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DIVISION OF WATER AND LAND DEVELOPMENT

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REMARKS:

Let's discuss 24

Integrated water level elevs. at Pokaku
1. At Humula = 6700ft - 1600ft = 5100ft
2. Opposite Training Area = 6175ft - 1800ft = 4375ft
3. West of Training Area: 6000ft - 1800ft = 4200ft
March 1, 1966

Mr. Robert T. Chuck  
Dept. of Land and Natural Resources  
Division of Water and Land Development  
P.O. Box 373  
Honolulu, Hawaii  96809

Dear Bob:

Enclosed is a copy of the preliminary report on the electrical resistivity work in Hawaii. Another copy is mailed to Mr. M. Miller of the U.S. Geological Survey.

Sincerely yours,

Adel A. R. Zohdy  
Geophysicist
Preliminary Report on the Resistivity Measurements on the Islands of Oahu and Hawaii Hawaii

By Adel A. R. Zohdy
INTRODUCTION

The effectiveness of the resistivity method in solving geohydrological problems and in minimizing drilling costs has been established in many parts of the world (Breusse, 1963). On the Hawaiian Islands, the method was used by Swartz more than a quarter of a century ago (Swartz, 1937, 1939, 1940). Since then the state-of-the-art has improved considerably through the calculation of a large number of theoretical curves for a variety of earth models, as well as through the development of new scientific methods of interpretation in lieu of the old empirical procedures.

During the months of December, 1965 and January, 1966, a feasibility study was conducted by the U.S. Geological Survey in cooperation with the Department of Land and Natural Resources of the State of Hawaii and the Institute of Geophysics in Hawaii. The purpose of the investigation was to determine the usefulness of the resistivity method in augmenting the solution of hydrogeological problems on the islands of Hawaii. Electrical measurements were carried out on the northern part of the island of Oahu near Waialua, as well as on the island of Hawaii near Pohakulua and Humula. The electrical measurements consisted of intermediate and deep soundings using the Schlumberger as well as the equatorial configurations. In the following the basic fundamentals of the method will be briefly outlined then the results of the investigation will be presented and analyzed.
An electrical sounding consists of a series of electrical measurements conducted at the surface of the ground by which the subsurface electrical properties of rock formations may be determined. An electric current of given intensity is introduced into the ground via two electrodes that are driven into the ground 4 - 12 inches deep; then by measuring the resulting potential difference between another pair of electrodes the electrical specific resistance or the resistivity of the medium may be calculated. Theoretically the farther away from the current source the measurements of the potential difference (or the potential gradient) are made, the deeper the probing would be. In this regard, a variety of electrode arrangements are used by different geophysicists to achieve this goal, and depending on the electrode configuration used, a formula may be derived for computing the resistivity. A general formula for computing the resistivity, $\rho$, using any arrangement, may however be given by

$$\rho = K \frac{\Delta V}{I},$$

(1)

where $K$ is the geometric factor of the arrangement used, $\Delta V$ is the potential difference in millivolts, and $I$ is the electric current in milliamperes. The value of the geometric factor $K$ is a function of the distances between the electrodes.
In the present investigation, two different electrode configurations were used: The Schlumberger configuration and the Bipole-Dipole Equatorial array. Using the Schlumberger arrangement (figure 1a), four electrodes are placed at the surface of the ground along a straight line such that the distance between the current electrodes (\(AB\)) is at least five times the distance between the potential electrodes \(MN\) i.e. \(AB \geq 5\ MN\). In this fashion the potential gradient, rather than the potential difference, is measured to a good approximation. The formula for computing the resistivity, \(\rho\), in this case is given by

\[
\rho = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \frac{AV}{I} \]

(2)

\[
\approx \pi \frac{(AB/2)^2}{I} \frac{dV}{d(AB/2)} = \pi \frac{r^2}{I} \frac{dV}{dr}.
\]

The electrode spacings (\(AB, MN\)) may be measured in feet whereas the resistivity may be expressed in ohm-meters through multiplication by a proper factor.
Figure 1.---Electrode Configurations (Plan View)

a. Schlumberger array.

