

MAP LOCATION AND DIMENSIONAL
DEFINITION OF SUBSURFACE CAVERNS

A Senior Honors Thesis
Presented to
the Faculty of the Department of Geology and Geophysics
University of Hawaii

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Science with Honors

By
James E. Wolfe
December 1975

U of Hawaii
Hamilton Library
Hawaii Collection
GB 605 H3
W64

TABLE OF CONTENTS

	Page
LIST OF FIGURES	iii
LIST OF TABLES	iv
ABSTRACT	v
INTRODUCTION	1
PREVIOUS INVESTIGATIONS	9
PHYSICAL CONDITIONS	10
GEOLOGIC AND HYDROLOGIC CONDITIONS	12
GEOLOGIC HISTORY	16
METHOD	18
Subject Research	18
Theoretical Pilot Study	18
Equipment	24
Data Acquisition Procedures	24
DATA REDUCTION	27
Microgal Conversion	27
Earth Tides	27
Drift of the Instrument	28
Latitude	31
Free Air	33
Bouguer	33
Terrain	34
Simple Bouguer Anomaly	36
RESULTS	42
MODELING	44
CONCLUSIONS	48
ACKNOWLEDGMENTS	50
LIST OF REFERENCES	52
APPENDIX	54

LIST OF FIGURES

	Page
Figure 1. Shows location of past sinkholes.	8
Figure 2. Shows elevations, latitude and areal extent of caverns	11
Figure 3. Defines variables used in discussion of Theoretical Pilot Study	19
Figure 4. Drift curves for each day	30
Figure 5. Diagram of building slabs used in making building corrections.	37
Figure 6. Simple Bouguer Anomalies.	43
Figure 7. Models.	45
Figure 8. Best-fit model compared to observed	47

LIST OF TABLES

	Page
Table 1. Records data of Theoretical Pilot Study Model.	23
Tables 2 & 3. Earth Tide Data	29
Data Tables.	38-41

ABSTRACT

This study attempts to locate and define a small-scale, shallow subsurface cavern by the use of a gravity micro-survey in which station spacings of about 10 feet are used.

The results show that two caverns exist underneath Kuilei Lane. They are filled with water and strike in a N. 15° E. direction. One cavern is 12 feet high, 38 feet wide in cross section, and has 4 feet of rock separating the roof from the ground surface. The second cavern is separated 9 feet laterally from the first cavern and is 8 feet high, 14 feet wide in cross section, and has 5 feet of rock between the roof and the ground surface. Lack of time and operational knowledge prevented direct verification of the results by drilling.

INTRODUCTION

Cavities produced in the subsurface by erosional processes operating on soluble rock have resulted in engineering problems for modern civilization. In the United States, this problem of subsurface cavities resulted in dam failures during the earlier part of this century.

One example is the Lone Pine Reservoir failure of Arizona. Within a month after dedication of an earth-fill dam constructed from 1934 to 1936, sinkholes developed in the limestone of the reservoir's floor due in part to cavities underneath the reservoir. As a result of the sinkholes, a major leak developed which dropped the water level of the reservoir from a high of 74 feet to 43 feet without net loss due to other causes (Kiersch, 1958).

In 1913, the Johnson City, Tennessee, dam collapsed due to a clay-filled cave which was underneath the dam (Purdue, 1913). Another Tennessee dam, constructed privately from 1905 to 1913, required a major engineering effort to correct the leakage due to solutioning of limestone cavities beneath the dam and the abutments. By 1939 the solutioning had proceeded to where it became necessary to emplace a cut-off wall and to grout all discovered cavities ("American Society of Civil Engineers' Discussion in Unusual Cut-off Problems--Dams of the Tennessee Valley Authority," 1945).

Highways have been built over soluble strata which poses the potential for the occurrence of sinkholes. Interstate 10, constructed across the Florida panhandle, is one of these highways. Here the Florida Department of Transportation has taken precautionary steps to prevent accidents resulting from sinkholes by locating subsurface cavities through the use of infrared aerial photography (Jacksonville, Florida Times-Union and Journal, June 3, 1973).

In Moiliili, caverns exist in the soluble coral limestone underlying this district of Honolulu. Sinkholes have resulted from these caverns in the past and remain a potential threat today.

A gravity survey, which determines the relative gravitational attraction of the earth, is one way to locate the position of these caverns on a map and define the caverns with respect to depth below the surface, width, height and density. A gravity micro-survey uses a relatively closer spacing of stations which is necessary to produce significant results for relatively small bodies.

The purpose of this study is to attack the problem of the Moiliili caverns by conducting a gravity micro-survey over a suspected cavern in order to locate the cavern on a map and to define the cavern's dimensions.

The survey is taken along Kuilei Lane on the west side of University Avenue, which is near the intersection of King Street and University Avenue. The survey site is in the

Moiliili district of Honolulu, Hawaii, which is about 2 miles northwest of Diamond Head Crater on the island of Oahu, Hawaii. Oahu extends from 21°43' N. to 21°16' N. and from 158°17' W. to 157°39' W. Access to the area is easily obtained since the area is well endowed with paved roads and Kuilei Lane itself is a public road.

The elevations encountered are from 12 feet to about 9 feet above sea level. The area that the survey covers is 4000 feet square.

Hawaiian legends and the literal translation of street names and landmarks in the area indicate that the caverns exist. Kapaakea, which is the name of the street that borders the profiles literally means "the coral or limestone surface" (Pukui, et al., 1974). Paakea means literally "the coral or limestone bed" (Pukui, et al., 1974). Kapaakea was also the name of a large pond which extended over what is now the Willows Restaurant on Husten Street, according to a Honolulu Board of Water Supply map done by S. E. Bishop (1883). This map can be obtained from the volume entitled "Moiliili Caverns" at Walter Lum, Associates. This pond was the same pond to which a Star-Bulletin article gave the name of Kumalae Spring (Williams, January 5, 1935). This same article tells of a Hawaiian legend which indicates that the Hawaiians had a hypothesis that there were caverns and that they extended to the sea. The legend concerns Kanewai Pool which

was the name of a large underground pool on the mauka side of King Street, near the present UH quarry parking lot, which is a half-mile north of the profiles. Its waters were said to be the "healing waters of Kane." The ancients said that "wise fish from the sea used to swim up this pool, overhear the plans of the native fishermen who frequented the vicinity, and then float back to the ocean to warn their friends" (Williams, January 5, 1935).

Another legend, recorded by Westervelt (1916) which hints at the presence of underground caverns and sinkholes is about the pig-god, Kamapuaa. One day Kamapuaa was walking in Moiliili when he saw two beautiful women coming from the stream which flows from Manoa Valley. Kamapuaa called to them. They recognized him by his rough clothing made from pig skins and by his tattooed body and fled. He pursued them, but possessing miraculous powers, they disappeared when he was about to place his hands upon them. "They sank into the earth." Kamapuaa changed himself into a great pig and began to root up the stones and soon he began to break his way through "the layer of petrified coral through which they had disappeared." He followed the descent of the woman nearest him, but suddenly a burst of water came pushing through the coral almost drowning him. The legend indicates that Kamapuaa went back to where the women had appeared and again rooted, causing another spring of "living water" to appear. The name

given to these wells, according to Westervelt is "The Wells of Kamapuaa." From the landmarks mentioned in the legend, it seems that these two springs are the Paakea and Kanewai Pools mentioned above.

That the caverns exist has been made known to modern day Hawaii by three recorded cave-ins in the area. In December of 1934 certain events allowed direct observation of a cavern near the University Avenue and King Street intersection. While installing a new sewage-pumping station at the intersection of University Avenue and Kapiolani Boulevard, The Hawaiian Contracting Company struck a gushing flow of water while unwatering a pit for the pumping station. The rate of flow was 10 million gallons per day. The Board of Water Supply took observations in the area for a four-month period beginning September 10, 1934. During this time a general recession of the water level occurred over a large area. The Hausten Pond (Paakea Pond) was emptied, two sinkholes or cave-ins developed and "huge" caverns were exposed to view. On December 19, 1934, observations by a party revealed a seemingly continuous channel from near this pit to mauka of Waialae Road having a depth of up to 10 feet, a width of 20-40 feet, with a shell of coral overlain only occasionally by a cover of soil a few inches thick (Honolulu City and County Board of Water Supply, Water Resources Report, 1933-1934, see Appendix).

