Lawrence Berkeley National Laboratory

Recent Work

Title

INDUCED-POLARIZATION EFFECTS FROM GROUNDED STRUCTURES

Permalink

<https://escholarship.org/uc/item/22x6z5nw>

Author

Nelson, P.H.

Publication Date

1977-06-01

U 0 0 0 4 8 0 1 2 3 1

UC-66
LBL-6380
C.1

Published in *Geophysics*, Vol. 42, No. 6,
1241 - 1253 (October 1977)

RECEIVED
LAWRENCE
BERKELEY LABORATORY

JUL 10 1978

LIBRARY AND
DOCUMENTS SECTION

For Reference

Not to be taken from this room

Energy and Environment Division

**Induced-Polarization Effects
From Grounded Structures**

P. H. Nelson

June 1977

Lawrence Berkeley Laboratory University of California/Berkeley
Prepared for the U.S. Department of Energy under Contract No. W-7405-ENG-48

66

LBL-6380
C.1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

INDUCED-POLARIZATION EFFECTS FROM GROUNDED STRUCTURES

P. H. NELSON*

Fences, power lines, pipelines, and other extensive man-made structures with earthed grounds produce spurious induced polarization anomalies by acting as secondary sources and sinks of current. This problem is especially difficult to detect because the redistributed current waveforms are similar to the desired induced-polarization signal. If the structure grounds were purely resistive there would be no problem; but because most grounds are polarized, currents flowing through them undergo phase shifts that contaminate the desired measurements. The patterns and magni-

tudes of such spurious anomalies can be calculated using a mathematical model that incorporates the position of each ground in relation to the transmitter and receiver dipole locations. The model also requires an estimate of the grounding impedance, the resistance per unit length of the structure, and the earth resistivity. All three parameters influence the received signal, but the effect of high earth resistivity is particularly dramatic in increasing the undesired phase shifts. Comparison of the predictions with field tests helps confirm the validity of the model.

INTRODUCTION

Man-made grounded structures have always plagued geophysical survey work, especially electrical surveys, and the problems are growing more acute recently as suburban sprawl and irrigated agriculture increase. In the case of porphyry copper exploration in the southwestern U.S., induced-polarization (IP) surveys of the dipole-dipole type often intersect several structures along a single survey line. Some of these structures will generate a false anomaly (often referred to as "culture" or a "civil effect") which resembles a valid anomaly. In another case, a structure might not generate a false anomaly, but will cause the interpreter to question a valid anomaly because of its proximity to the structure. In the worst case, a false anomaly can obscure a valid one. This paper provides no pat solutions to these operational difficulties, but it does provide a model for understanding and quantitatively assessing the general problem.

Grounded structures can cause problems for IP surveys in two ways. Noise from electrical machinery

or power systems propagates along the structures, spilling into the earth at the grounding points and masking the desired signal if the IP receiving dipole is too close. This problem can be overcome by a combination of electronic filtering, simple avoidance, and interchange of the transmitter and receiver dipoles. The second problem, which is the subject of this paper, arises because the grounded structure extends across a significant voltage differential in the field of the IP transmitter dipole so that although it cannot generate a net current, it does redistribute current along its length, acting as a current source in one place and as a current sink in another. If the grounds of the structure were purely resistive, then their only effect would be to change the apparent resistivity with no effect on the IP. However, most grounds are polarized so that currents flowing through them do undergo phase shifts which show up in our IP measurements. Hence, a necessary part of this work has been the measurement of grounding impedances on fences and power lines.

The second aspect of the problem is formulating

Presented at the 45th Annual International SEG Meeting, October 15, 1975, in Denver. Manuscript received by the Editor December 2, 1976; revised manuscript received March 17, 1977.

*Lawrence Berkeley Lab, Berkeley, CA 94720; formerly Kennecott Exploration, Inc., Salt Lake City, UT.

© 1977 Society of Exploration Geophysicists. All rights reserved.