b. Bipole-Dipole Equatorial array.
In the Bipole-Dipole Equatorial arrangement (figure 1b), the potential electrodes (M and N) are placed at right angles to the perpendicular bisector, R, of the line AB. It can be shown (Berdichevskii and Petrovsky, 1956) that in the case of horizontally homogeneous and isotropic media, the same value of apparent resistivity would exactly be measured as with the regular Schlumberger configuration. Consequently the equatorial arrangement may be used to extend data obtained by the Schlumberger array over a longer distance of electrode spacings. This can be done since the effective spacing \( \bar{R} = \sqrt{R^2 + (AB/2)^2} \) of the equatorial arrangement is equivalent to the spacing \( AB/2 \) of the Schlumberger. The formula for computing the resistivity by the equatorial array may be written as:

\[
\rho = \pi \frac{AM \cdot AN}{AN \cdot AM} \frac{\Delta V}{I}.
\] (3)
Finally in order to make an electrical sounding with the Schlumberger array, the distance between the current electrodes $\overline{AB}$ is expanded whereas with the equatorial set up, the distance $R$ is increased. The value of the resistivity is then computed using formula (2) or (3) according to the configuration used. To simplify matters however, a table of precalculated values of the factor $K$ may be prepared: then by adjusting the electric current $I$ to be equal to the value of $K$, the potential difference $\Delta V$ becomes numerically equal to the resistivity, $\rho$. Sounding curves are plotted on a bilogarithmic set of coordinates with the electrode spacing $\overline{AB}/2$ (or $\overline{R}$) on the abscissa and the apparent resistivity $\overline{\rho}$ on the ordinate. The field sounding curve is then interpreted by matching it to theoretically calculated sets of master curves (Compagnie General de Geophysique, 1963; Zohdy, 1965). Finally, the abscissa axis of $\overline{AB}/2$ or $\overline{R}$ may also be used as a depth axis to plot the results of the interpretation on the same diagram.

The above constitutes the basic procedure of conducting the electrical measurements and interpreting the results obtained in the present survey.
Geoelectrical Measurements
on the Island of Oahu

A total of 32 electrical soundings were made on the northern part of the island of Oahu, near Waialua (figure 2). The maximum AB/2 spacings of the Schlumberger arrangement ranged from 600 to 6,000 feet. Interpretation of the electrical soundings, suggests the following ranges for the "true" resistivities of the various rock formations:

- Clay saturated with brackish to saline water: 1 - 3 ohm·m
- Clay saturated with brackish to fresh water: 5 - 8 ohm·m
- Clay, silty sand, and some gravel with fresh water: 11 - 25 ohm·m
- Sand and coral: 80 - 400 ohm·m
- Weathered basalt with fresh water: 30 - 60 ohm·m
- Fresh basalt with saline water: 30 - 40 ohm·m
- Fresh basalt with fresh water: 300 - 700 ohm·m

Unfortunately there are no electric logs available to check the above given values of resistivity. Nevertheless a number of sounding curves were sufficiently diagnostic to warrant the validity of the above given resistivity values.
Figure 2.--Location of electrical soundings on the Island of Oahu.
In the Waialua area there are essentially six layers of rocks that are electrically distinguishable from one another. These layers may or may not all be present in the geologic section at a given locality. The six layers from top to bottom are: (1) Cultivated top soil; (2) Coral and sand (First Coral); (3) clay; (4) Coral, sand, and clay (Second Coral); (5) clay, silt, and sand, and (6) Basalt (Weathered or fresh). In some cases it was difficult to electrically distinguish the second coral reef from the underlying basalt because of the absence, or insufficient thickness, of the clay bed separating the two layers, and because both the coral and the basalt are of high resistivity in comparison to the overlying clay layer. In such cases the presence of the second coral was either inferred from other soundings or from nearby wells. Let us now consider these various geoelectric layers.
The First Coral Zone:

The first sand and coral was found almost exposed at the surface near the ocean shore. Its presence was detected on the electrical soundings (E.S.) 1, 3, and 32 in the form of a high resistivity first layer (figure 3). Its thickness varies from about 5 to 12 feet. In