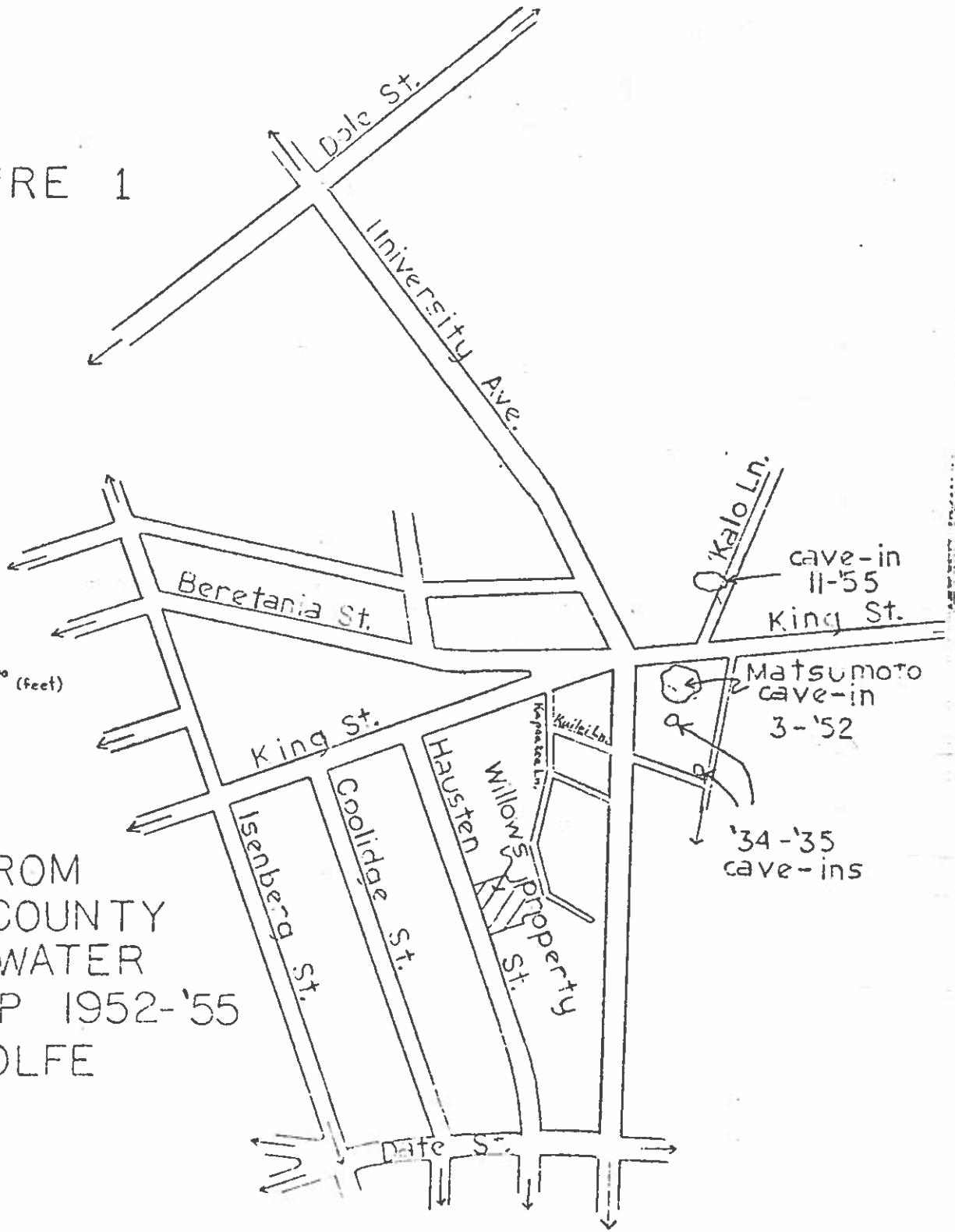
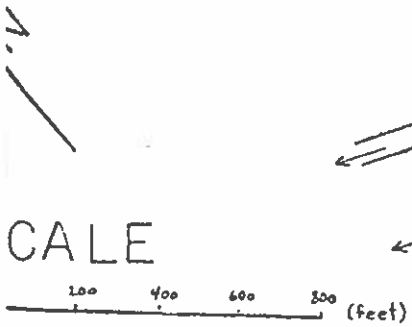
A report to J. Williams entitled "Mammoth Caves Under King Street" by J. F. Kunesh, who was an observer in the party that entered the cavern on December 19, 1934, places the sinkhole 100 feet makai of the center line of King Street at University Avenue. This report places the bottom of the cavern about 10 feet below the surface of the ground and says the height to be about 6 feet. The report also says that the bottom is filled with "fine ooze." The width is said to range from 20 to 40 feet, the cross section varying because of the coral irregularities. The party also heard the rumbling of cars passing above them along King Street and saw tree roots hanging down from the roof of the cavern (Kunesh, 1934; see Appendix). Williams, the man who wrote a newspaper article entitled "The Romance of Honolulu's Prehistoric Caves" later added that "large rocks or chunks of coral" lay on the floor of the cavern "that had fallen from the roof of the cavern" (Williams, January 5, 1935). Figure 1 locates two sinkholes mentioned in the Water Resources report of 1933-1934 above as being on the east side of present-day University Avenue on the makai side of King Street.

It was not until twenty years later that another cave-in sank the rear portion of the Moiliili Department Store three feet. This cave-in, marked in Figure 1 as the Matsumoto cave-in, allowed a City and County diver to explore the cavern on April 24, 1952. The diver went as far as 75 feet mauka

from the entrance. The diver said that the cavern is as wide as 30 feet under King Street, 8 feet deep and filled with about 3 feet of mud on the bottom (Honolulu Star-Bulletin, April 24, 1952).

Then, on November 11, 1955, another cave-in occurred, this time on the mauka side of King Street along Kalo Lane (see Figure 1). The cave-in produced a 60-foot diameter sagging section ringed by a crack, which in some places was a foot wide and more than 6 feet deep. The sag was about 4 feet below what used to be the ground surface. Also, in one place a hole 12 feet deep appeared at the surface. (Honolulu Star-Bulletin, November 11 and 19, 1955).

FIGURE 1



TRACED FROM
 CITY AND COUNTY
 BOARD OF WATER
 SUPPLY MAP 1952-'55
 BY J.E. WOLFE

PREVIOUS INVESTIGATIONS

The general geology and ground-water of Honolulu has been studied by many (Palmer, 1927; Stearns and Vaksvik, 1935; Wentworth, 1926 and 1951), but detailed investigations concerning solution cavities in Hawaii are few in number. Wentworth gave an explanation of the mechanism that forms the caverns in a paper entitled "Geology and Hydrology Relating to the Hausten Spring and Fishpond, Honolulu, Hawaii" (December 3, 1953; see Appendix). Walter Lum Associates have a volume of information concerning the Moiliili caverns including photographs of cave-ins and many articles on the subject. A study conducted by Estes, et al. (1973), which included a gravity survey, was the initial source for my study and provided sources regarding the history of the cave-ins. A copy of this study is available at the University of Hawaii (Manoa) Library, in the Hawaiian Archive.

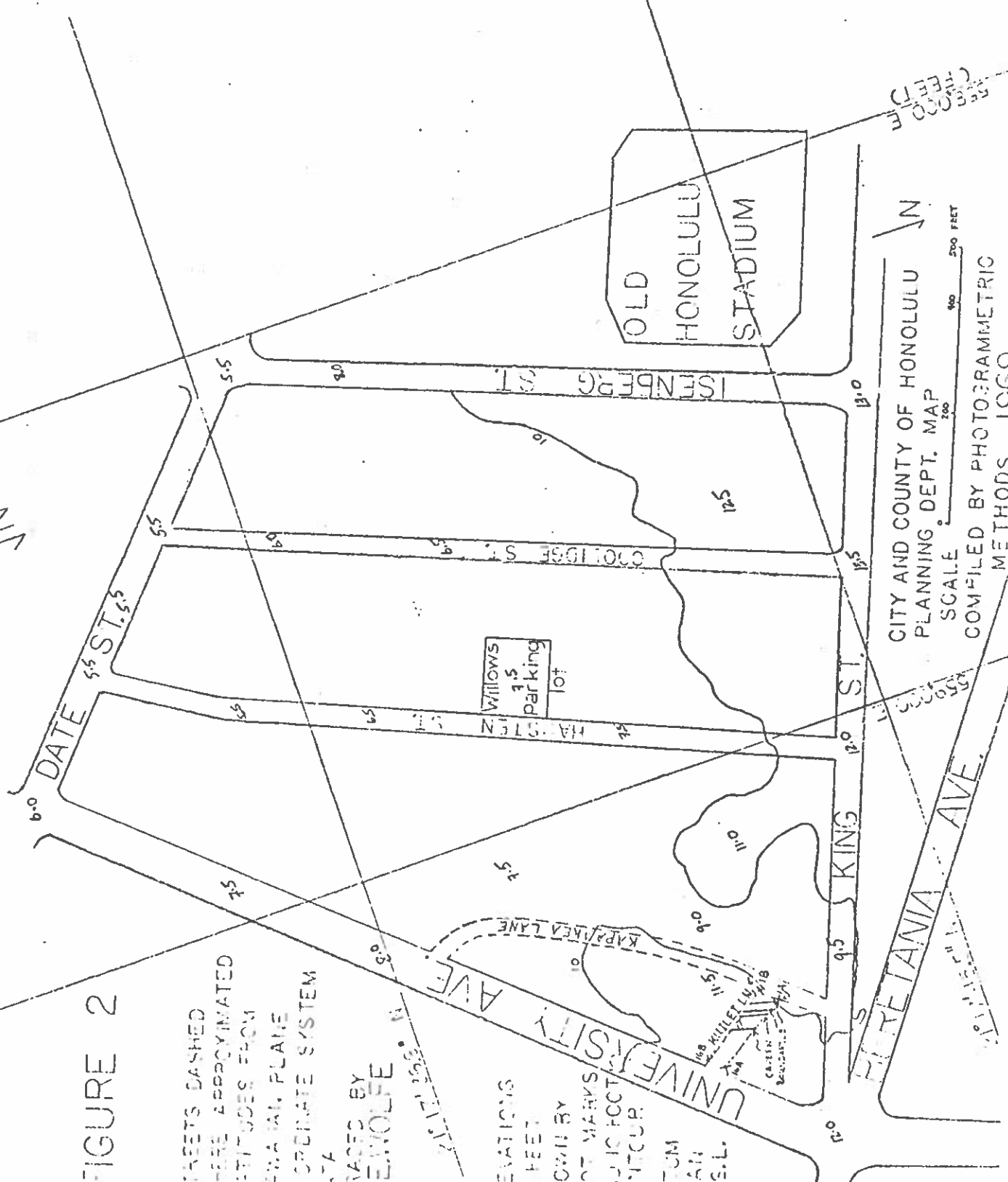


FIGURE 2

STREETS DASHED
 WERE APPROXIMATED
 ELEVATIONS FROM
 SPATIAL PLANE
 OPERATE SYSTEM
 DATA
 DASHED BY
 ENOLFE

ELEVATIONS
 IN FEET
 CONTROL MARKS
 100 FOOT
 INTERVAL

CITY AND COUNTY OF HONOLULU
 PLANNING DEPT. MAP
 SCALE 1" = 200 FEET
 COMPILED BY PHOTOGRAMMETRIC
 METHODS 1969

SEE OPPOSITE
 PAGE

PHYSICAL CONDITIONS

The area surveyed is in a densely populated area of Honolulu covered for the most part by asphalt. The topography is flat and the elevations range from 12 to 9 feet above sea level in the area over which the data is taken (Figure 2).

GEOLOGIC AND HYDROLOGIC CONDITIONS

Geologic conditions are determined by direct observations and by drill hole data. Direct observations indicate that the area surveyed is underlain by coral deposits of a hard or consolidated nature, in places. Several outcrops of this coral limestone were observed along the two profiles at and east of station 10A and east of 5B. No outcrops are observed west of these stations. The outcrops consist of well consolidated coralline limestone which proved impossible to drive a nail into due to the hardness of the coral, using a 2 lb. hammer.

Drill hole data consists of information from 3 locations in the immediate vicinity of the survey site. The first location is at the southeast corner of University Avenue and King Street. The data from three holes spaced 10 feet apart indicates a sandy soil with coral fragments which extends to 2 feet below the surface. The rest of the substratum down to 19 feet below the surface consists of "soft" coral to coral interspersed with cavities of a small scale, sand and loose coral (Honolulu Department of Public Works Map, June 6, 1952, obtained from Walter Lum Associates).

The second location is to the west of the survey site on the grounds of the Moiliili Community Center. Five test holes, spaced about 40 feet apart, were drilled on the site

of the new community center building of which the easternmost drill hole was 140 feet west of station 1A. The two westernmost sites indicate coral deposits down to 15 feet but the three easternmost (the closest to the survey area) only indicate dense to soft sands with coral fragments down to 20 feet below the surface. (Walter Lum Associates, Boring Log for Moiliili Community Center, July 10, 1973; see Appendix).

