GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: Sept. 25, 1968

Project Title: Electroseismic Determination of Soil & Rock Types

Project No.: A-1124

Project Director: Wayne K. Rivers, Jr.

Sponsor: U. S. Army Research Office

Effective . . . . October 1, 1968 . . . . Estimated to run until: September 30, 1969

Type Agreement: Grant No. DA-ARO-D-31-124-G-1060 . . . . Amount: $ 19,600*

Reports: Semiannual Progress Report - within 30 days after period ending March 31, 1969
Interim Technical Report - only if unusual results are obtained
Final Technical Report - within 30 days after grant termination
Final Fiscal Report - as soon as possible after all work completed
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*Cost sharing required in amount of $1,805 chargeable to E-200-402, making total available funds of $21,405.

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PROJECT TERMINATION

Date October 24, 1973

PROJECT TITLE: Electroseismic Determination of Soil and Rock Types

PROJECT NO: A-1124

PROJECT DIRECTOR: W. K. Rivers, Jr.

SPONSOR: U.S. Army Research Office—Durham

TERMINATION EFFECTIVE: Grant expired 7-31-72 (Final Report due).

CHARGES SHOULD CLEAR ACCOUNTING BY: All have cleared

GRANT CLOSEOUT ITEMS REMAINING: Final Fiscal Report

Final Report submitted

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PROGRESS REPORT

1. ARO-D PROPOSAL NUMBER: 7266-EN

2. PERIOD COVERED BY REPORT: 1 October 1968 through 31 March 1969

3. TITLE OF PROPOSAL: Electroseismic Determination of Soil and Rock Types

4. CONTRACT OR GRANT NUMBER: DA-ARO-D-31-124-G-1060

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Wayne K. Rivers

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO-D SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Arthur B. Abeling

Albert McSweeney

Wayne K. Rivers

CRDARD Form IP-129
16 Mar 67

BRIEF OUTLINE OF RESEARCH FINDINGS

The purpose of the investigation being conducted is to develop a technique to map the distribution of soil and rock types below the earth's surface by means of measurements made only over the surface. The measurements required are of the surface electrical potential distribution in the presence of local seismic shock waves propagating through the volume of interest and generated at the surface explosively.

In carrying out this investigation a thorough survey has been made of available data on the electrical properties of rocks and soils as a function of type and physical conditions. The electrical properties of interest are the conductivity and rate of change of conductivity with pressure. A moderately wide range of data are available although most of it has been obtained under static pressure conditions. In addition a tentative simplified model for shock wave propagation in the earth has been established for purposes of implementing the first surface potential calculations.

The required calculations will be based on the work of Stevenson,* who not only formulates the problem of calculating the surface potential field as a function of a known three-dimensional conductivity distribution beneath the surface but also prescribes the inversion of the calculation in which an unknown conductivity distribution can be calculated from a large number of surface potentials by a method of successive approximations. Professor Stevenson's formulation of the direct problem is being programmed for numerical solution. This program will be used with a wide variety of assumed volume conductivity distributions to investigate the detectability of underground features and distributions of conductivity. There are four distinct steps in the process of this theoretical phase of investigation which can be identified:

(1) Direct calculation of surface potentials from volume conductivity distributions.
(2) Inversion of 1.
(3) Direct perturbation of surface potentials resultive from seismic perturbation of conductivities.
(4) Inversion of 3.

It is planned that the results of 1 and 2 will be incorporated in a manuscript to be submitted for publication in September 1969. It is also anticipated that a substantial part of the required perturbation predictions of 3 and 4 will be completed to serve as a guide for selecting parameters of experiments to be designed and performed in future work.

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*Stevenson, A. F., "On the Theoretical Determination of Earth Resistance from Surface Potential Measurements," Physics, Vol. 5 (April, 1934).

A 1124

PROGRESS REPORT 2

1. ARO-D PROPOSAL NUMBER: 7266-EN

2. PERIOD COVERED BY REPORT: 1 April 1969 through 30 September 1969

3. TITLE OF PROPOSAL: Electroseismic Determination of Soil and Rock Types

4. CONTRACT OR GRANT NUMBER: DA-ARO-D-31-124-G-1060

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Wayne K. Rivers

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None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Arthur B. Abeling

Albert McSweeney

Wayne K. Rivers

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16 Mar 67

BRIEF OUTLINE OF RESEARCH FINDINGS

The purpose of the investigation being conducted is to develop a remote subsurface survey technique to map the distribution of soil and rock types below the earth's surface by means of measurements made only over the surface. The measurements required are of the surface electrical potential distribution in the presence of local seismic shock waves propagating throughout the volume of interest and generated at the surface explosively.

The technique being developed is a direct method of interpreting earth-resistivity data by numerical manipulation of field data. The development has been based on the equation of electrical conduction derived by Stevenson[1] and as extended in two doctorate studies by Vozoff[2] and Ness[3] and in additional work by Bukhari and Lennox[4]. A linear approximation is developed for the equation of conduction in a medium where the resistivity is an arbitrary function of x, y, and z. This is applied by assuming the earth to be subdivided into small, homogeneous blocks of arbitrary resistivity. Under this approximation, the surface electrical potential is just the sum of the effects of the individual blocks. The equations are linear, and the surface electrical potential data can be inverted to yield block resistivities. During the reporting period software has been developed for exploring the use of the above theory and determining its limitations. A description of the calculations used in the software follows.

A general physical situation to which Stevenson's potential equation applies is shown in Figure 1. The equation for the potential Φ_{rs} at a point

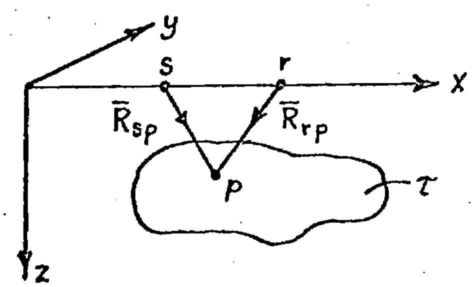

Figure 1.

r on the surface of a half-earth due to a source of current I_s located on the surface at point s, for the case of the half-earth of uniform conductivity σ_0, except for the volume τ is:

$$\Phi_{rs} = \frac{I_s}{2\pi\sigma_o R_{rs}} + \frac{1}{2\pi} \iiint \frac{\nabla\sigma_p \cdot \nabla\Phi_p}{\sigma_p R_{rp}} \, d\tau$$

$$= \Phi^o_{rs} + \Phi'_{rs} \qquad (1)$$

where Φ_p and σ_p are the potential and conductivity, respectively, at a point p in the volume τ, and Φ^o_{rs} and Φ'_{rs} are the primary and secondary potential, respectively.

The derivation of (1) requires the same conductivity at points r and s which can be satisfied by assuming a thin surface layer of uniform conductivity. The primary potential is the potential for a uniform half-space, while the secondary potential is due to the existence of the charge distributions whenever current passes through the region τ of nonuniform conductivity.

Vozoff points out that in a finite number of terms there is no exact solution to (1) and approximates σ_p under the integral sign by

$$\sigma_p \simeq \frac{I_s}{2\pi\sigma_o R_{sp}} , \qquad \text{yielding}$$

$$\Phi'_{rs} \simeq \frac{-I_s}{4\pi^2 \sigma_p} \iiint \frac{\nabla \ln \sigma_p \cdot \bar{R}_{sp}}{R_{rp} R^3_{sp}} \, d\tau$$

Three additional assumptions are required to arrive at a practical solution:
(1) The nonuniform subsurface region is replaced by a model subsurface array of small homogeneous blocks of given geometries but unknown conductivities embedded in a homogeneous medium. The blocks are of rectangular shape with surfaces parallel to the planes defined by the coordinate axes. Figure 2 shows a typical block.
(2) There is no interaction between blocks so that the effect of each block at any point of measurement on the surface combines linearly with the effect of other blocks.
(3) There exists on the surface of the earth a thin layer of conductivity.

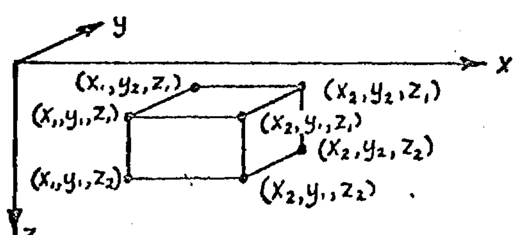

Figure 2.

For a single block of conductivity σ_i, we have now

$$\Phi'_{rs} \simeq \frac{-I_s \Delta \ln \sigma_p}{4\pi^2 \sigma_o} \iint \frac{\bar{n} \cdot \bar{R}_{sp}}{R_{rp} R_{sp}^3} \cdot dS \qquad (2)$$

where $\Delta \ln \sigma_p = \ln(\sigma_i/\sigma_p) = \ln(\rho_o/\rho_i)$, $\bar{n}$ represents the outward normal of each surface of the block in turn, and ρ denotes resistivity. The right-hand side of (2) can be replaced by the sum of six similar expressions for the six surfaces of a block, each expression consisting of a resistivity-contrast factor and a geometric factor.

Vozoff points out the behavior of the resistivity-contrast factor $\ln(\rho_o/\rho_i)$ is contrary to experience and suggests, based on laboratory data that it be replaced by f_i expressed as

$$f_i = 3.6 \frac{\rho_o - \rho_i}{\rho_o + 2\rho_i} \qquad (3)$$

Ness suggested averaging a similar expression to (2) with the source and receiver positions interchanged to obtain source-receiver symmetry in the geometric factors. This results in

$$g_{sri} = \frac{1}{4\pi} \iint \frac{R_{rp}^2 \, \bar{n} \cdot \bar{R}_{sp} + R_{sp}^2 \, \bar{n} \cdot \bar{R}_{rp}}{R_{rp}^3 \, R_{sp}^3} \qquad (4)$$

where g_{sri} is the modified geometric factor due to the ith block for the source at s and receiver at r.

For a subsurface made up of n blocks with resistivities $\rho_1, \rho_2, \cdots, \rho_n$, embedded in a half-space of resistivity ρ_o, we have

$$\Phi_{rs} = \Phi_{rs}^o - \frac{I_s \rho_o}{2\pi} \sum_{i=1}^{n} g_{sri} \, f_i \qquad (5)$$

and we will have one equation for each source-receiver configuration.

It is convenient to talk about the solution (5) in matrix notation. Consider that m measurements have been taken on the surface of the earth yielding m equations of the form (5). In matrix notation then

$$\bar{G}\bar{F} = \bar{\Psi} \qquad (6)$$

where $\bar{G}$ is an m x n matrix of the geometric factors g_{sri}, $\bar{F}$ is a column vector of n unknown resistivity-contrast factors and $\bar{\Psi}$ is a column vector of m potentials given by

$$\psi_t = \frac{2\pi}{I_s' \rho_o} (\Phi_t^o - \Phi_t) \tag{7}$$

where each value of t (= 1, 2, ..., m) represents a source-receiver configuration. The inverse problem or solution of (6) by least squares yields

$$\bar{F} = \bar{H}\,\bar{\Psi}$$

where $\bar{H} = (\bar{G}^T\,\bar{G})^{-1}\,\bar{G}^T$.

Once the geometry of the blocks is known and the source receiver-configuration of the electrodes is known, then the elements of the $\bar{G}$ and $\bar{H}$ matrices can be calculated and postmultiplication of $\bar{H}$ by the surface measurements $\bar{\Psi}$ yields the solution vector $\bar{F}$ and the unknown block resistivities.

Using the above described calculations, matrix coefficients have been obtained for three useful model geometries and investigation begun on the closure properties of these models. The numerical errors in the calculations are satisfactory when the deepest depth of the blocks is approximately equal to the largest spacing of the surface electrodes, and when the resistivities of the blocks are less than 25 times that of the background resistivity.

Surface electrode array geometries are being studied for both static (resistivity mapping) and dynamic (electroseismic) measurements. The static measurements require sampling the potential at a minimum of n points on the surface for characterization of n subsurface blocks, whereas the electroseismic measurements can be made with far fewer electrodes because of the time-modulation of the potentials. For example, for 128 subsurface blocks, one attractive static surface array samples the potential at 18 points and yields 153 source-receiver pairs. The dynamic measurements for this case require only 6 recording channels.

Preliminary calculations indicate that surface potential changes caused by seismic pressure become marginally small at a depth of about half that useful for static measurements in the models considered to date. Further work is planned to optimize surface array coordinates.

Future work planned includes exploring the relationship of magnitude of signals to typical instrumentation characteristics, both static and dynamic (e.g., noise levels, accuracy, bandwidth) so that the best choice of instrumentation can be made. Preliminary estimates of bandwidth requirements for instrumentation make laboratory experiments previously proposed inadvisable. However, preliminary estimates of signal characteristics indicated that full scale field experiments are advisable to verify and evaluate the technique. Therefore, work will begin on the design of an experiment to be performed in an area which has already been surveyed by logging.

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1. Stevenson, A. F. (1934): "On the Theoretical Determination of Earth Resistance from Surface Potential Measurements"; Physics, Vol. 5, p. 114-124.

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3. Ness, N. F. (1959): "Resistivity Interpretation in Geophysical Prospecting"; Ph.D. thesis, Massachusetts Institute of Technology, 193 pages.

4. Bukhari, S. A., and Lennox, D. H. (1966): "Geometric Coefficients for Use in Numerical Resistivity Analysis"; Research Council of Alberta, Bulletin 19.

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PROGRESS REPORT

1. ARO-D PROPOSAL NUMBER: 7266-EN

2. PERIOD COVERED BY REPORT: 1 October 1969 through 30 March 1970

3. TITLE OF PROPOSAL: Electroseismic Determination of Soil and Rock Types

4. CONTRACT OR GRANT NUMBER: DA-ARO-D-31-124-G-1060

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Wayne K. Rivers

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO-D SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

   None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

   A. B. Abeling

   C. H. Bonham

   W. K. Rivers

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16 Mar 67

BRIEF OUTLINE OF RESEARCH FINDINGS

The purpose of the investigation being conducted is to develop a remote subsurface survey technique to map the distribution of soil and rock types below the earth's surface by means of measurements made only over the surface. The measurements required are of the surface electrical potential distribution in the presence of local seismic shock waves propagating throughout the volume of interest and generated at the surface explosively.

The formalism outlined in the Semiannual Report dated 30 September 1969 has been used to compute the matrices required to calculate the resistivities of a set of subsurface volumes from potential measurements made at a number of designated surface points. Matrices for two specific choices of geometry have been studied, one with 128 subsurface blocks and 18 surface points, the other with 16 blocks and 8 surface electrodes. These cases were used to establish the influence of procedure and choice of parameters on the following factors:

(1) accuracy of numerical integration to obtain resistivity-to-surface potential coefficients

(2) accuracy of obtaining the inverse matrix

(3) effect of random instrument noise on accuracy of estimated resistivities as a function of depth

(4) ratio of perturbation of resistivities to corresponding perturbation of surface potential signals

In most of the above the less complex array of the two was used in order to minimize the cost.

In addition to the above, estimates have been made of the magnitudes of the sources of noise which seem likely, and a comparison of these levels made with the signals estimated from the perturbation study. From this comparison estimates are made of the maximum useful depth that seismic-resistivity-perturbation signals are likely to be observable. A brief summary of these results follows.

It has been established that numerical integration of the subsurface block surface integrals relating the resistivity of a block to a surface potential can be performed with accuracy better than 1% using a rectangular integration rule with each edge of a block being incremented in 10 parts, provided the radial distance between the surface point and the nearest point of the block is at least five increment units. The numerical precision (number of significant digits of the machine) required is about 2 greater than the desired accuracy of the result.

The accuracy of the elements of the matrix inverse ($\bar{H}$), which is used to obtain block resistivities from potential measurements, is such that about 5% error is estimating conductivities a factor of 10^5 away from the assumed background is incurred when the inverse matrix is calculated with a 9-digit machine. Thus there is a loss of about 4 digits in the matrix-inverse calculation for the smaller of the two arrays alone (16 blocks, 8 potential points). For the larger array the loss would be about six digits, and the use of double precision is indicated for most machines for this step.

The calculation of block resistivities from surface potentials using the $\bar{H}$ (inverse) matrix can be done realistically in single precision on most analytic machines, including the newer desk-calculator computer types, once the elements of the $\bar{H}$ matrix have been calculated. This conclusion about the needs for precision and the one of the paragraph above are in contradiction to previous claims [1], and the identification and correction of the difficulty is a significant contribution to the feasibility of electrical survey technology. The background and essential details of this step in the process are being described in a paper which is in its final stages of preparation. Its title is "Numerical Resistivity Analysis," by C. H. Bonham and A. B. Abeling.

The properties of the 16-block array were used to estimate the maximum useful depth for seismic resistivity perturbation. The results for one representative case of this system study are summarized in Table I. The depths attainable appear to be limited by the noise background created by spontaneous fluctuations of resistivity. Little seems to be known about this aspect of the problem and the estimates shown are not based on documentation at this time.

