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Use of Geophysical Methods in a Geotechnical Investigation

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SYNOPSIS This paper describes a case study in which a geotechnical investigation encountered complex subsurface conditions requiring geophysical methods to supplement test boring data. Electromagnetic (EM) and seismic refraction methods were used to model subsurface conditions at the site of a proposed three-story office building. The three investigative techniques used in this study all revealed bedrock to be at a shallow depth. The test borings provided vertical resolution while the EM and seismic studies yielded lateral resolution. Good correlation was achieved when comparing the results of each method. The EM and seismic methods in conjunction with a test boring program can provide a better understanding of subsurface conditions than can be obtained by any single technique.

INTRODUCTION

A geotechnical investigation was undertaken at a four-acre site located in Chester County, Pennsylvania. The objective of the study was to collect subsurface information at the proposed building site for recommendations pertinent to the design and construction of foundations for a 11,520 sq. m., three-story office building.

Near-surface pinnacles and solution activity were suspected at this site, based on previous geotechnical reports from the area and the known geology. Deep cuts were required to achieve finished floor elevations; therefore it was very important to accurately define the limits of shallow rock. The significant costs associated with rock excavation would be estimated based on the subsurface investigation. When irregular conditions were observed during the test boring program as anticipated, geophysical methods were chosen to supplement the boring data.

GEOLOGY

The area of study lies in the Piedmont physiographic province, comprised of gently sloping uplands. The rocks in this region are found in vertical or steeply-inclined positions, evidence of severe compression. The site is located in the long, narrow Chester Valley Syncline, a prominent geologic and topographic feature enclosing Cambrian and Ordovician limestones and renowned for its shallow rock.

The Elbrook Formation (upper-Cambrian) reportedly contacts with the Conestoga Formation (Ordovician) in a east-west orientation south of the site. Both formations are described as impure limestones with the Conestoga containing phyllite members. Both formations weather to a clayey, residual soil overburden as the carbonates are dissolved by infiltrating surface water, however, intact limestone pinnacles are not uncommon.

Aerial photographic review and field observations have confirmed sinkhole activity in the study area. The site has discernable remnants of surface cavities resulting from solution activity in the underlying shallow limestone. A relationship is known to exist between fracture traces and zones of incipient sinkhole development in this region. Based on the aerial photographs, fracture lineaments are oriented sub-perpendicular to bedrock strike in the local area. These traces along with the proposed building footprint, study area and site and geologic features are shown in Figure 1.

TEST BORING METHODS

Thirty-four test borings and twelve auger probes were drilled as part of the initial site evaluation and the final building investigation. The boring locations were chosen to provide an overview of the subsurface conditions with an emphasis on the building pad area. Soil samples for identification and laboratory analysis were taken at 0.9 to 1.5 m. intervals at the test boring locations. Six to ten inches of topsoil was encountered throughout the site. The investigation did not encounter any existing fills on the site. The character and condition of the intact limestone was examined by coring rock in four test borings. The test boring locations are shown in Figure 2. Major soil/rock horizons defined by the test boring program are described below in the general order of their occurrence.

Residual Soils

The residual soils showed the highest degree of limestone decomposition, with none of their original rock structure being retained. A stiff to very stiff red-brown silty clay grading to clayey silt with limestone fragments covers the site with an irregular thickness. The irregularities result from differential weathering along the bedding surfaces and fractures. The strength and consistency of the soils reflected