The third location is 1000 feet makai of the survey site at 739 Hausten Street. Three holes were drilled which indicate that the property is underlain by 1 to 4 feet of gravelly silt. Below this is, in some places, an organic swamp deposit up to three feet in thickness. Four to 6 feet below the surface exists "the remains of a cemented coral ledge." The upper 5 to 7 feet of this coral deposit is well cemented and very dense. Below the dense portion exists a dense, poorly graded, sandy coral gravel which extends to 30 to 40 feet below the surface. A reddish-brown sandy silt is below the coral gravel to 50 to 59 feet below the surface. After this the sandy silt interbeds with a "coralline material." (Dames and Moore, Foundation Investigation for Makaua Corp., July 29, 1975; see Appendix).

From the information obtained, the geologic conditions vary from dense coral deposits to alluvium.

Coral or alluvial deposits such as the silts encountered in the drill logs occur interchangeably throughout the area

studied and ensure no continuity. Only sedimentary rocks are encountered in the survey area.

The mechanism by which solution caverns form is set forth in a report by C. K. Wentworth, entitled "The Geology and Hydrology Relating to the Hausten Spring and Fishpond, Honolulu, Hawaii" (December 3, 1953; see Appendix). The Honolulu coastal plain is underlain by a thick wedge of sedimentary rocks, late lava flows and tuff cones which continue two to three miles out to sea, Wentworth explains, and extend to at least 1,200 to 1,500 feet below sea level. The permeable Koolau Volcanic Series Flows which underlie this wedge, would lose infiltrating water produced from rainfall were it not for the wedge which serves as a caprock. The caprock is so effective in preventing the escape of the ground water that the ground water level stands 20 to 30 feet above sea level in the lava flows of the margin of the Koolau Range. Ground water confined by this caprock can exist in two forms, free basal water and artesian water. The distinguishing characteristics are that free basal water has a free upper surface and artesian water is confined under pressure beneath the caprock at levels beneath the free head or level of water. Although the caprock is relatively tight, it still has some permeable layers and has a ground water circulation of its own, separate from the artesian water. This circulating water is called caprock water. The caprock water

is supplied by freshwater and a floating freshwater lens is created "which in general has a slope and a flow toward the shore and whose height above sea level is determined by the amount of fresh water" (Wentworth, December 3, 1953). In the masses of limestone at about sea level "circulation of fresh water in the caprock body has produced an extensive system of caverns of which the outlines are only incompletely known" (Wentworth, December 3, 1953).

The reef limestone, being composed of "coral heads and coralline algae cemented by a lime matrix" (Stearns and Vaksvik, 1935), contains for the most part the mineral calcium carbonate, CaCO_3 . CaCO_3 in the presence of hydrogen ions (H) and carbon dioxide (CO_2) has a strong tendency to break down. The hydrogen ions are supplied by the fresh water and the carbon dioxide, derived from organic materials, is supplied in solution by the fresh water. Thus, the breaking down of the coralline limestone can be represented by the following reaction taken from Huang (1962).



The mechanism by which these rocks are eroded is aided by the presence of cavities created during the growth of the coral deposits.

GEOLOGIC HISTORY

Moiliili lies on the eastern volcano of Oahu, the Koolau Mountain Range. Oahu is composed of two volcanoes, a plateau between them and a coastal plain (Stearns and Vaksvik, 1935). Both volcanoes were built from the ocean floor over three sets of fissures which intersected at the summit crater (Stearns, H. T., 1939).

The western Waianae Volcano is the older and formed what is now the Waianae Mountain Range, and the eastern or Koolau Volcano formed the Koolau Mountain Range. Each formed a shield volcano structure made up of basaltic flows forming the Waianae Volcanic Series and the Koolau Volcanic Series, respectively (Macdonald and Abbott, 1970). The Koolau volcano underwent an early shield building stage which was followed by a period of quiescence and erosional activity (Stearns, H. T., 1939). During this period of erosional activity, wide valleys on the leeward side of the Koolau Volcano were formed which extended several thousand feet in depth (Stearns and Vaksvik, 1935). Moiliili lies at the foot of one of these valleys, Manoa Valley, which is known to have deep accumulations of alluvial material.

After this period the entire island was inundated by more than 1200 feet and the valleys became filled with sediments (Stearns and Vaksvik, 1935). Also during this

period, a renewed period of volcanic activity, the Honolulu Volcanic Series, occurred which involved intermittent flow eruptions and phreatomagmatic eruptions (Stearns and Vaksvik, 1935). Diamond Head and Punchbowl tuff cones are a part of this series. After this deep submergence Oahu underwent a series of submergence and reemergence. It was during the last period of submergence of the island, at a sea level 25 feet higher than the present level, that probably most of the reef materials of the coastal plain were developed (Macdonald and Abbott, 1970)

METHOD

Subject Research

A study of the literature regarding the caverns indicates that the problem deserves detailed investigation. A working map is obtained by tracing an aerial photogrammetric map of a section of Moiliili, prepared by R. M. Towill Corporation for the City and County of Honolulu Planning Department. This map is shown as Figure 2 with the addition of the approximate location of Kuilei Lane and Kapaakea Lane. The aerial photogrammetric map is of a scale too small to allow direct tracing of these relatively small streets.

Theoretical Pilot Study

It is also necessary to calculate the gravitational effect of a theoretical body in order to know what spacing is needed for the field observations to indicate the anomaly of the body. A two-dimensional computer program is used in this preliminary model study. The program is made available through the Indiana University by Dr. A. Rudman and is based on a paper by Talwani, Worzel, and Landisman (1959). A discussion of the theory behind the program follows.

Consider the following body:

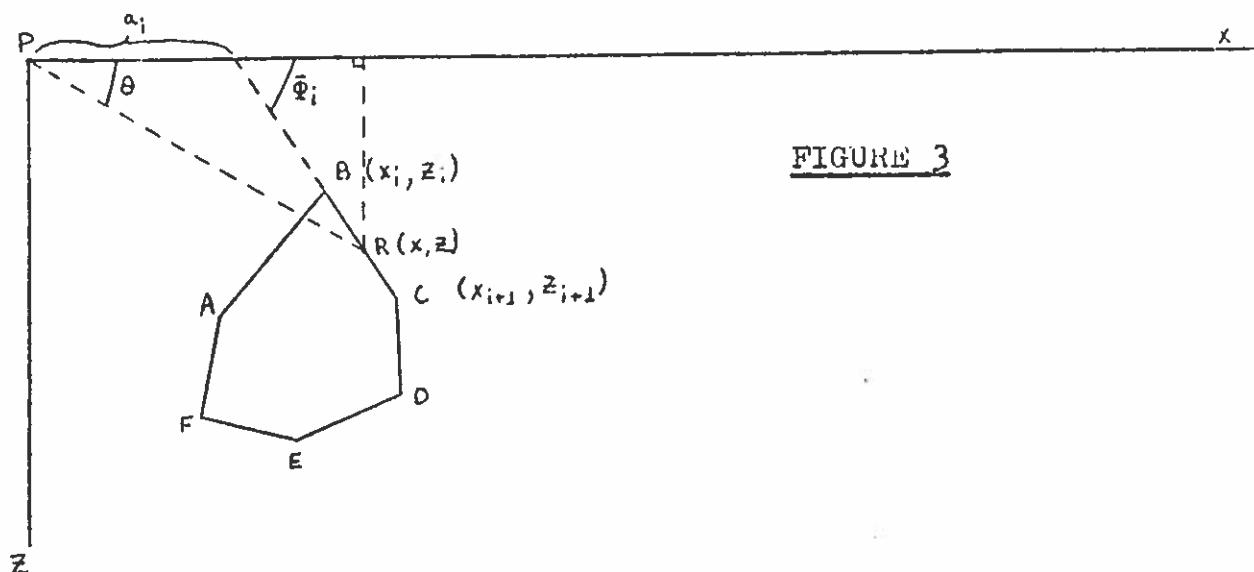


FIGURE 3

Hubbert (1948) has shown that at the origin the vertical component of gravitational attraction, g_z , of a two-dimensional body represented by the polygon in Figure 3 can be determined by the following formula,

$$g_z = 2Gd\oint z d\theta \quad (1)$$

where the integral is taken around the body's periphery, G is equal to the universal gravitational constant, d is the volume density of the body and the remaining variables are defined by Figure 3.

For any point R on the side \overline{BC} we can see that

$$z = x \tan \theta \quad (2)$$

If we extend a vertical line to the x -axis from the point R it is obvious that

$$z = (x - a_i) \tan \phi_i \quad (3)$$

Eliminating x from equations 2 and 3 yields

$$z = \frac{a_i \tan \theta \tan \phi_i}{\tan \phi_i - \tan \theta} \quad (4)$$

Substituting this value for z into the line integral of side \overline{BC} , we see that

$$\int_B^C z d\theta = \int_B^C \frac{a_i \tan \phi_i \tan \theta}{\tan \phi_i - \tan \theta} = Z_i$$

Therefore the vertical component of gravitational attraction for the entire polygon can be written as

$$g_z = 2Gd \sum_{i=1}^n Z_i, \text{ where } n \text{ is equal to } (5)$$

the number of sides of the polygon.

For the most general case, it can be shown that

$$Z_i = a_i \sin \phi_i \cos \phi_i [\theta_i - \theta_{i+1} + \tan \phi_i \log_e \frac{\cos \theta_i (\tan \theta_i - \tan \phi_i)}{\cos \theta_{i+1} (\tan \theta_{i+1} - \tan \phi_i)}] \quad (6)$$

where (see Figure 3):

$$\theta_i = \tan^{-1} \frac{z_i}{x_i}$$

$$\phi_i = \tan^{-1} \frac{z_{i+1} - z_i}{x_{i+1} - x_i}$$

$$\theta_{i+1} = \tan^{-1} \frac{z_{i+1}}{x_{i+1}}$$

Substituting the above values into equation 4 we can see that

$$a_i = x_{i+1} + z_{i+1} \frac{x_{i+1} - x_i}{z_i - z_{i+1}}$$

Noting that $\theta_i, \theta_{i+1}, \phi_i$ and a_i are all expressed in terms x_i 's and z_i 's and noting the form of equations 5 and 6, we can express the vertical component of gravitational attraction, g_z , in terms of x_i 's and z_i 's, the horizontal and vertical parameters. Before calculating g_z , we must also define the density of the body and the point at which the calculation is to be made.