Figure 3. Near here.

these soundings the top soil layer is essentially absent or of a thickness of less than 2 feet. Note that the second coral zone is clearly indicated on E.S. 32 by the maximum near AB/2 = 160 feet, whereas it is less obvious on E.S. 1; and probably absent, or at a depth of more than 150 feet, at E.S. 3. In all three soundings however, the first coral is underlain by a very conductive clay layer. As one moves away from the shore line the top soil layer becomes somewhat thicker and the first coral is buried under a cover of about 8 feet of clay. Its presence however is unmistakeably clear as indicated by the maxima of E.S. 4, 5, 9, and 19 (figures 4 and 5). In all the above soundings the first coral

Figures 4 and 5. Near here.

is followed by clay then by the second coral or by basalt as indicated by the given interpretations.
Figure 3.--E. S. 1, 3, and 32.
Figure 5.—E. S. 5 and 19.
On the basis of the electrical soundings and the available wells and test holes, an isopach (equal thickness) map of the first coral was prepared and is shown in figure 6. According to this map it can be easily seen that the first coral diminishes in thickness and probably disappears to the south of State Highway 99.

**The Second Coral Zone:**

The second coral zone is probably an important aquifer. Its detection on an electrical sounding, however, is subject to some limitations. On one hand the layer should be of sufficient thickness with respect to its depth of burial. On the other hand, it would be more easily detected if it is underlain by another clay layer separating it from the underlying lava flows. A cross-section based on two wells and three electrical soundings is shown in figure 7 and indicates the presence of the second coral zone as encountered in Well 319 and as interpreted in E.S. 19.
Figure 6.--Isopach map of the first coral in the Wailua area.
Figure 7.--A north-south section.
The Alluvial Deposits:

To the south of State Highway 99, both coral reefs seem to disappear and the sediments appear to be composed mainly of clay with scattered thin lenses of gravel, boulders as well as a few coral fragments. The geoelectric section however is fairly homogeneous and has a resistivity range of about 5 to 15 ohm-m. The electrical soundings E.S. 7, 11, 14, and 17 (figure 8) testify to the relative simplicity of the section in this part. It is interesting to note the effects of near surface heterogeneities on E.S. 14 where a small heterogeneity near one of the potential electrodes (M or N) caused the set of measurements with MN = constant to be shifted to a higher value. Then as the MN spacing was changed at AB/2 = 500 feet the resistivity values fell back to continue the proper trend of the curve. On the other hand a near surface heterogeneity at one of the current electrodes (A or B) produces a disturbance in the measurements at one place only, e.g. the measurement on E.S. 7 and AB/2 = 160 feet. Such effects are generally easily recognized on sounding curves of the Schlumberger type. This property is among the many advantages of the Schlumberger configuration over the conventional Wenner arrangement.
Figure 8.--E. S. 7, 11, 14, and 17.
The variation in the magnitude of the true resistivity of the clay (5 to 15 ohm-m) is not a random one. A definite increase in the value of the clay resistivity is observed as we move away from the shore line. This is obviously in agreement with what is to be expected. The clayey sediments near the ocean are saturated with saline water whereas the inland sediments are expected to be saturated with fresher water. None the less this is not the only factor governing the resistivity of a clay. An enrichment in sand and gravel content will also tend to increase the resistivity. Furthermore the inland clay, in the studied area, occurs at higher elevations (mainly above sea level) whereas the one closer to the shore line is at lower elevations (mainly below sea level). Thus the latter is subjected to a larger degree of saline water flushing, e.g. see figure 7.

To illustrate the dependency of the clay resistivity on its distance from the shore line, a plot of the estimated true resistivity of the clay as a function of the distance of the sounding from the nearest shore line was prepared and is shown in figure 9.

Figure 9. Near here.
Figure 9.—Dependency of the clay resistivity on distance of an electrical sounding from the shore line.
The Wainai and the Koolau Volcanic Series:

A map of the estimated configuration for the top of the Wainai basalt is given in figure 10. This map is based on the estimated depths to the top of the basalt below sea level. The indicated depths are based on electrical soundings as well as few wells and test holes that are sufficiently deep to penetrate the basalt. The map clearly indicates the probable buried drainage pattern. It is interesting to note that the axes of the buried channels tend to coincide with a line of discontinuity in the level of the water table in that area.