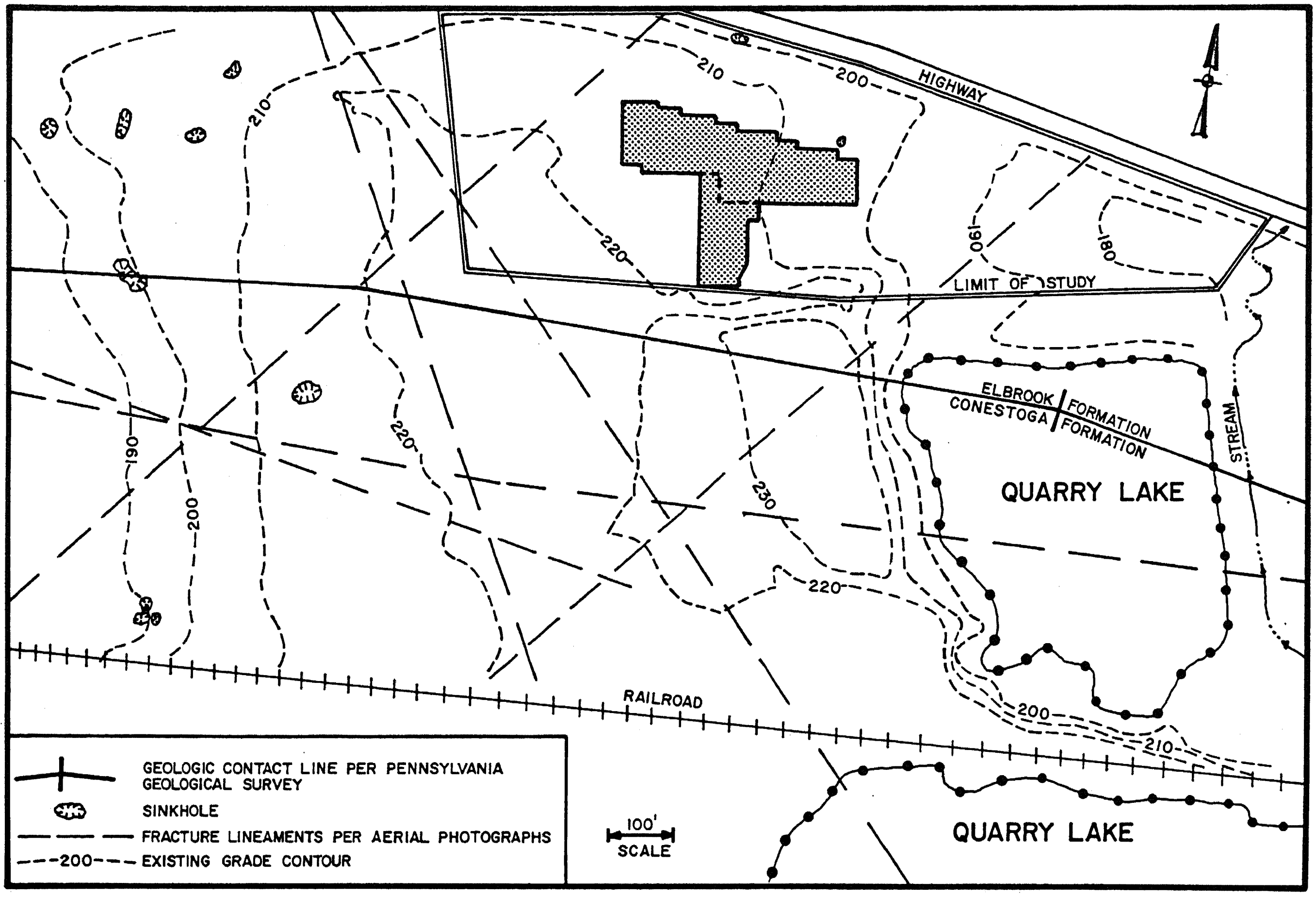

FIGURE 1 SITE CONDITIONS PLAN

in the Standard Penetration Resistance (SPR) values indicate a gradual increase in strength with depth. Some low readings were documented in the lower 20 percent of the profile and are attributed to a loss of strength in the overburden due to solution activity.

Decomposed Limestone

The residual soil overburden and intact limestone interface is very irregular and is characterized by discontinuous zones of limestone fragments and sand intermixed with residual soils. The decomposed limestone soils tend to be less plastic than the overlying clayey residual soils.

Intact Limestone

Rock cores identified the bedrock immediately underlying the proposed building footprint as a hard to very hard, fractured limestone with occasional clay seams. Some voids and soil infilled cavities were also identified. The investigation identified a rugged rock pinnacle interface located primarily along the northern portion of the building footprint. The ridge of weathered resistant limestone appeared to be aligned with strike at N80°E. Deep weathering and solutioning typically occurred along the steep dipping beds and in fracture joints perpendicular to strike. Phyllite was encountered in eleven borings as a member of the Conestoga Formation, moving the contact previously mapped north at least 90 meters.