A calculation of g_z across a body of minimum dimensions is performed using the computer program mentioned above. The dimensions are obtained by using an average description of the caverns which is a body with a longer horizontal axis than vertical, on the order of 3 to 4 times as great. A rectangular-shaped body is used since such a shape fits this description and is a simple shape to define.

A good estimate for the station spacing model is a body with a 20-foot horizontal dimension (width), a 6-foot vertical dimension (height) and a depth to the roof of the cavern of 4 feet. The density of a dry sample taken in the laboratory is determined to be 2.09 g/cc (Estes, et al., 1973). Even though this density is suspected of being too small, it is a good density to use in this case, since we are looking for a minimum effect. The body is assumed to be filled with

water since it is below the water table (Kapaehulu Sewage System Map, Honolulu Board of Water Supply, April 4, 1934) in this area. Some reports say that the caverns are filled with a fine ooze in the lower 2 to 3 feet of the cavern. However, not enough information is available to determine the density of the material. Thus, it is not taken into consideration and it is assumed that the ooze is fine enough to not contribute significantly to the body density. Therefore, the body density is 1.00 g/cc, yielding a density contrast of 1.09 g/cc. The calculation of g_z is made for horizontal intervals of 5 feet.

The maximum effect of the body is -50 microgals (a microgal is 1/1,000,000 of a centimeter per second squared) to the nearest ten microgals, directly over the middle of the body (see Table 1). At 20 feet off center, the gravitational effect decreased to -10 microgals. If we assume that the maximum variation in gravitational attraction due to noise will be no more than 10 microgals, the effect of the body at 5 feet off center may show up as -30 microgals, at the worst. Beyond 5 feet the effect of the body drops to lower values than will provide conclusive evidence as to the presence of a cavern. Thus, the horizontal spacing between the stations may be twice this length in order to obtain the desired effect, since a station of 5 feet off center in one direction would give the desired effect and a station 5 feet

off center in the other direction would give the same effect, which is the worst possible circumstance.

Equipment

The materials used for the data acquisition are: a Lacoste and Romberg Geodetic No. 1 gravimeter used for obtaining relative observations of gravitational attraction; a differential level to obtain both relative elevations and horizontal distances between stations; a 12-foot "rod" or measuring device marked in hundredths of feet used with the level; and large-headed nails used as station markers.

Data Acquisition Procedures

The gravitational attraction data were taken over a period of three days (October 8, 9 and 10), while the data taken with the level was obtained during two days (October 8 and 11). On October 8, the data was taken by the GG 465 class since it was their assignment to obtain data in the same area. The instructions to this class and pre-lab write-up is in the appendix of this paper. The rest of the data was taken by myself and my wife, Sheila, who helped on October 11 to collect the remaining level data. Two profiles, spaced by a distance of 23 to 30 feet were obtained perpendicular to the suspected strike of the cavern in order to check for consistency in the observed values and to determine the local strike of the cavern.

Two readings of the gravimeter were taken at each of the stations to ensure precise readings. If the two readings did not agree to 0.005 units of a dial unit, a third reading was obtained. The readings were repeated by turning the dial of the device to a higher value and then bringing the cross-hair inside the machine to the null position on the reading scale from higher to lower values. All of the readings were taken by this high to low procedure to ensure that no error would be introduced by insensitivity of the dial to different directions of dial movement.

On the 8th, the class took the readings by orienting the instrument in the same direction relative to the length of Kuilei Lane to ensure that no error would be introduced by the magnetic effects of the earth. The operator always faced southward. On October 9 and 10, it was necessary to take the gravimeter readings from a different orientation due to parked cars in the area.

Before the class went into the field to collect the data, I went to the area and marked the stations with a nail driven into the asphalt, where the substratum allowed, and green spray paint. The distance between stations was determined by pacing the distance based on my pace factor of 5.2 feet per full (2 strides) pace.

In addition, the gravimeter needs to be kept at a constant temperature, so the temperature was frequently checked

by reading the thermometer inside the gravimeter to ensure that the reading was taken under stable conditions of the instrument.

A check for precise readings on the relative elevations of the stations was obtained by repeating stations whose elevations were determined earlier. Accurate elevations are important since one of the corrections applied to the data is a function of the change in elevations between stations.

DATA REDUCTION

Microgal Conversion

In order to convert the readings to values in microgals, Table B (see Appendix) is used which is the most current calibration table for the gravimeter. The table gives the value of gravity in milligals (a milligal is 1/1000 of a centimeter per second squared) for each 100 units of the first four digits of the dial reading or counter units. First, we obtain the value in milligals for the reading in the table which is nearest but less than the observed reading. Note that for all of the readings the counter value is 2100. Next, we obtain the difference between the observed reading and 2100. We then multiply this difference by the interval factor corresponding to the 2100 counter units value. Finally we add this product to the milligal value obtained in the first step to obtain the reading in milligals. We then convert the reading in milligals to microgals by multiplying the value obtained in the last step by 1000.

Earth Tides

Before any interpretation of the results can be determined, it is necessary to correct the relative gravitational attraction data for various factors which can affect the values obtained.

Due to the swelling and contracting of the mass of the earth caused by the effect of other bodies acting upon it, the gravitational attraction measured at the earth's surface will vary as a function of time. Fortunately the variation is a predictable one and is found to be of a cyclic nature. A study by Woolard, et al. (1973), produced a computer program which calculates the earth tides for any given day. A copy of this report can be obtained from the Hawaii Institute of Geophysics Publication Office. Using this program, I have obtained the earth tides for October 8, 9 and 10 and these are found in Tables 2 and 3. Since these are the tidal effect, the correction applied to the data is opposite in sign to the effect.

Drift of the Instrument

The instrument is prone to drift with respect to the values of gravitational attraction that it records. In order to determine how much the instrument drifts, readings must be repeated at stations to obtain the drift for each day. Three readings for each day taken at station 1A are used to plot the drift curve for each day (see Figure 4). With the drift of each day, the readings are corrected to the first station reading of each day.

The instrument also drifts while it sets overnight. This can be accounted for by "normalizing" the readings for the 9th and 10th to the first reading at station 1A on the 8th of

0.75767159

TABLE 2

GRAVITATIONAL TIDE PREDICTION

LOCATION: LATITUDE = 21 18.1 LONGITUDE = 157 49.2 ELEVATION = 21.9 METERS

TIME ZONE CORRECTION USED 10

STARTING: DAY 8 MONTH 10 YEAR 1975 HOUR 1 MINUTES 0 : PCR

HOUR	TIDE	TIDE
1.0	0.141	A
2.0	0.165	A
3.0	0.163	A
4.0	0.136	A
5.0	0.091	A
6.0	0.038	A
7.0	-0.011	A
8.0	-0.046	A
9.0	-0.061	A
10.0	-0.055	A
11.0	-0.032	A
12.0	0.000	A
13.0	0.031	A
14.0	0.050	A
15.0	0.054	A
16.0	0.039	A
17.0	0.011	A
18.0	-0.023	A
19.0	-0.053	A
20.0	-0.068	A
21.0	-0.064	A
22.0	-0.039	A
23.0	0.002	A
24.0	0.050	A
1.0	0.094	A

0.75769895 0

TABLE 3

GRAVITATIONAL TIDE PREDICTION

LOCATION : LATITUDE = 21 18.1 LONGITUDE = -157 49.2 ELEVATION = 22.0

TIME ZONE CORRECTION USED 10

STARTING : DAY 9 MONTH 10 YEAR 1975 HOUR 1 MINUTES 0

TIDE

DAY	HOUR	TIDE	TIDE
282	1.0	0.094	.
282	2.0	0.126	.
282	3.0	0.142	.
282	4.0	0.136	.
282	5.0	0.111	.
282	6.0	0.075	.
282	7.0	0.034	.
282	8.0	-0.002	.
282	9.0	-0.029	.
282	10.0	-0.040	.
282	11.0	-0.036	.
282	12.0	-0.021	.
282	13.0	-0.000	.
282	14.0	0.019	.
282	15.0	0.031	.
282	16.0	0.031	.
282	17.0	0.020	.
282	18.0	0.000	.
282	19.0	-0.022	.
282	20.0	-0.040	.
282	21.0	-0.046	.
282	22.0	-0.039	.
282	23.0	-0.017	.
282	24.0	0.015	.
283	1.0	0.050	.
283	2.0	0.083	.
283	3.0	0.106	.
283	4.0	0.116	.
283	5.0	0.111	.
283	6.0	0.094	.
283	7.0	0.068	.
283	8.0	0.038	.
283	9.0	0.010	.
283	10.0	-0.011	.
283	11.0	-0.023	.
283	12.0	-0.026	.
283	13.0	-0.019	.
283	14.0	-0.007	.
283	15.0	0.006	.
283	16.0	0.015	.
283	17.0	0.018	.
283	18.0	0.014	.
283	19.0	0.004	.
283	20.0	-0.009	.

October. The normalizing factor is obtained by taking the difference between the first reading at station 1A on the 8th and the first reading of each of the other two days, separately. The normalizing factor for each of the two days is applied to their respective readings for the entire day.

Initially a single drift curve was determined which combined the inter-day and intra-day drift into a single curve. This method was less consistent with the data and therefore was not used.

Latitude

The latitude correction is necessary since the gravitational attraction on the earth's surface changes due to the shape of the earth. Since the radius of the earth changes from a mean equatorial radius of 6378.388 km to a polar radius of 6356.912 km (Jacobs, et al., 1959), the gravitational attraction will change as a function of latitude. The international gravity formula given by Jacobs, et al. (1959) is as follows:

$$g = 978049(1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)$$

where g is the gravitational attraction, and ϕ is latitude. We can compute the relative change in gravitational attraction by using this formula.

Before ϕ can be used in the equations, the latitude given by the R. M. Towill map has to be converted to degrees from Hawaiian Plane Coordinates in feet. This is done by using

Tables I through VI and the table of constants in the Appendix, which are based on the Clarke spheroid of 1866. Calculations involving two points formed by the intersection of the coordinate grid in Figure 2 are computed to obtain the latitudes of the two horizontal lines of the grid.

Let us define the longitude value given in feet as x . Finding the appropriate constant, C , from the table of constants for the zones in the Hawaiian Islands, we then subtract C from x to yield x' . Note that C is 5,000,000.00 feet for both calculations, since both points are in zone #3.

$$x' = x - C$$

Obtaining two variables P and d from Tables III and IV, respectively, we can solve for a variable, w , defined by

$$w = P \left(\frac{x'}{10,000} \right)^2 - d$$

Finally subtracting w from the coordinate of latitude in feet, y , we obtain a value defined as y_0 which gives us the latitude from Table 1.

$$y_0 = y - w$$

Once the latitudes for the grid coordinates are obtained it is necessary to plot the location of the stations on Figure 2 to find the stations' respective latitudes. To avoid calculating g from the international gravity formula for each station, g is calculated at the two end stations. The change in g per horizontal distance is determined from the

g values at the two end stations and a latitude correction is applied to each station in the survey. The latitude correction is made relative to station 1A.

