive gravity anomaly; and B3 is centered on drainage conduits. Approximately 80% of the survey area has a residual gravity anomaly of $>-10\,\mu$Gal (i.e., more positive than $-10\,\mu$Gal).

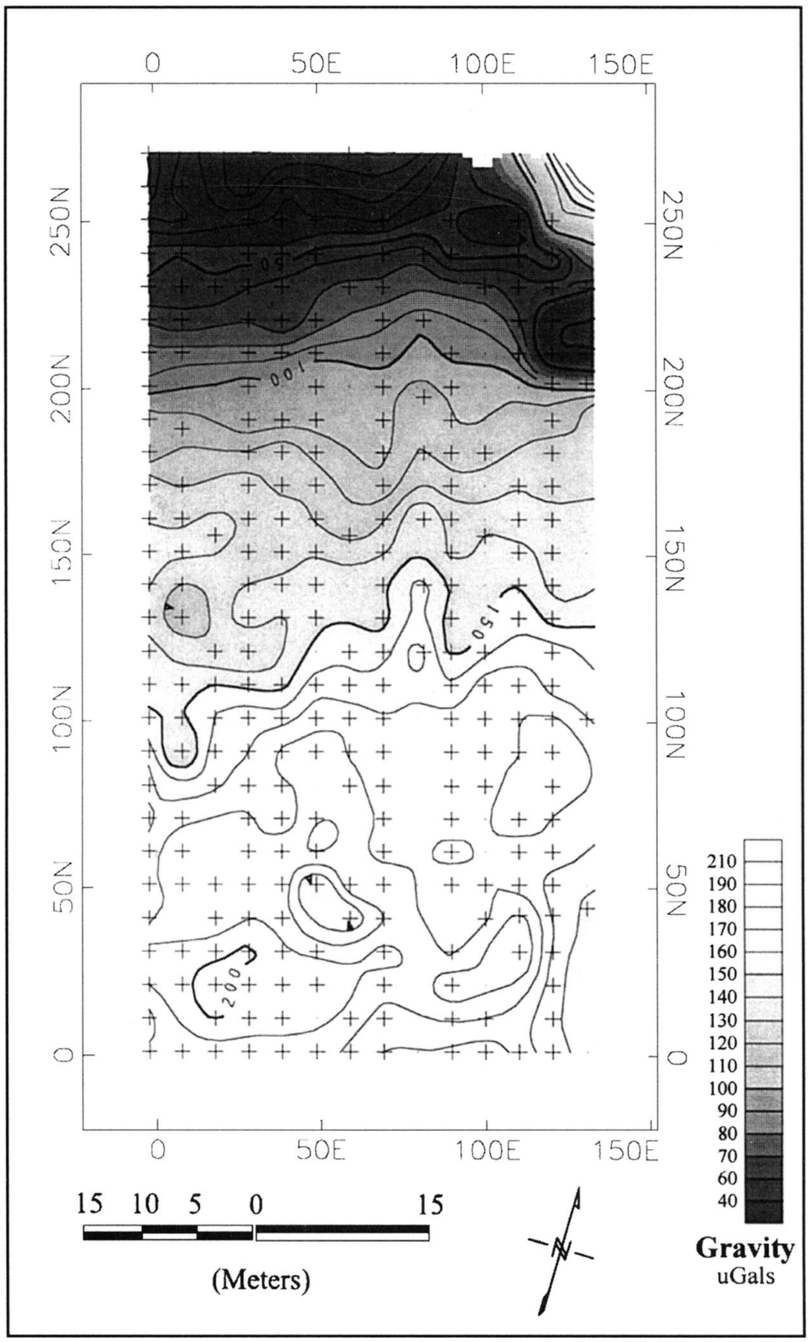

FIG. 3. Bouguer gravity map for the downstream switchyard.

VERIFICATION DRILLING

The selected anomalous areas were investigated through a drilling program (Tennessee Valley Authority, 1989). The recommended drilling depth for all borings was to the top of limestone or refusal. In the downstream switchyard, 16 borings were placed to validate the anomalous conditions. Of the 10 borings into negative anomalies, 4 borings encountered mud zones (saturated) above the top of rock, 1 boring encountered a soft zone at a shallow depth (consistent with the gravity depth prediction), and 1 boring encountered a significant zone (about 9 m thick above the top of rock) described as very soft and possibly a void. The borings placed in positive-anomaly areas were described as encountering no voids or soft zones.