The depths resulting for the hypothetical case chosen here are discouragingly small and suggest that some care in refining experiment parameters is warranted before elaborate field experiments are attempted. Some comment is appropriate on the entries of Table I. The pressure law is inevitably limited to z^{-1}, but with the addition of loss in some subsurface materials. Thus the figure shown is perhaps somewhat optimistic. The value of the seismic impulse is difficult to increase with the use of more explosive because of nonlinear dissipative effects near the charge [7], so no help can be expected from brute force. The estimate of electroseismic coefficient is probably on the low side, so in some materials under certain moisture conditions a quite large increase in this figure may be seen.

Instrument noise is not considered to be a problem, but rather external sources are the important factor. Of the two external spontaneous fluctuations, the e.m.f. source can probably be made weaker than the resistivity fluctuations, so that the latter deserves immediate attention. Another effect not yet mentioned is the frequency-dependent damping caused by the conductive earth, which may produce a noticeable loss of the transient signal of interest, especially in highly conductive surface layer. In average cases this effect is tolerable for the depths of the order of 100 meters.

The goal described in the last progress report of having a completed experiment design has not been met, because the completion of the validation of the computer programs involved was more tedious than anticipated. At this point it seems marginal to expect a complete and workable experiment design for fielding within the current year. The crucial factor of spontaneous resistivity fluctuation noise will be investigated further to establish more clearly its bounds and its effect on the expected performance. Also, additional specific geologic situations will be examined to test the utility of perturbation survey. Complete documentation of the remaining work will be made by a technical report in which the software which represents a significant contribution can be appropriately published and by a paper describing the research essentials and referencing the rather important and tedious detailed results.

Table I. RESISTIVITY PERTURBATION ANALYSIS

Variable or Function	Value	Source
Seismic pressure, $p(z)$ z = depth in meters	$p(z) \simeq \frac{0.1}{z}$ kb	[2]
Electroseismic coeff. J $J = \frac{1}{R}\frac{dR}{dp}$	$J \simeq 10\ (\text{kb})^{-1}$	[3]
Resistivity-potential coupling, $\frac{R}{\varphi}\frac{d\varphi}{dR} = g_t$ ΔX = max. surface array diameter	$g_t = \frac{.03}{(z/\Delta X)^2}$	This study
$z_{max}/\Delta X$	$\frac{z_{max}}{\Delta X} = 1.0$	Assumed, to limit error due to size of g_t and area of array
Noise sources: Instrument	.01% of signal (A,B) 1.5μv	12-bit quantization Thermal noise
Atmospheric	$.5\mu v/m/Hz^{\frac{1}{2}}$	[4]
Conductivity Fluctuation Noise	≈.1% (A) .01% (B)	[5] [6]
Result: ΔX = (Case A) (Case B)	30 m 100 m	

REFERENCES

1. S. A. Bukhari and D. H. Lennox, "Geometric Coefficients for Use in Numerical Resistivity Analysis," Research Council of Alberta, Bulletin 19. (1966)

2. G. Morris, "Some Considerations of the Mechanism of the Generation of Seismic Waves by Explosives," Geophysics 15, 61 (1950)

3. W. F. Brace, A. S. Orange and T. R. Madden, "The Effect of Pressure on the Electrical Resistivity of Water-Saturated Crystalline Rocks," Journal of Geophysics Research 70, 5669 (1965)

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5. C. Ostrander and T. Long, Private Communication

6. E. L. Maxwell, Private Communication

7. J. Taylor, G. Morris and T. C. Richards, "The Effect of Velocity of Detonation on the Efficiency of Explosives Used in Seismic Prospecting," Geophysics 11,350 (1946)

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PROGRESS REPORT 5

1. ARO-D PROPOSAL NUMBER: 7266-EN

2. PERIOD COVERED BY REPORT: 1 October 1970 through 31 March 1971

3. TITLE OF PROPOSAL: Electroseismic Determination of Soil and Rock Types

4. CONTRACT OR GRANT NUMBER: DA-ARO-D-31-124-71-G25

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Leland Timothy Long

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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

William Free
Leland Timothy Long
Steven Gordy
Wayne K. Rivers

Mr. Wayne K. Rivers
Georgia Institute of Technology
Atlanta, Georgia 30332

7266-EN

BRIEF OUTLINE OF RESEARCH FINDINGS

The objective of the investigation being conducted is to field test the refined direct resistivity method developed previously and to evaluate the usefulness of seismically induced variations in resistivity. During the report period, emphasis was placed on developing instrumentation appropriate for the field operation.

Components completed to date include the following:

Cables, electrodes, and switching circuits for direct simultaneous recording of D.C. or A.C. potentials to be used respectively for determining resistivity and seismic perturbations of resistivity.

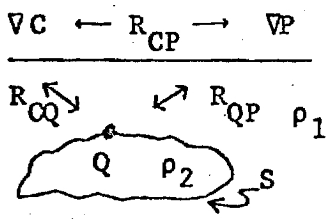
A.C. coupling and filtering preamplification circuit for seismic recording system to allow up to one full day's monitoring of electrical noise and correlations with seismic or other factors.

Weather and instrument noise problems in the high impedance preamplification circuit have prevented field testing the above to date. The multichannel recorder modification is in the design stage pending further testing of the preamplification circuit.

In addition to possibly generating a change in resistivity, a seismic wave within the earth may generate an electrical potential. This electrical potential manifests itself at the surface prior to the arrival of the seismic waves regardless of whether or not a D.C. current is introduced into the ground. Martner and Sparks (1959) designate this potential as the "electroseismic" effect and describe measurements relating it to the seismic disturbance at the bottom of the weathering layer. The electrical potential variation caused by the variation of earth resistivity by elastic deformation they designate as the "seismic-electric" effect. This investigation will be directed toward evaluating the latter. However, field methods will be designed to test for the existence of the former and mitigate its effect on the analysis of the changes in resistivity which are seismically induced.

An examination of some of the assumptions involved in the theory was carried out during the period covered by this report. The analysis revealed an alternate derivation of the equations for the geometric factors as given by Vozoff (1960) which were used as a base for the inversion technique developed in this investigation. A significant theoretical improvement developed in the alternate derivation is the elimination of the requirement for a continuous conductivity function. This results in a more realistic consideration of blocks with a constant value of conductivity and a rigorous derivation of the resistivity contrast factor which Vozoff (1960) assumed arbitrarily to satisfy reasonable limits as the resistivity contrasts increase. The alternate derivation as outlined below follows the presentation of Dieter et al. (1969) and is based on the solution to the boundary value problem.

The geometry of the general case requires a free surface on which is located a current source C and the potential probe P and a second surface S separating material of resistivity ρ_2 from material of resistivity ρ_1. Q is an arbitrary point on S.



The problem is to find the electrical potential $V = V_1$ in medium with resistivity ρ_1 and $V = V_2$ in medium with resistivity ρ_2. The boundary conditions V must satisfy are:

$$\frac{\partial V}{\partial Z} = 0, \; Z = 0 \tag{1}$$

$$\left.\frac{1}{\rho_1} \frac{\partial V_1}{\partial n}\right)_S = \left.\frac{1}{\rho_2} \frac{\partial V_2}{\partial n}\right)_S \tag{2}$$

$$\left.V_1\right)_S = \left.V_2\right)_S \tag{3}$$

These boundary conditions are equivalent to (1) no current leaves the ground; (2) electrical charges are conserved at the surface; and (3) the potnetial is continuous at the surface. In addition, in the close vicinity of C, the potential will approach the solution for a medium of uniform resistivity, namely,

$$V_1 = \frac{I\rho_1}{2\pi R_{cp}} \tag{4}$$

where

I = current

R_{cp} = distance CP

If V satisfies these boundary conditions and if the boundary conditions are sufficient, V will be unique. To find a solution at the surface Z = 0, divide the potential V_1 into the potential due to the source alone, V_1^o, and the secondary potential, V_1^s, such that:

$$V_1 = V_1^o + V_1^s \tag{5}$$

If V_1^s is written in the form

$$V_1^s(P) = \iint_S \frac{\sigma(Q)}{R_{QP}} ds \tag{6}$$

then V_1^s is a solution of Laplace's equation everywhere except at Q and is therefore a suitable function to use. V_1^o will have the form specified in condition (4).

In order to obtain a valid solution in the half-space, the boundary condition (1) at Z = 0 is satisfied by using the concept of images and extending the analysis over all space. The resulting expression for V_1^s is

$$V_1^s(P) = \iint_S \frac{\sigma(Q)}{R_{QP}} ds + \iint_{\bar{S}} \frac{\sigma(\bar{Q})}{R_{\bar{Q}P}} ds = \iint_S \sigma(Q)\left(\frac{1}{R_{QP}} + \frac{1}{R_{\bar{Q}P}}\right) ds \tag{7}$$

where $\bar{R}$, $\bar{S}$, and $\bar{Q}$ are obtained by replacing Z by -Z in R, S, and Q respectively, and $\sigma(Q) = \sigma(\bar{Q})$ by symmetry about $Z = 0$. The form of the equation suggests that $\sigma(Q)$ might be interpreted as a surface charge density function.

According to Gauss' law, the electric field intensity at a surface layer of charges suffers a discontinuity of the type

$$\bar{n} \cdot (\bar{E}_1 - \bar{E}_2) = 4\pi\sigma \tag{8}$$

where σ represents the charge density on S.

Since $E = -\nabla V$, Gauss' law can also be written

$$\left.\frac{\partial V_2}{\partial n}\right|_S - \left.\frac{\partial V}{\partial n}\right|_S = 4\pi\sigma \tag{9}$$

Therefore the continuity condition (2) requires that

$$\left.\frac{\partial V_1}{\partial n}\right|_S = 4\pi\sigma \frac{\rho_1}{\rho_2 - \rho_1} \tag{10}$$

or by substituting into this the expression for V_1, it is found that $\sigma(Q)$ must satisfy

$$\frac{4\pi\rho_1}{\rho_2 - \rho_1}\sigma(Q) = \frac{I\rho_1}{2\pi}\left.\frac{\partial}{\partial n}\frac{1}{R_{CQ}}\right|_S + \iint_S \sigma(Q)\frac{\partial}{\partial n}\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right) ds \tag{11}$$

(P on S)

The surface integral, however, is singular at Q = P. Therefore, to remove the singularity, write the integral as

$$\iint_{S'} \sigma(Q)\frac{\partial}{\partial n}\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right) ds' - 2\pi\sigma(Q) \tag{12}$$

where S' excludes the singular point at Q = P.

Therefore, when $\sigma(Q)$ satisfies

$$\frac{2\pi}{\lambda}\sigma = \frac{I\rho_1}{2\pi}\left(\frac{\partial}{\partial n}\ \frac{1}{R_{CQ}}\right)_S + \iint_{S'}\sigma\frac{\partial}{\partial n}\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right)ds' \qquad (13)$$

(P on S')

where $\lambda = \dfrac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$

The solution to the potential problem is

$$V_1 = \frac{I\rho_1}{2\pi R_{PC}} + \iint_S \sigma\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right)ds \qquad (14)$$

P on free surface

The remaining difficulties are associated with the solution of the integral equation for $\sigma(Q)$. Once this is found the solution for V_1 follows directly but this process is possible only for a few simple geometrics.

If the integral in the equation for $\sigma(Q)$ can be assumed significantly less than the first term, then an approximation to V_1 can be given as

$$V_1 = \frac{I\rho_1}{2\pi R_{CP}} + \frac{\lambda I\rho_1}{4\pi^2}\iint_S\left(\frac{\partial}{\partial n}\ \frac{1}{R_{CQ}}\right)\left(\frac{1}{R_{PQ}} + \frac{1}{\bar{R}_{QP}}\right)ds + \ldots \qquad (15)$$

or

$$V_1 = \frac{I\rho_1}{2\pi R_{CP}} + \frac{\lambda I\rho_1}{2\pi^2}\iint \frac{\bar{n}\cdot\bar{R}_{CQ}}{R_{CQ}^3 R_{QP}}\ ds \qquad (16)$$

at the surface. This assumption is equivalent to neglecting the effects of curvature on surface charge distributions or the interaction of neighboring charge distributions.

A direct comparison with the results derived by Vozoff (1960) show that the resistivity contrast factor he assumed to be

$$3.6(\rho_1 - \rho_2)/(\rho_1 + 2\rho_2) \qquad (17)$$

can now be derived and is

$$2(\rho_1 - \rho_2)/(\rho_1 + \rho_2) \quad . \qquad (18)$$

References

Martner, S. T. and N. R. Sparks, "The Electroseismic Effect," Geophysics, Vol. XXIV, No. 2, pp. 297-308, 1959.

Dieter, K., N. R. Paterson, and F. S. Grant, "IP and Resistivity Type Curves for Three Dimensional Bodies," Geophysics, Vol. XXXIV, No. 4, pp. 615-632, 1969.

Vozoff, K., "Numerical Resistivity Interpretation: General Inhomogeneity," Geophysics, Vol. XXV, No. 6, pp. 1181-1194, 1960.

PROGRESS REPORT 6

1. ARO-D PROPOSAL NUMBER: 7266-EN

2. PERIOD COVERED BY REPORT: 1 April 1971 through 30 September 1971

3. TITLE OF PROPOSAL: ELECTROSEISMIC DETERMINATION OF SOIL AND ROCK TYPES

4. CONTRACT OR GRANT NUMBER: DA-ARO-D-31-124-71-G25

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Wayne Rivers

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO-D SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Leland Timothy Long
Wayne Rivers
John Capps

Mr. Wayne K. Rivers
Georgia Institute of Technology
Atlanta, Georgia 30332

7266-EN

BRIEF OUTLINE OF RESEARCH FINDINGS

Georgia Tech letter of 26 August 1971, which requested an extension of time on the subject grant, contained a report of activity and findings under the grant up to 20 August 1971. Since that date, additional data have been taken which establish that:

1. Electric waveforms are similar to seismic signatures recorded at the same location for explosive charges of the order of 1# of Dupont Nitromon S at ranges from 250 to 350 feet;

2. For such explosives the frequency range of exciting waves is well placed in the band of the electric amplifier and the signatures are of sufficient magnitude for detailed analysis and comparison;

3. For repeated shots in holes near each other, the reproducibility of electric signatures appears to be good; and

4. The electric signatures observed are from bulk electroseismic effects, rather than mechanical effects at the electrodes.

On August 14, 1971, these results were discussed with Dr. Finn E. Bronner of ARO-D. No detailed analysis of the signatures collected to date has been attempted.

Signature data will be obtained and analyzed in future excursions to the previously used field site near McIntyre, Georgia, to explore the following parametric effects in detail:

(1) Correlation of electric signature features with 3-component seismic signature features,

(2) Distance of seismic source from electric array,

(3) Depth of placement of charge,

(4) Angle of arrival of seismic wave with respect to electric array axis,

(5) Size of electric array, and

(6) Subsurface structure.

This sequence of experimental observations will provide the remaining data needed to evaluate the feasibility of using this electroseismic technique for prospecting.

A-1124-002

ENGINEERING EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

14 April 1972 7

Dr. Finn Bronner
Army Research Office-Durham
Box CM, College Station
Durham, North Carolina 27706

Subject: Contract DA-ARO-D-31-124-71-G25 "Electroseismic Soil and Rock Mapping"

Dear Dr. Bronner:

This letter reports activities under the subject contract for the period 1 October 1971 through 31 March 1972 and the status of the work at the end of that period. A review of the data obtained indicates that adequate experimental data are on hand to allow good characterization of the electroseismic technique being explored. However, desired and planned analysis of the data is not complete and documentation of the instrumentation and results remains to be done.

In Table I the history of experiments is summarized; the data were obtained jointly by Dr. L. T. Long and W. Rivers. Most of the significant good quality data were obtained in the same location, where the strata are described approximately by 3' clay-sand mixture over 10' stiff clay sand over 10' clean loose sand over 2+' kaolin over sand.

The more interesting of the results are illustrated by the attached reproduction of seismic and electric signals, which indicate the relative response of the electric signal to the seismic components.

Only a few of the records have been digitized and processed to date. One set has been Fourier transformed, and the vertical seismic and electric spectra compared. The electric spectra contain more high frequency energy, and the seismic more low frequency energy. The relationship suggests that the electric signal may be proportional to the derivative of the vertical seismic velocity. Comparison of the electric spectra with spectra of other seismic components has not been made. In reference to the attached signatures, it is not yet known if the apparent 90 degree phase relationship of certain parts of the electric and seismic waves is real or an artifact of the instrumentation. Careful gain and phase measurements of the amplifiers is one of the important remaining items to be done in completion of the current program.

These tasks remain to be done to complete the planned program and are considered essential to validate the results to be reported.

