SCALE MODEL EXPERIMENTS WITH THE HORIZONTAL LOOP ELECTROMAGNETIC TECHNIQUE OF GEOPHYSICAL PROSPECTING

by

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ABSTRACT

This study deals with the construction and application of a scale model horizontal loop electromagnetic system whose function is to quantitatively measure the in-phase portion of the vertical component of an anomalous secondary field induced by a conductor. The case modelled is that of a conducting half-plane possessing a low resistivity. For the interpretation of this type of anomaly fifteen type curves based on scale model experiments, one characteristic curve and four interpretation examples are presented to illustrate the application of these measurements towards the interpretation of horizontal loop anomalies obtained from field observations. An effort has been made to briefly compare the results obtained from these experiments against those formulated from electromagnetic theory.

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a	Coil separation
h	Vertical distance from the top of a conducting sheet to the plane of observation
h/a	Dimensionless ratio
α	Dip angle of a conducting sheet
d	Thickness of a conducting sheet
f	Frequency
ω	Angular frequency = $2\pi f$
σ	Conductivity
μ	Magnetic permeability = $4\pi \times 10^{-7}$ henry/m
α	Dimensionless response parameter = $\sigma\mu\omega ad$
x	Horizontal distance from the centre of the transmitter/receiver unit to the centre of the conducting sheet
L	Inductance of a conducting sheet
H_z^s	Magnitude of the in-phase portion of the vertical component of the secondary field measured at the receiver
H_z^p	Magnitude of the vertical component of the primary field measured at the receiver
Q	Response parameter of a conducting sheet

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I. INTRODUCTION

In this study the electromagnetic response of the half-plane conductor is investigated through scale model experiments. These experiments utilize the horizontal loop technique of geophysical prospecting.

To the author's knowledge, this is the first attempt at Dalhousie University to construct such a modelling system capable of quantitatively measuring the response of a conducting body. Upon completion, it is the intent of this study to test the measuring system on a simple, well understood concept such as the half-plane conductor. Many detailed investigations pertaining to this subject have been performed at the University of Toronto and the Geologic Survey of Finland in particular. Hence, a good background of experience exists for the present study.

Scale model experiments were performed 1.) to determine the electromagnetic response a conducting sheet of finite size has at various dips and depths, 2.) to permit a comparison of the character of these profiles to those obtained from electromagnetic theory and 3.) to decide how well the results from these experiments can predict the actual parameters of half-plane conductors in the field.

II. MOVING SOURCE/RECEIVER METHOD

2.1 Introduction

A primary magnetic field is generated in the ground by passing an alternating current through a transmitting coil. The magnitude of this field is measured with an identical receiving coil which is connected to an amplifier. The transmitting frequency is such that a small eddy-current field is induced if the ground has an average electrical conductivity.

When the transmitter/receiver combination is brought close to a more conductive zone, stronger eddy-currents may be caused to circulate within this zone creating an induced secondary field having the same frequency as the primary field. This secondary field, in combination with the primary field is observed at the detector as a change in magnitude and/or phase in the primary signal.

2.2 Phase

In general the anomalous field is not in phase with the primary field. The phase difference between the primary and secondary fields is an important parameter in determining information about the conductivity of an anomalous zone. It is, therefore, beneficial to have a phase measuring divice incorporated into the measurement system .

2.3 Compensation

Since the vertical components of the primary and secondary fields are superimposed at the receiver, it is necessary to know the magnitude of the primary field at the receiver in order to measure the magnitude of any residual secondary field induced by a conductive zone. Since the secondary field is generally small with respect to the primary field (between zero and fifty percent of the primary), this is often accomplished by eliminating the effect of the primary field through a compensator. The compensating device introduces a signal at the receiver equal in magnitude and frequency to the primary field but opposite in phase, thereby producing a null at the receiver in the presence of no conducting body.

Telford *et al*. (1976) states that compensation of this sort is sufficient to permit measurement of the in-phase component of the secondary field. This will prove to be adequate for the model experiments comprising this study.

2.4 Horizontal Loop Electromagnetic Method

The horizontal loop electromagnetic technique is unique in that the transmitting and receiving coils are mutually horizontal and the coil spacing (usually 25 - 100 m) is held constant by a connecting cable.

The coils move along picket lines perpendicular to the geologic strike where possible. Measurements are taken at regular station intervals. The field activity at the receiver is usually measured as a percentage of the primary field on electrically neutral ground.

A great advantage to the horizontal loop technique is that reversing the traverse direction does not affect the measurements obtained (Grant and West 1965). Grant and West (1965) state that by the rule of reciprocity measurements cannot by affected by interchanging source with receiver. It is for this reason that horizontal loop data is most easily interpreted.

2.5 Qualitative Response

In the sections to follow the direction of the primary field at the receiver is defined to be positive at all times. Furthermore, it is assumed that the effect of the primary field at the receiver has been eliminated such that the receiver responds only to the presence of an anomalous secondary field.

Fig. 1a illustrates the instance where no conducting sheet is present. The only effect on the receiver is from the transmitting coil. Since this effect has been neutralized the receiver exhibits no impulse from the transmitting coil.

When a conducting sheet is introduced below the plane of the transmitter/receiver unit, whose geologic strike is perpendicular to the traverse direction, the primary field intersects the sheet as illustrated in fig. 1b. This causes eddy-currents to circulate within the plane of the conducting sheet, thereby inducing an anomalous secondary field opposite in direction to that of the primary field. By definition, this anomalous field is positive.

At the point where one coil is directly over the edge of the conducting sheet no secondary field is induced (see fig. 1c). As a result, no anomalous field is sustained at the receiver.

When the transmitter/receiver unit straddles the conducting sheet, the primary and secondary fields are opposite in direction and hence opposite in sign. Since the effect of the primary field has been compensated for, the receiver experiences an anomalous field whose sign is negative (see fig. 1d).

Fig. 1e is similar to fig. 1c in that the receiver experiences no secondary field since the coupling coefficient appropriate to that coil vanishes (Telford *et al.* 1976).

As the trailing coil passes over the edge of the conducting sheet the primary and secondary fields present at the receiver are in the same direction. As a result, the sign of the secondary field is positive. As the transmitter/receiver unit moves away from the conductor, the magnitude of the secondary field diminishes as the distance between the transmitter/receiver and the conducting sheet increases.

In accordance with the above analysis we should expect the results to plot as a profile whose character is similar to that of fig. 2.

2.6 Theoretical Quantitative Response

In the case of the half-plane possessing a large conductivity, the induced currents flow mainly along the upper edge of the sheet and vertically at the ends. Provided the dimensions of the sheet are large enough, one can approximate this situation by current flowing in a long wire (Telford *et al.* 1976). From the circuit analogy for the long wire, Telford *et al.* (1976) derives the expression for the in-phase portion of the ratio of vertical components of the secondary field to primary field given by

$$\mathrm{Re}\left|\frac{H_z^s}{H_z^p}\right| = \frac{4(x/a)^2 - 1}{6.25(L/a)((2h/a)^2 + (1 - 2x/a)^2)((2h/a)^2 + (1 + 2x/a)^2)}\,(Q^2/(1 + Q^2)).$$

In the case of a good conductor whose conductivity is greater than 25 mhos/m, Q is large (Telford *et al.* 1976). Therefore, the response function given by

$$Q^2/\ 1 + Q^2$$

is approximately equal to one. The case under study possesses a conductivity approximately equal to 3.6×10^7 mhos/m. Hence, the condition above is satisfied and the approximation regarding the response function holds. Telford et al. (1976) further suggests a value of 1/3 is appropriate for the ratio L/a. For the purpose of this study, we modify this value to 0.3721 in order for the magnitudes of the negative maximums of the theoretical and experimental curves to coincide. The expression given above simplifies to

$$\mathrm{Re}\left|\frac{H_z^s}{H_z^p}\right| = \frac{4(x/a)^2 - 1}{2.33((2h/a)^2 + (1 - 2x/a)^2)((2h/a)^2 + (1 + 2x/a)^2)} .$$

A profile calculated from this expression for $h/a = 0.3$ is plotted in fig. 2a, which also shows the type curve for $h/a = 0.3$ obtained from experimental data. Although the calculated profile is quite similar to the experimental type curve, the positive maxima are too large, the negative maximum is slightly flattened and the slope near $x/a = \pm \frac{1}{2}$ is too steep. These observations are evident from fig. 2a and documented by Telford et al. (1976).

Note: As $h/a \longrightarrow 0$ in the expression, a discontinuity exists at $x/a = \pm \frac{1}{2}$. This is characteristic of tightly coupled electric circuits making the simple circuit analogy of little value since the inductive coupling between the source and conductor must vary with source position (Telford et al. 1976).