In the upstream switchyard, 13 borings were placed to investigate the anomalous conditions. Five were placed in negative-anomaly areas, six were placed in positive-anomaly areas, and two were placed in a transitional area ($-10\,\mu$Gal to $+10\,\mu$Gal). Four of the borings in positive-anomaly areas were closely spaced in anomaly area B2. Two additional borings were placed on the basis of other, nongeophysical factors. Of the five borings in negative-anomaly areas, three (in A3, A4, and B3) encountered very soft zones in which the standard penetration test blow counts were very small (N value, <3).[1] The other two borings detected no voids. Of the six borings placed in positive-anomaly areas, the four borings in anomaly area B2 encountered an extensive, shallow, very hard chert mass (either a large cherty limestone remnant or a pinnacle). The remaining borings encountered no voids. One of the two borings placed without the help of the microgravity survey detected a very soft zone or possible void.

CONCLUSION

A microgravity survey of the upstream and downstream switchyards of the Wilson Dam powerplant was performed with the objective of detecting subsurface cavities or other anomalous conditions in the switchyard foundations that could threaten the stability of switchyard structures. The microgravity survey and treatment of the terrain effects led to the development of residual gravity maps that allowed identification of shallow foundation anomalies. Exploratory boring locations were selected on the basis of a prioritization of the gravity anomalies in the two switchyards. The drilling program was guided by anomaly size and depth estimates and encountered zones classified as voids, mud zones, or very soft zones in both switchyards, as expected from the low gravity readings in these areas. The microgravity surveys allowed the formulation and execution of a limited and rational foundation investigation plan in a difficult and dangerous drilling environment.