In summary, the test boring program identified steeply dipping, near-surface pinnacles with deep overburden troughs. Based on the test boring program, Figure 2 infers zones where shallow rock (less than 3 meters) may be encountered. Experience indicates that additional limestone pinnacles may occur anywhere on site. Based on the data obtained and the poor lateral resolution test borings offer, geophysical methods were needed to supplement the data.

SEISMIC REFRACTION METHODS

A seismic refraction survey was performed at the site to further delineate areas of possible shallow bedrock, and evaluate compressional wave velocities in the soils and bedrock. The test boring program previously identified a ridge of near-surface limestone pinnacles. The seismic refraction method was useful in determining orientation and limits of the fractured bedrock on site.

A total of 6,630 linear feet of seismic pro-

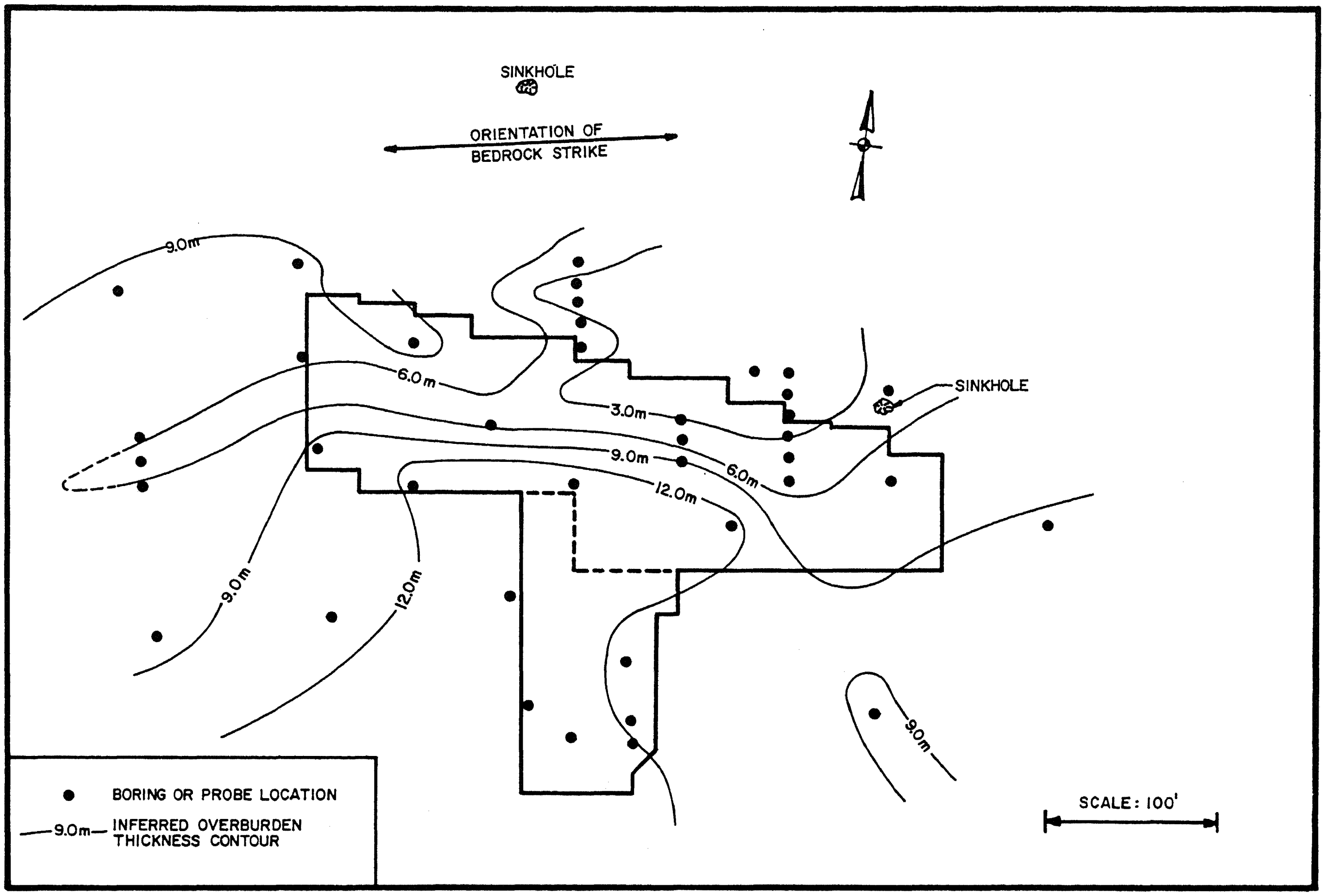

FIGURE 2 TEST BORING LOCATION AND OVERBURDEN ISOPACH

filing was completed using standard shallow seismic refraction techniques. A grid system of traverse lines was laid out perpendicular to bedrock strike. Three traverses also ran parallel to strike, as shown in Figure 3. Spreads of twelve geophones, with 10 ft. or 20 ft. spacing between geophones, were placed along the ground surface.

Because of the way seismic energy travels through the earth it is possible to determine two parameters, depths to materials of increasing velocity and compressional seismic wave velocities. The seismic velocity is a direct measure of the strength, hardness and degree of compaction of the material. Unconsolidated soil overburden would have a low velocity (1000-2000 ft./sec.), whereas hard, unweathered bedrock would have a high velocity (10,000 ft./sec.).

The seismic data indicated a ridge of shallow, intact limestone (3 meters deep or less) running parallel to strike along the northern section of the proposed building. The intact limestone surface dips steeply to the south at 60 to 80 degrees and is in contact with a more deeply weathered, softer phyllite.