The resistivity of the Wainai basalt seemed to be exceptionally low (~ 30 to 50 ohm-m). This low resistivity value is probably due in part to the fact that the top basaltic layers are probably highly weathered. At greater depths where the flows may be more fresh, the quality of the water might possibly be poorer (more saline), thus reducing the resistivity of the rocks. The greater degree of weathering (and consequently the low resistivity) of the Wainai basalt might also be indicative of its older age.
Figure 10.—Map of the top of the Wainai basalt.
In contrast to the Wainai basalt we may now consider the soundings conducted on the sloping range of the Koolau volcanic series NW of Schofield Plateau. The soundings E.S. 21, 22, 24, 25, 26, 27, 28, 29, and 30 were carried out in that area. According to these measurements the resistivity of the Koolau basalt is much higher than that of the Wainai range in the studied area. This is primarily due to the fact that the former was studied at higher elevations than the latter thus putting its upper layers beyond the reach of the saline waters of low resistivity. As a result all the sounding curves obtained over the Koolau basalt were of the maximum type whereas those over the Wainai were mainly of the minimum type. In regards to the resistivity of the saline-water saturated basalt, of the Wainai or the Koolau type, it is of the order of 30 ohm-meters. This conclusion is based on comparing the results of two deep soundings E.S. 6 (over the Wainai basalt) and E.S. 22 (over the Koolau basalt) figure 11. With E.S. 6, AB reached 12,000 feet and with E.S. 22 AB

Figure 11. Near here.

reached 10,000 feet. Although the two soundings are basically of different shapes, yet their terminal branches seem to approach the same asymptotic value of about 30 ohm-m. The question however arises of how can we conclude that this is the resistivity of saline-water saturated basalt? The answer is reached by considering E.S. 6. If 30 ohm-m is the resistivity of fresh-water saturated basalt, then the thickness of the fresh water lense beneath E.S. 6 should be of the order of 5 to 6 thousand feet thick.
But this is highly improbable since the center of E.S. 6 is less than one mile from the shore line, its elevation is less than 40 feet above sea level, and the ground water in that location of the island is not dike impounded water. Consequently the conclusion may be reached that the resistivity of the saline-water saturated basalt in that area of the island is of the order of 30 ohm-meters.
Figure 11.--Comparison between electrical soundings, E. S. 6 and 22, over the Wainai and the Koolau basalts, respectively.
The resistivity of the basalt with fresh water (partial to complete saturation) seemed to range from 300 to 500 ohm·m. A lower limit of about 250 ohm·m is still possible on the sounding E.S. 25 (figure 12).

Figure 12. Near here.

There is however no definite upper limit on the value of the resistivity except that it is rather unlikely to exceed 1,000 ohm·m. In other words, the interpretation of maximum-type curves is generally very delicate because of the principle of equivalence (Kalenov, 1957). Considering the interpretation of E.S. 24 (figure 13) the depth to the fresh-salt water interface is estimated as 800 feet below the ground surface or 600 feet below sea level. If the Ghyben-Hertzberg relationship (Todd, 1959) holds in this area, then the fresh water level should be about 15 feet above sea level. This figure is comparable with the level of standing water in wells, near that sounding, which is about 12 to 13 feet above sea level. If we assume that the resistivity of the basalt in E.S. 24 is 400 ohm·m, say, instead of the chosen value of 350, then we would probably be closer in our calculations to the actual case of the observed water levels in the wells at that location. However the assumption that the Ghyben-Hertzberg relationship does hold in this place may very well prove to be false especially under the existing hydrodynamic conditions.
Consequently the attempt to change the estimated depths to achieve an exact correspondence with the predicted Ghybe -Hertzberg relationship would be futile. In fact the depth of 600 feet below sea level to the salt water interface is in better agreement with what might be expected under hydrodynamic conditions.
Figure 12.--E. S. 25 and 26.
Figure 13.—E. S. 24, 27, and 30.
Finally according to E.S. 26, 27, 29, and 30 (figures 13 and 14),