FIG. 1. Plan view of general dipole-dipole array in presence of a linear grounded structure.

it so the IP phase response can be computed for any structure given the electrode geometry, earth resistivity, and electrical parameters of the structure. Hallof (1967) did scale modeling of the in-line dipole-dipole array in the presence of continuously grounded and intermittently grounded structures, giving good information on the IP anomaly patterns and relative magnitudes as a function of array geometry. However, there was no effort to keep track of the model's electrical parameters so the absolute values of the IP effect are unknown. A theoretical approach was taken by Madden and Cantwell (1962) to evaluate the effects of a fence upon a resistivity survey along the Massachusetts Turnpike. They assume zero longitudinal resistance along the structure and evaluate an elliptic integral to get the voltage contributed by the fence. Our approach is in discrete notation, easily implemented on a digital computer, and allows incorporation of all the pertinent electrical parameters.

FORMULATION

Figure 1 shows a plan view for the problem under consideration. A grounded dipole transmitter transmits a current I through electrodes a and b with the positive sign at a signifying current injection into the ground. The voltage V_{mn} is measured between electrodes m and n with m taken as positive. The grounded structure has N grounds of electrode impedance $Z_1, Z_2, \dots, Z_N \Omega$, and longitudinal resistance $R_L \Omega$ between each ground. The earth is homogeneous of resistivity ρ .

The received voltage will be the primary voltage plus the secondary voltage, due to currents flowing into the earth through each ground of the structure.

$$V_{mn} = \frac{\rho I}{2\pi} \left(\frac{1}{r_{am}} - \frac{1}{r_{an}} - \frac{1}{r_{bm}} + \frac{1}{r_{bn}} \right)$$

$$+ \sum_{i=1}^N \frac{\rho I_i}{2\pi} \left(\frac{1}{r_{im}} - \frac{1}{r_{in}} \right), \quad (1)$$

where r_{am} is the distance between electrodes a and m in meters, and the secondary currents are

$$I_i = (V_i^F - V_i^E)/Z, \quad (2)$$

with V_i^F and V_i^E the voltages on the structure and in the earth at the i th electrode, and $Z = Z_1 = Z_2 = \dots = Z_N$ is the electrode resistance in ohms. The voltage in the earth is simply

$$V_i^E = \frac{I\rho}{2\pi} \left(\frac{1}{r_{ia}} - \frac{1}{r_{ib}} \right). \quad (3)$$

So far, two assumptions have been made. The first is that the grounded structure draws so little current that the primary potential field in the earth is indeed unaltered or is altered so little that it does not affect the solution. In fact, the above formulation is zeroth order approximation to a complete formulation of the problem which would be an integral equation. This approach has been justified numerically by a recursive procedure which we tested to see if the phase of the receiver voltage was significantly altered by taking into account the earth potential generated by the secondary currents. The results were negative. A second assumption concerns the electrode current, which is taken above as being driven by the voltage drop between the structure and the earth at the point of grounding. This cannot be true because by definition the electrode impedance involves the entire half-space. However, the potential drops off quickly enough so that we can ignore this as long as all our electrode separations are large compared to the dimensions of the grounds. For instance, Tagg (1964, p. 100-101) shows that for an electrode with the approximate dimensions of a fence stake, 90 percent of the total resistance occurs within a hemispherical volume of a five-foot radius.

The next step is determining the structure voltage V_i^F and then computing the magnitude and phase of the apparent resistivity at the receiver. The method of computing V_i^F depends upon the type of structure and its resistances. Before considering separate cases, it is convenient to define the geometric factors.

$$G_{abmn} = \frac{1}{r_{am}} - \frac{1}{r_{an}} - \frac{1}{r_{bm}} + \frac{1}{r_{bn}}, \quad (4)$$

$$G_{imn} = \frac{1}{r_{im}} - \frac{1}{r_{in}},$$

$$G_{iab} = \frac{1}{r_{ia}} - \frac{1}{r_{ib}},$$

and the apparent resistivity is

$$\rho_a = 2\pi \frac{V_{mn}}{IG_{abmn}} \quad (5)$$

Case 1. $V^F = 0$

This simple approximation can be justified for high-voltage transmission lines which extend for great distances (potential goes to zero at infinity) and have negligible longitudinal resistance. For this case, equations (1)–(5) can be combined to yield

$$\rho_a = \rho \left(1 - \frac{\rho}{2\pi Z} \frac{1}{G_{abmn}} \sum_{i=1}^N G_{iab} G_{imn} \right). \quad (6)$$