Differential weathering of the limestone has created pinnacles aligned parallel to bedrock strike (N80°E). This was made more apparent by the fact that the seismic velocities calculated from the data collected in the east-west direction were higher than the volocities calculated with the data from the north-south lines. The reason for this discrepancy is that the seismic refraction method uses the seismic energy traveling the minimum time path from the explosive source to each geophone location. For geophones aligned east-west, the minimum time path to each geophone would be along the high-velocity, east-west trending rock pinnacles. The seismic energy traveling in the north-south direction was slower because it travelled through a series of pinnacles and troughs or high velocity and low velocity zones respectively. The anisotropic seismic wave velocities are a direct result of the differential weathering of the underlying calcareous rock and the geologic structure.

Some travel time delays were also observed in the seismic data. A travel time delay is caused by the seismic energy being slowed down crossing a fracture system or a zone that has a lower compressional wave velocity than the material on either side of it. The most prominent time delay was noted at the interface between the shallow, intact limestone ridge on the north end of the site and the softer, deeply weathered phyllite to the south. It is likely that this is a zone of more severe solution activity. Several smaller travel time delays were also noted on other traverse lines. These delays are interpreted to represent fracture zones traversing across bedrock strike and are roughly parallel to other lineaments in the area. Depth to bedrock has been calculated and an overburden isopach is shown, along with areas containing travel time delays in Figure 3.

ELECTROMAGNETIC METHODS

The purpose of the electromagnetic (EM) survey was to identify conductivity anomalies within the limit of study and correlate the findings with the results of the boring program and seismic survey to produce lateral limits of major subsurface conditions. The primary objective was to attempt to locate shallow rock and weak compressible soils associated with sinkholes.

The EM field survey was conducted utilizing an EM-34 Terrain Conductivity meter manufactured by Geonics, Ltd. The instrument uses a magnetic induction method to measure apparent conductivity in millimhos/meter (mmho/m). The EM-34 operates with two coils that can be spaced at 10, 20 or 40 meters apart for successively greater penetration. The effective penetration is about .75 times the intercoil spacing in the horizontal dipole position, and 1.5 times the spacing in the vertical position. Two people are required to operate the instrument.