1. Measurements in detail of the relative gain and phase transfer functions of the seismic and electric amplifiers.

2. Documentation of the instrumentation used.

3. Digitization of the remaining records.

4. Analysis of the records appropriate to the parametric study being made.

5. Formal preparation of a report of the results of the experiments.

It is planned and believed practical to complete these tasks in the next quarter.

The funds remaining under the contract as of 1 April 1972 were in the amount of $12.87. No increase of funding is requested for the completion of the work.

If you have any questions concerning the above results please call me or Dr. Tim Long. The telephone numbers are (404) 894-3501 or 894-3631 respectively.

Yours very truly,

Wayne Rivers
Principal Research Physicist

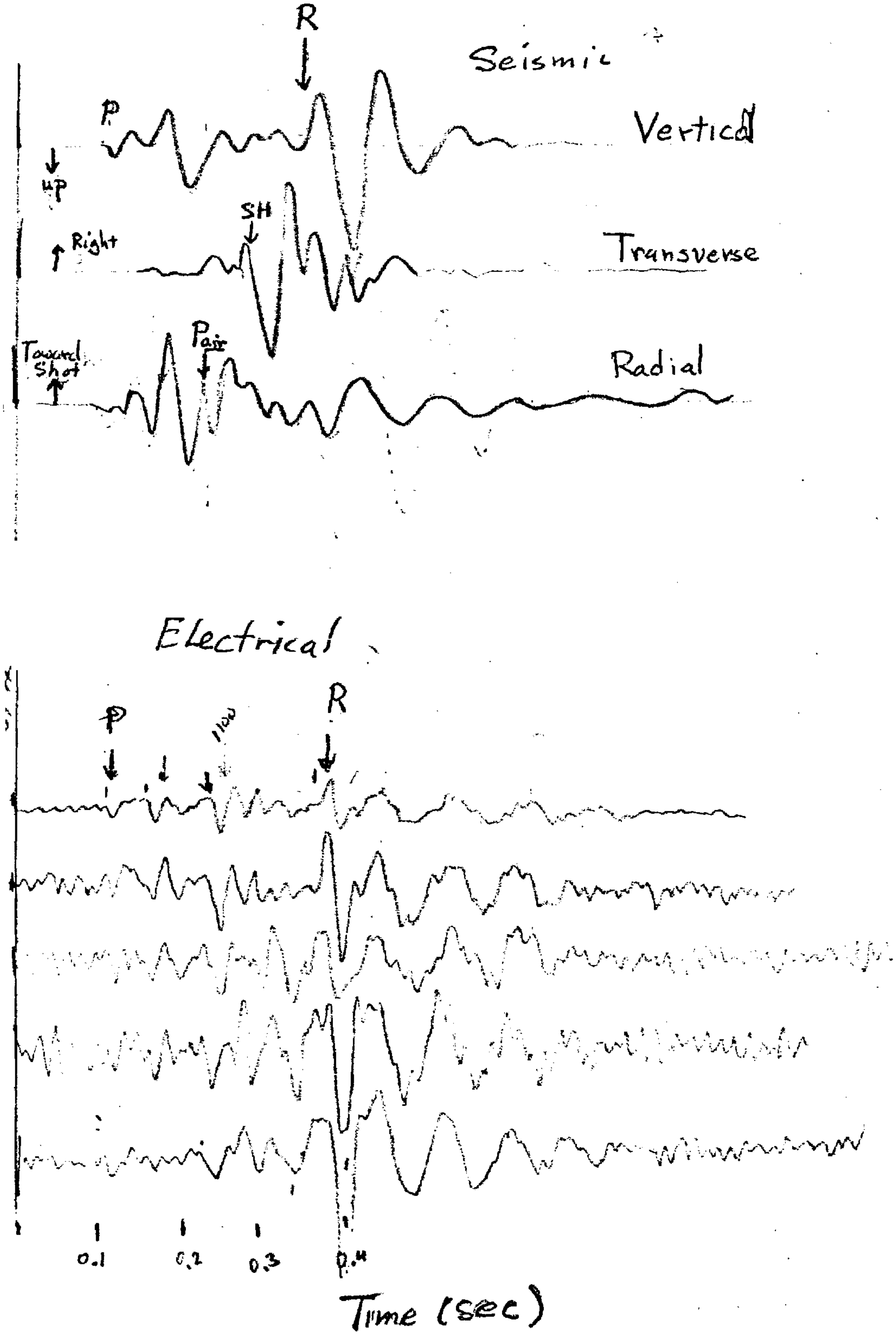
Approved:

J. W. Dees, Chief
Special Techniques Division

TABLE I. Summary of Electroseismic Experiments

Date	Location	Activity	Results
	Seismic Vault	Attempted correlation with natural seismic activity.	Excessive power line interference. Indicated need for amplifier redesign.
	Allatoona	Electrical survey;	
19 Jun 71	Allatoona	Rock drops;	Weak response in clay/loose rock
21 Jun 71	Allatoona	Tests of instrumentation	Strong response to seismic energy in water-saturated sandy mud.
26 Jul 71	Allatoona		
5 Aug 71	Englehard Clay Mine	Electrical survey. 1st explosive shot - 250'	Excessive atmospheric noise. Indicated need for noise cancellation.
13 Sep 71	Englehard Clay Mine	3 shots - 250' - 300' - 350'	Test of noise cancellation scheme.
14 Sep 71	GIT campus	Demonstration	Very weak response to rock drops.
28 Dec 71	Englehard Clay Mine	5 shots - 250' Array size variation	Electroseismic response maximum for electrode spacing near 30', less for larger and smaller spacings.
7 Jan 72	Englehard Clay Mine	6 shots - 250' Correlation with seismic components	Strong coupling to Rayleigh wave weak coupling to P and shear.
28 Feb 72	Englehard Clay Mine	6 shots - 250' Variation of azimuth angle Comparison of topographical effect Variation of shot depth (5',20',40')	Coupling stronger off end of array. Substantial reduction when shelf between shot and array. Deeper shot below water table strongly coupled.

Jan 7, 1972



All shots
2 lb at 5ft depth
275ft from array

PROGRESS REPORT

1. ARO-D PROPOSAL NUMBER: 7266-EN

2. PERIOD COVERED BY REPORT: 1 April 1972 through 31 October 1972

3. TITLE OF PROPOSAL: Electroseismic Determination of Soil and Rock Types

4. CONTRACT OR GRANT NUMBER: DA-ARO-D-31-124-G-1060

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: W. K. Rivers

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO-D SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

L. T. Long

Mr. Wayne K. Rivers
Georgia Institute of Technology
Atlanta, Georgia 30332

7266-EN

Preliminary examination of the data has lead to the interpretation that the electrical ignatures are caused be changes in subsurface resistivity produced by shear strain in he subsurface material. This interpretation is drawn from correlations of electric nd seismic signatures and from the difference in response obtained from different oil types. A striking form of signature was obtained over a saturated clay mud, in hich the electric signature resulted from resistivity change induced by the seismic ave energy (distinguised from the linear amplitude effects in dry material).

At this time, the formal analyses of the data are nearly complete, and all of the lectric and seismic signatures have been digitized and instrumental effect corrections ave been incorporated into the data files. Spectral analyses have been made, an ross correlation estimates illustrating the relation of electric signatures to she rain will be made. The aggregate results and the background for the interpretation ill be prepared in the form of a paper by L. T. Long and W. Rivers for submission r publication about 31 January 1973. Preliminary results were presented at the eview of the Military Theme: "Military Geographic Analyses" on 31 October 1972.

The data obtained in the above described experiments suggest one uncertainty out the proper interpretation of the results and one potential application. The uncerinty in interpretation concerns whether the seismic-induced resistivity changes cur in bulk material or at interfaces between strata. The importance of resolving is ambiguity is evident in its impact on the proper geophysical interpretation of ismic-electric observations.. If the shear-strain relation between seismic waves d electrical resistance proves valid, then its application to the measurement of echanical shear properties of subsurface media may be practical. The further ploration of both of these questions is recommended.

FINAL REPORT

PROJECT NO. A-1124

ELECTROSEISMIC DETERMINATION OF SOIL AND ROCK TYPES

By
Leland Timothy Long, and Wayne K. Rivers

U. S. ARMY RESEARCH OFFICE-DURHAM

DA-ARO-D-31-124-G-1060

September 1973

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

ELECTROSEISMIC DETERMINATION OF SOIL AND ROCK TYPES

FINAL REPORT

LELAND TIMOTHY LONG

WAYNE K. RIVERS

SEPTEMBER, 1973

U. S. ARMY RESEARCH OFFICE-DURHAM

DA-ARO-D-31-124-G-1060

GEORGIA INSTITUTE OF TECHNOLOGY

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

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INTRODUCTION

Blau and Statham (1936) reported detecting a modulation of an electric current in the earth surface during the passage of a seismic wave. This modulation was attributed (Thompson, 1939) to a change in the conductivity of the earth produced by the seismic waves. The object of work under Grant number DA-ARO-D-31-124-71-G25 "Electroseismic Determination of Soil and Rock Types" has been to investigate theoretically and with field measurements this seismic-induced perturbation of the conductivity and the resulting modulation of currents in the ground. We have designated the total net effect simply the "electroseismic effect" in order to avoid confusion with definitions which describe specific generic relations (e.g., piezoelectric, electroseismic "J",etc.). The investigation was carried out in two distinct parts. The first was a theoretical analyses of a technique to interpret the voltage perturbation in terms of conductivity changes. The second was a field measurement of the "electroseismic" effects.

In retrospect the study encompassed only two aspects of a very large and potentially important line of research. Following the development of a limited inversion technique during the first two years of the research program, Parker (1970) described some significant advances in the understanding of the generalized inversion of observed data which render the inversion technique developed here and the software implementing it effectively obsolete. The inversion technique developed on this program is now seen as only one of many preliminary attempts at numerical inversion of observed data. Nevertheless, the theoretical development is included in this report since it does contain some important innovations. Many theoretical aspects of the analysis of electrical potentials in the earth as well as the many possible mechanisms for the generation of electric potentials were not considered.

The field program was based on measurements in the Wenner configuration and, unfortunately, only one sub-surface type was well documented. Multiple-trace electrical and seismic measurements or measurements utilizing other types of arrays and measurements at depth would have been most helpful in a final interpretation. The field measurements do confirm the feasibility of using the "Electroseismic" phenomenon in an exploration program or in currently unperceived applications.

PART I, A DIRECT NUMERICAL INVERSION TECHNIQUE FOR RESISTIVITY ANALYSIS.

Introduction

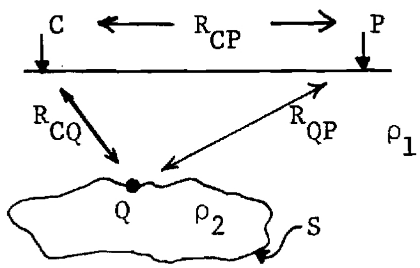
The direct numerical inversion of field data consisting of surface potentials can in some cases simplify the solution for the resistivity of subsurface materials. Part I of this research project was concerned with the development and refinement of a direct numerical inversion technique which could be used both for the interpretation of resistivities and for the interpretation of seismic perturbation of the resistivity.

Stevenson (1934) derived the equations for electrical conduction in geological subsurfaces characterized by a continuous resistivity function. Vozoff (1956) and Ness (1959) expanded the perspective on Stevenson's work to develop the technique for manipulating surface measurements to obtain resistivity as a function of subsurface coordinates. Vozoff (1960) performed a linearization which results in formulation of the equations into a matrix solution. For interpretation of the field data, the subsurface was broken into homogeneous blocks of arbitrary resistivity embedded in a constant resistivity material. Under this approximation, the surface electrical potential becomes the sum of the effects of the individual blocks. The equations are linear, and the surface potential data can be inverted to yield block resistivities.

A difficulty in the theory as applied to blocks of constant finite resistivity pointed out by Stevenson (1934) was that the method used may cease to be valid at a discontinuity, even though a discontinuity might, in principle, be treated as a limiting case. The exact solution must satisfy the boundary conditions at all discontinuities including the ground surface. The number of models which can be used for making comparison interpretations is severely limited by mathematical considerations since for each a coordinate system must be found in which the boundaries are level surfaces and Laplace's equation separates (Grant and West, 1965). The problem then reduces to finding conditions under which these restrictions can be relaxed. The solution method presented below follows the analysis of Dieter, et al (1969). The results for the first order approximation are similar to the formulation presented by Vozoff (1960) and hence his linearization remains valid with minor modifications.

Mathematical Model

The geometry of the general case requires a free surface on which is located a current source C and the potential probe P and a second surface S separating material of resistivity ρ_2 from material of resistivity ρ_1. Q is an arbitrary point on S.



The problem is to find the electrical potential $V = V_1$ in the medium with resistivity ρ_1 and $V = V_2$ in the medium with resistivity ρ_2. The boundary conditions V must satisfy are:

$$\frac{\partial V}{\partial Z} = 0, \; Z = 0 \tag{1}$$

$$\frac{1}{\rho_1} \left. \frac{\partial V_1}{\partial n} \right|_S = \frac{1}{\rho_2} \left. \frac{\partial V_2}{\partial n} \right|_S \tag{2}$$

$$\left. V_1 \right|_S = \left. V_2 \right|_S \tag{3}$$

These boundary conditions are equivalent to (1) no current leaves the ground; (2) electrical charges are conserved at the surface; and (3) the potential is continuous at the surface. In addition, because of (3), in the close vicinity of C the potential will approach the solution for a medium of uniform resistivity, namely,

$$V_1 = \frac{I\rho_1}{2\pi \, R_{cp}} \tag{4}$$

where

I = current

R_{cp} = distance CP

If V satisfies these boundary conditions and if the boundary conditions are sufficient, V will be unique. To find a solution at the surface Z = 0, separate the potential V_1 into the potential due to the source alone, V_1^o , and the secondary potential, V_1^s, such that:

$$V_1 = V_1^o + V_1^s \tag{5}$$

If V_1^s is written in the form

$$V_1^s(P) = \iint_S \frac{\sigma(Q)}{R_{QP}} ds \qquad (6)$$

then V_1^s is a solution of Laplace's equation everywhere except at Q and is therefore a suitable function to use. V_1^o will have the form specified in condition (4).

In order to obtain a valid solution in the half-space, the boundary condition (1) at Z = 0 is satisfied by using the concept of images and extending the analysis over all space. The resulting expression for V_1^s is

$$V_1^s(P) = \iint_S \frac{\sigma(Q)}{R_{QP}} ds + \iint_{\bar{S}} \frac{\sigma(\bar{Q})}{\bar{R}_{\bar{Q}P}} ds = \iint_S \sigma(Q) \left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{\bar{Q}P}} \right) ds \qquad (7)$$

where $\bar{R}$, $\bar{S}$, and $\bar{Q}$ are obtained by replacing Z by -Z in R, S, and Q, respectively, and $\sigma(Q) = \sigma(\bar{Q})$, thus producing symmetry about Z = 0. The form of the equation suggests that $\sigma(Q)$ might be interpreted as a surface charge density function.

According to Gauss' law, the electric field intensity at a surface layer of charges suffers a discontinuity of the type

$$\vec{n} \cdot (\vec{E}_1 - \vec{E}_2) = 4\pi\sigma, \qquad (8)$$

where σ represents the charge density on S.

Since $\vec{E} = - \vec{\nabla}V$, Gauss' law can also be written

$$\left.\frac{\partial V_2}{\partial n}\right|_S - \left.\frac{\partial V}{\partial n}\right|_S = 4\pi\sigma \qquad (9)$$

Therefore the continuity condition (2) requires that

$$\left.\frac{\partial V_1}{\partial n}\right|_S = 4\pi\sigma \frac{\rho_1}{\rho_2 - \rho_1} , \tag{10}$$

or by substituting into this the expression for V_1, it is found that $\sigma(Q)$ must satisfy

$$\frac{4\pi\rho_1}{\rho_2-\rho_1}\sigma(Q) = \frac{I\rho_1}{2\pi}\left.\frac{\partial}{\partial n}\frac{1}{R_{CQ}}\right|_S + \iint_S \sigma(Q)\frac{\partial}{\partial n}\left(\frac{1}{R_{QP}} + \frac{1}{R_{QP}}\right) ds \tag{11}$$

(P on S)

The surface integral, however, is singular at Q = P. Therefore, to remove the singularity, replace the integral with

$$\iint_{S'} \sigma(Q)\frac{\partial}{\partial n}\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right) ds' - 2\pi\,\sigma(Q) , \tag{12}$$

in which S' excludes the singular point at Q = P.