We see that whenever the grounding impedance Z is complex, then a high observed apparent phase shift can be caused by a high earth resistivity, a low grounding resistance, or a high geometric factor which can occur when an IP current or potential electrode is close to a ground of the structure. Physically, any of these three circumstances results in increased current flow through the grounds. Of course, if the grounds have no reactance then there will be no observed phase shift, and the only effect will be a change in the apparent resistivity. Equation (6) also shows that the sign of the apparent phase and the increment of resistivity change is controlled by the sign of the geometric term. Roughly speaking, for a dipole-dipole array intersecting a linear structure at some angle, the geometric term is positive when the dipoles straddle the structure, thereby decreasing the apparent resistivity and producing positive phase lags. The opposite occurs when both dipoles lie on the same side of the structure.

Case 2. $V^F = V^E$

It can be shown that for a structure of finite length and of negligible longitudinal resistance, the voltage on the structure will equal the average earth potential along its length. This value can be produced analytically but it is simpler to retain the discrete notation.

$$\overline{V^E} = \frac{\rho I}{2\pi N} \sum_{i=1}^N \left(\frac{1}{r_{ia}} - \frac{1}{r_{ib}} \right) = \frac{\rho I}{2\pi} \overline{G_{iab}}. \quad (7)$$

Thus, we get an equation similar in form to equation (6),

$$\rho_a = \rho \left[1 - \frac{\rho}{2\pi Z} \frac{1}{G_{abmn}} \sum_{i=1}^N G_{imn} (G_{iab} - \overline{G_{iab}}) \right]. \quad (8)$$

The geometric term is now reduced compared to equation (6), so the observed effects are reduced for a structure of finite length versus one of infinite length. Physically, this comes about by requiring that the net current flow through the grounds of the structure be zero, thereby producing a dipolar or multidipolar current distribution.

Case 3. V^F varies along structure

In application, case 2 is limited because it ignores the longitudinal resistance that is important for the barbed wire fences which are common in the southwestern U.S. Although the resistance per length of a fence, on the order of $1.0 \Omega / 1000$ ft, is small compared with the grounding resistance of an individual stake, on the order of 100 to 1000 Ω , it is significant when an entire length is considered. To solve for V^F , we consider the model of Figure 2.

Summing node currents gives the matrix equation

$$\begin{bmatrix} y_0 & y_1 & 0 & 0 & \cdots \\ y_1 & y_2 & y_1 & 0 & \cdots \\ 0 & y_1 & y_2 & y_1 & 0 \cdots \\ \cdots & 0 & y_1 & y_2 & y_1 & 0 \\ \cdots & \cdots & 0 & y_1 & y_2 & y_1 \\ \cdots & \cdots & 0 & y_1 & y_0 \end{bmatrix} \begin{bmatrix} V_1^F \\ V_2^F \\ V_3^F \\ \vdots \\ V_N^F \end{bmatrix} = \frac{1}{Z} \begin{bmatrix} V_1^E \\ V_2^E \\ V_3^E \\ \vdots \\ V_N^E \end{bmatrix}, \quad (9)$$

where

$$y_0 = \frac{1}{Z} + \frac{1}{R_L}, \quad y_1 = -\frac{1}{R_L}, \quad y_2 = \frac{2}{R_L} + \frac{1}{Z}.$$

FIG. 2. Circuit equivalent for a fence. Impedances Z are complex-valued.

FIG. 3. Hemispherical electrode with injected current $+I$ and the potential decay with distance.

We solve for the fence voltage V_f^F using a recursion relation from Carnahan et al (1969, p. 441). It is possible to retain the format of equations (6) and (8), but it is more useful to use equations (1)–(3) after finding V^F according to (9). This allows us to examine the behavior of the fence voltage and current directly.