FIG.1 RECEIVER RESPONSE TO A HALF-PLANE CONDUCTOR

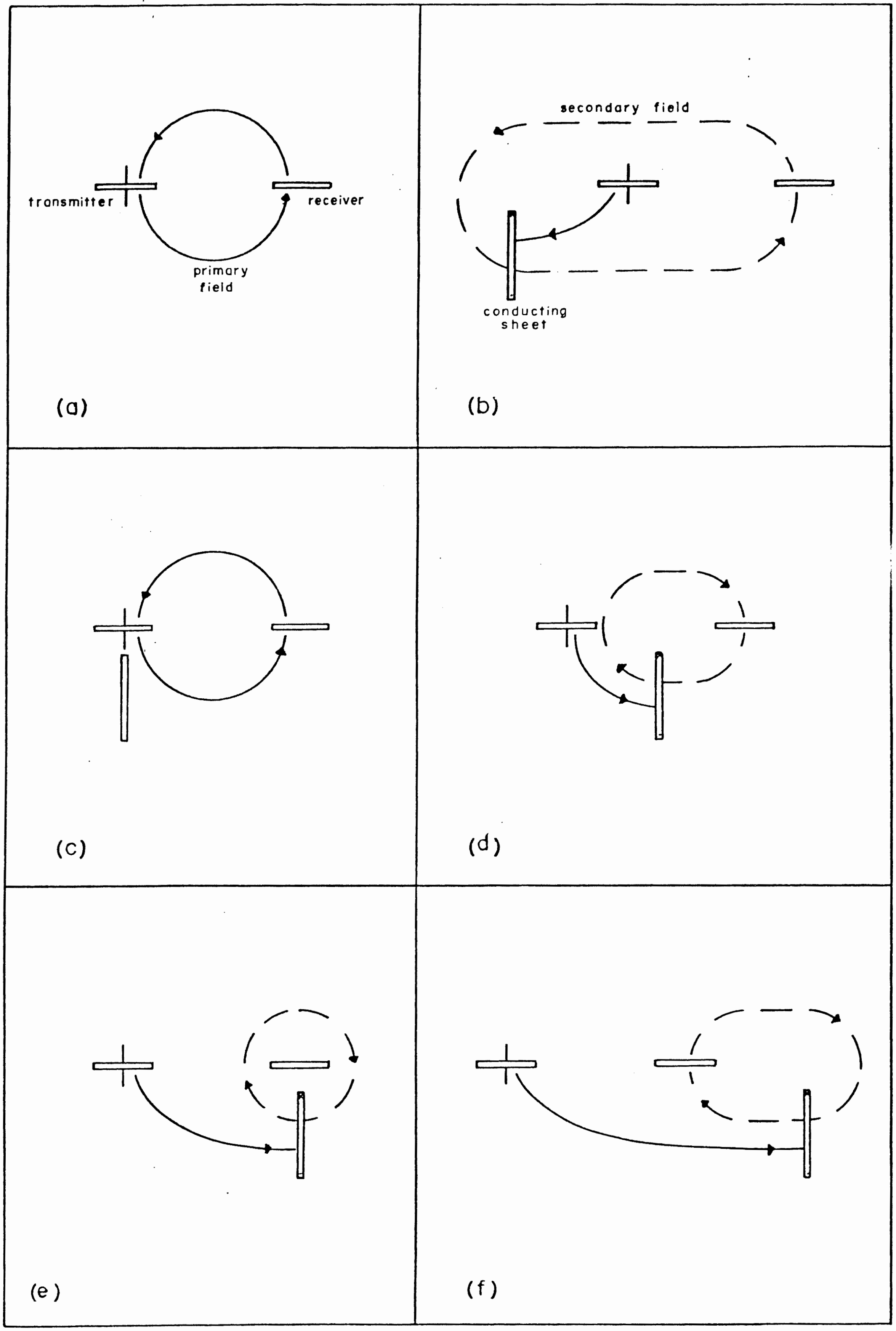
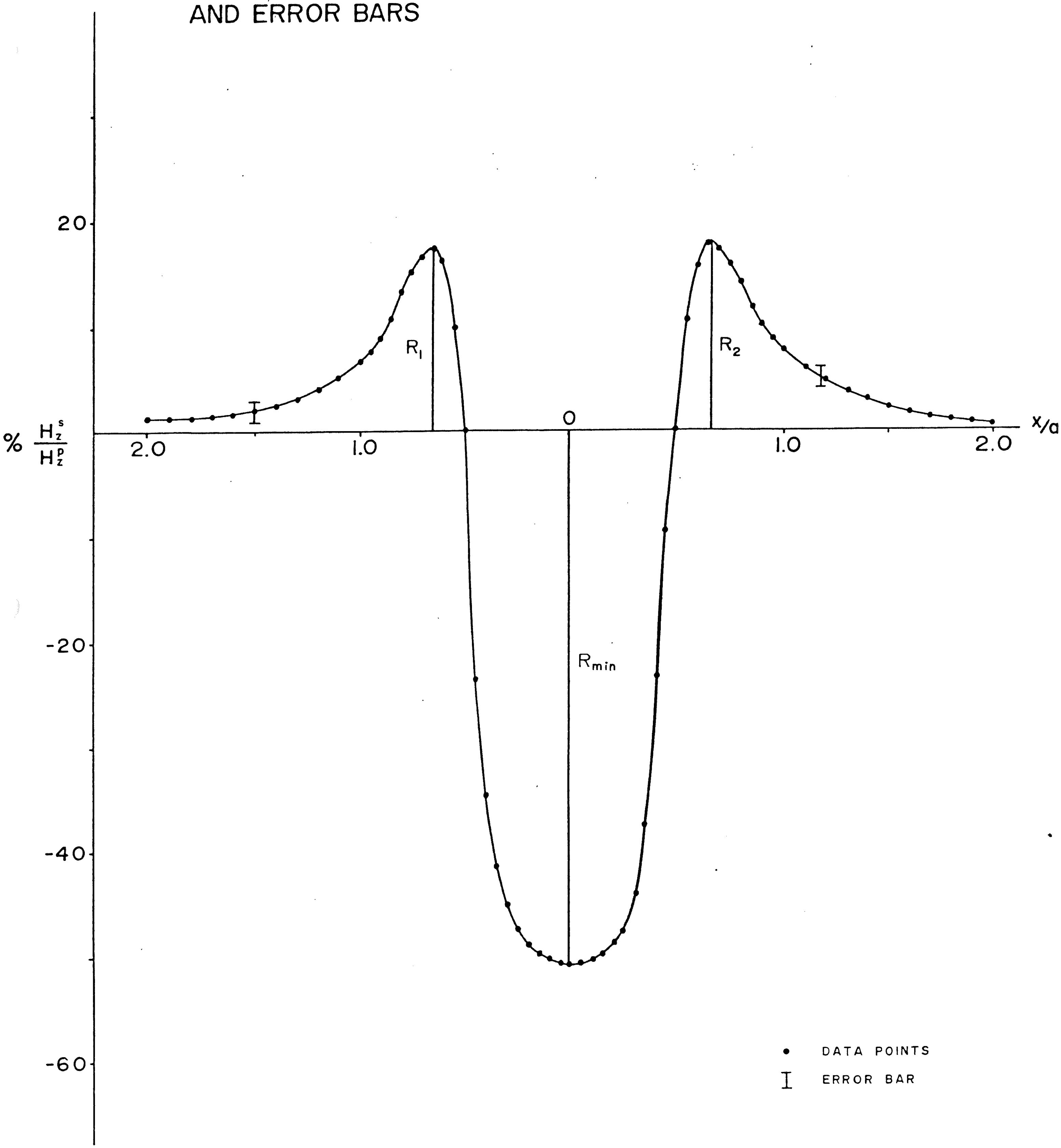