Approximately 12 hours were needed to adequately cover the four-acre site. The same grid used for the seismic study was used for the EM survey. Over two hundred readings were taken at 10 and 20 meter spacings. Several readings with the 40 meter spacing were attempted, but yielded fluctuating values of less than 1.0 mmho/m. Most readings were measured in the horizontal dipole (HD) orientation since vertical dipole (VD) measurements are more time consuming and prone to coil misalignment.

Variations in terrain conductivity are influenced by several factors including near-surface bedrock, soil porosity and soil moisture. Intact fractured bedrock is a relatively poor conductor in comparison to clayey overburden soils; therefore low conductivity may be indicative of shallow rock.

The 10 meter spacing in the HD mode produced conductivity values ranging from 1.9 mmho/m to

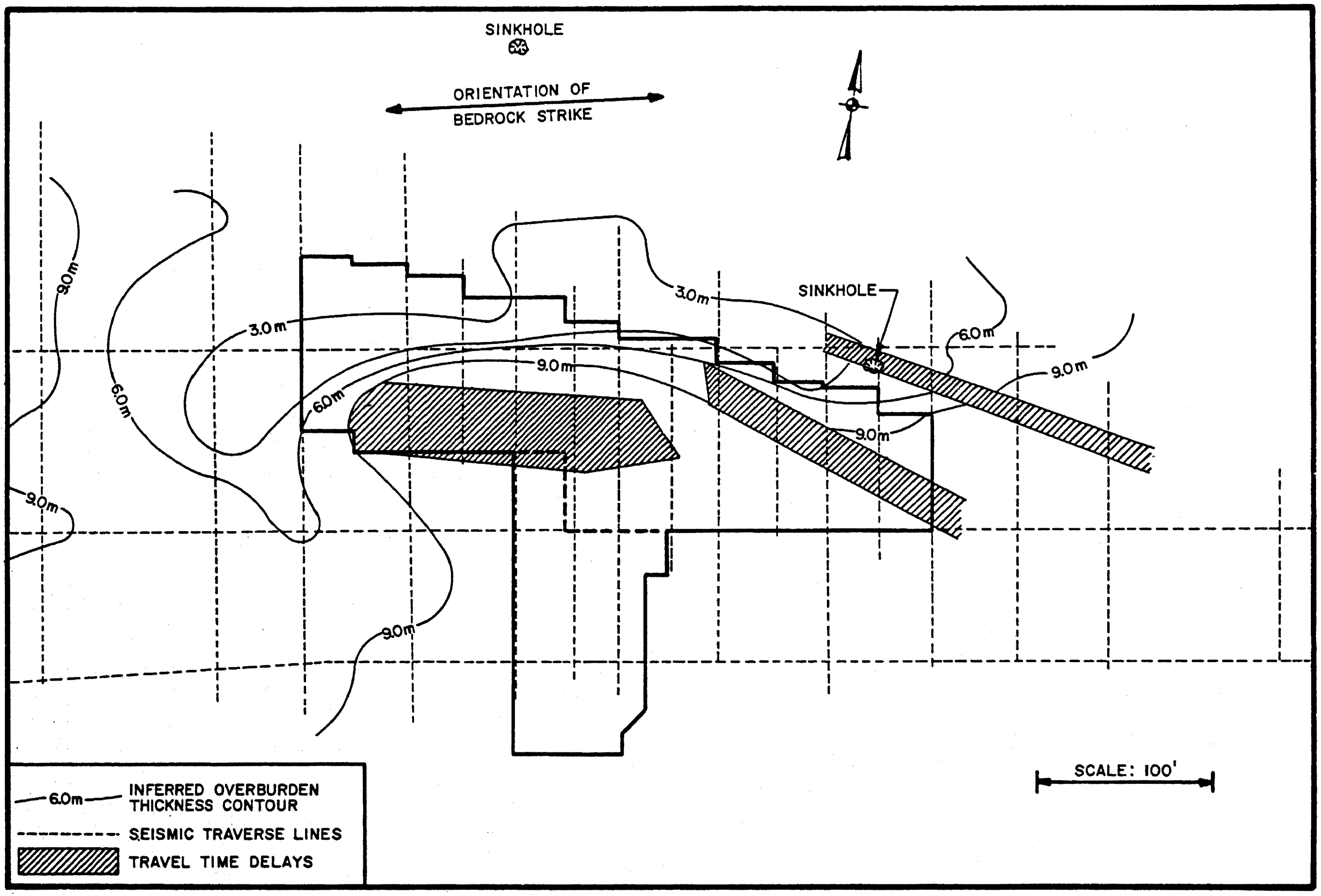

FIGURE 3 OVERBURDEN ISOPACH BASED ON SEISMIC SURVEY

7.6 mmho/m across the site. The data generated is contoured and presented in Figure 4. The 20 meter spacing in the HD mode produced conductivity values ranging from 1.0 mmho/m to 5.1 mmho/m across the site. The contoured data is similar to the 10 meter results, with 20 meter conductivity values reduced overall due to the greater penetration and therefore increase in bedrock effects, shown in Figure 5.

When utilizing information obtained from the test borings, interpretation of the conductivity data allows for several inferences. Since results from the 20 meter spacing confirm the orientation of trends and are not as representative of the overburden, interpretation is based on the more contrasting data provided by the 10 meter spacing. Based on test boring data, zones of near-surface bedrock or pinnacles less than 3 meters below the ground surface occur in areas with conductivity values less than 