To confirm the validity of this assumption we calculate g from the formula for station 14B which was far enough from station 1A to expose any error in the method. The two means of obtaining the latitude correction for 14B compared to the nearest microgal, and this confirms the method used for computing the corrections.

Free Air

The next correction, the free air correction, is due to the change in elevation between stations. Since the gravitational attraction of the earth decreases as the distance from the center increases, this correction is positive for elevations above the reference level (station 1A) and negative for elevations below the reference level. The correction factor is 0.09406 mgal/foot (Jacobs, et al., 1959).

Bouguer

The next correction, the Bouguer or flat-slab correction, is necessary since the rock between 1A and stations other than 1A produce higher gravity values than 1A if their elevation is higher since 1A's elevation is defined as the reference level. Lower gravity values are generated if their elevations are lower. Thus, where the free-air correction is

positive, the Bouguer correction is negative, and vice versa. The effect of the rock is given by: $2\pi Gdh$, where G is the gravitational constant, d the density of the rock and h the height above the reference level. The density is taken as being 2.09 g/cc (Estes, et al., 1973) since this is a dry density. A dry density is the best density to use since the rock above station 1A is above the water table. With G and d constant, the factor becomes 0.02669 mgal/foot.

Terrain

The next correction, the terrain correction, is due to the effect of the surrounding topography such as hills, valleys and buildings, on the gravitational attraction. The correction for the hills and valleys is not necessary for this survey since the drastic changes in topography are far enough away and the survey site so small in length that the effect of the topography will be essentially a constant for all of the stations. The anomaly produced by the cavern will be the same relative to station 1A since all of the stations will be affected in the same way by the same amount.

We must calculate the gravitational effect of the building on the makai side of Kuilei Lane which extends for most of the length of the survey and is about 5 feet away from profile B and 25 feet away from profile A. The building extended from stations 3B to 15B. In order to calculate the effect of the building for all stations, a 3-dimensional method will have to be used. Before any such method is

investigated it seems a good idea to calculate the effect of the building using a 2-dimensional graticule of the King-Hubbert type.

The 2-dimensional method requires that the anomalous body have an infinite dimension perpendicular to the direction over which the calculation is computed. The building length is sufficiently long, relative to the distance at which the calculation is made, to call the building length infinite, at the center of the profiles. At the middle-most station, the gravitational effect will be the maximum.

The building consists of 3-inch slabs separating the floors and hollow concrete block constituting the vertical walls. The effect of the hollow blocks can be ignored since it will be small. The slabs, being of a solid nature, are the masses used to calculate the effect of the building.

The slabs are shown with their longest dimension into the paper (see Figure 5), and the graticule is laid over the slabs with the center of the graticule placed at the point of calculation. The number of solenoids, n , enclosed by a change in vertical distance, dz , and the change in the graticule angle, $d\theta$, is found by simply counting the solenoids. The change in vertical distance, dz , is chosen to be the width of the slabs and $d\theta$ is chosen to be 5° . It is found by using the graticule, that the maximum effect of the building is 2 microgals for profile A and 6 microgals for profile B (see

Figure 5), where the effect is determined by the following formula:

$$g = n2Gd(d\theta)(dz)$$

G is the gravitational constant; d is the density of the slabs, taken as 2.5 g/cc for common building concrete obtained from a previous study in GG 361; $d\theta$, the graticule angle; and dz is the incremental change in vertical distance. Since 2 or 6 microgals is small compared to the anomaly obtained of 125 microgals, the building effect can be ignored.

Simple Bouguer Anomaly

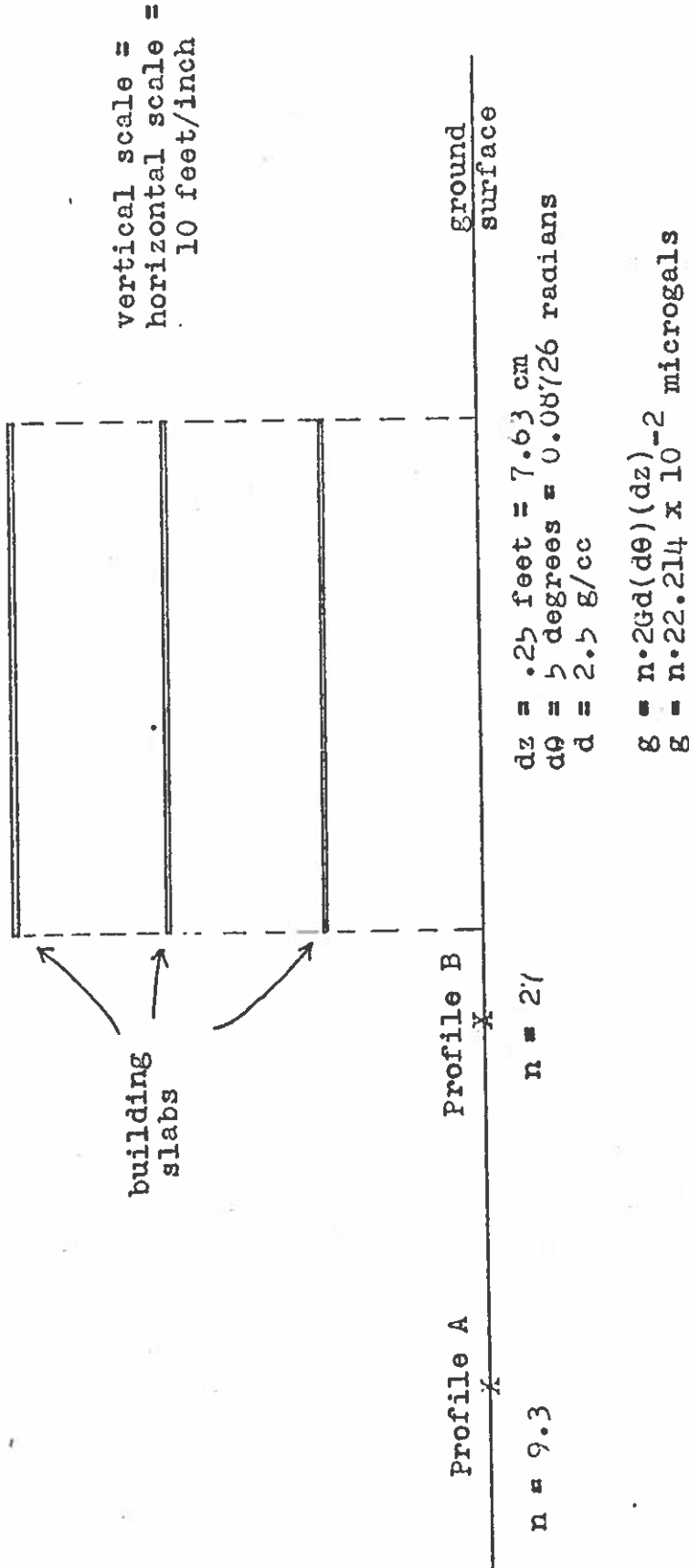
The final calculation is obtained by the following formula:

$$SBA = (g_{obs.} + g_{FA} - g_B) - g_{1A} \quad , \text{ for profile A and by}$$

$$SBA = (g_{obs.} + g_{FA} - g_B) - g_{1B} \quad , \text{ for profile B, where}$$

$g_{obs.}$ is the gravity value with the drift, earth tide and latitude corrections applied; g_{FA} is the free air correction; g_B is the Bouguer correction; g_{1A} is the gravity value for station 1A on the 8th and g_{1B} is the gravity value for station 1B. This calculation simply puts the values into relative terms, namely relative to station 1A for profile A and relative to 1B for profile B.

FIGURE 5



$g = 6 \text{ microgals}$

$g = 2 \text{ microgals}$

DATA TABLE

Time (H.S.T.)	1975 Oct. Day	Average Reading	9obs. (microgals)	9obs. (microgals) w/F. Tide Correction	9obs. w/Drift Correction (microgals)		9obs. w/ Latitude Correction (microgals)	Elev. rel. to Sta. LA (feet)	Free Air Corr. (microgals)	Bouguer Corr.	Simpl Boug. Anom.
					Each Day	"Normalized" to Sta. LA for inter- day drift					
1415	8	2165.907	2178459	2178408	2178408	2178408	2178408	0	0	0	0
1430		2165.890	2178442	2178390	2178380	2178380	2178381	.03	3	1	-25
1440		2165.853	2178405	2178352	2178335	2178335	2178337	.32	30	9	-50
1500		2165.876	2178428	2178374	2178344	2178344	2178348	.80	75	21	-6
1505		2165.774	2178325	2178271	2178237	2178237	2178242	1.38	130	37	-73
1515		2165.940	2178492	2178441	2178401						
1540		2165.713	2178264	2178220	2178163	2178163	2178169	1.92	181	51	-109
1545		2165.700	2178251	2178208	2178147	2178147	2178154	2.21	208	59	-105
1555		2165.727	2178278	2178238	2178171	2178171	2178179	2.36	222	63	-70
1610		2165.742	2178293	2178259	2178181	2178181	2178190	2.39	225	64	-57
1630		2165.984	2178537	2178512	2178421						
1055	9	2165.953	2178506	2178542	2178542	2178408					

DATA TABLE

Time (H.S.T.)	1975 Oct. Day	Average Reading	9obs. (microgals)	9obs. (microgals) w/E. Tide Correction	9obs. w/Drift Correction (microgals)		9obs. w/ Latitude Correction (microgals)	Elev. rel. to Sta. LA (feet)	Free Air Corr. (microgals)	Bouguer Corr.	Sim- Bou- Anc. (mic)
					Each Day	"Normalized" to Sta. LA for inter- day drift					
1105	9	2165.826	2178378	2178413	2178409	2178275	2178285	2.54	239	68	+
1120		2165.820	2178372	2178403	2178393	2178259	2178271	2.61	245	70	+
1135		2165.852	2178404	2178431	2178415	2178281	2178294	2.39	225	64	+
1150		2165.829	2178381	2178404	2178382	2178248	2178262	2.23	210	60	+
1210		2165.843	2178395	2178412	2178382	2178248	2178264	2.08	196	56	-
1225		2165.847	2178399	2178411	2178375	2178241	2178258	2.06	194	55	-
1240		2165.876	2178428	2178435	2178393	2178259	2178277	1.71	161	46	-
1255		2166.083	2178636	2178638	2178590						
1350		2166.008	2178561	2178545	2178475	2178341	2178345	- .13	-12	-3	
1400		2165.938	2178490	2178471	2178397	2178263	2178269	.66	62	18	-
1420		2165.898	2178450	2178426	2178344	2178210	2178217	.94	88	25	-