FIG. 2 TYPICAL HLEM PROFILE IN RESPONSE TO A HALF-PLANE CONDUCTOR ILLUSTRATING DATA SAMPLING INTERVAL AND ERROR BARS



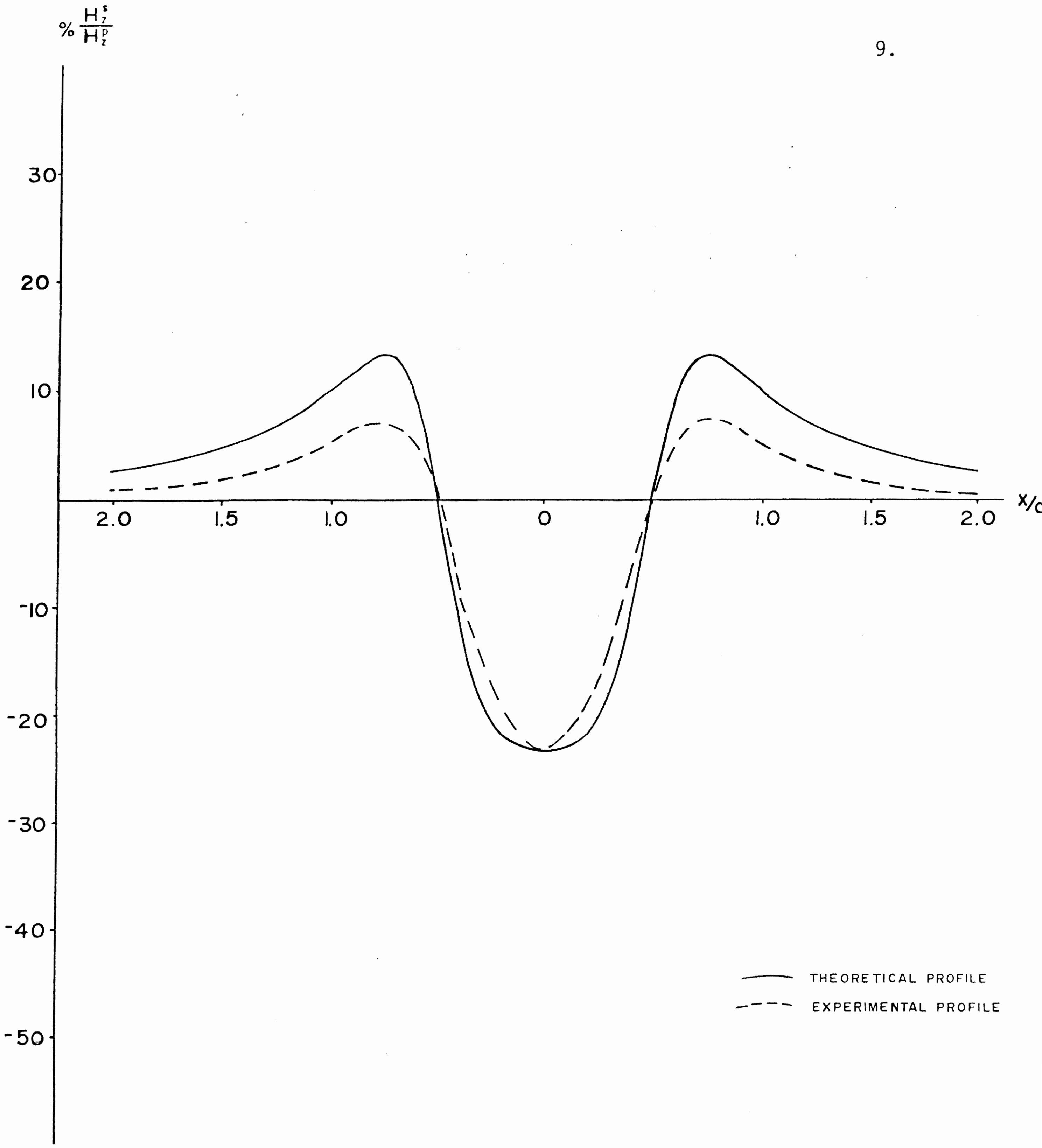


FIG. 2A THEORETICAL TYPE CURVE FOR HALF-PLANE, $\alpha = 90°$
H/A = 0.3

III. MODEL EXPERIMENTS

3.1 Introduction

The electromagnetic response of a naturally occurring conductor can be exactly duplicated in the laboratory on a small scale (Hedström and Parasnis 1967). However, more than one model having different characteristics can yield virtually indistinguishable profiles. Hence, modelling is said to be non-unique.

This concept is best illustrated if we consider the response of a conductor as measured in the dimensionless form H_z^s/H_z^p where H_z^s and H_z^p are respectively defined as the vertical components of the secondary and primary fields experienced at the receiver at a particular point.

Grant and West (1965), Ketola and Puranen (1967) and others use the dimensionless expression given by

$$\alpha = \sigma\mu\omega a d$$

to characterize a specific model configuration. Hence, any model configuration possessing the same dimensionless quantity (α) will produce the same dimensionless response (H_z^s/H_z^p) irrespective of the actual values assigned to α, μ, ω, a or d (Hedström and Parasnis 1967). Consider the following argument:

The expression for the field response parameter is given by

$$\alpha_f = \sigma_f\mu\omega_f a_f d_f \ .$$

The expression for the experimental response parameter is given by

$$\alpha_e = \sigma_e\mu\omega_e a_e d_e \ .$$

Therefore, the ratio of the two response parameters can be written

$$\frac{\vartheta_e}{\vartheta_f} = \frac{\sigma_e \mu \omega_e a_e d_e}{\sigma_f \mu \omega_f a_f d_f} \; .$$

Since magnetic permeabilities do not vary to any extent,

$$\frac{\vartheta_e}{\vartheta_f} = \frac{\sigma_e \, \omega_e a_e d_e}{\sigma_f \, \omega_f a_f d_f} \; .$$

If we wish to simulate the electromagnetic response of a zone of sulfide mineralization through experimental modelling we require $\vartheta_e = \vartheta_f$. Thus,

$$\frac{\sigma_e}{\sigma_f} = \frac{\omega_f (ad)_f}{\omega_e (ad)_e} \; .$$

Since a and d are both measured in units of distance, we can generalize the above expression to the form

$$\frac{\sigma_e}{\sigma_f} = \frac{(l_f)^2 \, \omega_f}{(l_e)^2 \, \omega_e} \; .$$

If we are now given the conductivity of a mineralized zone in the field (σ_f), a length such as coil separation (a_f), and the frequency used in the field (ω_f), we can duplicate the response of this mineralized zone in the laboratory by adjusting either the modelling frequency (ω_e), coil separation (a_e) and/or model conductivity (σ_e) such that the above expression is satisfied.

3.2 Measurement System Construction

The measurement system used in this study is schematically illustrated in fig. 3. The main components of the system are the: transmitter, transmitting coil, compensating circuit, receiver and receiving coil. The compensating circuit was a modified version of that found in a study by Ketola and Puranen (1967). The transmitter was a Hewlett-Packard frequency generator, model 208A, and the receiver a Hewlett-Packard dual channel oscilloscope, model 1200A. In constructing the measurement system particular care must be taken in the shielding and grounding of cables leading to the receiver.

All measurements were made using a frequency of 3600 hertz. The transmitting and receiving coils were approximately identical, each having 1800 turns of enameled copper wire (diameter ≐ 0.1 mm) on a cylindrical, ceramic core (diameter ≐ 8 mm). The mean diameter of the coils was approximately 15 mm. The approximate thickness of each coil was 3 mm. As a rule, the system specifications in a study by Ketola and Puranen (1967) were followed as closely as possible.

3.3 The Model

The conductive body under study was the infinite half-plane (thin dyke). The dimensions of the model toward the sides and downward were at least 3.5 times the coil separation. Several authors have done experiments to determine the effect of conductor size on the response of vertical and inclined conductors in free space. West (1960), Nair (1968) and Villegas-Garcia (1979) agree that for a distance greater than twice the coil separation from the sides of the conductor, the response can be considered to be the same as for an infinite half-plane. This is reasonable for an inclined conductor, where the response comes from the current concentration in the top edge of the seet (Villegas-Garcia 1979).

The model was constructed from a sheet of aluminum possessing dimensions 430 mm x 430 mm x 5 mm.

Model experiments by Ketola and Puranen (1967) exhibit a maximum response parameter (α) value of 29.7, where a large response parameter (α) indicates a good conductor response to the system. Applying the dimensionless response parameter (α) to the model currently under consideration yields $\alpha \doteq 300$. This dissimilarity in the response parameter value is due principally to the model thickness (d = .005 m) utilized in this study as compared to the model thickness (d = .00045 m) utilized in the study by Ketola and Puranen (1967). Since the model experiments in this study deal with such a large response parameter value, it is reasonable to assume that a good correlation between the depth and dip of the model and the depth and dip of a naturally occurring conductor in the field will only result when the latter possesses a large response parameter value. This condition is satisfied when the ratio of the maximum negative in-phase to maximum negative quadrature response is greater than or equal to 2.0 (Ketola and Puranen 1967).

3.4 Helipot Calibration

The actual measuring device for the in-phase component of the anomalous field was a 200Ω, eleven-turn variable resistor supplied with a dial calibrated to 0.01 revolutions. The helipot, in combination with a 500Ω variable resistor in the compensating circuit, were adjusted to produce a 2.9 mv signal 180° out-of-phase with the 2.9 mv primary signal from the transmitting coil. This combination produced a null on channel B of the oscilloscope except for 0.1 mv of ambient noise

(Suppressing the effect of the primary field at the receiver while on electrically neutral ground allows the oscilloscope to respond only to the presence of an induced secondary field). The calibrated dial was set to 0.00 at this point.

As the dial was rotated, dial values were recorded at signal increments of 0.1 mv. These results are tabulated in table 1. The noise level (0.1 mv) was subtracted from each signal voltage to give the adjusted voltage. Fig. 4 is a plot of the adjusted voltage (mv) against dial value.

A least squares fit to a straight line was performed on the experimental data for interpolation purposes. This process resulted in an expression for the vertical component of the secondary field as a function of dial value, given by

$$\text{Voltage (mv)} = 0.3886(\text{dial value}) - 4.2829 \ .$$

Note: 11.0 must be added to any dial value between 0.00 and 3.00 in order for the above expression to yeild correct voltage values.

This procedure now allows a conversion of any dial value into a corresponding voltage value.

3.5 Model Measurements

During the measurement process the transmitter/receiver unit was moved in a horizontal plane, in increments of 0.05 - 0.10 times the coil separation. Fig. 2 illustrates the sampling interval graphically. The error bars illustrate how well the type curves are resolved from each other. The error was calculated by assuming a maximum error in setting the calibrated dial of $\pm$ 7 dial divisions. This is equivalent to a voltage error of $\pm$ 1 %. All profiles were measured along a horizontal line which ran across the centre of the model, perpendicular to the geologic strike.

The dip of the sheet varied in steps of 15 degrees, producing values of α = 90, 75, 60, 45 and 30 degrees. The ratio h/a received the values 0.1, 0.3 and 0.5. At each measurement station the distance to the centre of the model was recorded as well as the dial value needed to produce the minimum signal response on channel B of the oscilloscope. Since only the in-phase portion of the vertical component of the secondary field can be compensated for by the dial, the minimum signal response was not always zero in amplitude. The quadrature component of the secondary field is always present. Fortunately, the phase difference between the in-phase and quadrature components of the secondary field is 90 degrees, as is the phase difference between the quadrature component of the secondary field and the primary field displayed on channel A of the oscilloscope. It was discovered that dial rotation varied the amplitude and phase of the secondary field on channel B with respect to the primary field displayed on channel A. Therefore, adjusting the peak of the sine wave on channel B (secondary field) such that it is alligned with the zero crossover of the sine wave on channel A (primary field) ensures that the voltage represented by the dial value on the helipot is in phase with the primary field and is a measure of the in-phase portion of the secondary field. Any residual voltage displayed on channel B is 90 degrees out of phase with the primary field and is a measure of the quadrature portion of the secondary field. This phase matching concept between channel A and channel B was essential to the consistent attainment of an accurate dial representation of the in-phase portion of the secondary field.