Therefore, when σ (Q) satisfies

$$\frac{2\pi}{\lambda}\sigma = \frac{I\rho_1}{2\pi}\left(\frac{\partial}{\partial n}\frac{1}{R_{CQ}}\right)_S + \iint_{S'}\sigma\frac{\partial}{\partial n}\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right) ds' , \tag{13}$$

(P on S')

where $\lambda = \dfrac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$,

The solution to the potential problem is

$$V_1 = \frac{I\rho_1}{2\pi R_{PC}} + \iint_S \sigma\left(\frac{1}{R_{QP}} + \frac{1}{\bar{R}_{QP}}\right) ds \tag{14}$$

(P on S')

The difficulties encountered in applying these equations to physical examples are primarily associated with the solution of the integral equation for $\sigma(Q)$. Once this is found the solution for V_1 follows directly, but a closed solution is possible only for a few simple geometries.

If the integral in the equation for $\sigma(Q)$ can be assumed to be significantly less than the first term, then an approximation to V_1 can be given as

$$V_1 = \frac{I\rho_1}{2\pi R_{CP}} + \frac{\lambda I \rho_1}{4\pi^2} \iint_S \left(\frac{\partial}{\partial n}\frac{1}{R_{CQ}}\right) \left(\frac{1}{R_{PQ}} + \frac{1}{\bar{R}_{QP}}\right) ds + \ldots \tag{15}$$

or

$$V_1 = \frac{I\rho_1}{2\pi R_{CP}} + \frac{\lambda I \rho_1}{2\pi^2} \iint \frac{\bar{n} \cdot \bar{R}_{CQ}}{R_{CQ}^3 R_{QP}} ds \tag{16}$$

at the surface. This assumption is equivalent to neglecting the effects of curvature on surface charge distributions, or neglecting the interaction of neighboring charge distributions.

A direct comparison with the results derived by Vozoff (1960) shows that the resistivity contrast factor he assumed to be

$$3.6(\rho_1 - \rho_2)/(\rho_1 + 2\rho_2) \tag{17}$$

can be derived and is

$$2(\rho_1 - \rho_2)/(\rho_1 + \rho_2) \tag{18}$$

Matrix Solution

For use in numerical calculation, the right hand side of equation (16) can be replaced by the sum of six similar integrals over the six surfaces of each block. The expression for V will then consist of a resistivity-contrast factor λ and a geometric factor computed from the sum of the six integral expressions for the six surfaces of the block.

For a subsurface made up of n blocks with resistivities ρ_i embedded in a half-space of resistivity ρ_o we have

$$V_1 = V_o + \frac{I\rho_o}{2\pi} \sum_{i=1}^{n} G_{cpi} \lambda_i,$$

in which

$$\lambda_i = 2 (\rho_o - \rho_i)/(\rho_o + \rho_i) , \qquad (19)$$

and $$G_{cpi} = \frac{1}{\pi} \iint \frac{\vec{n} \cdot \vec{R}_{cQ}}{R^3_{CQ} R_{QP}}$$

The integral in G_{cpi} is over the surface of the ith block. If m measurements have been taken on the surface of the earth, W_i, i=1,...m, one from each of m (m>n) source-receiver configurations, then one can form m equations of the form:

$$W_j = \sum_{i=1}^{n} G_{ji} \lambda_i , \qquad j = 1,m \qquad (20)$$

in which

G_{ji} is a m x n matrix of the geometric factors G_{cpi},

λ_i are the n resistivity contrasts factors, and

$W_j = \frac{2\pi}{I\rho_o} (V_1 - V_o)_j$ is the measured deviation from the homogeneous case of the trans-resistance between a current source terminal and a receiver terminal.

The solution of equation 20 for the λ_i by least squares (Rust, 1966) yields:

$$\lambda_i = H_{ij} W_j \qquad (21)$$

where the operator matrix H_{ij} is the generalized inverse of G_{ji} given by (Rust, 1966):

$$H_{ij} = (G^T G)^{-1} G^T \qquad (22)$$

Once the geometry of the subsurface blocks and the source-receiver configuration of the electrodes are chosen, then the elements of the G and H matrixes can be calculated. Post multiplication of H by the surface measurements W yields the solution vector λ and the unknown block resistivities or perturbations in the resistivities.

Computation

The computer program (Appendix I) written to calculate the elements of the G and H matrixes was based on the original formulation of Stevenson (1934), Ness (1959), Vozoff (1956) and Bukhari and Lennox (1966). The derivation presented above results in equations which would require only minor modifications in the computer program (see equations 17 and 18). However, the program was never revised because the block geometry chosen generated ill-conditioned matrixes. Correction of this default requires a reformulation of the problem (see following section).

The model programmed for this study consisted of sixteen subsurface blocks, four layers of four blocks each. Eight probes located on a spiral around the center of the blocks were used for the surface measurements. As Bukhari and Lennox (1966) pointed out, the resolution of the model is greatly influenced by the nature of the matrix of geometric factors. They attributed poor resolution to ill-conditioned matrixes. In ill-conditioned matrixes, a large variation in the resistivity of the deeper blocks generate nearly insignificant changes in the potentials at the surface. An additional problem is that the probe locations are required to be linearly independent and that at least sixteen independent equations to solve for the resistivities are required.

Of practical consideration is the variability of soil resistivities, particularly near the surface or probe locations. In practice the variation can be greater than 50 percent, and this will violate basic assumptions in the theory. A field test, which eventually led to a revision of the theory, was singular in the sense that the inversion was unstable and no reliable answers were obtained. The singularity was probably caused by variations in surface resistivity.

Discussion and Recommendations

In the common Wenner or Schlumberger analysis of the depth variation of resistivity using surface potentials, only three to five depth or resistivity parameters can be determined in practice even with the best of data. The inherent nature of the potential data is to lose resolution with increasing depth. In addition, resistivity is perhaps the most widely varying and irregular of the physical constants. Consequently no numerical inversion scheme can be entirely successful unless it can utilize the error distribution in the data to compute the maximum allowable number of independent components (with confidence limits) in the model.

The indirect approach to analysis of resistivity data after Wenner (1915) or Schlumberger (1920) in which observed data are compared to pre-computed curves based on stratified resistivity distribution is the most common applied solution technique, perhaps because it allows flexibility in the interpretation of questionable data and in the choice of the model parameters. Pekeris (1940) improved on the indirect approach by systemizing the analysis and developing an iterative technique for the direct computation of layer parameters successively with increased depth. Vozoff (1958) further automated the numerical resistivity analysis for depth-varying resistivities by linearizing the equations for flat layers and utilizing a successive approximation to search for the "best" fitting model for the data. Vozoff (1958) was also able to compute confidence levels for the solutions. Madden (1971) pointed out the inadequacies of one dimensional variations in resistivity, particularly in considering the resolving capabilities for resistivity zones in the earth's crust.

Computations involving two or three dimensions are considerably more complex. Vozoff (1960) using the technique of Stevenson (1934) and Ness (1959) showed computation for the potentials to be expected from rectangular-shaped bodies in the subsurface. Dieter, et al (1969) utilized an exact solution for an elliptical body to generate theoretical potential curves.

Ness (1959) attempted the inversion of three dimensional resistivity data by linearizing the equations for rectangular elements. This research has shown that the theoretical development of potential equations in Dieter , et al (1969) can be similarly linearized and thus some of the ambiguities relating to choice of contrast factors and evaluation of boundary conditions in the theory presented by Ness (1959) can be removed.

Some improvement in the stability of the inversion technique could be attained directly if the geometry of the subsurface blocks were changed to give each element equal and independent influence in the observed data. Also some consideration would have to be given to the error distribution on the data. However, the preferred and recommended changes would be to reformulate the problem in the form of the general solution of inverse problems outlined by Parker (1970) and originally presented by Backus and Gilbert (1967, 1968, 1970).

PART II, FIELD MEASUREMENTS OF THE ELECTROSEISMIC RESPONSE

Introduction

The most highly variable of all the physical properties of minerals, rocks, and soils is their ability to conduct electricity. In determining the conductivity of most rocks and soils, the effect of chemical composition of the minerals is of small importance in relation to the effects of other factors such as porosity, moisture content, and fracturing. In addition to simple conductivity, more complicated electrical effects which encompass a very wide range of electrochemical phenomena are observed. These include potentials at interfaces between minerals or electrolytes, potentials caused by gradients in the concentration of certain solutes, and potentials caused by motion of fluid in permeable materials. By far the most common determining factor in the electrical properties of all rocks and sediments in place is the conductivity of the electrolyte which permeates the rock. Relations between resistivity and the porosity, electrolyte saturation, and other observable attributes of sediments have been studied extensively because of wide spread use of electrical well logging methods in the oil industry.

The more specific relation between resistivity and stress which is the object of this research, however, is complicated by the many possible effects of porosity and electrolyte properties. In general, laboratory studies (Brace and Orange, 1968a, 1968b, Wyble, 1958, Glanville 1959) show the greatest variation in resistivity with stress change at low pressures and near the fracture stress. These two stress regions are the most susceptible to significant pressure variation relations with the electrolyte saturation and pore pressure. In some cases a very significant variation in resistivity with stress occurs in those regions.

In any measurement of the stress dependencies of resistivity in the field, the causative factors can not easily be separated. The net effect or change in apparent resistivity induced by seismic excitation for purposes of this project has been designated the "Electroseismic response". Hopefully this will avoid confusion with definitions which describe specific generic effects such as piezoelectric, electroseismic "J" etc.

For large underground nuclear tests a low-frequency electrical transient has been observed at the instant of detonation (Zablocki, 1966). In the vicinity of the shot chamber the transients were so large that quantitative measurement of resistivity changes would have been extremely difficult. The source of potential, however, was predominantly magnetohydrodynamic in origin and similar effects have not been observed with the small chemical explosives used in this study. The generation of an electrical signal was observed (Martner and Sparks, 1959) at the instant a seismic wave intersected the base of the weathered layer. However, there exists ambiguity as to whether the electric signal was derived from a change in resistivity near the boundary and subsequent disturbance of existing potentials, or from some boundary-dependent mechanism which generates new potentials.

Theory of Measurement

For the field measurements of this research, a Wenner array was adopted and the changes in the electric potentials during passage of seismic waves were monitored across the inner two electrodes. The voltage was maintained constant through the outer two electrodes. The voltage versus distance relation for a single electrode at the surface of a horizontally layered medium can be expressed in the general form (Grant and West, 1969) as

$$V(r) = \frac{I \rho_1}{2\pi r} G(r;k) \tag{1}$$

where I = current

ρ_1 = surface resistivity

r = radial distance from electrode

k = function of the resistivities

and $G(r;K)$ = function dependent on layering.

During the passage of a seismic wave, changes in the resistivity of any layer will cause $V(r)$, I, and $G(r;k)$ to become functions of time. However, since $V(r)$ was maintained constant at the electrode ($r = r_o$) the current can be evaluated from:

$$V(r_o) = V_o = \frac{I(t)\ \rho_1(t)}{2\pi\ r_o} G(r_o;k(t)) \tag{2}$$

Hence,

$$I(t) = \frac{V_o \quad 2\pi r_o}{\rho_1(t)\ G(r_o,k(t))} \tag{3}$$

and

$$V(r,t) = \frac{V_o\ r_o\ G(r;k(t))}{r \quad G(r_o;k(t))} \tag{4}$$

In equation (4) the regulated voltage V_o and the effective electrode radius r_o are measurable quantities. The resistivity layering function G(r;k) can be computed for the static condition so long as the resistivity versus depth relation is known. The resistivity versus depth relation can generally be obtained from either a down-hole resistivity survey or a Wenner depth sounding. The voltage across the inner two electrodes of the Wenner array with electrode spacing "a" can be computed from equation (4). This voltage $\Delta V(t)$, given by

$$\Delta V(t) = \frac{V_o r_o}{aG(r_o,k(t))} \left[2G(a;k(t)) - G(2a;k(t))\right], \qquad (5)$$

is the total voltage difference between the inner electrodes and includes a dc component which is considerably larger than the seismically induced voltage perturbations. However, for a transient seismic excitation the resistivity perturbations are primarily dependent on the ac voltage components. The dependence of the voltage, V(t), on resistivity is governed by the functions G(a,k(t)) and G(2a,k(t)). Although these functions can, in general, be computed they do not allow direct solution for the changes in resistivity in a general layered medium. A solution, however, can be obtained by expanding the voltage expression (equation (5)) according to Taylor's expansion. Hence

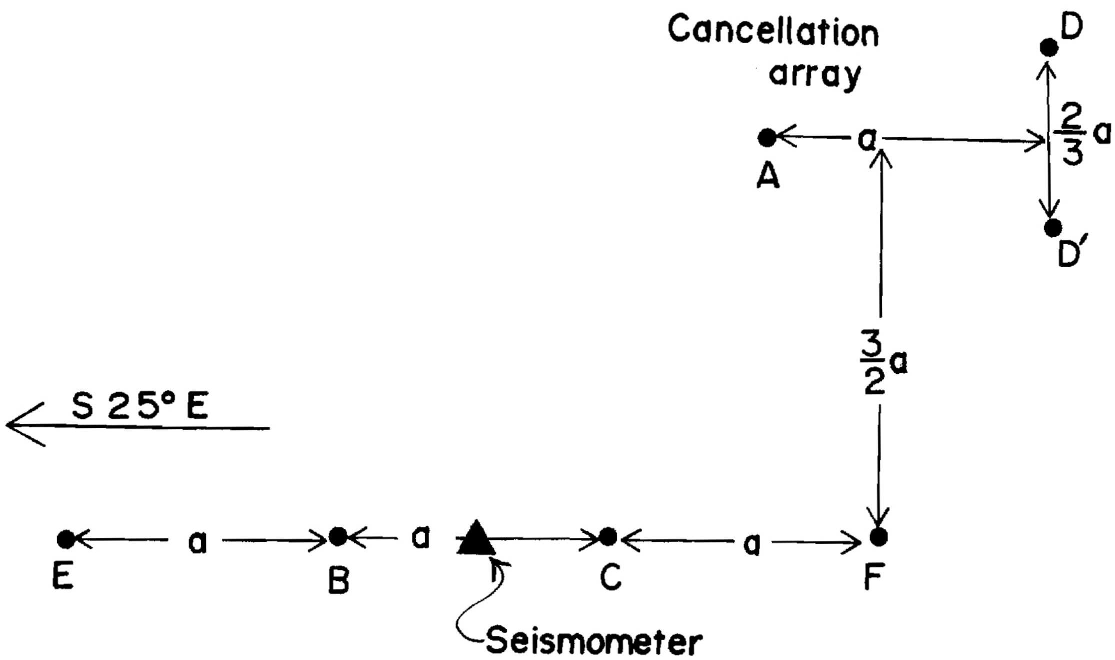
$$\Delta V(t) \simeq \Delta V(o) + \frac{\partial}{\partial \rho_1}(V(o))\ \Delta\rho_1(t) + \frac{\partial}{\partial \rho_2}(V(o))\ \Delta\rho_2(t) \ldots \qquad (6)$$

where $\Delta V(o)$ is the static condition. The quantity $\Delta V(t)-\Delta V(o)$ is the ac component across the inner electrodes which can be recorded. The derivatives of the static condition can be computed numerically, if not exactly. Higher order terms could be included in the expansion if warranted by the data.

The solution of equation (6) for resistivity perturbations could be achieved by at least two techniques. The first technique would be to record $\Delta V(t)$ at a set of electrode separations in a manner similar to a Wenner depth sounding. The derivatives will be a function of the electrode separation, and, if the separations are chosen carefully, they will generate a set of linearly independent or over-determined equations from which the resistivity perturbations can be obtained. The resistivity perturbations can then be directly compared to the amplitudes of seismic excitation in their respective layers to obtain a proportionality coefficient for the electroseismic response. In the second technique, the resistivity perturbations are assumed proportional to the amplitude of the seismic excitation. A single electrode separation is used. The independent relations are derived from the variation in the resistivity layers of the seismic excitation as a function of frequency. Rayleigh waves, for example, could be used since their depth of penetration is proportional to wave length. The solution would give the proportionality coefficient for the electroseismic response directly.

Instrumentation

Geometry of Electrodes: A Wenner array was used for the measurement of the electroseismic response. The geometry used is shown in Figure 1. The voltage was monitored across electrodes B and C. A high-impedance ac-coupled circuit was used to prevent perturbation of the ground potentials and pass only frequencies above one Hertz. A constant voltage was maintained between electrodes E and F with a voltage regulator with response significantly higher than 60 Hertz. The electrodes D, D' and A were placed so that their axes



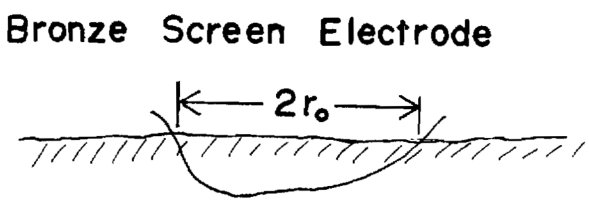


Figure 1. Geometry of electrodes and relative location of the seismometer used to record the electroseismic response.

would be parallel to the Wenner array and also close to an equipotential line of the current electrode pair E and F. The contributions of electrodes D and D' to a net D-D' potential were adjusted with a potentiometer to give a dc potential equal to the dc potential at A. The potential between A and D-D' contained the ac component of atmospheric noise which was used to cancel correlated noise between B and C. This resulted in a significant reduction of that noise and without changing the apparent-resistivity signals, because in its location the A-D-D' subarray would have slight or zero signal associated with changes in resistivity. This noise reduction scheme was essential for efficient measurement of the electroseismic effect.