In calculating the response of a structure, the dipole-dipole results are voltage differences taken between electrode positions according to equation (1) and should be exactly equivalent to its ideal field equivalent. However, for experimental purposes, it was desirable to map the electric field behavior in greater detail than permitted by large dipole systems. In these cases, we made orthogonal receiver measurements on short electrode separations to approximate the electric field at a point location (x, y) . In this case, the electric field components are given by

$$E_x(x, y) = \frac{\rho I}{2\pi} \left(\frac{x - x_a}{r_a^3} - \frac{x - x_b}{r_b^3} \right) + \sum_{j=1}^N \frac{\rho I_j}{2\pi} \frac{(x - x_j)}{r_j^3}, \quad (10)$$

$$E_y(x, y) = \frac{\rho I}{2\pi} \left(\frac{y - y_a}{r_a^3} - \frac{y - y_b}{r_b^3} \right) + \sum_{j=1}^N \frac{\rho I_j}{2\pi} \frac{y}{r_j^3},$$

where

$$r_a = \sqrt{(x - x_a)^2 + (y - y_a)^2}, \quad (11)$$

$$r_b = \sqrt{(x - x_b)^2 + (y - y_b)^2},$$

$$r_j = \sqrt{(x - x_j)^2 + (y - y_j)^2}.$$

The transmitter electrodes are located at (x_a, y_a) and (x_b, y_b) and the structure grounds are at (x_j, y_j) with secondary currents I_j . The superscripts R, Q denote

in-phase and quadrature components of the electric field.

The total phase from the orthogonal measurement is defined as,

$$\phi = \sqrt{\frac{(E_x^Q)^2 + (E_y^Q)^2}{(E_x^R)^2 + (E_y^R)^2}}, \quad (12)$$

i.e., the ratio of quadrature to in-phase electric field. Note that the phase, as defined by (12), is always positive.

ELECTRODE IMPEDANCE

The impedance of a single electrode is the voltage at the electrode (referenced to the potential at infinity) divided by the current flow into the electrode. This discussion of electrode resistance is modified from Tagg (1964) to include a contact reactance which produces a phase shift. For most grounding problems which arise in electrical power systems, this contact reactance is negligible, but for our problem it is quite important.

Consider the hemispherical electrode of Figure 3 in a homogeneous half-space of resistivity ρ . The potential within the highly conductive electrode is a constant V_e . The voltage drop across the metal-soil interface is IZ^* , where Z^* includes a phase shift due to electrochemical effects at the interface. Exterior to the electrode the potential decays as $1/x$ so the voltage between the electrode and a point at x is (see Figure 3),

$$V = V_e - V_x = IZ^* + \frac{I\rho}{2\pi} \left(\frac{1}{a} - \frac{1}{x} \right), \quad (13)$$

or

$$V/I = Z^* + \frac{\rho}{2\pi a} - \frac{\rho}{2\pi x}, \quad (14)$$

FIG. 4. Impedance measurements at a transmission tower footing.

or

$$V/I = Z^* - \frac{\rho}{2\pi x}, \quad (15)$$

where $Z = Z^* + \rho/2\pi a$ is the electrode impedance, which appears in equations (6)–(9).

For an electrode of arbitrary shape, the radius a becomes a general length parameter which in fact is the electrostatic capacity C/ϵ of the electrode with its image in free space. We expect that the contact resistance will contribute very little to the in-phase portion of the electrode impedance, so that

$$Z \approx \frac{\rho}{2\pi a} + jZ_q^*, \quad (16)$$

where the q subscript represents the out-of-phase component.

The following cases illustrate different techniques employed to measure the impedance of various

grounds using a field IP receiver and transmitter. It is impossible to measure the impedance without first disconnecting the ground from the structure.

Case 1. Transmission line towers

These cross-country towers are large structures, generally of four footings spaced 20 to 30 ft on a side with grounding resistance typically 4Ω per footing. For the purpose of lightning protection, the towers are connected together by one or more conductors before they are put into service. We measured several footings on a new line northwest of Phoenix, Ariz. before the towers had been installed. The method was to use one footing as a transmitter electrode with the other transmitter electrode far enough away (>1000 ft) so it did not influence the measurement. The IP receiver was carefully insulated from the ground and read between the footing and a "porous pot" electrode at several distances between

FIG. 5. Field layout for impedance measurement of twin power poles.