At this point in the measurement process the magnitude of the quadrature component of the secondary field can be semi-quantitatively determined by a value measured directly from channel B. Values for the quadrature component of the secondary field were recorded for $h/a = 0.1$ only. Subsequently, background noise levels increased to a point where semi-quantitative measurements were difficult to obtain. Since the essence of this study is not concerned with the quadrature component of the secondary field these measurements are not incorporated into the text. A type curve for the quadrature component of the secondary field ($h/a = 0.1$, $\alpha = 90°$) is enclosed for verification that the ratio of the maximum negative in-phase to maximum negative quadrature response is greater than 2.0 (see fig. 5). This condition is required by Ketola and Puranen (1967) to signify the presence of a good conductor (large σ).

The dial values obtained from the procedure outlined in section 3.5 were converted to corresponding voltages using the expression in section 3.4. These voltage values were subsequently converted into a percentage of the primary field. The results are presented in the form of type curves (see figs. 6 - 10).

FIG. 3 SCHEMATIC DIAGRAM OF HORIZONTAL-LOOP ELECTROMAGNETIC SYSTEM

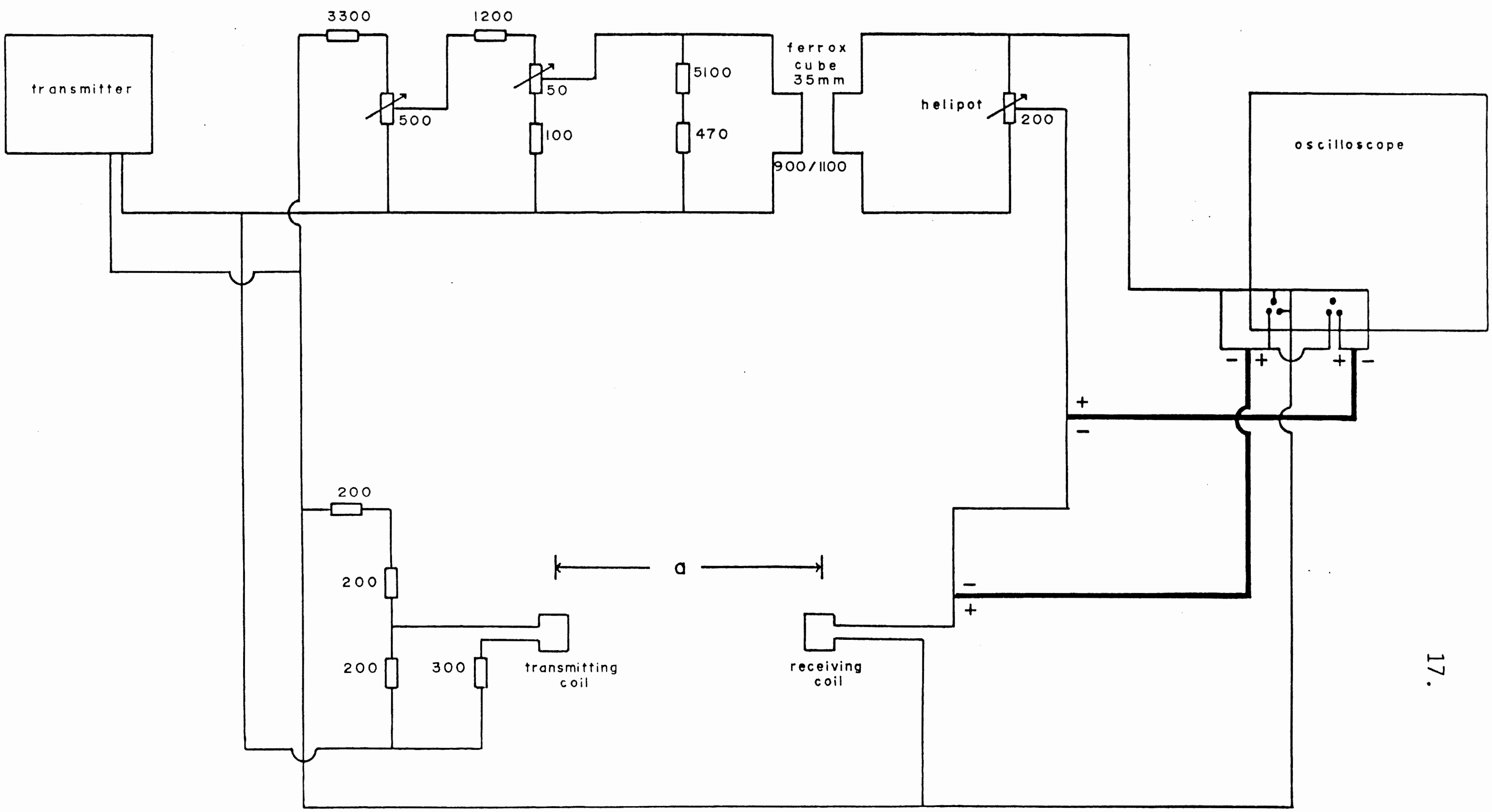


TABLE 1.

HELIPOT CALIBRATION

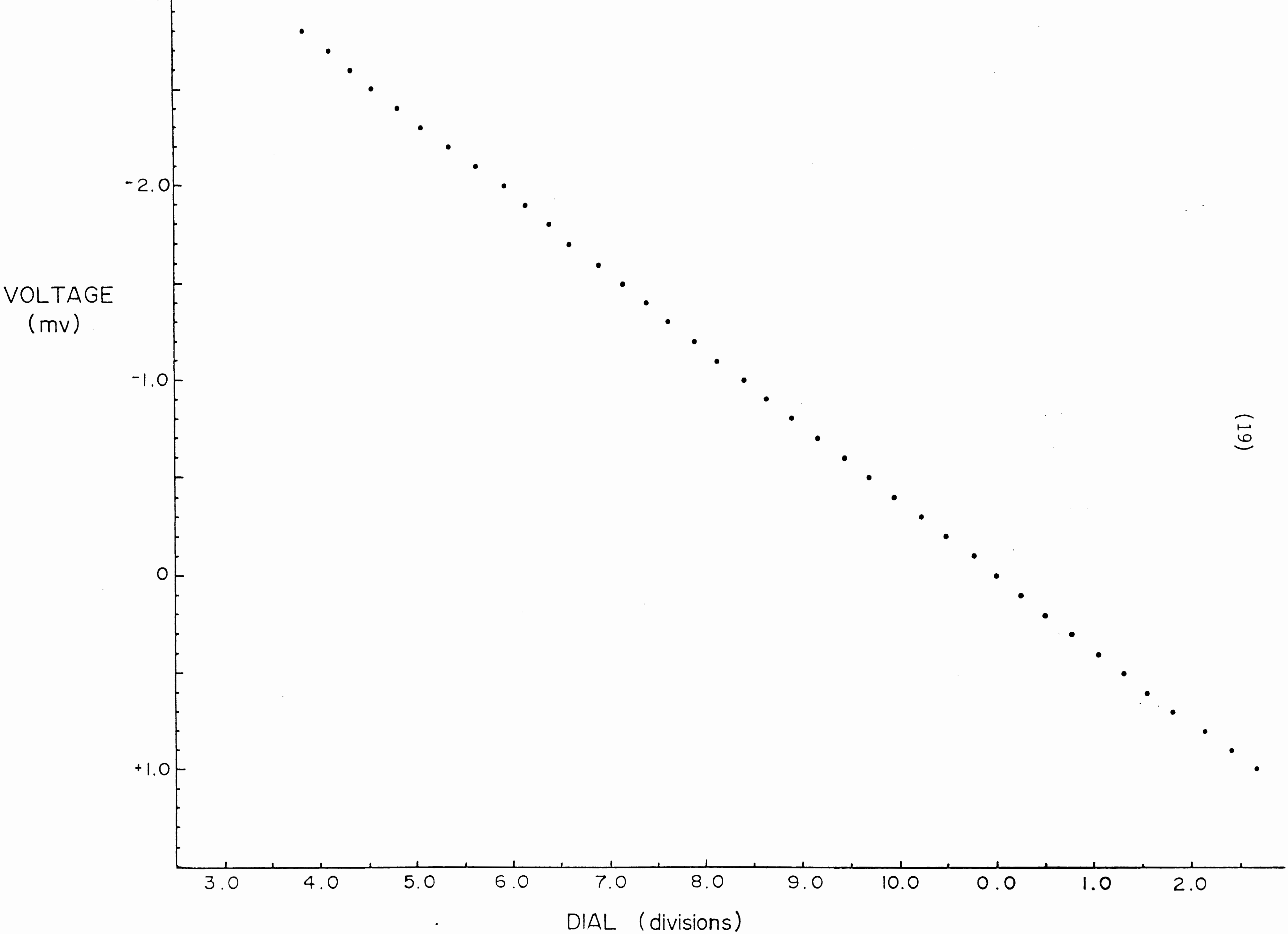
Dial Value	Voltage (mv)	Adjusted Voltage (mv)
3.86	-2.9	-2.8
4.13	-2.8	-2.7
4.35	-2.7	-2.6
4.57	-2.6	-2.5
4.84	-2.5	-2.4
5.07	-2.4	-2.3
5.37	-2.3	-2.2
5.64	-2.2	-2.1
5.93	-2.1	-2.0
6.16	-2.0	-1.9
6.41	-1.9	-1.8
6.69	-1.8	-1.7
6.92	-1.7	-1.6
7.16	-1.6	-1.5
7.41	-1.5	-1.4
7.63	-1.4	-1.3
7.90	-1.3	-1.2
8.13	-1.2	-1.1
8.41	-1.1	-1.0
8.65	-1.0	-0.9
8.91	-0.9	-0.8
9.17	-0.8	-0.7
9.46	-0.7	-0.6
9.70	-0.6	-0.5
9.97	-0.5	-0.4
10.25	-0.4	-0.3
10.50	-0.3	-0.2
10.78	-0.2	-0.1
0.00	$\pm$0.1	0.0
0.25	0.2	0.1
0.51	0.3	0.2
0.78	0.4	0.3
1.06	0.5	0.4
1.32	0.6	0.5
1.55	0.7	0.6
1.82	0.8	0.7
2.13	0.9	0.8
2.42	1.0	0.9
2.67	1.1	1.0