The electrodes consisted of copper screen buried approximately 6 inches deep (see Figure 1) in a two foot diameter bowl-shaped hole. When necessary the soil was moistened with a copper sulfate solution to improve the contact. A number of electrode types were tried, such as simple rods, or four inch diameter plugs, but the screen provided adequate and the most reliable contacts. It was observed by test that these electrodes did not generate an observable electrical signal when disturbed with a localized ground vibration significantly greater than the vibrations in the seismic waves which were used to generate the electroseismic effect.

Amplifier and Recorders The recording system developed after a number of modifications is shown schematically in Figure 2. The electrical and a single seismic signal were recorded simultaneously on a two-channel strip-chart recorder. Its response (see Figure 3) was flat from dc to about 80 Hz. Seismic amplifiers (Geotech AS-330) were used to amplify the conditioned signals for recording. Their

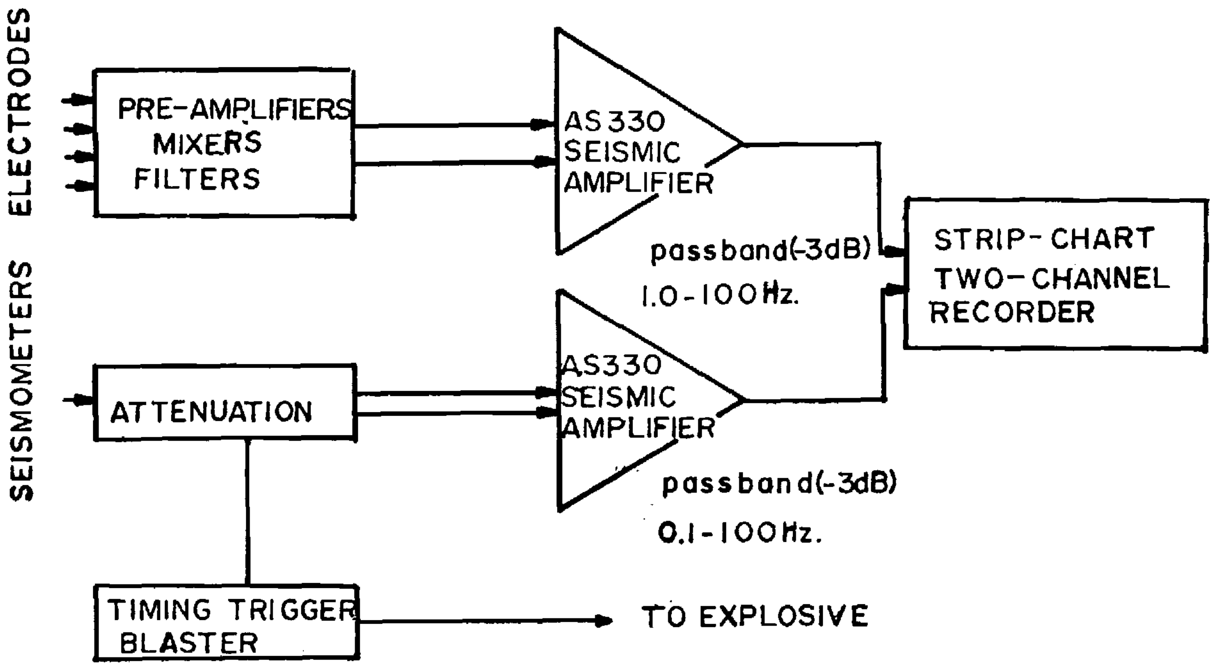


Figure 2. Recording system developed for simultaneous recording of electrical and seismic signals.

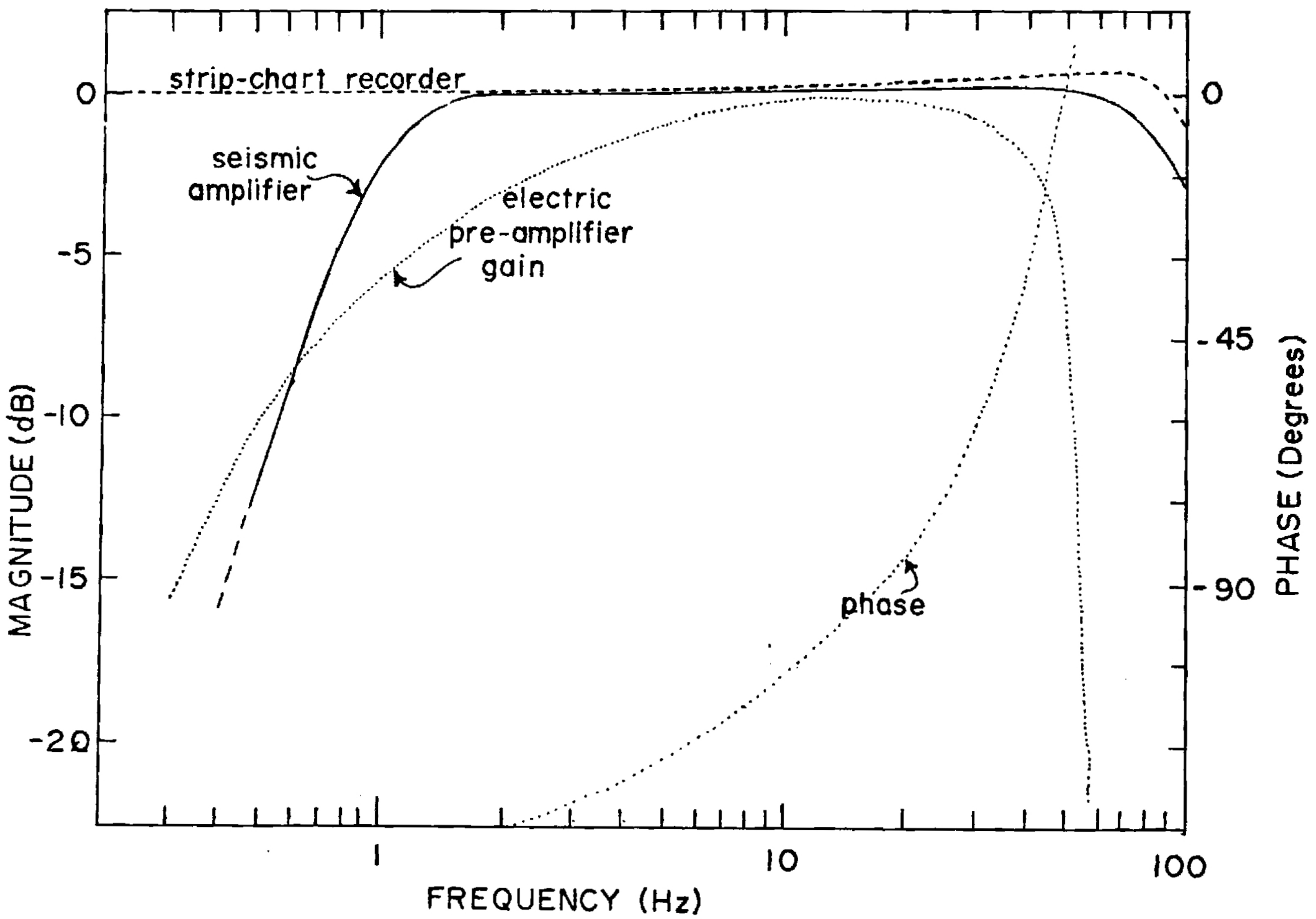


Figure 3. Frequency response of pre-amplifiers, amplifiers and recorders.

response (Figure 3) was nearly flat between -3dB points at 0.1 Hz (seismic) or 1.0 Hz (electrical) to 100 Hz (both). The seismometer used was a Hall Sears HS-10, 1.0 Hz geophone with 1 volt/cm/sec response. An attenuator was designed for the seismic channel to mix in a signal from the blaster giving explosion detonation time. The pre-amplifier for the electric signal was designed specifically for the electroseismic measurements. The schematic, Figure 4, gives the details of its construction. Basically it consists of high-impedance inputs for signal and noise, a signal mixer, 60 Hertz notch filter, signal conditioner and calibration circuit.

Atmospheric noise cancellation takes place in the preamplifier mixing networks. The capacitors in the electrode inputs are required to remove the dc bias from the amplifiers and to prevent current-induced noise in the potentiometers. The signal-conditioning amplifier corrects some of the bandpass distortion of the overall amplifier introduced by the Twin-T rejection filter as well as rolls off the high-frequency response. It was found that the notch filter was marginally able to control the dominant power line component in the strong 60 Hz environment because of the need to cancel 60 Hz as well as 57-59 Hz induction motor slip components. Because of the grounding practices of rural power systems, the reduction of power-line signals is not a trivial matter. The combination of the noise cancellation subarray, high input impedance, common mode and notch rejection features of the amplifier, and the use of a single chassis power supply ground at the center of the Wenner array, gave satisfactory overall performance.

Calibration of the electric pre-amplifier was achieved by measuring phase and amplitude of the output signal for a known sine wave

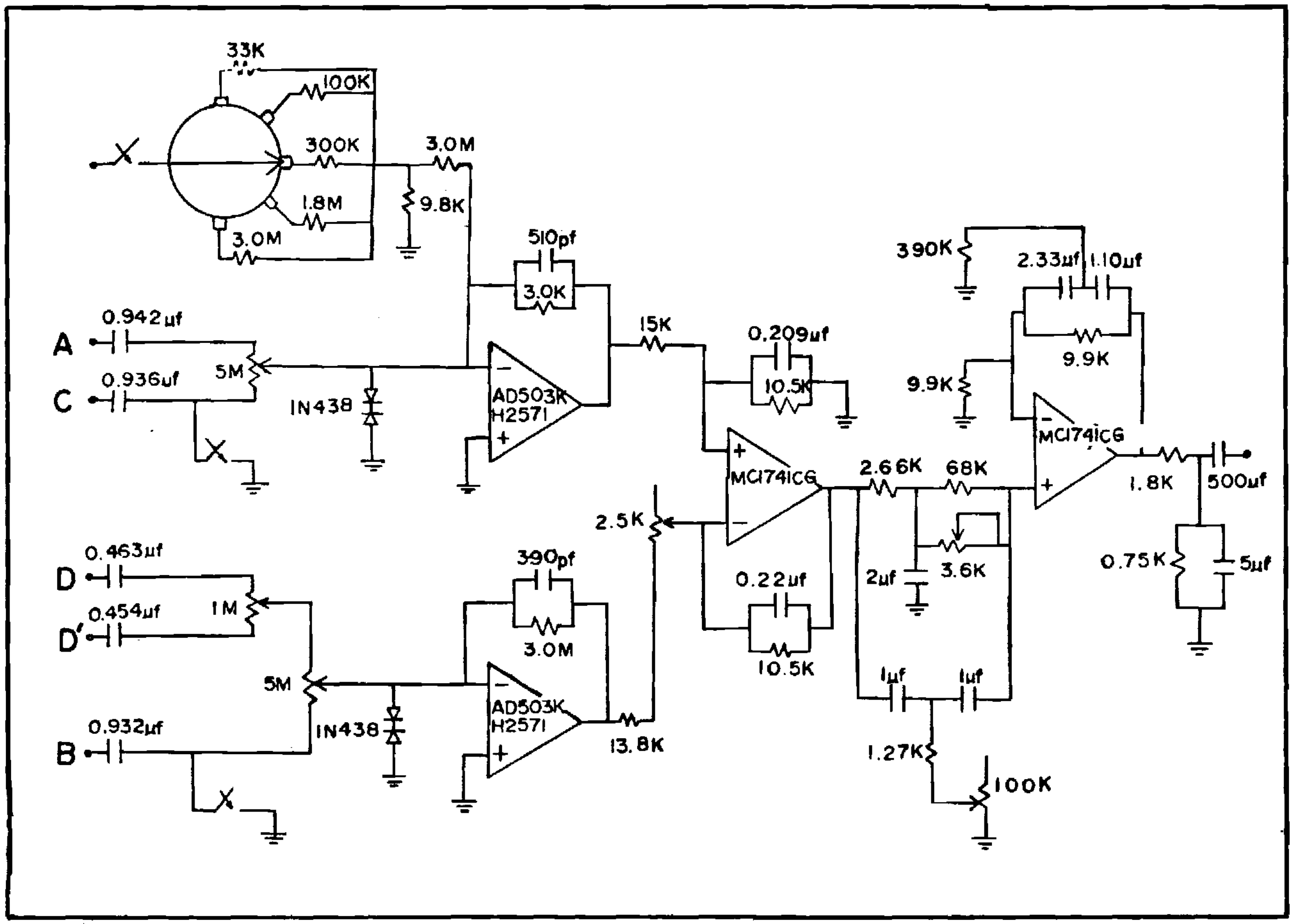


Figure 4. Schematic of pre-amplifier for measurement of electrical component of electroseismic response.

input. The frequency response was computed also by recording the impulse response of the system and computing its Fourier spectrum (see Figure 5). The system response of the seismic recording channel was computed from the known responses of its components. Although the response of the two channels differs significantly below 1.0 Hertz or above 50 Hertz most of the seismic energy in the ground was within the frequency range of 6 to 40 Hz. Since both systems were nearly identical in this frequency range the recorded signals can be compared directly. In the analysis, the digitized seismic traces were filtered to match the system response for the electrical channel. For the most part the filtering consisted of a removal of the insignificant 60 Hz seismic signal and noise introduced by the digitizing of the records.

Field Measurements

Introduction The field tests were naturally divided into two parts. The individual experiments are summarized in Table I. The first six experiments served primarily to indicate necessary modifications or improvements to the instrumentation. In particular, they showed the need for a seismic signal with significant energy below 50 Hz and a scheme to reduce atmospheric and 60 Hz noise. The remaining field experiments served to obtain data which would allow some evaluation for the various factors that could affect the electroseismic response. They were all carried out at the same test site, northeast of Gordon, Georgia in horizontally stratified coastal plain sediments.