5 and 200 ft from the footing. Typical data are shown in Figure 4 where V/I is plotted against $1/x$. From equation (15) the slope gives the resistivity divided by 2π , and the y-intercept gives the electrode resistance. The phase values (Figure 4) gradually approach a true value as x increases, so after subtracting a 6 milliradian (mrad) background effect (independent measurement), 21 mrad at 0.1 Hz and 7 mrad at 1.0 Hz are good values for the tower, which was typical. With such low phase values, two interconnected towers did not contribute any anomalous effects to a 500-ft dipole IP line, even though a transmitter electrode was only 100 ft from one of the towers.

Case 2. Grounds on wooden power poles

Frequently the power distribution and lower-voltage transmission lines are supported by one or more wooden poles with the shield wire grounded to a copper base plate on the bottom of the pole. The method of impedance measurement described in the previous section did not work on these grounds because the results were current-dependent even at low (5 milliampere) currents. It was necessary to arrange the transmitter electrodes so the power pole grounds were in a known voltage gradient, then form the grounds into a closed loop and measure the secondary current flowing in the loop (see Figure 5).

The summed grounding impedances are

FIG. 6. Phase versus resistance of individual fence stakes at six field sites in Arizona. Large symbol denotes "typical worst case" fence parameters.

$$Z_1 + Z_2 = \frac{I}{I'} \frac{\rho}{3\pi a} \quad (17)$$

where

- I is the transmitter current,
- I' is the current through the 1Ω resistor,
- ρ is the earth resistivity, and
- a is the distance (meters) between poles.

Values obtained at the test site discussed in the next section (Figure 8) were 100 (50) Ω and 160 (96) mrad at 0.1 (1.0) Hz.

Case 3. Fence stakes

The most efficient way to measure fence stake resistance was to put the transmitting electrodes some convenient distance (100 ft and 1000 ft) from the fence, then remove the fence clips, isolate an individual stake from the fence, and measure the voltage between the fence and a pot some 10 ft away to get the driving voltage. To get the current, measure across a 10Ω resistor between the fence and the stake (and then replace the clips). More than 60 stakes at six field sites in central Arizona were measured in this way (Figure 6). The resistance varies from 100 to 5000 Ω and the phase lag from 30 to 600 mrad. As evident from both Figures 6 and 7, the stake impedance will vary from site to site, although this is masked somewhat by the large amount of scatter at any site.

At all six sites except one, the phase and resistance decrease with increasing frequency (Figure 7). One would hope that the observed spectra at a receiver

site would behave in a similar fashion to provide diagnostic fence spectra. Unfortunately, this was not the case. At one test site, where the fence stake spectra had the largest slopes, the observed spectra were almost flat or exhibited decreasing phase lag with decreasing frequency. A possible reason for this is that the increasing stake resistance allows less current to be dumped at the lower frequency, thereby compensating for the higher phase lags. A more hopeful example occurred at another fence site where spectra on a 500-ft dipole-dipole line over an anomalous fence increased slightly at the lower frequencies. The conclusion here is that spectra with slopes less than, or reversed to, the expected inductive coupling contribution are good evidence of contamination when they do occur, but they will not necessarily be present. Our work on this topic was cursory and further test work, over a broader frequency range, might produce more encouraging results.

FIELD EXAMPLES

Power line example

The measurements of grounds on wooden power poles mentioned in the preceding section were used to calculate the response for an IP line at a 45-degree angle to the power line. The phase lag values from the computed model and the field results are shown in Figure 8. Significant features are the "chevron" shape of the anomaly, similar to that of thin dikes; and the negative values of phase on the diagonals immediately exterior to the chevron, a feature due to the sign of the geometric factor. Agreement is quite good.

FIG. 7. Selection of fence stake spectra from five sites.