Least Squares Fit to a Straight Line

V = 0.3886 * (dial value) - 4.2829

Correlation coefficient (r) = 0.9999

FIG. 4 HELIPOT CALIBRATION



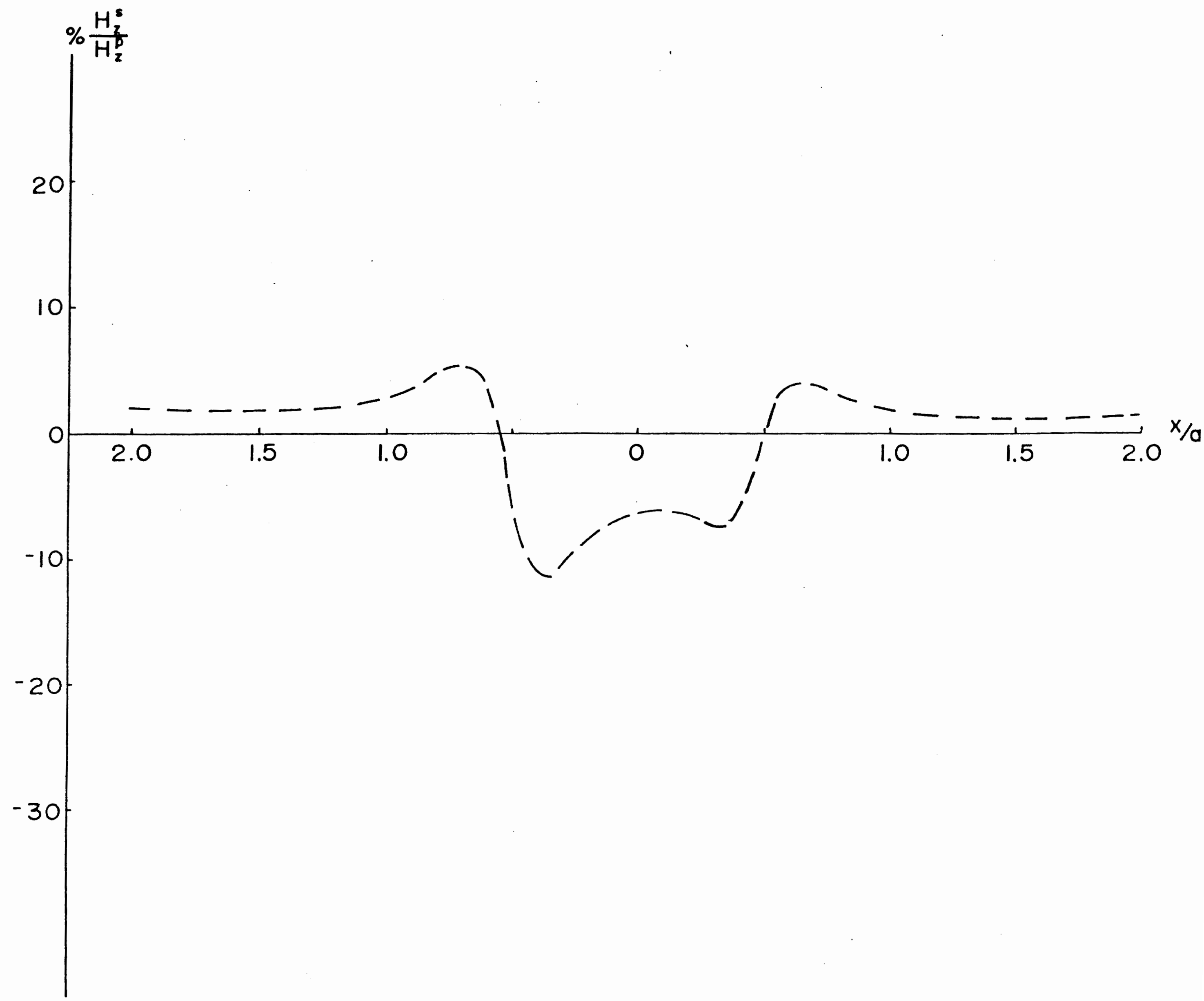


FIG. 5 PROFILE OF THE IMAGINARY VERTICAL COMPONENT OF THE SECONDARY FIELD INDUCED BY A CONDUCTING HALF-PLANE WITH PARAMETERS $\alpha = 90$, H/A = 0.1