Geological Setting and Resistivity Structure Data on the resistivity of the sedimentary layering under the test site were obtained with a Wenner depth sounding. The data have been interpreted as

TABLE I - SUMMARY OF ELECTROSEISMIC EXPERIMENTS

DATE	LOCATION	ACTIVITY OR OBJECTIVE
April 71	ATL Seismic observatory	Test instruments and record natural background noise
6 Jun 71 19 Jun 71 21 Jun 71 26 Jun 71	Allatoona Allatoona Allatoona Allatoona	Test instruments in electrically quiet area; attempt electroseismic response with rock drop; measure resistivity depth relation
5 Aug 71	Englehard Clay Mine	1st explosive shot @ 250 feet, measure resistivity depth relation with Wenner depth sounding
13 Sep 71	Englehard Clay Mine	3 Shots @ 250,300,350 feet, test noise cancellation scheme
28 Dec 71	Englehard Clay Mine	5 Shots @ 250 feet, test array size variation
7 Jan 72	Englehard Clay Mine	6 Shots @ 250 feet, correlate with seismic component signatures
28 Feb 72	Englehard Clay Mine	6 Shots @ 250 feet, variation of azmuth, topography and shot depth

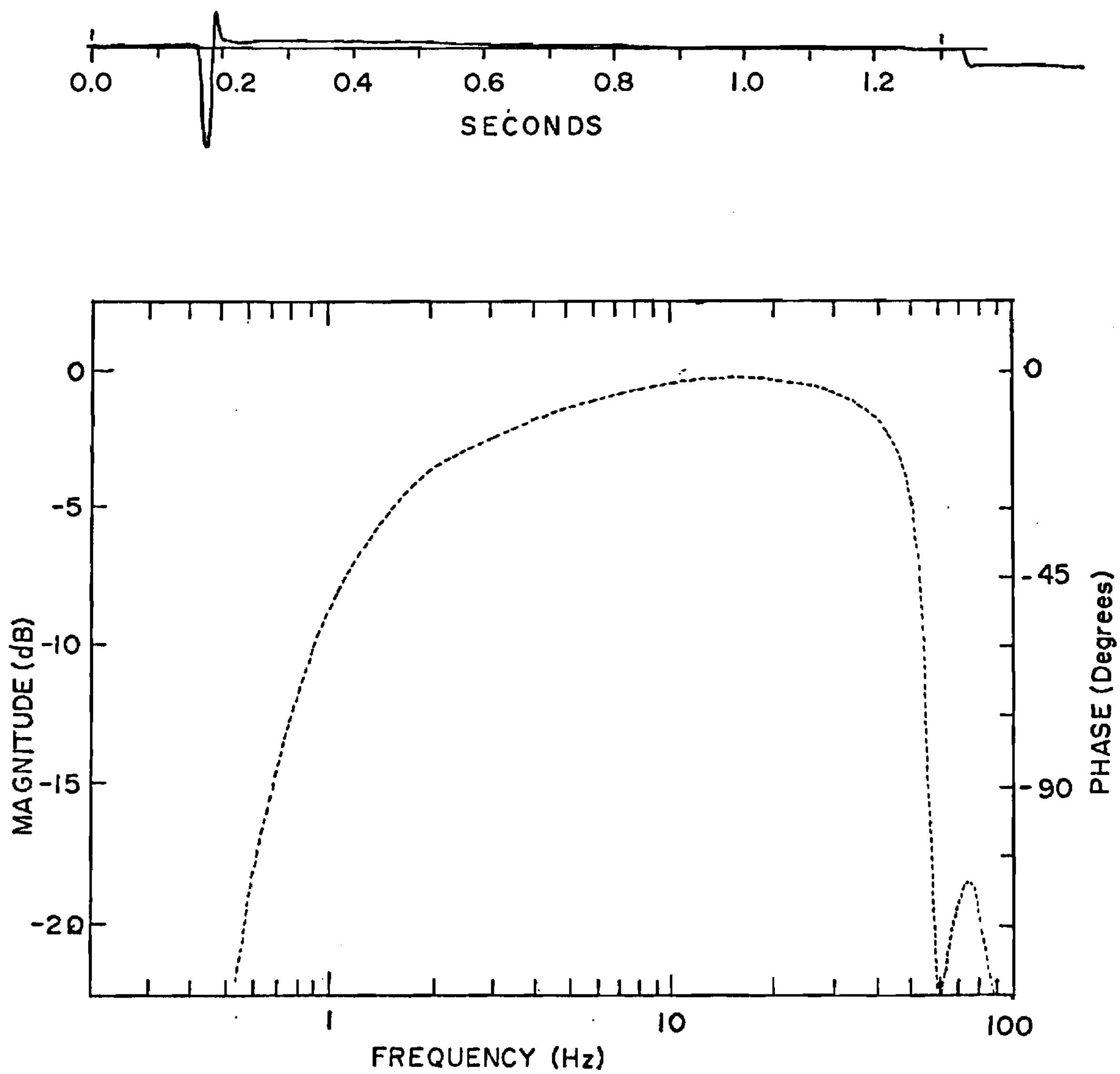


Figure 5. Impulse response of the electrical signal recording channel and its Fourier transform.

implying four distinct resistivity layers (see Figure 6). The data were adequately fitted by curve 1623 (Mooney & Wetzel 1959). Deviations from the fit are easily explained by deviations of the observed layers from the theoretical model and the uncertainty in the measurements. The actual layering was observed directly since half of the array was excavated to a depth of 22 feet prior to the final field survey. This allowed depth constraints to be put on the interpretation of the resistivities. A description of the individual layers with their interpreted resistivities is given in Figure 7. The observed contrast, 200 to 1, in the resistivities is unusually high but not unexpected considering the type of materials present; the high contrast may have been advantageous for the recording of the electroseismic effect. The seismic source for most shots was placed approximately 4 feet below ground surface. Consequently, they were in or near the base of the stiff clay-sand layer near the surface. The explosive consisted of one or two pounds of primer and high velocity seismic explosive. Two shots were placed at depths of 20 and 40 feet in available 6 inch diameter core holes.

Electrical Noise The electrical background noise consisted primarily of noise from 60 Hertz line circuits and noise from other, probably atmospheric, sources. Noise derived from the instruments was estimated from specifications of the operational amplifiers to be $0.3\mu V(rms)/Hz^{\frac{1}{2}}$ At 50 Hz, near peak response of the amplifier, this would imply instrument noise of less than $2\mu V(rms)$. The noise level recorded with inputs shorted was also $2\mu V(rms)$. For comparison, the atmospheric noise was measured as a function of electrode spacing and was found to give a linear relation. The slope varied from

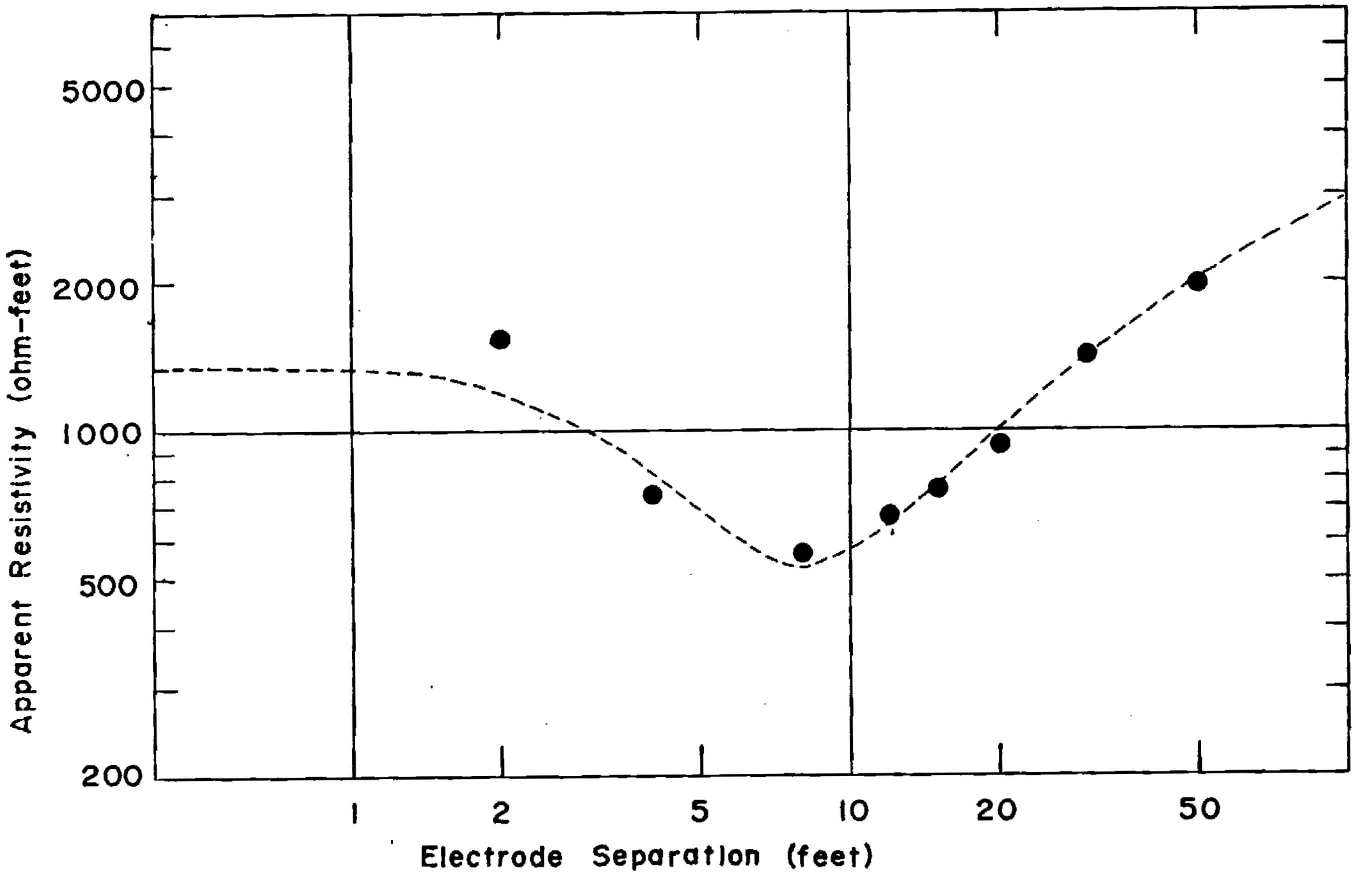


Figure 6. Apparent resistivities observed with a Wenner depth sound. The dashed curve is model 1623 (Mooney and Wetzel, 1959).

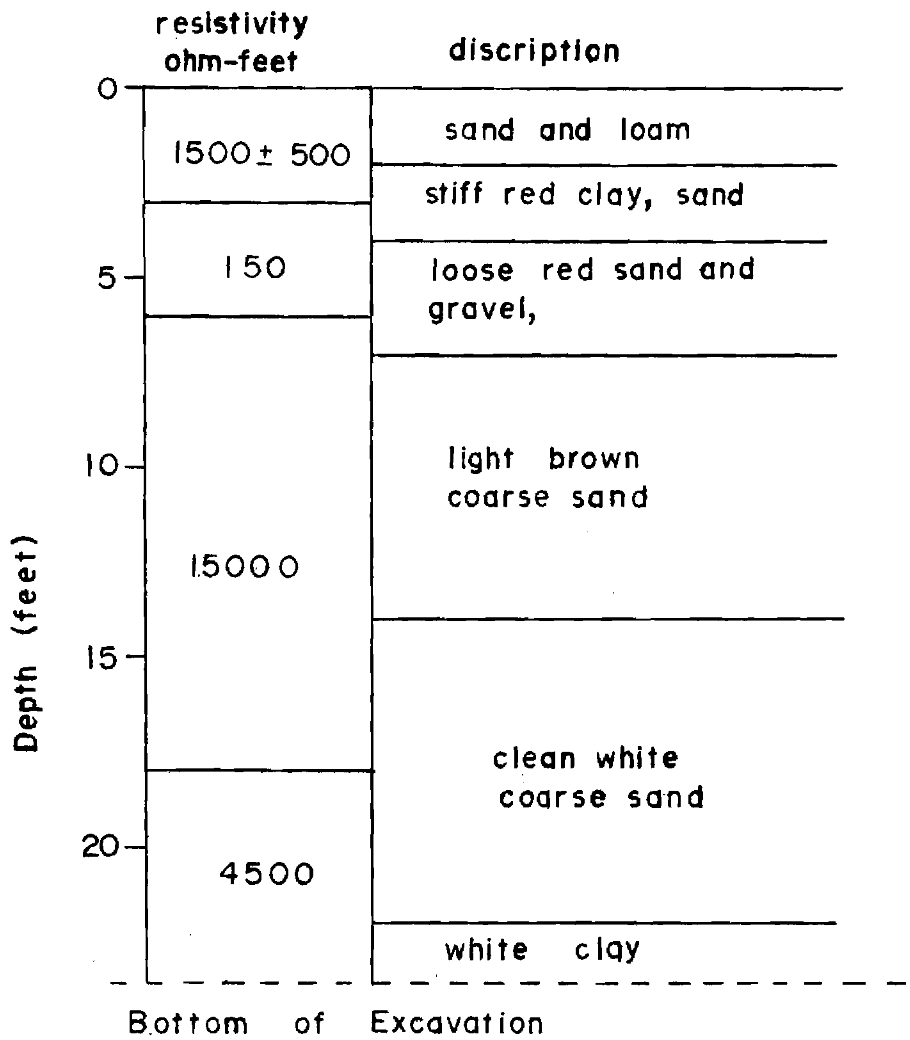


Figure 7. Description of observed layering of sediments under array showing interpreted resistivities

0.5 μV (rms) /meter to 15 μV(rms)/meter depending on location (i.e., resistiviies), soil conditions and time of measurement. At the Gordon, Georgia test site the slope was generally about 2.5μV(rms)/meter. A sample of the electrical noise as recorded by the system including the noise cancellation scheme is shown in Figure 8. Its Fourier spectrum shows the signal to be essentially flat from 0 to 50 Hertz with a prominent 60 Hz peak in spite of severe attenuation in the amplifier network. Above 60 Hz the noise level is attenuated by over a factor of five and is probably below the level of digitizing noise.

Comparison With Seismic Waves In homogeneous isotopic elastic media two types of waves can exist, rotational and compressional. Rotational waves represent propagation of a pure rotation and compressional waves a pure compression. However, in a layered medium surface waves, Love and Rayleigh, and guided waves may also exist. In addition, the compressional and rotational components are not always separated. The different waves in general represent different or mixed types of stress which do not necessarily perturb the resistivity in the same manner.

In order to examine possible relations between stress type and electroseismic response, a three-component seismogram was composited from similar two-pound shots (Figure 9). The first compressional arrival, P, was probably a refracted wave from a deeper layer since it was significantly lower in amplitude on the horizontal traces. The second compressional arrival, P', is probably a direct or guided P-wave in the hard red-clay layer near the surface. A direct vertical shear was not identified in these shots. However, it would arrive at the time indicated and was possibly observed in subsequent shots.

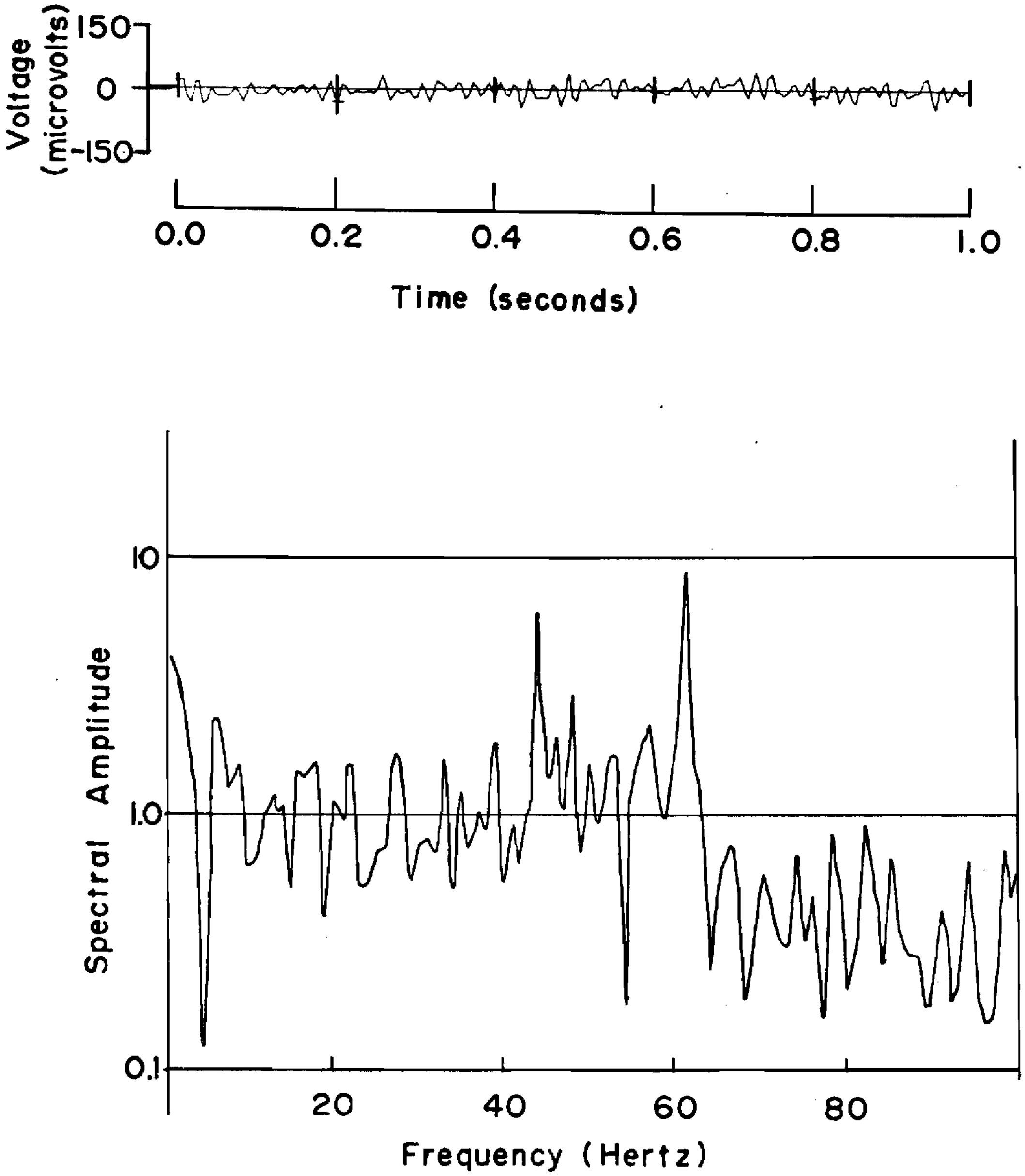


Figure 8. Example of electrical background noise trace and Fourier transform as recorded by the total system including the noise cancellation scheme.