DATA TABLES

Time (H.S.T.)	1975 Oct. Day	Average Reading	9obs. (microgals)	9obs. (microgals) w/E. Tide Correction	9obs. w/Drift Correction (microgals)		9obs. w/ Latitude Correction (microgals)	Elev. rel. to Sta. LA (feet)	Free Air Corr. (microgals)	Bouguer Corr. (microgals)	Sirpi Bougu Anoma (microgals)
					Each Day	"Normalized" to Sta. LA for inter- day drift					
1440	9	2165.859	2178411	2178382	2178292	2178158	2178166	1.25	118	33	-85
1450		2165.747	2178298	2178268	2178174	2178040	2178049	2.41	227	64	-124
1505		2165.757	2178308	2178277	2178177	2178043	2178053	2.37	223	63	-122
1515		2165.762	2178313	2178281	2178177	2178043	2178054	2.27	214	61	-120
1525		2165.702	2178253	2178220	2178112	2177978	2177990	2.36	222	63	-18
1535		2165.716	2178267	2178234	2178122	2177988	2178002	2.33	219	62	-17
1550		2166.033	2178586	2178554	2178436						
1405	10	2166.132	2178686	2178692	2178692	2178408					
1420		2165.805	2178357	2178360	2178366	2178082	2178097	2.27	214	61	-8
1430		2165.807	2178359	2178360	2178371	2178087	2178103	2.19	206	58	-8
1440		2165.770	2178321	2178319	2178334	2178050	2178067	2.19	206	58	-1
1450		2165.791	2178343	2178339	2178359	2178075	2178094	2.09	197	56	-1

RESULTS

The SBA was plotted as a function of distance relative to station 1A for profile A and relative to station 1B for profile B. Figure 6 is this plot. The plot shows that there are two caverns underneath Kuilei Lane--one with a maximum anomaly of -109 microgals and another smaller cavern with a maximum anomaly of -50 microgals.

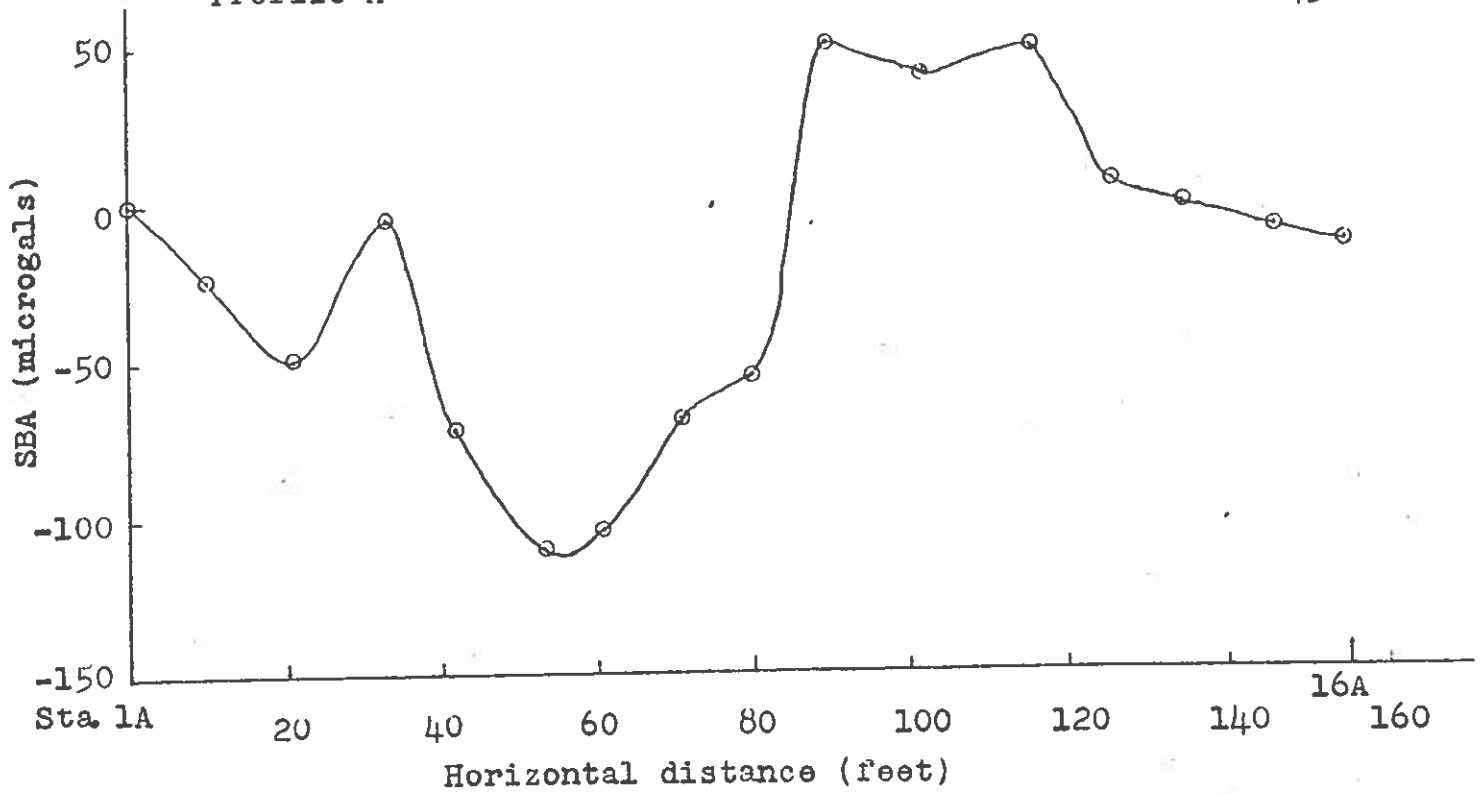
The caverns also are indicated in profile B with a higher maximum anomaly of -190 microgals and -125 microgals, respectively. Profile B's SBA does not return to the zero line but remains low to the end of the profile in contrast to profile A's SBA which returns to the zero line, going higher and finally slightly negative for the last three stations. These apparently conflicting trends in the data may be explained by changes in the subsurface conditions or a regional gravity effect between the two profiles since no consistent evidence emerges from the data to indicate another cavern to the east of the profiles.

In particular, the high anomaly recorded from station 10A to station 12A may very well be due to a dense portion of reef limestone underneath these stations while this dense rock does not extend to the other side of the lane to profile B.