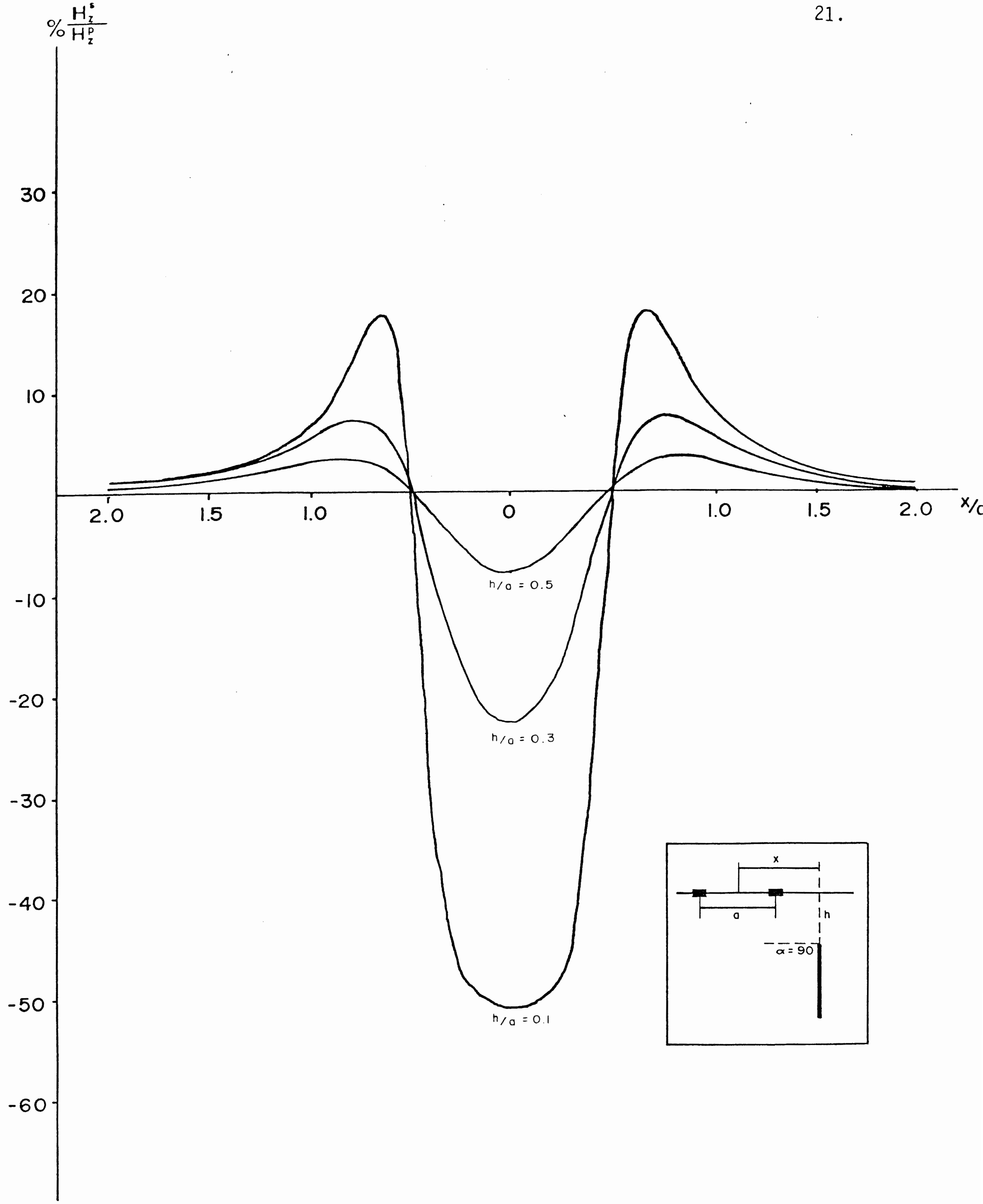


FIG. 6 TYPE CURVE FOR HALF-PLANE , $\alpha = 90°$

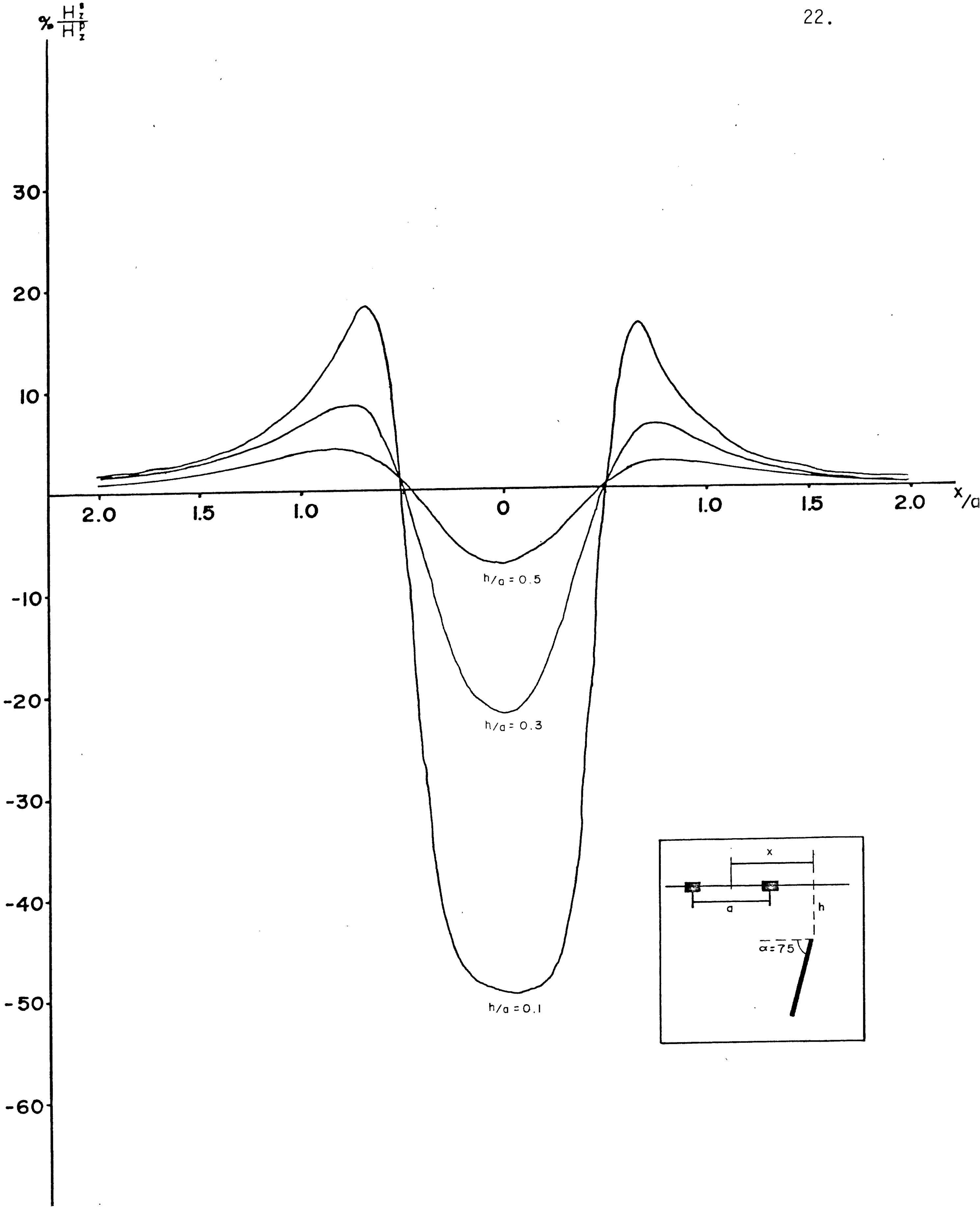


FIG. 7 TYPE CURVE FOR HALF-PLANE, $\alpha = 75°$

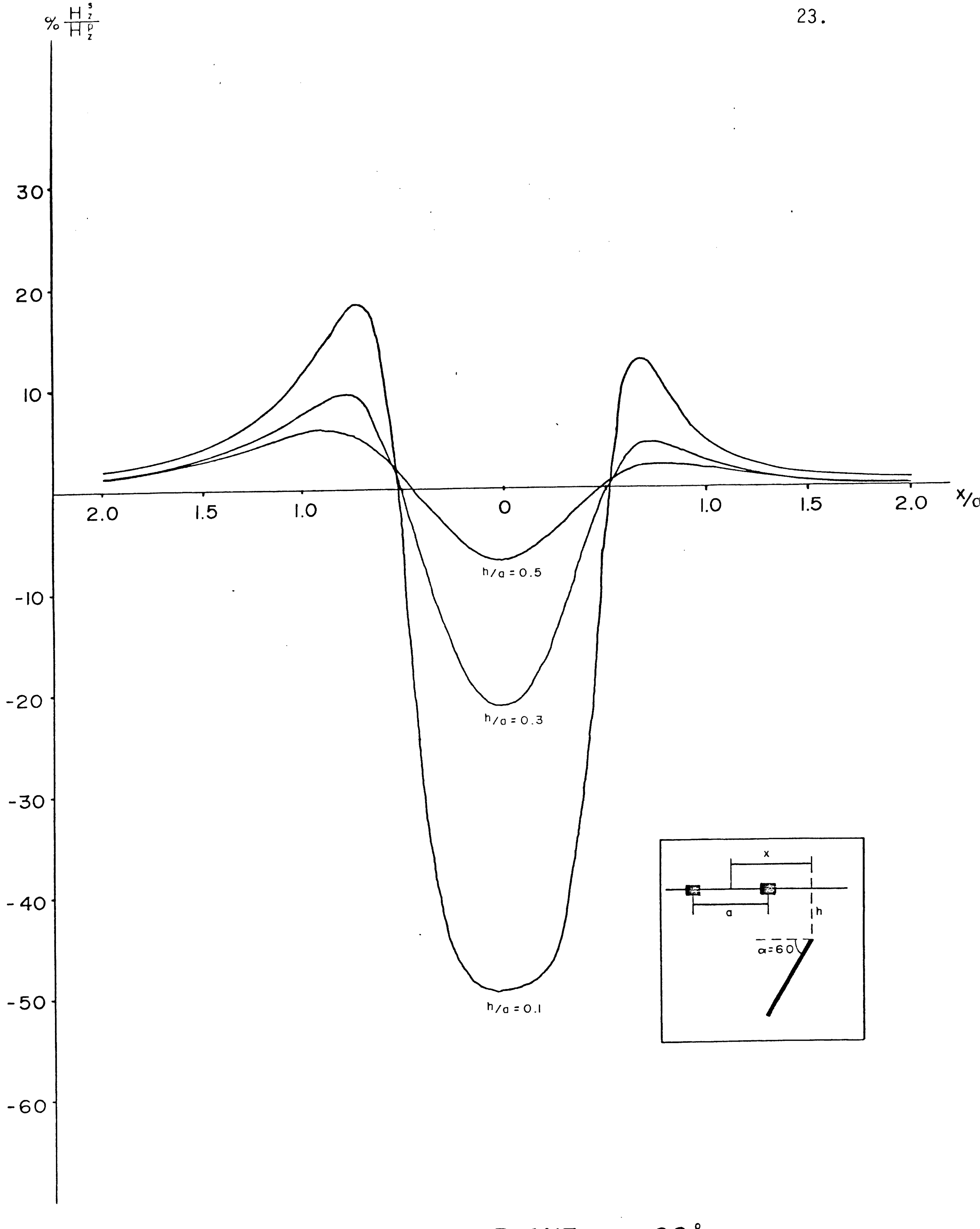


FIG. 8 TYPE CURVE FOR HALF-PLANE, $\alpha=60°$

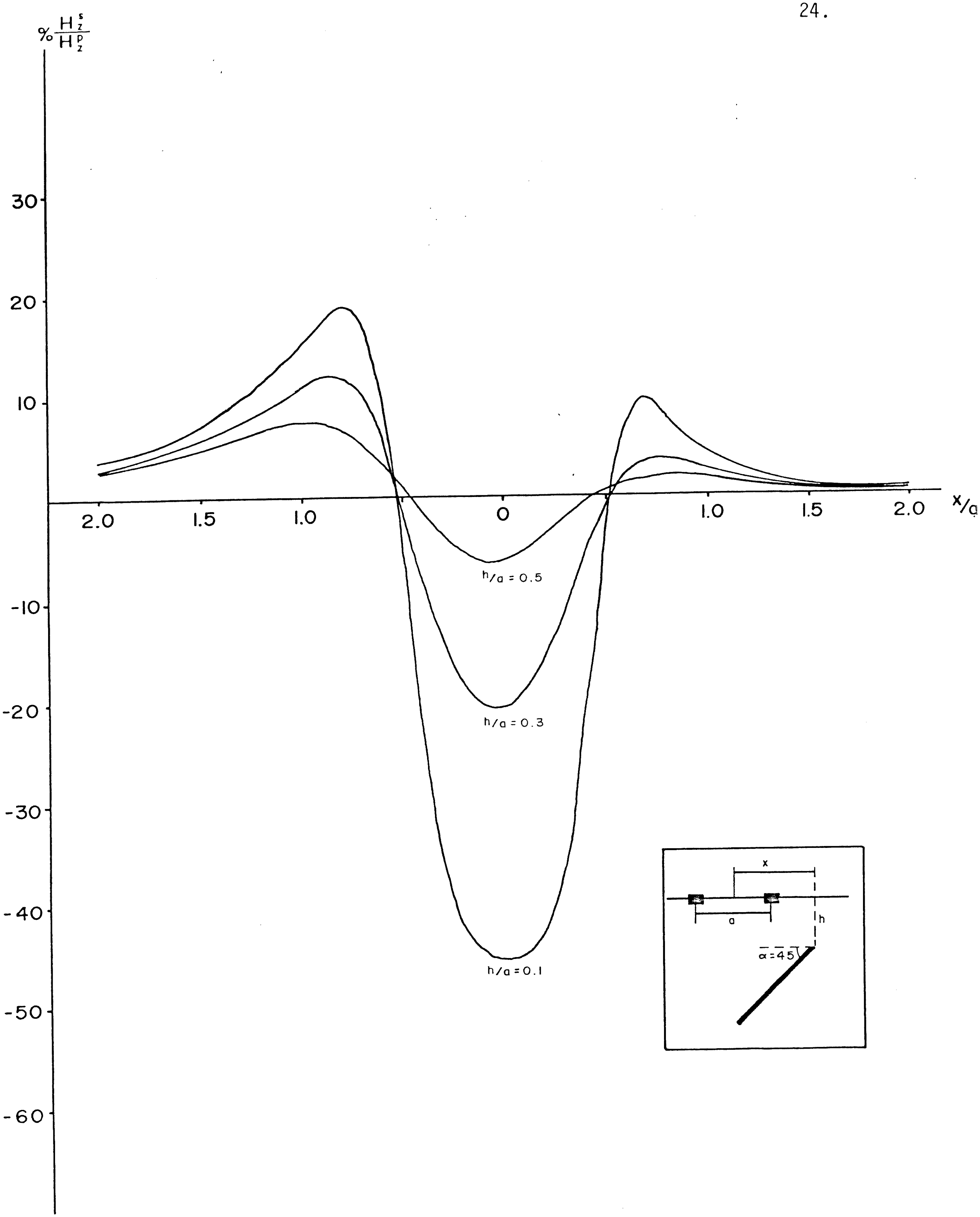


FIG. 9 TYPE CURVE FOR HALF-PLANE, $\alpha = 45°$

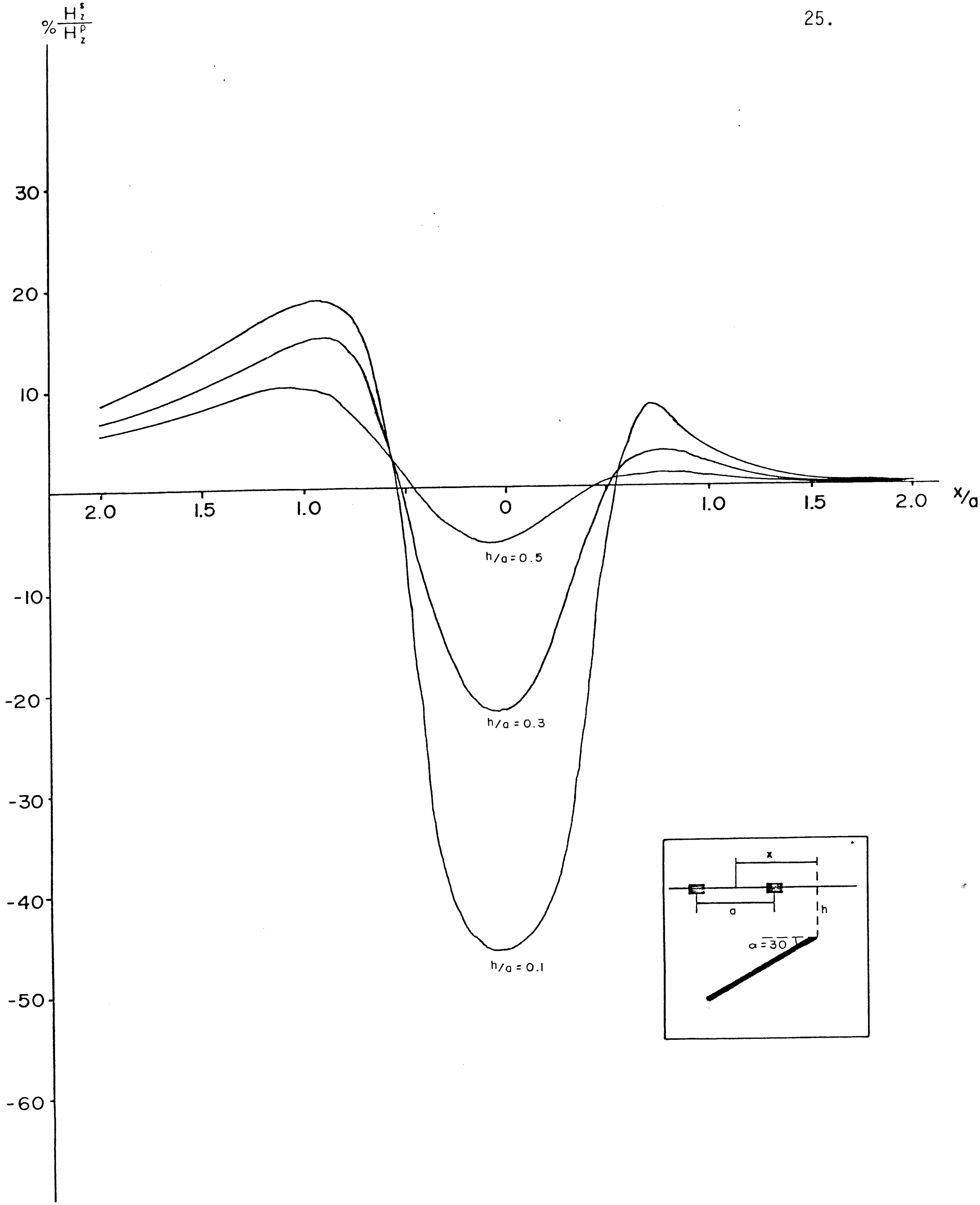


FIG. 10 TYPE CURVE FOR HALF-PLANE, $\alpha = 30°$

IV. INTERPRETATION

4.1 Introduction

As a rule, models employed as a basis for measurements are a highly abstracted representation of any geologic situation (Grant and West 1965). The model measurements presented in this study are based on a uniform conductor with a simple shape. This is not an accurate geologic representation. Naturally occurring conductors in practice are zones of sulfide mineralization which are notorious for not being homogeneous or geometrically regular. Secondly, horizontal loop field measurements are usually performed at station intervals the order of one-half the coil separation, for which reason the form of the anomaly is not accurately known (Ketola and Puranen 1967). Thirdly, the parameters h/a and α change by steps. Therefore, interpolation is necessary to obtain the intermediate values between these steps. Lastly, the model measurements contained in this study are accurate for only one value of the response parameter (σ). It is for these reasons that a high degree of accuracy should not be expected from an interpretation of horizontal loop field measurements.

4.2 Type Curves

Type curves for the half-plane model under study are presented in figs. 6 - 10. Although these figures are based on experimental data, no individual observation points have been drawn on the type curves to facilitate easier interpretation and avoid visual confusion. Nevertheless, by virtue of the high density of observation points the shape of each anomaly could be accurately defined (see fig. 2).

4.3 Characteristic Curve

The characteristic curve illustrated in fig. 11 is a compilation of the type curves presented in figs. 6 - 10. Only the extreme values of each type curve R_1, R_2 and R_{min} have been utilized in its construction (see fig. 2). These values are tabulated in Table 2.