Fence example

We used an unusually responsive fence with the geometry shown in Figure 10 as a test case. We read the fence to ground voltage for more than 1600 ft in each direction from the transmitter electrode while obtaining stake impedances, which in turn were used,

along with apparent resistivity values, to compute the fence-to-ground voltage and phase shift in accordance with equation (9). Both the measured and computed values are shown in Figure 9. The check is satisfying in that the right values of phase and voltage are predicted by the model. The fit is not exact, particularly

FIELD TEST

COMPUTED

MODEL

FIG. 8. Phase lag (milliradians) due to a power line and a computed model using the grounding impedance measured on one of the power poles. The computed model half-space parameters were $50 \Omega\text{-m}$ and 3 mrad . The grounding impedances were 100Ω at 160 mrad , with 11 grounds in the calculation. One of the grounds is 15 ft from the center IP electrode.

FIG. 9. Voltage and phase readings at 0.2 Hz between the fence (taken as positive) and a reference electrode 10 ft away. Ticks give the measurement locations. The computed model is specified in Figure 10.

near the corner where the null values are offset by 350 ft, even though the computed model accounted for the corner.

With the same transmitter configuration, we then read phase values using 200-ft orthogonal receiver dipoles at stations 200 ft apart on short lines 400 ft apart. Figure 10 displays the results, along with phase values computed with equation (12) for the same model as Figure 9. For this array and frequency, the electromagnetic coupling contribution is negligible. The computed model and field data are similar in the trend of the phase pattern and general direction of field but do not fit well in detail.

Two factors are believed to contribute to the discrepancies between the field and the computed cases. The earth resistivity of 145 Ω -m is uniform in the model, whereas in the real case lateral and vertical

variations do exist and can cause significant perturbations in the current geometry. The fence stake impedance, taken to be 500 Ω at -300 mrad, also is an average value and variations are large, as can be seen in Figure 6. Hence, the discrepancies are felt to be minor and the examples of Figures 8 and 10 constitute adequate checks on the model, the algorithms, and the programming for the model results described in the next section.

COMPUTED RESULTS

Figure 11 presents computed results in the same format as Figure 10 with the purpose of displaying the geometry of the current flow generated by a fence-like structure in the potential field of a single transmitter. The earth resistivity is 100 Ω -m. The fence grounds are spaced 25 ft apart, with an im-

FIG. 10. Phase values at 0.2 Hz and direction of out-of-phase field in the vicinity of a fence with a transmitter electrode 100 ft from fence. Computed fence model parameters: 145 Ω -m earth resistivity, fence wire resistance of 1.1 Ω /1000 ft, fence stakes 14.3 ft apart with resistance of 500 Ω and phase lag of 300 mrad.

FIG. 11. Total phase values and the direction of the quadrature electric field due to a fence. Scale given by the 2000-ft transmitting dipole.

pedance of 300Ω and -300 mrad representing a "typical worst case" selection (see Figure 6). The fence is 16,000 ft long with a longitudinal resistance of $1.1 \Omega/1000 \text{ ft}$.

By definition, the total phase [equation (12)] gives the ratio of the total quadrature to total in-phase electric field at a point. Examination of Figure 11 shows that the total phase increases along the structure away from the transmitter due to the decay of the primary field and the distribution of quadrature current along the structure. The position of the transmitter electrodes with respect to the structure controls the current flow geometry. The structure acts as a cur-

rent sink when a positive electrode is nearby. Comparison of the upper two portions of Figure 11 shows the effect of transmitter location upon the induced current flow patterns.

The lower two portions of Figure 11 demonstrate the strong control of the earth resistivity upon the observed phase. The change from 100 to $500 \Omega\text{-m}$ produces roughly a five-fold increase in the total phase. This type of behavior occurs only if the electrode impedance is independent of the earth resistivity, a situation which often occurs where the grounds are implanted in a thin layer of alluvium overlying the bedrock. In such cases, the grounding impedance

FIG. 12. Phase lag (milliradians) for a 1000-ft in-line dipole-dipole array across a fence, varying the offset of the fence from the center electrode. Computed model parameters: 100 Ω -m earth resistivity, fence wire resistance of 1.1 Ω /1000 ft, fence stakes 25 ft apart with resistance of 300 Ω , and phase lag of 300 mrad.

depends upon the properties of the alluvium, not the bedrock, and the results of Figure 11 apply. However, if the grounds are implanted directly in the bedrock, then the impedance will depend upon the earth resistivity, and in fact by combining equations (6) and (16), one would then predict that increasing the earth resistivity could actually decrease the observed phase. Further comment can only be speculative because the dependence of the reactive component of the grounding impedance upon the resistivity is unknown, and because surface conditions will in fact greatly influence the character of the grounding impedance. But it is safe to say that the results of Figure 11 represent the maximum dependence upon the bedrock resistivity.