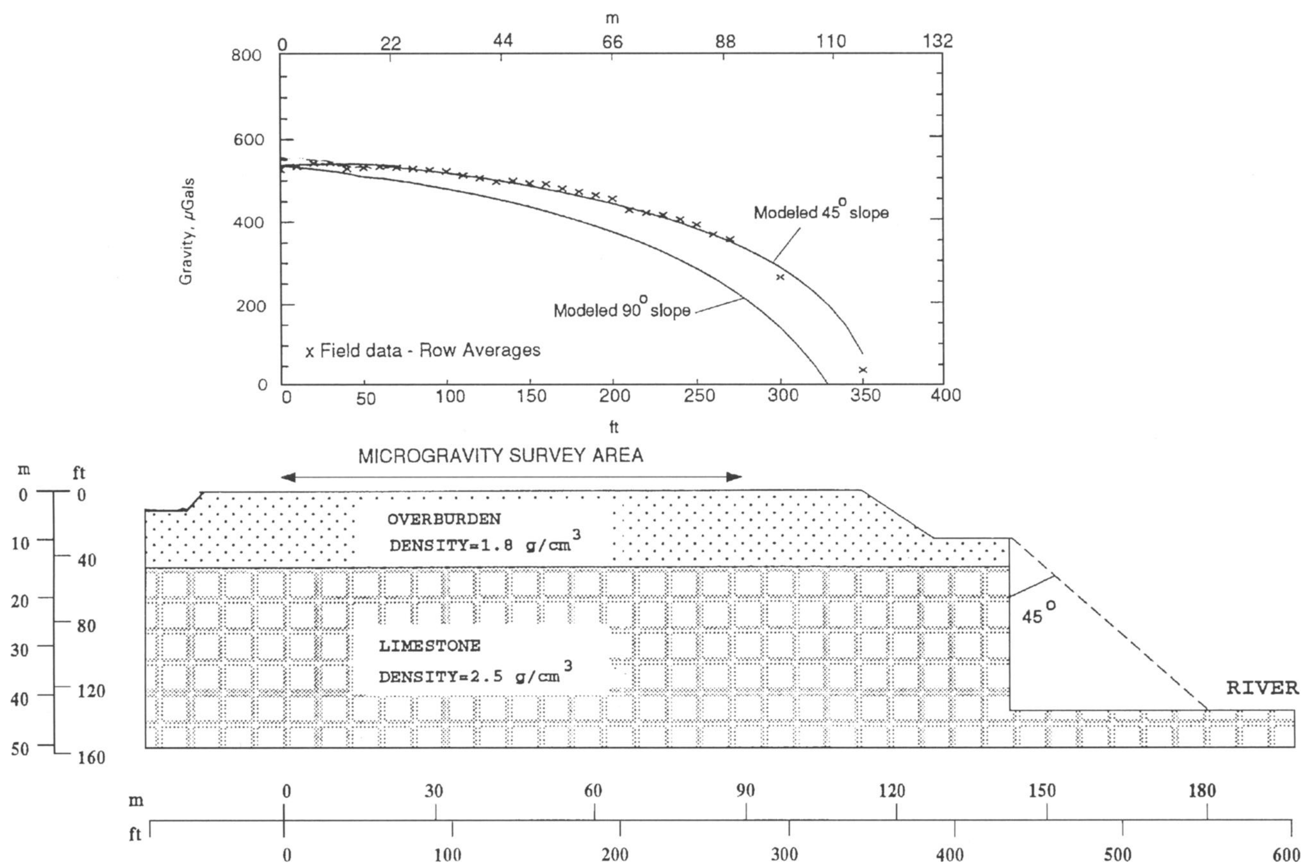

FIG. 4. Plot of row averages for the downstream switchyard (south to north), with a 2-D model of the site shown below the plot.

[1]The standard penetration test is a geotechnical in-situ borehole test conducted during soil sampling to estimate soil strength and relative density. The SPT N value is the number of drops of a standard mass required to drive a sampling tube 1 ft into the soil.