Interpolation was necessary to locate intermediate points needed for the construction of isopleth lines for h/a values of 0.2 and 0.4. In this interpolation procedure it must be noted that the isopleth line h/a = 0.3 does not fall mid-way between the isopleths h/a = 0.1 and h/a = 0.5. By the same argument we should not expect the isopleth lines for h/a = 0.2 and h/a = 0.4 to fall mid-way between h/a = 0.1 and h/a = 0.3, h/a = 0.3 and h/a = 0.5 respectively. Rather, there must be a continuous increase in the separation between the lines h/a = 0.5 and h/a = 0.4, h/a = 0.4 and h/a = 0.3, h/a = 0.3 and h/a = 0.2, h/a = 0.2 and h/a = 0.1, along any line of constant α. This argument was taken into consideration when constructing the interpolated isopleth lines h/a = 0.2 and h/a = 0.4.

Further interpolation will be necessary to determine interpretive values for the ratio h/a and α from actual field data.

The utilization of this characteristic curve is best illustrated by the following examples.

Note: Interpretations utilizing this particular characteristic curve are limited to those anomalies where the ratio of the maximum negative in-phase to maximum negative quadrature response is greater than 2.0.

Example 1

The first example was acquired from from data in a study by Ketola and Puranen (1967). Measurements were obtained using a frequency of 3600 hertz and a coil separation of 40 m. The anomalous profile produced the following extreme values

$$R_1 = 18.9 \%$$
$$R_2 = 12.5 \%$$
$$R_{min} = -40.0 \%$$
$$I_{min} = -14.5 \% \quad .$$

The ratio $R_{min}/I_{min} = -40.0/-14.5 = 2.8$, indicating the presence of a good conductor. Utilizing fig. 11, an abscissa value of 6.4 (18.9 - 12.5), and an ordinate value of 40.0, the values of the parameters for the half-plane are $\alpha \doteq 53$ degrees and $h/a \doteq 0.16$, $h = 0.16 * a = 0.16 * 40 \doteq 6$ m.

The conductive sheet has been pierced by two drill holes, which show its dip to be 53 degrees and the thickness of overburden to be approximately 4 m (Ketola and Puranen 1967). These results agree satisfactorily with the foregiven values determined from fig. 11.