2.5 mmho/m. Conductivity values greater than 3.5 mmho/m represent a thicker overburden associated with a more easily weathered phyllite. This contact is relatively parallel to bedrock strike except to the east where groundwater effects raise the composite conductivity. A relatively high conductivity anomaly (greater than 4.5 mmho/m) located in the southern portion of the proposed building footprint may represent a fracture zone or lineament that has been infilled with soil. Another conductivity trend in the northeast corner of the site is aligned with observed surface cavities and is parallel to the anomaly to the south. These features are both parallel to other lineaments in the study area (shown in Figure 1).

CORRELATION OF TECHNIQUES

By comparing the results of the test boring program, seismic refraction survey and electromagnetic survey, a high degree of confidence was achieved when interpreting subsurface conditions. Test boring data immediately identified the complexity of conditions when offsets indicated gross overburden thickness variations. However, the data provided an unclear picture of the exact nature of near-surface pinnacles and deep troughs, the lateral limits of which were poorly defined. When comparing EM data with known overburden thicknesses, an empirical correlation was made between apparent terrain conductivity and depth to bedrock. This allowed for delineation of trends and lineaments as well as the limits of shallow rock.

The seismic survey provided a well defined picture of overburden thickness, along with orientating and delineating subsurface features. Of significant importance was the identification of travel time delays representing fracture zones. These lineaments correlated well with other known lineaments in the area. Apparent conductivity data, primarily using the 10 meter coil spacing, generally correlated to those