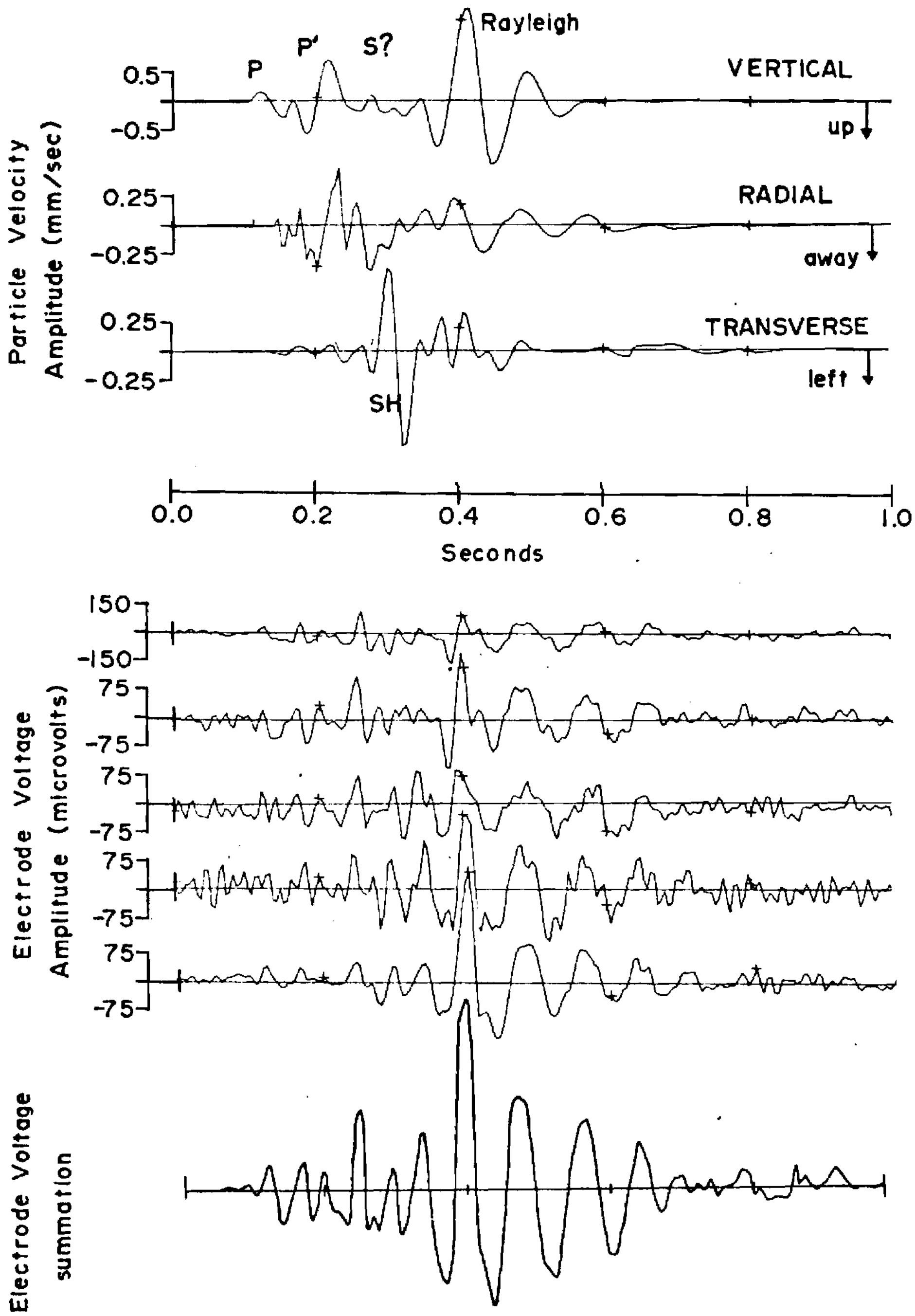


Figure 9. Comparison of three components of seismic motion with electroseismic response.

A distinct horizontal shear (or Love) wave was seen on the transverse seismogram indicating a SH velocity of 1000 ft/sec. The Rayleigh wave on the vertical was the largest amplitude wave observed. Its velocity was 550 to 800 ft/sec depending on frequency. The Rayleigh wave appears to be inversely dispersed providing evidence that either the coarse sand between 6 and 20 feet was lower in velocity than the near surface red-clay layer or the frequencies observed were less than the minimum in the group velocity for the structure.

The five electrical traces in Figure 9 were obtained at the same time as the three-component seismograms. Shots for the third and fifth trace (Figure 9) were placed near previous shots to provide some assymetry in the source and possibly generate higher amplitude shear waves. However, no significant difference in the SH wave generated could be detected from the seismograms for the third and fourth shot since the transverse traces were nearly identical. The electrical traces for the individual shots show variation in amplitude and high frequency character. The amplitude variations are largely due to the coupling of the shots. The high frequency variations in character were probably due largely to noise. The summation trace (Figure 9) removes much of the noise and enhances the correlated electroseismic signal. The most prominent feature of the summed electroseismic signal occurred during the Rayleigh wave. Near 0.4 seconds the electroseismic response correlated with the vertical component; however, at 0.6 seconds the correlation was with the horizontal component. Dilatation in the Rayleigh wave has the same phase as the vertical component of displacement indicating a correlation at 0.6 seconds of the Rayleigh phase with dilatation. There was no phase on the electroseismic trace which correlated with the distinct SH wave on the transverse seismogram. A significant electroseismic signal was associated with the initial P-phases but the correlation was not distinct, perhaps because of the higher frequencies and short wavelengths involved. In general, the electroseismic signal correlated most strongly with seismic signals with compressional components and did not respond strongly to rotational or shear stress.

<u>Effects of Array Size</u> The average depth of the material sampled is roughly proportional to the electrode spacing of a Wenner array. Consequently, the voltage differences observed with close electrode spacings are influenced most strongly by shallow materials, and the voltage differences observed with wide electrode spacings are influenced most strongly by the deeper materials. This principle provides the basis for the interpretation of the Wenner depth sounding used to obtain the resistivity structure for the Gordon, Georgia test site. Similarly, perturbations in the resistivity of the material at a particular depth would be expected to influence the voltages observed with close and wide electrode spacings differently. With sufficient independent measurements (see equation (6) and discussion) the resistivity perturbations as a function of time in each layer could be obtained. The effect of changing the resistivity in the second and third layer in the model for the test site is shown in Figure 10. The voltage differences needed to compute the proportionality constants in equation (6) are proportional to the change in apparent resistivity produced by a change in the resistivity of the layer and inversely proportional to the electrode spacing. Changes in the resistivity of the third layer in the model has significant influence only for electrode separations greater than about 30 feet. Whereas changes in the resistivity of the second layer have significant influence

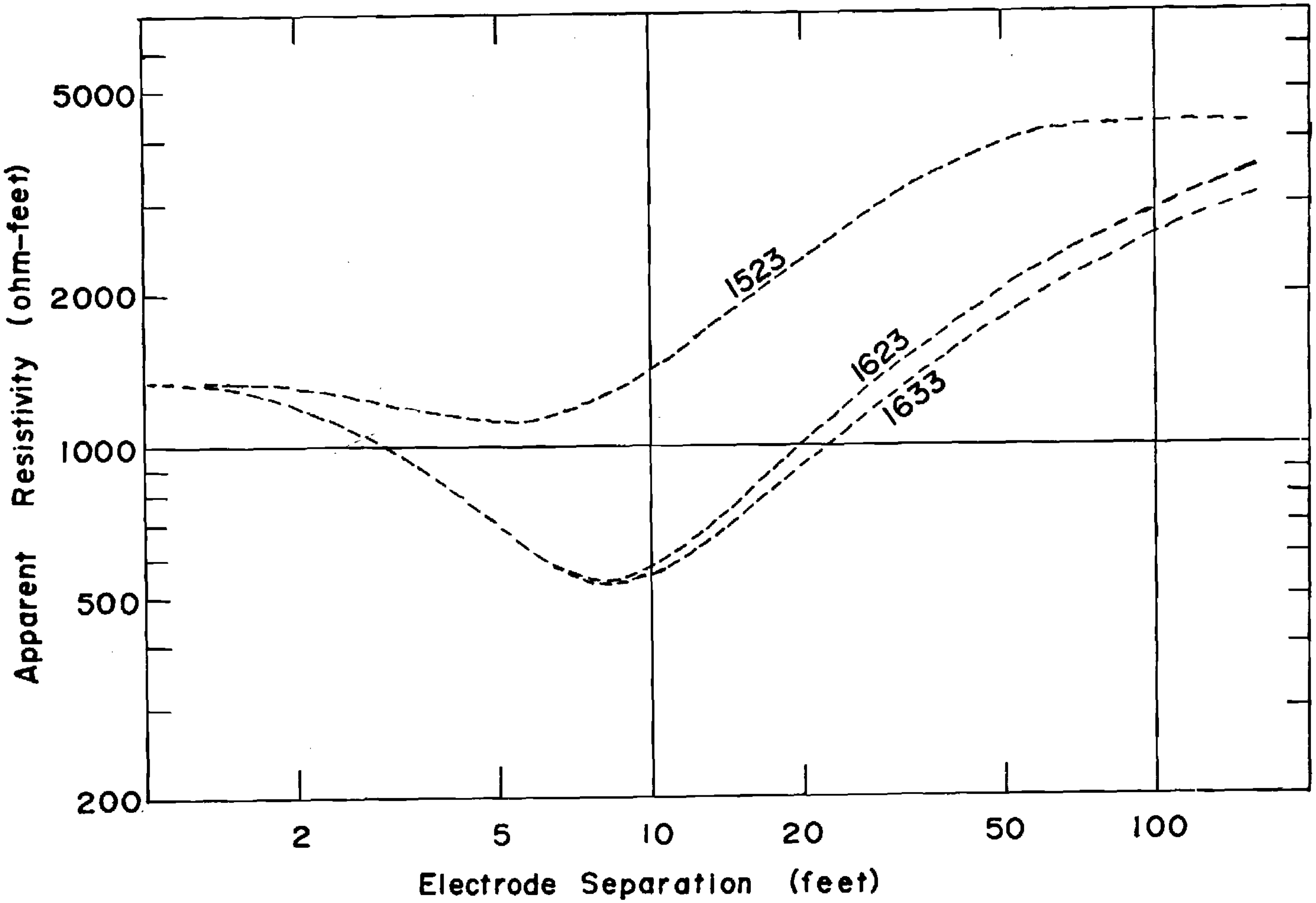


Figure 10. Effect of change in resistivity in the second and third layer of the model (curve 1623) (see Figure 7). In curve 1523 the resistivity of the second layer was increased by a factor of 3.33. In curve 1633 the resistivity of the third layer was decreased by a factor of 0.3.

for electrode separations as short as 4 feet. The wider electrode spacings pose two additional problems in measurement of the electro-seismic effect. One is that the voltage difference, and proportionally its perturbation, are reduced (see equation 5). The other is that the noise is increased.

At the Gordon, Ga. test site the electroseismic response from three electrode separations were obtained (Figure 11). Two pounds of explosive were used for each shot. The amplitudes of the resulting seismic signals were within a range of ten percent as determined by the amplitudes of the first compressional phases. Other phases saturated the amplifier and could not be compared. As expected the electro-seismic response for the 30-foot electrode spacing closely resembles the summation trace (Figure 9). However, the data were obtained a week apart. The electroseismic response from the 15-foot electrode spacing was similar to the response for 30 feet but about half the amplitude. This could have been caused by the reduced effect of the resistivity perturbations in the deeper layers.

The electroseismic response from the 60-foot electrode spacing is from one quarter to one half the amplitude from the 30-foot separation. The amplitude decrease was expected from theoretical considerations. However, the electroseismic response at 60-foot separation correlates poorly with the 30-foot separation response. Noise and the effects of curvature of the seismic wave front could have contributed to the signal reduction and poor correlation. For the 60-foot separation, the allignment of the Wenner array would deviate 20 feet from the curved wave front, which is significant when compared to a typical wave-

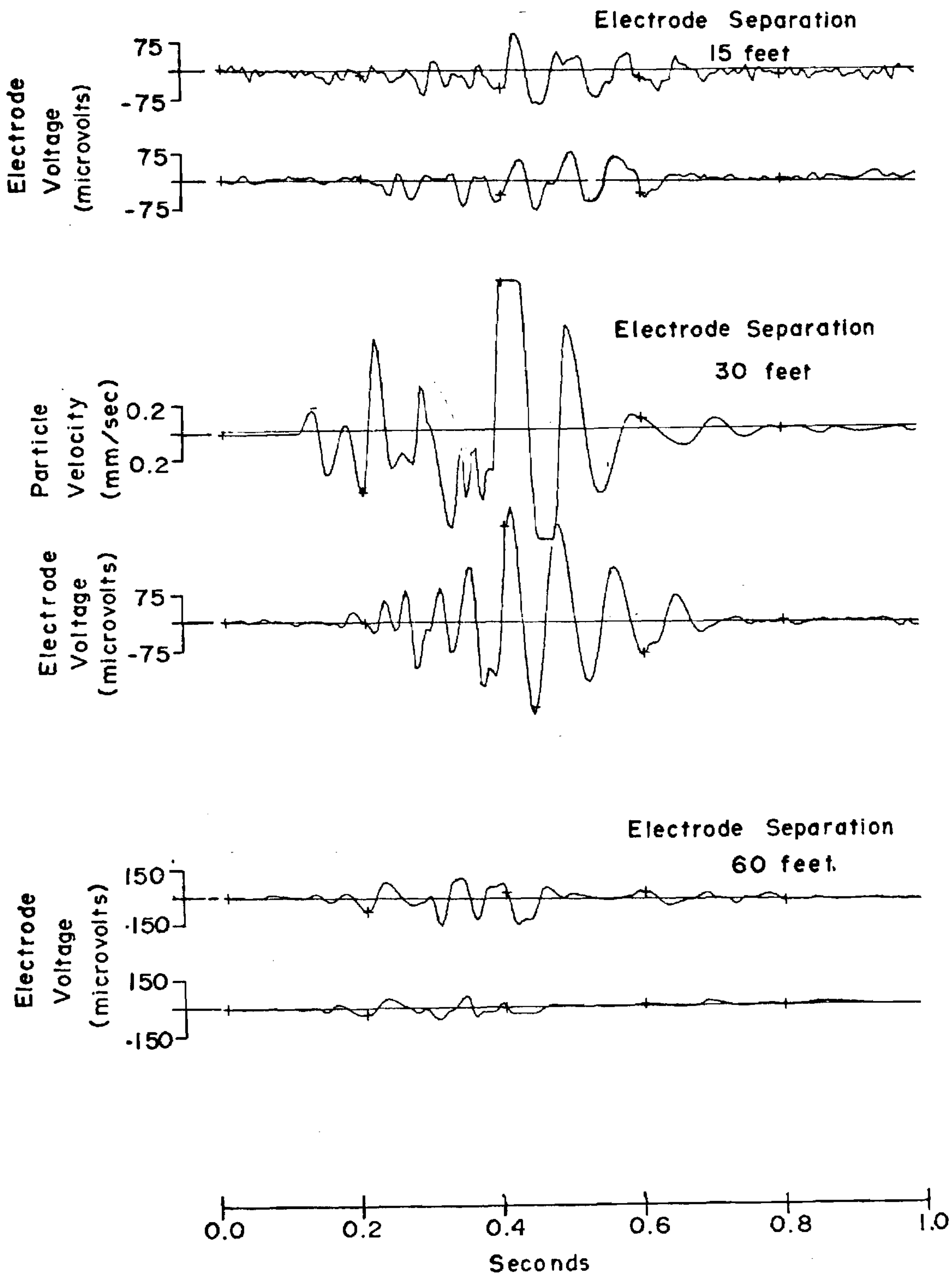


Figure 11. Comparison of electroseismic response for array sizes of 15, 30 and 60 feet.

length of 50 ft.

Using the observed amplitudes fot the electroseismic response in the leading portion of the Rayleigh wave (Figure 11) and changes in the apparent resistivity produced by changes in the resistivity in the second and third layer (Figure 10) at electrode separations of 15, 30, and 60 feet, equation 6 was solved by the least squares method. The results indicate a 0.06% and 0.28% change in the resistivity of the second and third layer respectively.