Figure 12 displays the phase lag profiles for a conventional "dipole-dipole" array crossing a fence at right angles. The figure demonstrates the wisdom of keeping the survey electrodes as far as possible from the structure, in this case by positioning the line so that it crosses the structure at the midpoint of a dipole. Note that there is zero phase response from such a dipole (0 to +1000) in the top portion of Figure 12 because the structure lies along an equipotential line. As the structure is offset from the midpoint in the lower two figures, the dipole generates anomalous values.

Changes in the apparent resistivity due to secondary current flow from grounded structures were not studied in detail, but it appeared that fairly exceptional circumstances would be required to alter the apparent resistivity by more than 10 percent under ordinary survey conditions. For example, consider the expected apparent resistivity values which would correspond to the lowermost phase lag profile of Figure 12. With no perturbations we would, of course, obtain a uniform apparent resistivity profile of 100 Ω -m. In this case, the computed fence model produced apparent resistivity values ranging from 95 to 102 Ω -m, all within 5 percent of the homogeneous values. For a particular situation, equations (6) or (8) can be used to quickly estimate apparent resistivity perturbations, assuming the longitudinal resistance is low. Note that the geometry and the ratio $\rho/2\pi Z$ combine to control the apparent resistivity.

SUMMARY

- 1) The first-order model shows that long, linear grounded structures contaminate induced polarization surveys by redistributing small amounts of current. The resulting secondary dipoles produce phase shifts at the reactive grounds of the struc-

ture. The model implies reciprocity; that is, interchange of transmitter and receiver will not reduce the contamination unless, of course, a transmitter electrode has been placed so close to a ground that it drives it in a nonlinear fashion.

- 2) Four parameters characterize a grounded structure: the grounding impedance, the density of grounds, the longitudinal resistance, and the length of the structure. Of these the most important and the most difficult to assess is the grounding impedance. Doubling the phase lag induced at the grounds will double the false anomaly, assuming all other parameters are held fixed. Changing the grounding density does not change the false anomaly very much if the density is high enough (greater than four grounds per 100 ft in the fence model). Reducing the grounding density causes a gradual reduction of the false anomaly. A high longitudinal resistance impedes the flow of current along the structure, and it appears that the false anomaly varies inversely with the longitudinal resistance. The effect of length must be evaluated in terms of individual geometries, although short structures generate anomalies which are limited in areal extent.
- 3) As is well known, close proximity of measurement electrodes and structural grounds must be avoided to minimize the potential drop along the structure. Generally speaking, an electrode arrangement which maximizes symmetry between the measurement array and the structure will minimize the contamination.
- 4) The earth resistivity affects the contamination quite strongly. A doubling of resistivity will double the false anomaly if all other parameters (including the grounding impedance) are held constant.
- 5) Currents flowing into the grounds of the structure are small. For the fence example, current magnitudes were a fraction of a microampere per ground. Changes in the apparent resistivity are not drastic, probably less than 10 percent under most survey conditions.

REFERENCES

- Carnahan, B., Luther, H. A., and Wilkes, J. O., 1969, *Applied numerical methods*. New York, John Wiley & Sons, Inc.
- Hallof, P. G., 1967, *Theoretical induced polarization and resistivity studies—scale model cases*. Don Mills, Ont.: McPhar Geophysics Ltd.
- Madden, T. R., and Cantwell, T., 1962, *Progress report on geomagnetic studies and electrical conductivity in the earth's crust and mantle*: Geophys. Lab., M.I.T.
- Tagg, G. F., 1964, *Earth resistances*. London, Pitman Publishing Corp.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720