Example 2

The data reproduced here were obtained from a report by Nair <u>et al</u>. (1968). The traverse was over a deposit in Desmazures Township, Quebec. In the measurements, the coil separation was 61 m and the frequency used was 3600 hertz. The following extreme values were observed

$$R_1 = 10.5 \%$$
$$R_2 = 4.5 \%$$
$$R_{min} = -21.0 \% \ .$$

These values translate into a dip angle of 56 degrees and $h/a \doteq 0.3$, $h = 0.3 * a = 0.3 * 61 \doteq 18$ m. Interpretations by Nair et al. (1968) and Bosschart (1961) supply a dip of 55 - 60 degrees and an overburden depth of 21 m. The agreement between these interpretations may be considered satisfactory.

Example 3

The results from a horizontal loop survey over the Caribou Lake deposit in New Brunswick produced the following extreme values using a frequency of 3600 hertz and a coil separation of 200 ft.

$$R_1 = 15.6\ \%$$
$$R_2 = 8.5\ \%$$
$$R_{min} = -54.0\ \%$$
$$I_{min} = -22.0\ \% \quad \text{(Strangway 1966).}$$

The presence of a good conductor is evident from the ratio $R_{min}/I_{min} = 2.45$. The drillings indicate a dip of 75 degrees and an overburden depth of 10 - 20 ft.

Although the data plots out of the range of the characteristic curve, interpolation allows a dip estimate of 55 degrees and $h/a < 0.1$, $h < 0.1 * a < 0.1 * 200 < 20$ ft. Although the dip estimate suffers from this interpolation the overburden depth approximation is satisfactory.

Example 4

The data for example 4 were obtained from a report by Ward (1967). The ratio $R_{min}/I_{min} \doteq 5.0$ implies the presence of a good conductor. In the measurements, a coil separation of 200 ft and a frequency of 3600 hz were used. The survey produced the following extreme values

$$R_1 = 8.1\ \%$$

$$R_2 = 6.5\ \%$$

$$R_{min} = -39.0\ \%\ .$$

Interpretation based on the utilization of the characteristic curve presented in this study shows a dip angle of 79 degrees and $h/a \doteq 0.17$, $h \doteq 0.17 * a = 0.17 * 200 \doteq 34$ ft. Actual drillings indicate the dip angle to be 85 degrees and the overburden thickness to be 45 ft. The agreement between the observed values from the drillings and those produced from the interpretation may be considered satisfactory.

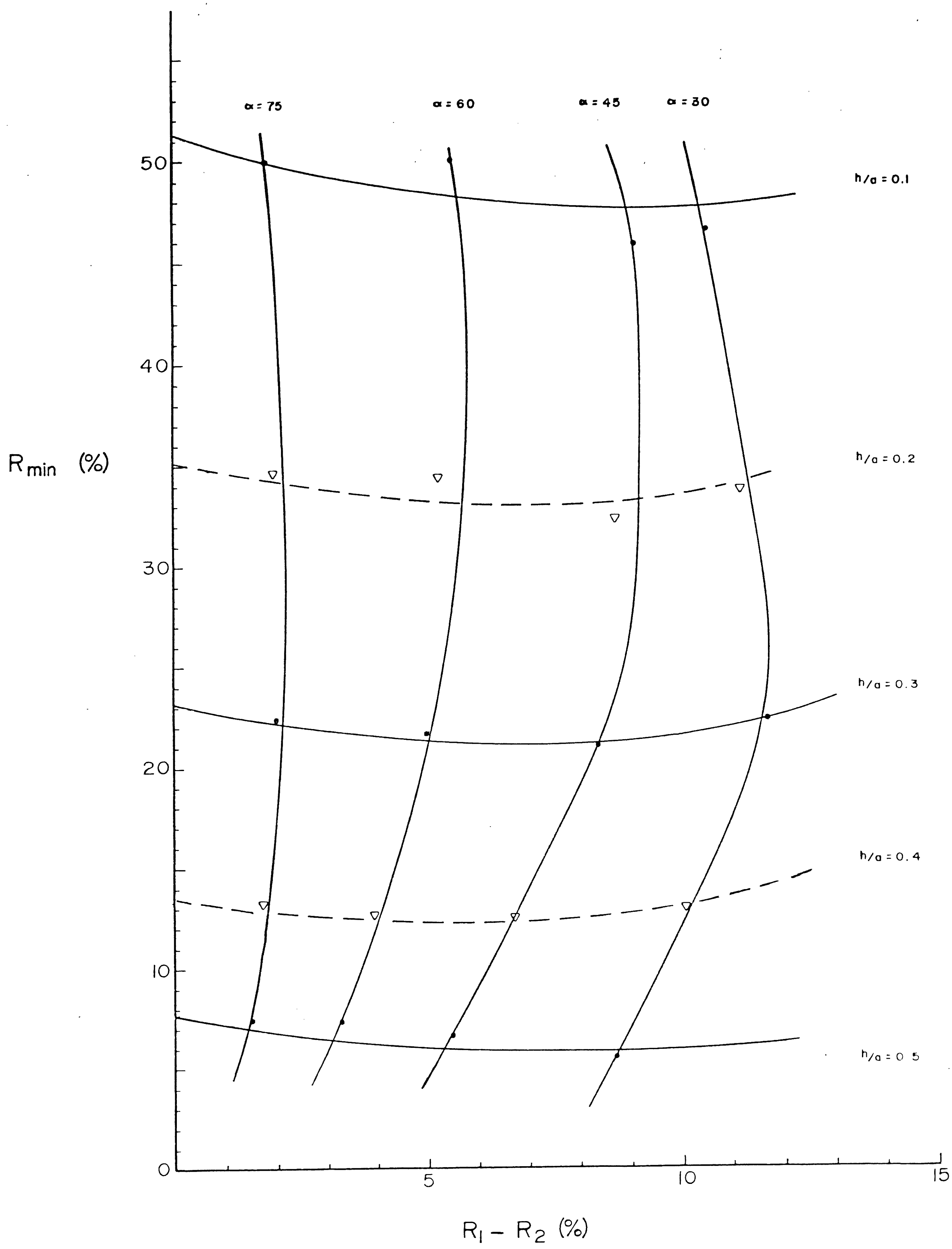
The foregiven numerical examples presented here illustrate the practical value of this interpretation technique and give an estimate of the degree of accuracy which may be considered acceptable when interpreting data obtained from actual field observations.

TABLE 2.

CHARACTERISTIC CURVE DATA

α	h/a = 0.1			h/a = 0.3			h/a = 0.5		
	R_1	R_2	R_{min}	R_1	R_2	R_{min}	R_1	R_2	R_{min}
90	17.6	17.8	-51.1	7.2	7.5	-22.9	3.5	3.5	-7.8
75	18.1	16.3	-49.9	8.2	6.2	-22.4	4.1	2.6	-7.4
60	18.1	12.6	-50.0	9.6	4.6	-21.6	5.6	2.3	-7.3
45	18.6	9.5	-45.8	12.1	3.7	-21.0	7.6	2.1	-6.6
30	18.4	7.9	-46.5	15.0	3.3	-22.3	10.0	1.3	-5.5

FIG. II CHARACTERISTIC CURVE FOR HALF-PLANES



V. CONCLUSIONS AND RECOMMENDATIONS

5.1 Recognition of Half-plane Anomalies

On the basis of scale model experiments carried out in this study it is possible to summarize characteristics of the half-plane response that will allow qualitative interpretation of an anomalous profile. These characteristics are derived from response obtained using a coil separation of 0.06 m and a frequency of 3600 hertz.

a) - General Characteristics

All profiles representing this specific model configuration, irrespective of dip or depth of burial, exhibit a single negative maximum located approximately over the upper edge of the conducting sheet. The profiles have two zeros located at a horizontal distance of approximately $\pm \frac{1}{2}$ times the coil separation from the upper edge of the conducting sheet. The profiles have two positive maxima located at a horizontal distance of approximately 0.7 times the coil separation from the upper edge of the conducting sheet, after which the flanks diminish to a value close to zero.

b) - Positive Peak Enhancement

The dipping sheet produces a profile whose positive peak on the downdip side of the conducting sheet is inhanced while the positive peak on the updip side of the conducting sheet is reduced. For any set of profiles with the same value of the ratio h/a, it appears that the magnitude of the dissimilarity between the two positive maxima increases as the dip angle of the conducting sheet decreases.

c) - Negative Peak Displacement

There is a slight suggestion that the negative peak of the in-phase component of the secondary field is displaced toward the hanging wall side of the dipping conductor. This characteristic, however, is not pronounced, especially in profiles representing dip angles of more than 60 degrees.

c) - Overburden Extent

No general statement can be made concerning overburden extent unless information is acquired regarding the quadrature component of the secondary field. Modelling is non-unique in that a poor conductor near the surface is capable of producing the same electromagnetic response as a good conductor at a greater depth. In this study, it was required that the ratio of the maximum negative in-phase to maximum negative quadrature response be greater than 2.0 in order for a quantitative statement to be made concerning the overburden depth overlying a conductive sheet.

5.2 Recommendations

It has been established by Ketola and Puranen (1967) and Grant and West (1965) that in the case of the half-plane conductor, the ratio R_{min}/I_{min} is quite diagnostic of its conductivity. Therefore, quadrature response clarifies the ambiguity between conductivity and depth of burial. This study illustrates that the interpretation technique utilized here and by Ketola and Puranen (1967) is a useful tool capable of disclosing information about the parameters of one specific model configuration ($\infty \pm 30°$). Hence, it would be desirable to develop a measurement system capable of quantitatively measuring both the in-phase and quadrature components of an anomalous field if the true potential of this electromagnetic system and interpretation technique are to be exploited.

Once developed, this electromagnetic system would have limitless applications and the potential to measure the response of virtually any conductor configuration.

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