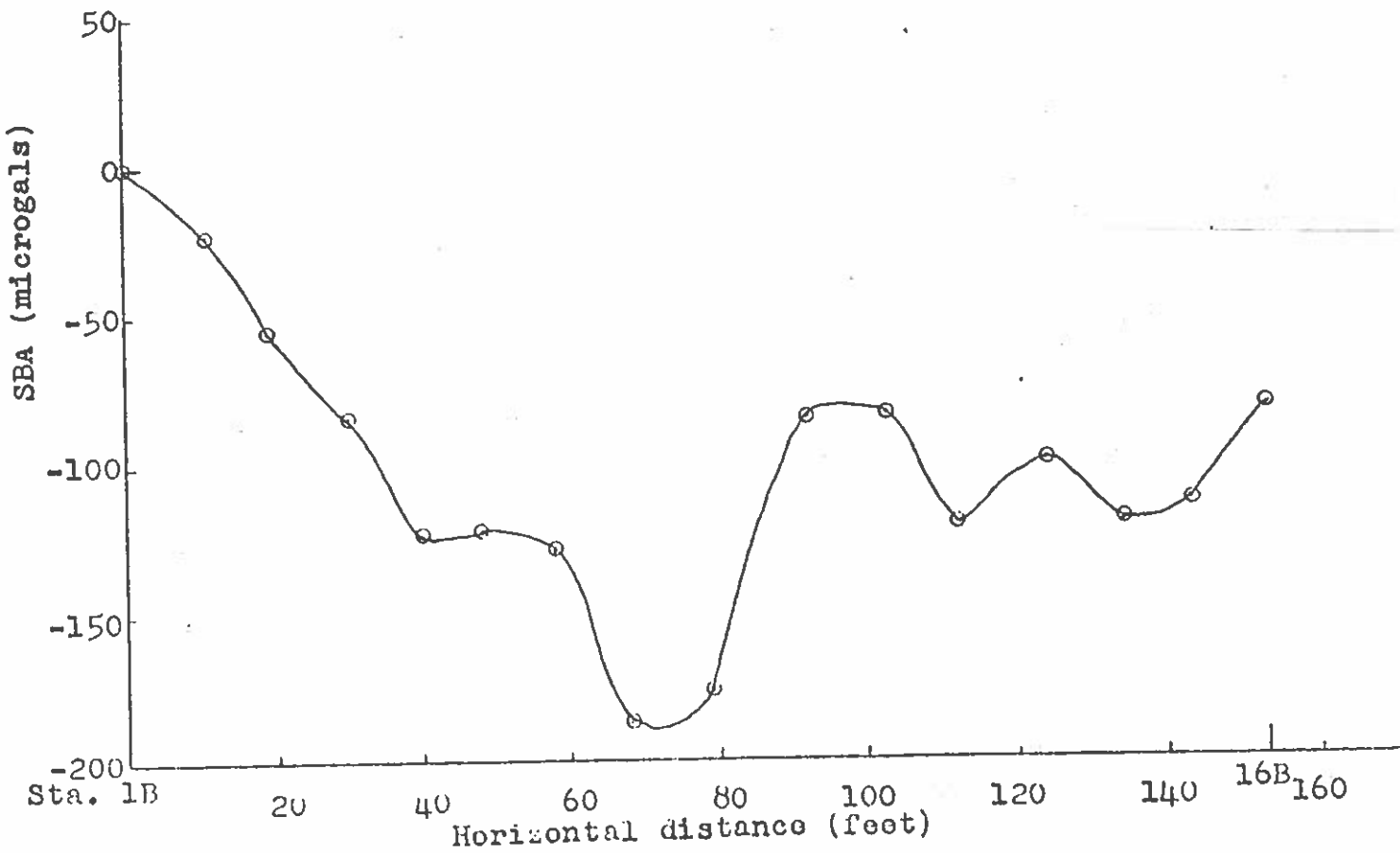
FIGURE 6

Profile A

43



Profile B



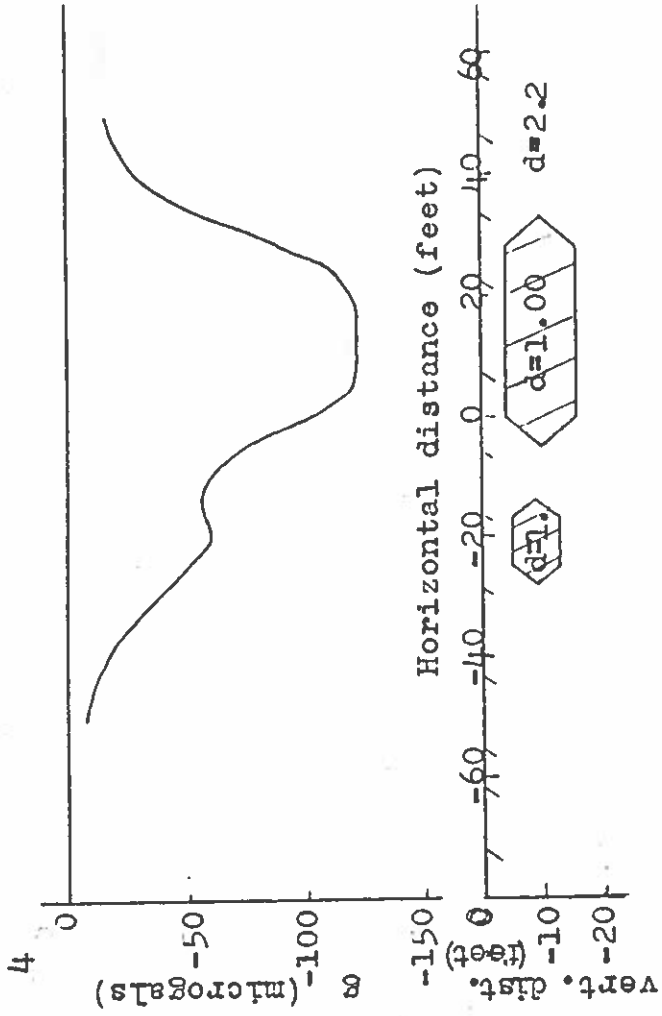
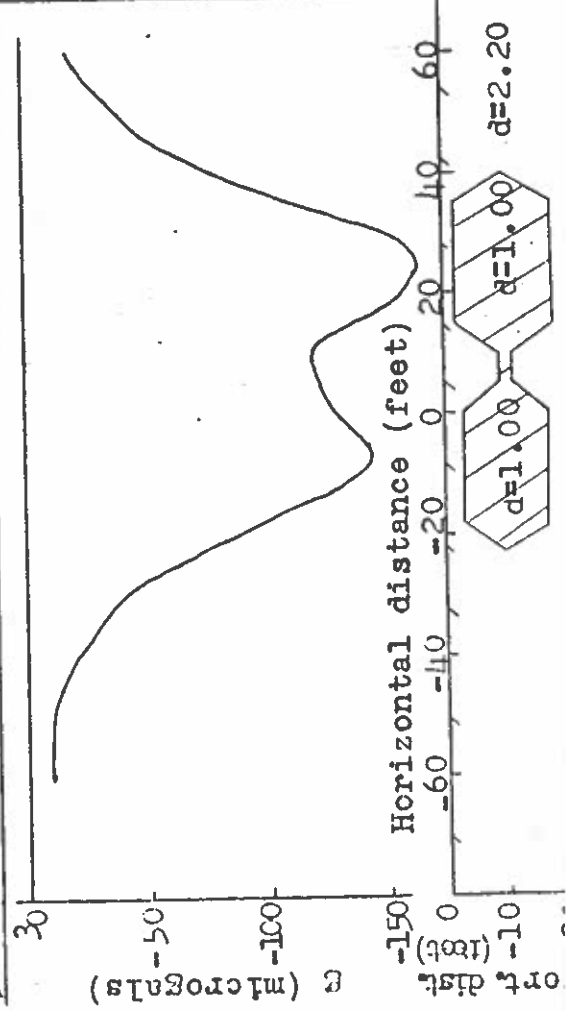
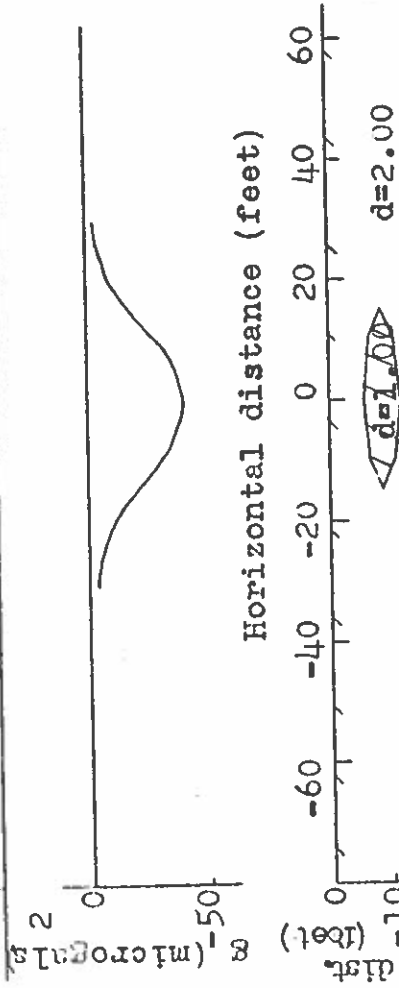
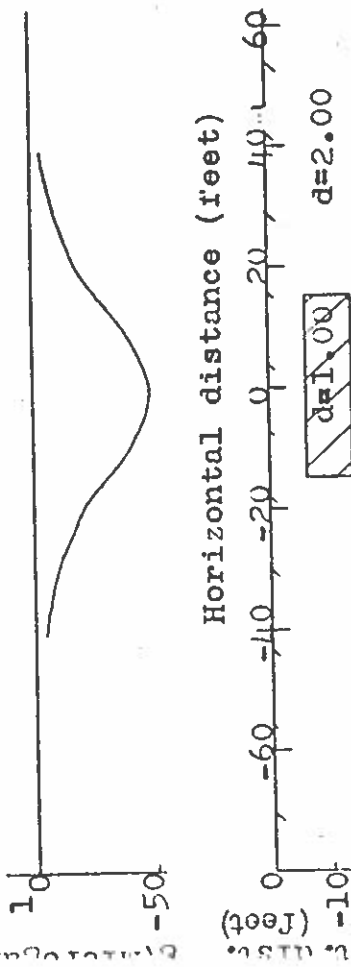
MODELING

Several models of the suspected anomalous body were calculated by the GG 465 class using the 2-dimensional gravity program mentioned earlier to obtain a theoretical model whose gravity anomaly would closely match that of the observed. Three models obtained by the students are plotted in order to show the effects of different models (see Figure 7).

The first model is an 8-foot high, 30-foot wide rectangle which has a body density of 1.00 g/cc (water-filled), and a country rock density of 2.00 g/cc (an approximate density of the coral). The depth to the roof of the cavern is 6 feet. The gravity effect of this body proves not to fit the observed very well for two reasons; the small maximum anomaly of the model and the shape of the model's curve which is much gentler on the flanks compared to the observed anomaly.

The second model used the same densities and the same depth to the roof, but changed the shape of the body to an elliptical shape keeping the horizontal and vertical dimensions the same. This didn't change the anomaly much except to make the maximum anomaly lower, which was the opposite to what the observed anomaly called for.

The third model, derived by John Meyer, uses the same body density of 1.00 g/cc. But he changed the shape to a



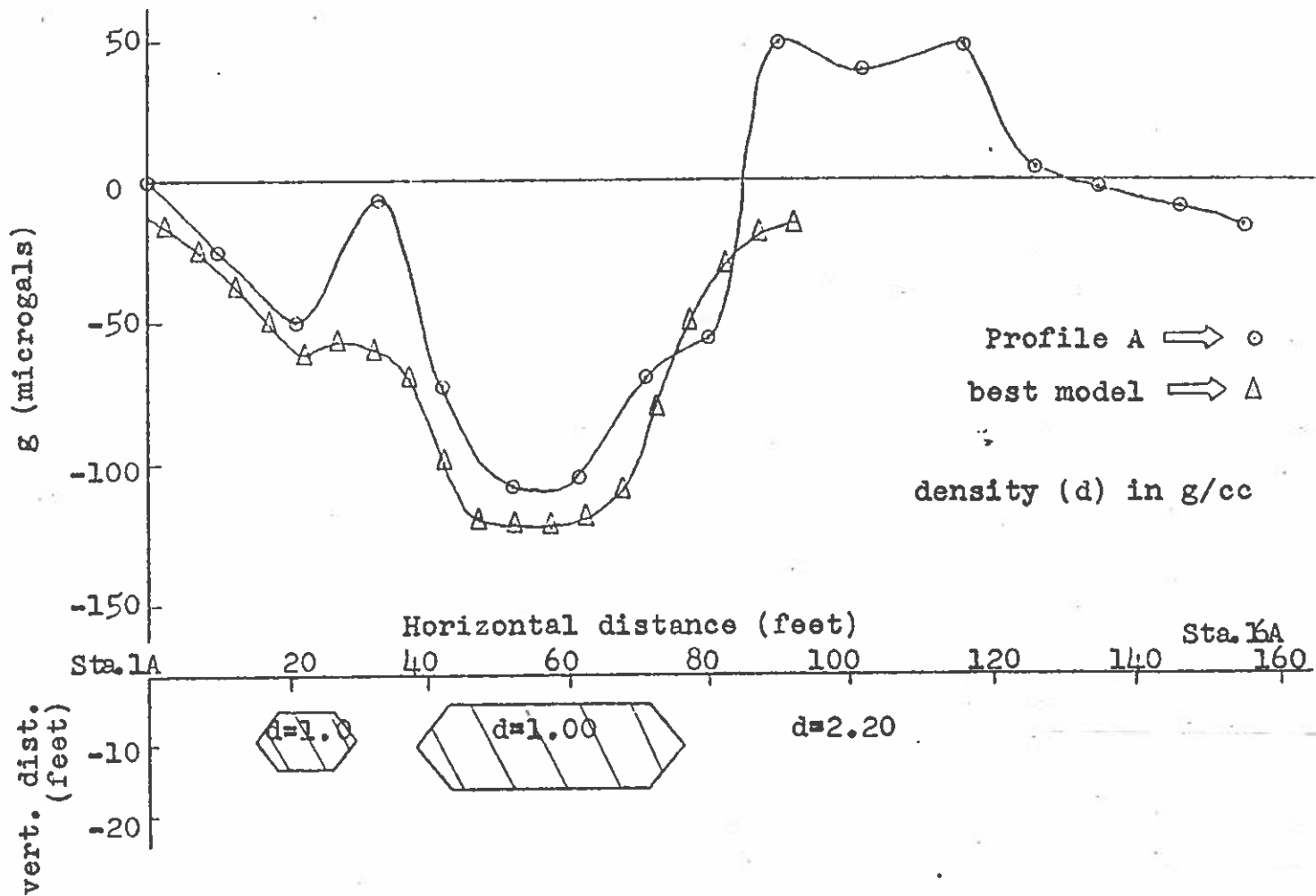
vertical scale = horizontal scale
density (d) in g/cc

FIGURE 7

hexagon, moved the body closer to the surface, and gave the country rock a density of 2.20 g/cc, which is reasonable since a wet condition of the coral could easily increase the density from 2.09 g/cc obtained by Estes, et al., to 2.20 g/cc. This model used two bodies beside each other with one body of a smaller size. This model does not fit the observed data well enough because the flanks of the anomaly are too steep and the maximum anomalies of the bodies do not match the observed.