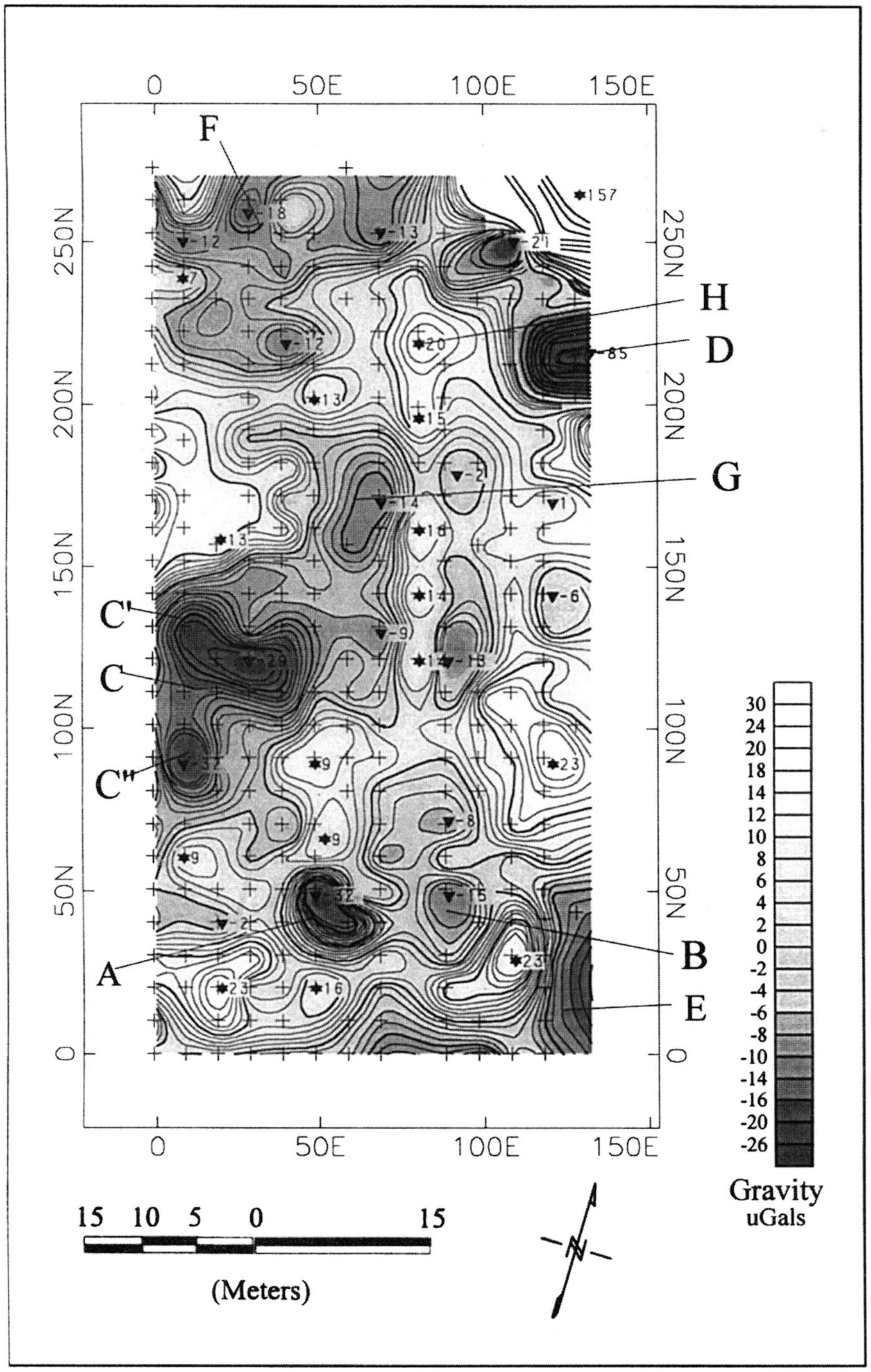

FIG. 5. Plot of downstream switchyard residual gravity anomaly map.

ACKNOWLEDGMENTS

The work described in this paper was conducted by the US Army Engineer Waterways Experiment Station. Permission was granted by the Chief of Engineers to publish this information. The views of the authors do not purport to reflect the position of the Department of the Army or the Department of Defense.

REFERENCES

Balch, S. J., and Thompson, G. T., 1989, An efficient algorithm for polynomial surface fitting: Comput. and Geosci., **15**, 107–119.

Butler, D. K., 1980, Microgravimetric techniques for geotechnical applications: US Army Engineers Waterways Experiment Station Misc. Paper GL-80-13.

——— 1984a, Microgravimetric and gravity gradient techniques for detection of subsurface cavities: Geophysics, **49**, 1084–1096.