Figure 14. Near here.

the Koolau basalt is probably weathered to depths ranging from 150 - 250 feet below the surface of the ground. This weathered zone seems to be primarily formed of three layers: (a) top layer of cultivated soil (25 - 40 ohm-m); (b) middle layer probably with boulders and gravel (about 60 ohm-m); and (c) clayey layer (20 to 40 ohm-m). The presence of a thick weathered zone is confirmed by Well 330-1B and 330-2B which are approximately 2 miles east of E.S. 27. In Well 330-1B the hard blue basalt is at a depth of 200 feet whereas in Well 330-2B it is encountered at 280 feet below the surface. The overlying material in these wells is described by the driller as "red clay", "mud rock", "clay and gravel", "mud rock and clinkers", and "boulders".

Such lithologic descriptions fit the resistivity ranges in that zone quite favorably, indicating that the weathered zone does extend over a large area and is of a thickness of the order of 200 feet.

In conclusion we find that the resistivity method has yielded valuable information that can be easily tied in with the known geology, and that it can be used as an effective tool to extend our knowledge into areas where little may be known about the geology.
Geoelectrical Measurements
on the Island of Hawaii

Four electrical soundings were made on the island of Hawaii. Two of these were made with the Schlumberger configuration and the other two with the Bipole-Dipole equatorial arrangement. The soundings were made near Pohakulua where a dry well has been drilled to a depth of 1,000 feet, and near Hanaula (figure 15). At each location an intermediate (up to $\bar{AB}/2 = 3,000$ feet) Schlumberger sounding was followed by a deep equatorial sounding (up to $R = 8,000$ feet, i.e. $\bar{R} = 8,139$ feet). The sounding curves are shown in figures 16 and 17 and their exact locations are shown in figures 18 and 19.
Figure 15.--Location of the studied area on the Island of Hawaii.
Figure 16.--E. S. 1 and 4 near Pohakulua.
Figure 17.—E. S. 2 and 3 near Rumuula.
Figure 18.--Exact location of E. S. 1 and 4.
Figure 19.--Exact location of E. S. 2 and 3.
The soundings near Kona, K.S. 1 and 4, indicate the presence of a thick conductive layer at a depth of approximately 1,800 feet below the surface. However, because of the slight scatter of the points on the curve, the depth to the conductive layer could be 1,600 feet (lowest limit) or 2,400 feet (upper limit). These depth estimates are based on the assumption of electrically isotropic layers. Anisotropy in general will reduce these depth estimates to shallower ones. The conductive layer at depth is interpreted in this case as fresh water basalt of a resistivity of less than 400 ohm-m, probably about 200 to 300 ohm-m.

The soundings near Humula Sheep station indicate the presence of near surface lava flows that are more resistive (10,000 ohm-m) than those encountered near Pohakula (2,000). The possible presence of lava flows of a resistivity of (4,500 to 5,000 ohm-m) at both localities was also indicated by the soundings. More important however is the existence of the same conductive layer at Humula as at Pohakula. Here the depth is estimated as 1,600 feet below surface and the conductive layer is interpreted as fresh water basalt of a resistivity of less than 400 ohm-m. The strong deformation of the equatorial sounding curve K.S. 3 between $\bar{R} = 300$ feet and $\bar{R} = 1,676$ feet (figure 17) is related to the crossing of a saddle between two cinder cones (figure 19). However the rest of the points on the curve do coincide with and extend the Schlumberger curve.
CONCLUSION

The use of the resistivity method on the Hawaiian Islands indicates that fruitful results can be obtained with the method. On Oahu the method was put to the test and the results of the survey seem to be in conformity with what is known of the geohydrology of that part of the island. Finally on the island of Hawaii, near Pohakulua and Humula, the method has indicated the presence of a thick conductive layer that is interpreted as fresh water saturated basalt at a depth of the order of 1,700 hundred feet from the surface.
References