Using Meyers' idea of hexagonal shapes and a country rock density of 2.20 g/cc, I calculated the anomaly over two bodies filled with water. The model puts the larger body 4 feet below the ground surface and assigns to its dimensions a height of 12 feet and a maximum width of 38 feet. The smaller body is separated laterally from the larger body by 9 feet at their closest approach. This body's roof is 5 feet below the surface and is 8 feet high and 14 feet at its maximum. This body and its anomaly are plotted in Figure 7 as model 4. This model proved to best fit the observed values (see Figure 8).

FIGURE 8



CONCLUSIONS

The Lacoste and Romberg gravimeter proved to be a precise instrument by repeating values for many stations to within 5 microgals which saved time in obtaining the data. The differential level proved a good instrument to use in obtaining horizontal distances and elevation changes. A check on the elevations obtained by repeating four stations showed the values to repeat one another exactly to .01 foot for two stations. The other two differed only by .01 and .02 feet, respectively, testifying that there was very good control on the elevations.

The results indicate that two caverns exist underneath Kuilei Lane. These caverns are not the same caverns located here by a Honolulu Board of Water Supply map of April 4, 1934 (see Appendix), since the strike of these caverns is quite different from that of the previously located caverns. The caverns observed in this study are closely approximated by two hexagonally-shaped bodies filled with water, being surrounded by coralline limestone of a wet density of 2.20 g/cc. The larger cavern has a maximum height of 12 feet, a maximum width of 38 feet, a minimum width of 28 feet and is buried 4 feet below the surface. The smaller cavern has a maximum height of 8 feet, a maximum width of 14 feet, a minimum width of 9 feet and is buried 5 feet below the surface. The

two caverns strike parallel to each other across Kuilei Lane in a N15°E. direction separated by 9 feet of rock. The two profiles indicate that the two separate caverns under profile A approach one another on the profile B side of the lane and become larger in dimensions.

Since the caverns are nameless, it seems appropriate to dub these caverns with a name which fits their description and geographic location. Therefore I have chosen to call these caverns with the help of Larry Kimura and an English-Hawaiian dictionary (Pukui and Elbert, 1964), Nāanawaielua o Ala Kuilei, which means "the two water caverns of Kuilei Road."

ACKNOWLEDGMENTS

I am grateful to everyone who helped me in any way to produce this thesis. In particular I thank my adviser, Dr. W. M. Adams for all of his thoughts, suggestions, and criticisms regarding this paper and for suggesting this topic to me. I also thank Dr. A. J. Rudman for all of his suggestions and guidance in planning the survey and Dr. J. C. Rose and John Meyer, Jr., for giving me instructions and advice regarding the operation of the gravimeter. I thank J. Meyer also for allowing me to use his idea for a model to fit the anomaly.

Thanks to the following people who aided me in finding literature concerning the Moiliili caverns: Robert Schank of the State of Hawaii Office of Civil Defense, Pat Akamine and Sam Cox of the Moiliili Community Center, Walter Lum Associates, Norma Olsen of Milton Sher Associates, Wallace Miyashiro of the Honolulu City and County Department of Public Works, Glen Bauer of the Honolulu City and County Board of Water Supply, Kazu Yato of Group Architects Collaborative, Dames and Moore, and Winfred Wong of Makaua Corporation.

I thank Dr. S. H. Laurila and Mr. Fisher of R. M. Towill Corporation for helping me convert the Hawaiian Plane Coordinates given in feet to degrees.

The GG 465 Fall 1975 class did an excellent job of collecting part of the data and I thank them for their assistance.

Thanks to Larry Kimura of the Indo-Pacific Languages Department of the College of Arts and Sciences at the University of Hawaii who helped me phrase in Hawaiian what I wanted to name the caverns.

I thank my wife, Sheila, for taking an active interest in this thesis by helping me collect a part of the data, editing my rough drafts and helping me type the rough drafts.

LIST OF REFERENCES

1. American Society of Civil Engineers, 1945, "Discussion in Unusual Cut-off Problems--Dams of the Tennessee Valley Authority," ASCE Transactions, Volume 110, paper #2250.
2. Dames and Moore, July 29, 1975, "Foundation Investigation for Makaua Corporation," includes boring logs.
3. "Diver Goes Down Under King Street to Explore Tube," April 24, 1952, Honolulu Star-Bulletin.
4. Estes, S., et al., 1973, "The Location of Solution Cavities in Coral Limestone by Gravity Meter Methods," 29 pp., GG 465 project write-up.
5. Honolulu Board of Water Supply, 1933-34, Water Resources Report, p. 255.
6. Honolulu Board of Water Supply Map, April 4, 1934, map with water level information for Kapahulu Sewage System.
7. Honolulu Department of Public Works, Bureau of Plans Map, June 6, 1952, map with bore hole data.
8. Huang, W. T., 1962, Petrology, McGraw-Hill, Inc., New York, 454 pp.
9. Hubbert, M. K., 1948, "A Line Integral Method of Computing the Gravimetric Effects of Two-Dimensional Masses," Geophysics, Volume 13, No. 2, pp 215-225.
10. Jacobs, J. A., et al., 1974. Physics and Geology, 2nd Edition, New York, 507 pp.
11. Kiersch, G. A., November 1958, "Geologic Causes for Failure of Lone Pine Reservoir, East Central Arizona," Economic Geology, Volume 53, No. 7, pp. 854-866.
12. Kunesh, J. F., 1934, "Mammoth Caves Under King Street," 4 pp., a report to J. Williams concerning the 1934 cave exploration.

13. Lum, Walter Associates, July 1973, "Boring Log for Moiliili Community Center."
14. Macdonald, G. A. and Abbott, A. T., 1970, Volcanoes in the Sea, University of Hawaii Press, Honolulu, 409 pp.
15. "Moiliili Lane is Closed to Traffic; Residents Alarmed," November 11, 1955, Honolulu Star-Bulletin.
16. "Moiliili Residents Avoid Collapsed Earth, Pits," November 19, 1955, Honolulu Star-Bulletin.
17. Pukui, M., et al., 1974, Place Names of Hawaii, University of Hawaii Press, Honolulu, 289 pp.
18. Pukui, M. and Elbert, S. H., 1964, English-Hawaiian Dictionary, University of Hawaii Press, Honolulu, 188 pp.
19. Sease, R., June 3, 1973, "Infrared Aerial Photos Spot Sinkholes," Jacksonville, Florida Times-Union and Journal, p. C-12.
20. Stearns, H. T., 1939, Geologic Map and Guide of Island of Oahu, Advertiser Publishing Company, Honolulu, 75 pp.
21. Stearns, H. T. and Vaksvik, K. N., 1935, Geology and Ground-water Resources of the Island of Oahu, Hawaii, Department of Lands, Division of Hydrography, Bulletin, Maui Publishing Company, Ltd., Wailuku, Maui, 479 pp.
22. Talwani, M., et al., 1959, "Rapid Gravity Computations for Two-Dimensional Bodies with Application to the Mendocino Submarine Fracture Zone," Journal of Geophysical Research, Volume 64, No. 1, pp. 49-59.
23. Wentworth, C. K., December 3, 1953, "Geology and Hydrology relating to the Hausten Spring and Fishpond Honolulu, Hawaii," 17 pages, a report in which a mechanism for producing solution caverns is detailed.
24. Westervelt, W. D., 1916, Legends of Old Honolulu, Ellis Press, Boston, 277 pp.
25. Williams, J., January 5, 1935, "The Romance of Honolulu's Prehistoric Caves," Honolulu Star-Bulletin.
26. Woolard, G. P., et al., December 1973, "A Comparison of Observed and Predicted Earth Tides Between Alaska and Mexico across the Zone of Crustal Transition Between Nebraska and Utah," 29 pp.

Geologic Secrets Revealed

(For Mr. Williams)

(By J. W. Kuroki)

1934

In yore old days, when a man was also a fisherman, ye could holes were pretty well known. And some holes were not trusted. For witness the legend:

There was then an underground waterway in Lanou Valley. A shrewd shark would swim up this channel to view the activities in that Region. At a hole located somewhere in the vicinity of the University of Hawaii, it is said, he would overhear the plans of his Hawaiian fishermen. Then, when all was ready and the fishermen were for Waikiki bound, this shark would turn about and navigate himself makai through his subterranean waterway to get there in time to devour them!

Aquatic grounds:

At an opening to this formidable waterway, armed in their oldest clothes, hip rubber boots, ropes, cameras, geologic hammers, and lights, rats of the cover and water engineer species have made geologic hoopee in mammoth caverns heretofore probably last empty during the dinosaurous ages of the negative-sixty-foot stand of the sea-ages and ages ago. (See Fringing and Fossil Coral Reefs of Oahu by James H. Collock, Bishop Museum, Bulletin 55; and, more recently, Geology of Oahu by H. T. Stearns).

Since early last August, when huge pumps of the Hawaiian Contracting Company began their enormous task of unwatering a pit 50 feet by 60 feet in area and 25 feet deep draining shallow underground water for miles around, things began to happen. First about September 9, a "usher" was developed by drawing the water down, almost in the middle of the large pit. For test purposes a tele phone pole was pushed into the hole about 20 feet deep or over 30 feet below sea level. Every day from 10,000,000 to 12,000,000 gallons of water was pumped out of the pit until Mr. Benson, with his ingenious staff and the City Engineering Department finally conquered the water and then, in one half day poured a floor of 560 cubic yards of concrete over a special chamber and 24-inch pipe outlet to this "usher", forming the floor of the sewage basins of the structure. For four months now the pumps have been running continuously at an average rate of about 10,000,000 gallons daily. In the meantime