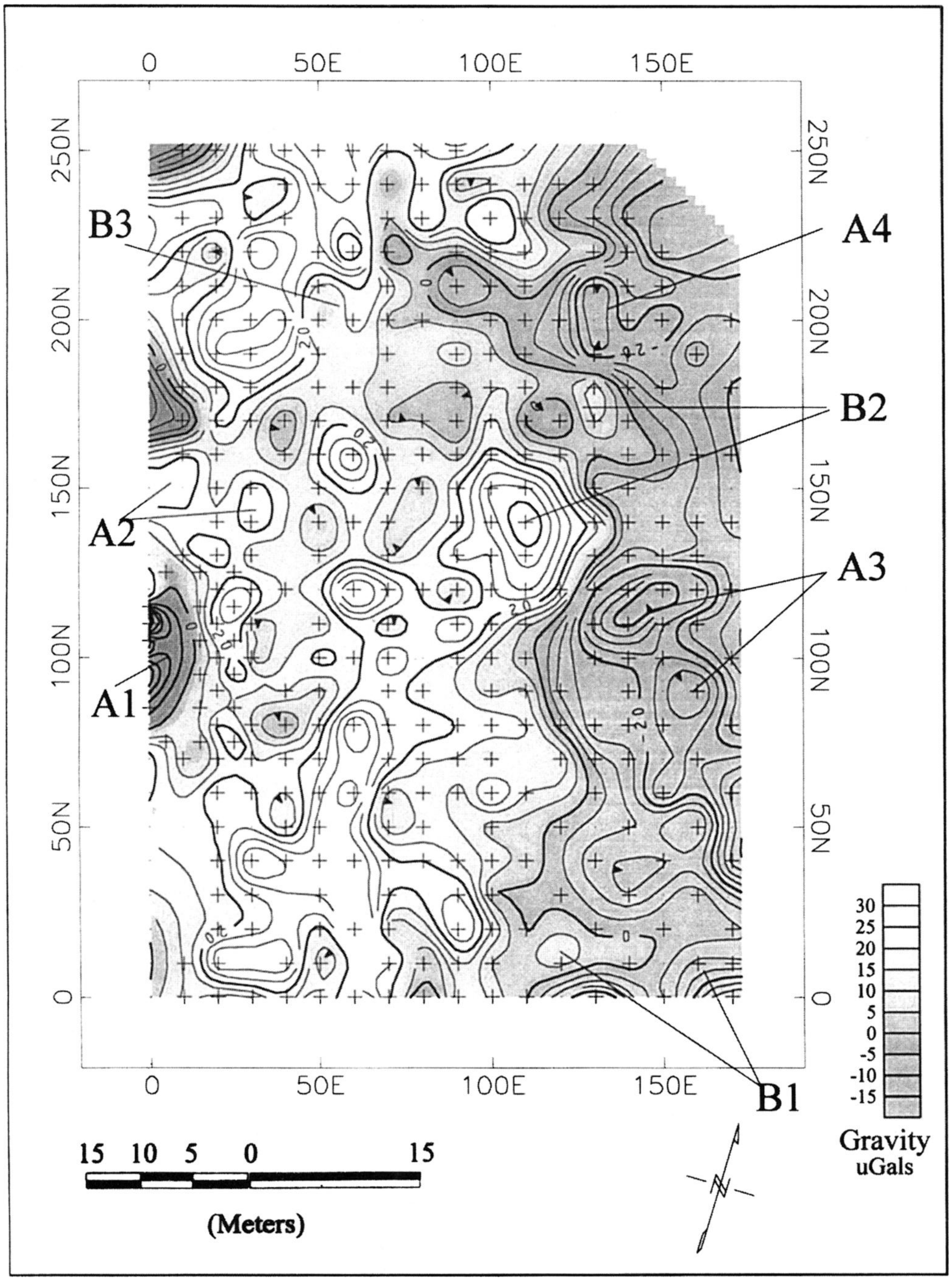

FIG. 6. Plot of upstream switchyard residual gravity anomaly map.

——— 1984b, Microgravimetric techniques for detection and delineation of subsurface cavities, *in* National Symposium and Workshops on Abandoned Mine Lands Reclamation: Science Reviews Ltd. 63–100.

——— 1985, Topographic effects considerations in microgravity surveying, *in* Proc. International Meeting on Potential Fields in Rugged Topography: Institute de Geophysique, IGL Bull. No. **7**, 34–40.

Butler, D. K., and Yule, D. E., 1984, Microgravity survey of Wilson Dam Powerplant switchyards, Florence, Alabama: US Army Engineers Waterways Experiment Station Misc. Paper GL-84-16.

Camacho, A. G., Vieira, R., Montesinos, F. G., and Cuellar, V., 1994. A gravimetric 3D inversion for cavity detection: Geophys. Prosp., **42**, 113–130.

Hinze, W. J., 1990, The role of gravity and magnetic methods in engineering and environmental studies, *in* Ward, S. H., Ed., Geotechnical and environmental geophysics: Soc. Expl. Geophys., **I**, 75–126.

Telford, W. M., Gedart, L. P., and Sheriff, R. E., 1990, Applied geophysics: Cambridge Univ. Press.

Tennessee Valley Authority, 1989, Wilson project, upstream switchyard subsurface investigation, Chattanooga, TN.

Wenjin, L., and Jiajian, X., 1990, The effectiveness of the high-precision gravity method in detecting sinkholes in Taian Railway Station of Shandong Province, *in* Ward, S. H., Geotechnical and environmental geophysics: Soc. Expl. Geophys., III, 169–174.

Yule, D. E., and Butler, D. K., 1984, Microgravity survey of a powerplant switchyard employing microcomputer data processing: 54th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 142–146.

Yule, D. E., Butler, D. K., and Sharp, M. K., 1990, Foundation investigation of a powerplant switchyard using microgravity: 60th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 627–630.