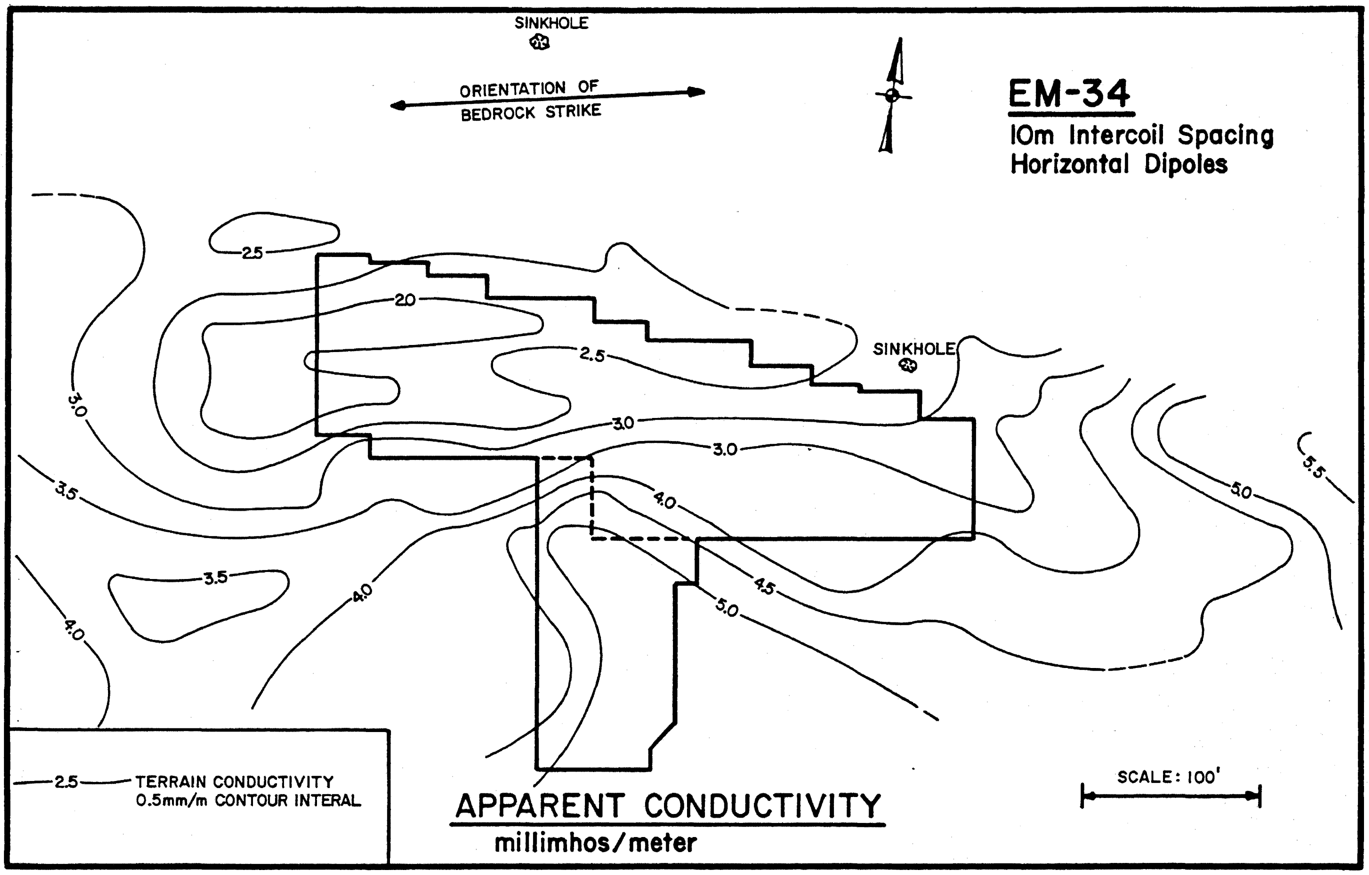

FIGURE 4 ELECTROMAGNETIC SURVEY PLAN

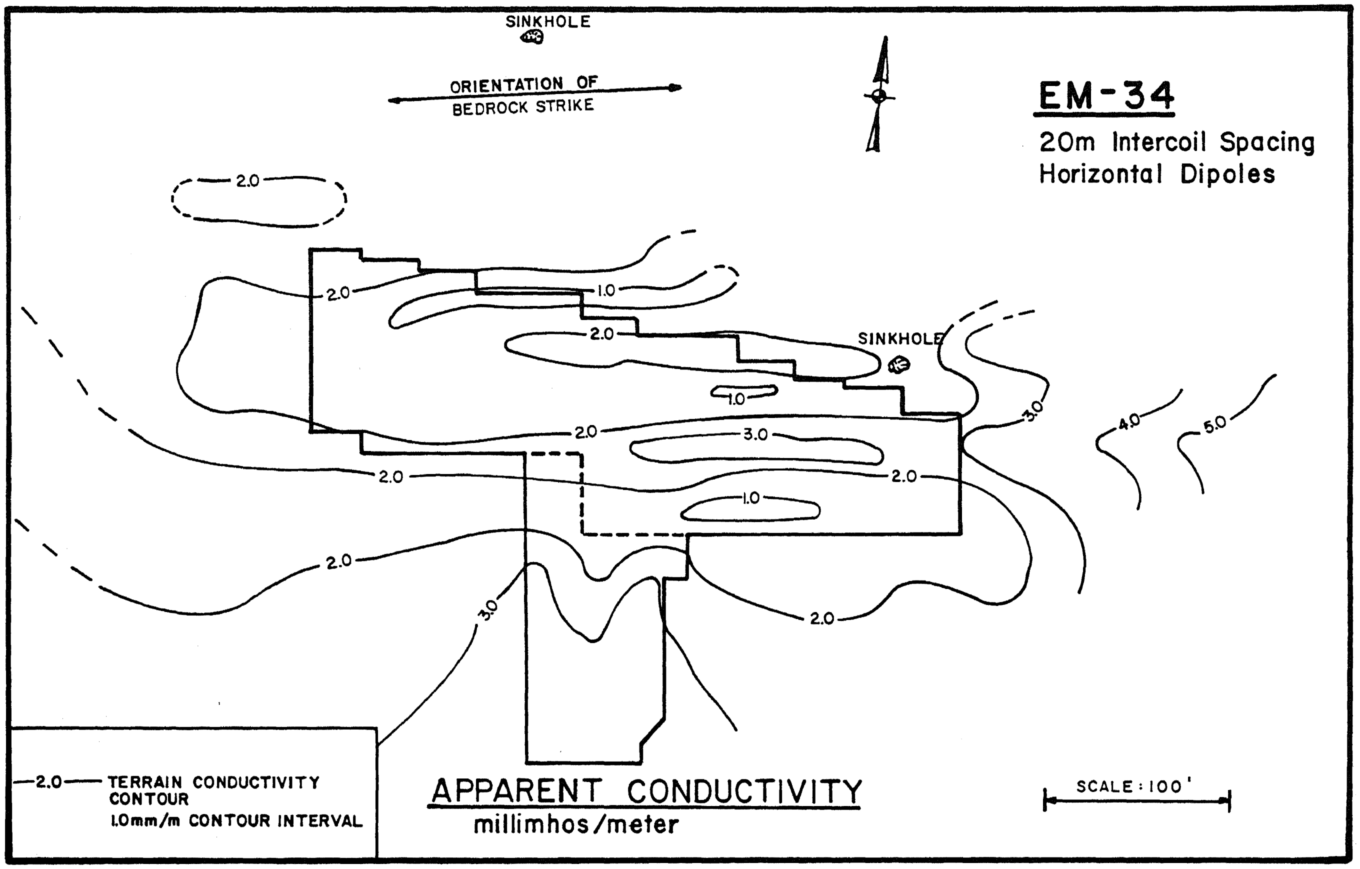

FIGURE 5 ELECTROMAGNETIC SURVEY PLAN

features. Travel time delays aligned with elevated or rapidly changing conductivity values due to either an increase in soil moisture content or a dramatic increase in overburden thickness. This did not hold true to the east, where groundwater effects raised the composite terrain conductivity. Overburden thickness calculations compared well with test boring data except when rock was very shallow (less than 2.0 m.); then overburden thicknesses were slightly overestimated.

In comparing the results of the three techniques shown in Figures 2, 3 and 4, it is clear that each method generally inferred similar subsurface conditions. Although each technique has limitations, the combination of techniques can enhance the interpretation.

CONCLUSIONS

It should be noted that neither test borings nor geophysical methods alone can be expected to provide all the information that an engineer may need in a subsurface investigation. However, the combination of the two can provide the lateral and vertical resolution needed in complex environments. A great deal of 'traditional' subsurface investigations are done based on a systematic examination of strata as determined by evenly spaced test borings located at the corners of a proposed building. This method may be adequate for smaller buildings situated over thick, uniform alluvial deposits or flat-lying, homogenous rock strata. However, in more complex conditions, the geotechnical engineer is left to infer conditions based on limited knowledge of actual conditions. Engineers would ideally like to cost-effectively locate "smart" test boring locations. The use of non-destructive geophysical methods, such as EM or seismic refraction, prior to a test boring program will not only assist in the proper location of borings, but will provide additional resolution to enhance inferred subsurface conditions.

At this site the geologic complexities warranted extensive drilling. However, the investigation demonstrates the use of geophysical methods as a supplemental, cost-effective technique in subsurface investigations; in many cases, the number of test borings required can be reduced by judicious use of geophysical methods.

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