Effects of Azimuth The Wenner array was oriented perpendicular to the direction of propagation in most shots in order to sample similar particle motion along the entire line of electrodes. Since most shots were at a distance of 250 feet, the 90-foot Wenner spread would deviate at most 6 feet from the wave front. However, typical wavelengths were on the order of 50 ft for most seismic waves which produced an electroseismic response. To investigate the effects of azimuth three explosions were set off at 0^o, 45^o and 90^o to the line of the electrodes (Figure 12). Unfortunately, the record for 90^o could not be compared to previous data since half of the test site, including one of the electrode positions, was stripped to a depth greater than 20 feet just prior to the field test. The resulting vertical surface severely altered the character of the seismic and electroseismic signals. The comparison of the arrivals at different azimuths (Figure 13) shows that electroseismic response was approximately twice as great for 0^o than for 90^o, and that at 45^o the signal was intermediate in amplitude. At all three azimuths the signal correlates with the Rayleigh phase. However, at 0^o and 45^o the amplitudes are greater than would be predicted by the seismic signals near the

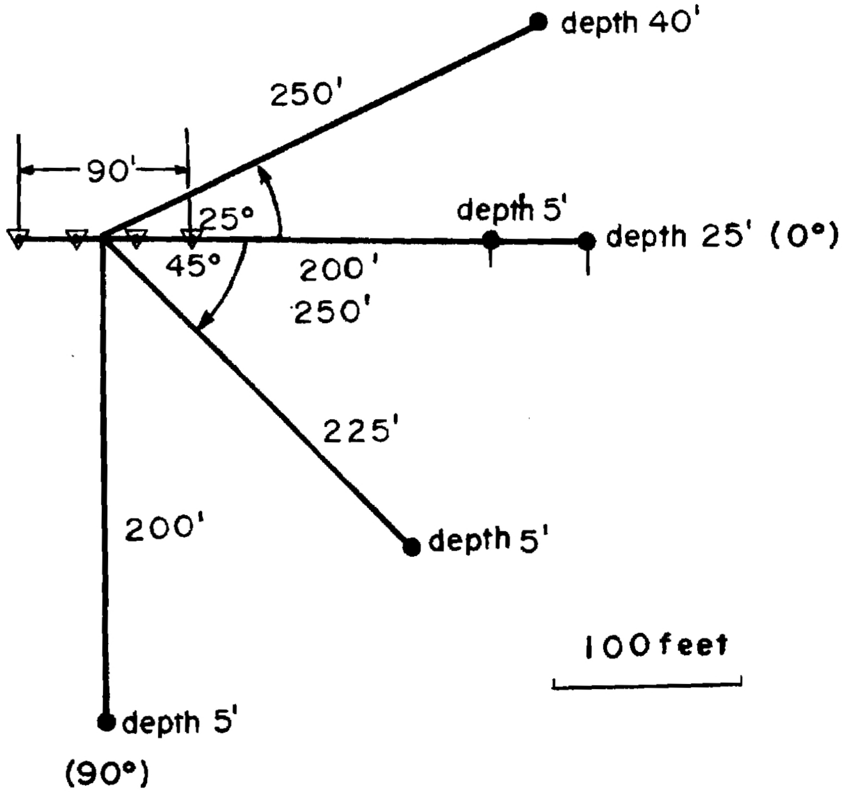


Figure 12. Location of explosive shots at different azimuths and depths with respect to the Wenner array.

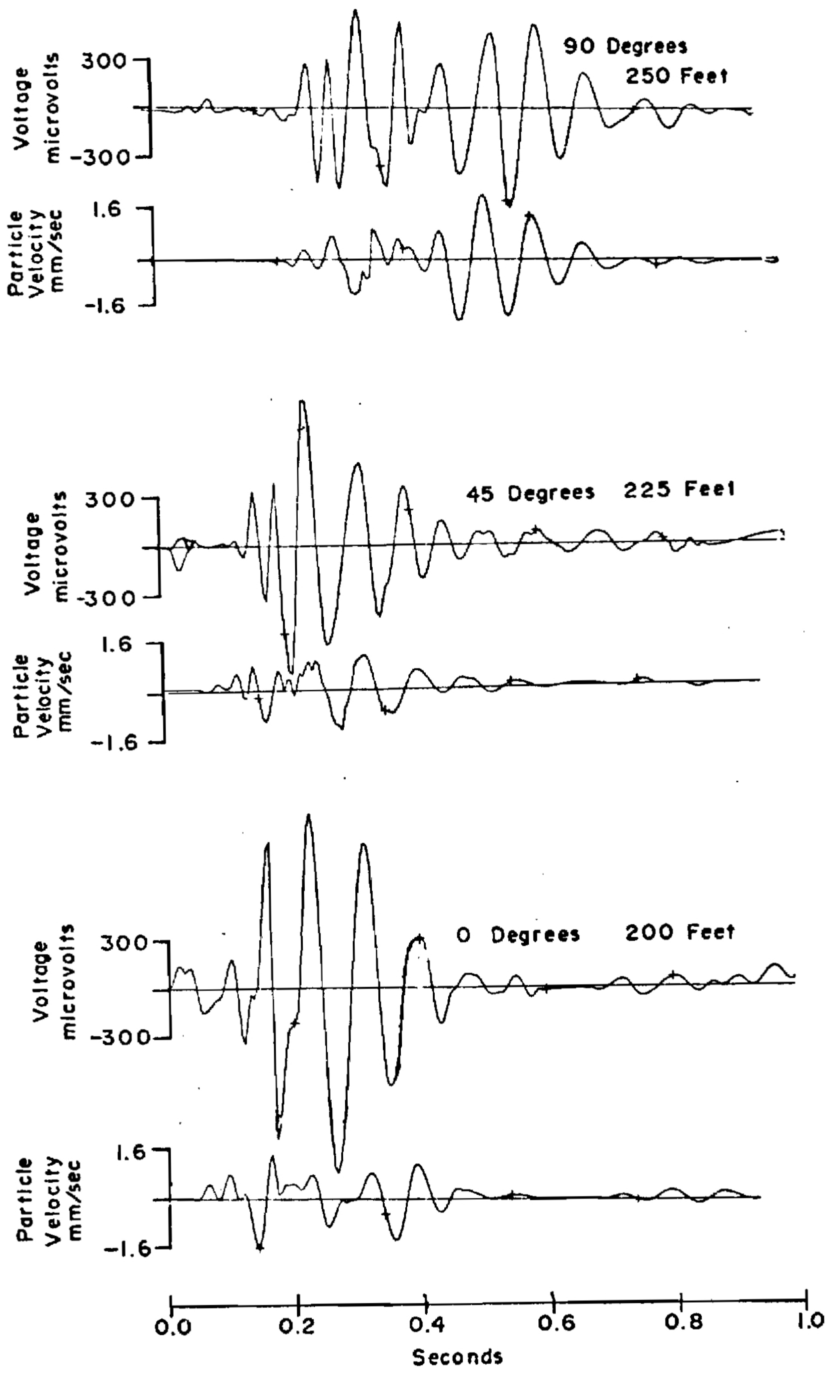


Figure 13. Electroseismic response at 0°, 45° and 90° incident to a 30 foot Wenner array.

leading portion of the Rayleigh phase. This may be accounted for partially by an azimuthal variation in the response to SH-Waves which arrive just prior to the Rayleigh phase. SH-waves were not observed to correlate at 90^{o} and the amplitudes at 90^{o} in Figure 13 accordingly correspond well to the seismic Rayleigh phase. The records did not allow evaluation of azimuthal variation in response to P-wave excitation .

Two additional shots were set off near 0^{o} azimuth to investigate the effect of depth of shot (Figure 14). The shot at a 20-foot depth was smaller than the shot at 0^{o} in Figure 14. However, the electroseismic response was proportionately smaller, and the variations in character of the arrivals can be explained by the different distances from the recorder. The shot at a 40-foot depth was below the water table, and the improved coupling of seismic energy caused both the seismic and electroseismic response to saturate the amplifiers. Nevertheless, the comparison of phases (Figure 14) showed the correlation again with the Rayleigh wave and the uncertain correlation of the response to the shorter wavelength compressional arrivals.

Summary and Conclusions

An electroseismic response in Georgia coastal plain sediments has been observed. The magnitude of the response was typically 250 μV per mm/sec at 15 Hz of particle velocity at the surface. Measurement of the electroseismic response required a high-impedance ac amplifier with a 60 Hertz filter. The ac signal was obtained from the center two electrodes of a Wenner array and an auxiliary array was designed to cancel correlated atmospheric electrical nosie. The

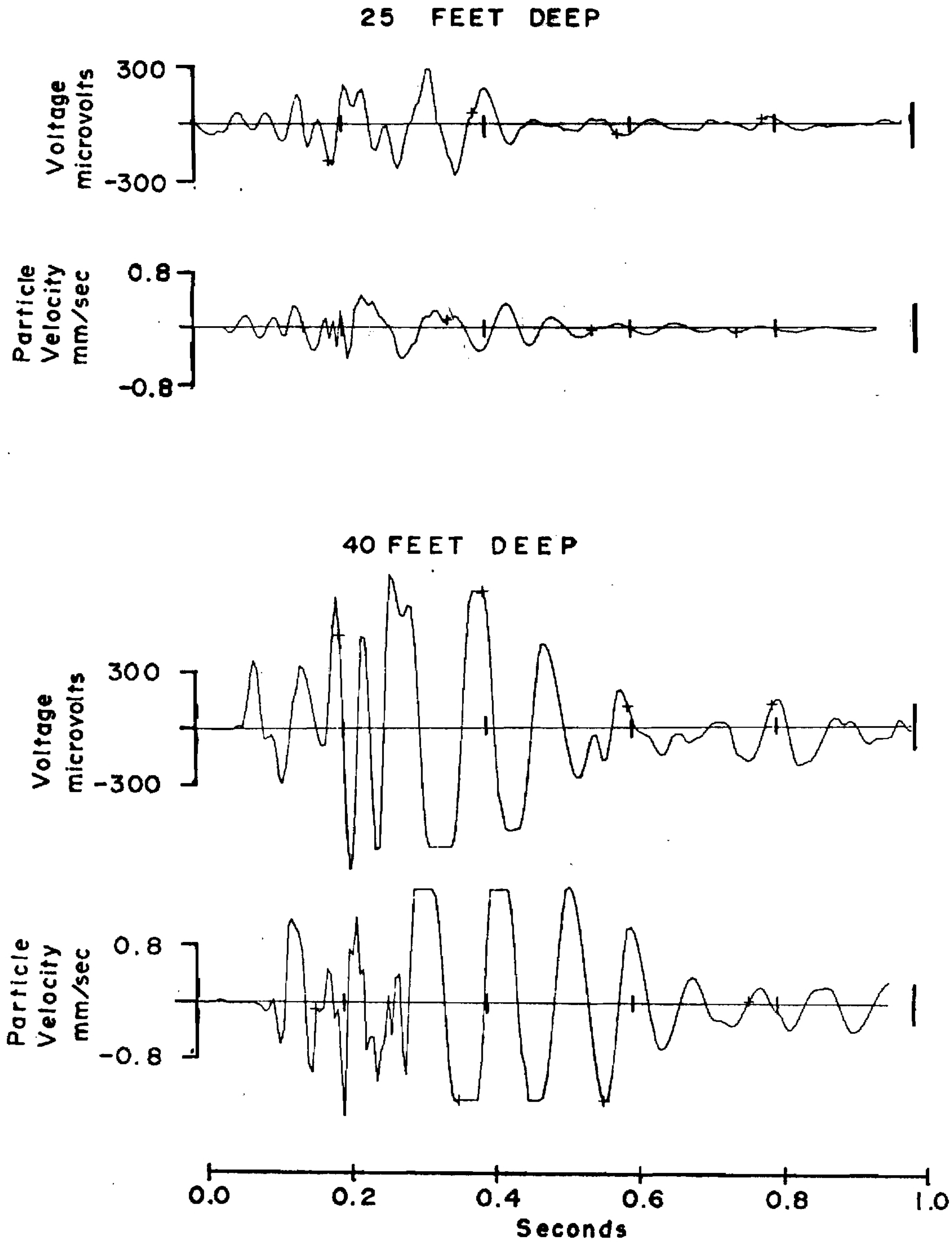


Figure 14. Seismic and electroseismic response for 25 and 40 foot depth of shot.

response correlated strongly with the Rayleigh wave. Correlations with other compressional phases were also observed. A strong correlation with shear wave arrivals was not observed but may exist.

Theoretical considerations showed that the electroseismic response could be approximated by a Taylor's expansion for determination of the resistivity perturbations. A simple inversion of field data showed that the second and third layer in the model for the Gordon field site were perturbed by 0.06 percent and 0.28 percent respectively. The stronger response was in a 12 foot thick coarse sand with resistivity of 15,000 ohm feet. Consideration of estimated elastic dilatation indicates a 0.03 change in resistivity is produced by a compressional strain of 1×10^{-6}.

The use of the method as an exploration technique would be limited by the depth limitations of the resistivity methods and the need for a more complicated array. However, a modified system might be designed for down-hole investigations.

Although the physical processes which generated the electroseismic response were not elucidated with these field tests, they are undoubtedly related to the condition of the water in the pore spaces and the state of stress. These factors could be important because of their relation to dilatancy and the role of dilatancy in recently identified measurements useful in predicting earthquakes (Nur, 1972).

Recommendations

This research has only partially developed the theory and measurement techniques for the electroseismic response. Many questions were left unanswered because of time and circumstances. It has, however, opened a field of research which could potentially be rewarding. In particular the relations between the electroseismic response and water in pore spaces or the state of stress of various earth materials could prove useful in soil mechanics or earthquake prediction. Consequently the following recommendations are offered.

1. Continue research on the study of the electroseismic response of earth materials.

2. Develop a more complete theory of the response of the Wenner array to transient changes in resistivity. This should include short wavelengths and possible influence of induced potentials.

3. Develop the theory for the interpretation of field data and formulate it in terms of standard curves or a general inverse solution.

4. Obtain more field data for a variety of soil and rock types and for different sizes of explosives.

5. In future instrumentation, include simultaneous three-component seismic measurements and multiple electrical arrays. When the state of the interpretation theory warrants it, direct digitization of signals should be implemented.

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APPENDIX

A Numerical Resistivity Inversion Implementation

```
PRITE
L     3
@SYSTEM$* LTPRO.FOR7C,IS  MAIN
C        THIS PROGRAM CALCULATES THE GEOMETRIC FACTORS AND THE
C    GENERALIZED INVERSE OF THEM FOR A SUB-SURFACE GEOMETRY OF 16 BLOCKS.
C        THE VARIABLES USED ARE -
C           XPP AND YPP = PROBE COORDINATES
C           SXPP AND SYPP = SOURCE PROBE COORDINATES FOR POLE-POLE PAIRS
C           RXPP AND RYPP = RECEIVER PROBE COORDINATES FOR POLE-POLE PAIRS
C           YSURF = VALUE OF SURFACE INTEGRAL, YZ PLANE, OF SUBSURFACE BLOCK
C           YSURF = SURFACE INTEGRAL, XZ PLANE
C           ZSURF = SURFACE INTEGRAL, XY PLANE
C           GPP = GEOMETRIC FACTOR FOR POLE-POLE PAIR
C           GDP = GEOMETRIC FACTOR FOR DIPOLE-DIPOLE PAIR
C           GDPI = DUMMY VARIABLE USED IN CALCULATING THE GENERALIZED INVERSE
C           HDP = INVERSE OF GDP
C           CKI = PRODUCT OF GDP AND HDP, IDENTITY MATRIX
C        THE INVERSE IS CALCULATED BY CALLING SUBROUTINE GIO.
C        EXAMPLE OF CALL
C        CALL GIO(NR,NC,MR,A,U,AFLAG,ATEMP)
C           NR = NO. ROWS IN MATRIX A
C           NC = NO. COLUMNS IN MATRIX A
C           MR = ORDER OF THE LARGEST SQUARE MATRIX THAT CAN BE HANDLED
C                BY THE SUBROUTINE
C           A = INPUT AND OUTPUT MATRIX
C           U = UPPER TRIANGLE BOOKKEEPING MATRIX
C           AFLAG = OUTPUT VECTOR INDICATING DEPENDENCE OF COLUMNS
C           ATEMP = TEMPORARY WORKING STORAGE VECTOR
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)                                  1
      REAL AFLAG(16)                                                       2
      DIMENSION SXPP(42),SYPP(42),RXPP(42),RYPP(42),XSURF(42,3,2,4),
     1   YSURF(42,3,2,4),ZSURF(42,5,2,2),GPP(42,16),GDP(20,16),
     2   GDPI(20,16),ATEMP(20),U(512),CKI(16,16),HDP(16,20),
     3   XPP(23),YPP(23)
      DIMENSION F?(16),FP(16),PSI(20),PHIT(20),PHIP(20),PHIS(20),
     1   RHOM(16),RHOP(16),T2(20),SX1(20),SX2(20),SY2(20),SY1(20),
     2   RX1(20),RX2(20),RY1(20),RY2(20)
      REAL T1,T3(4,20)
      REAL SXX1,SXX2,SYY1,SYY2,RXX1,PXX2,RYY1,RYY2
  100 FORMAT(1H1)                                                          6
  101 FORMAT(8PH DIPOLE-DIPOLE COEFFICIENTS (G MATRIX) FOR A SUBSURFACE    7
     1GEOMETRY CONSISTING OF 16 BLOCKS/)                                   8
  102 FORMAT(//9X,I3,9(9X,I3)/)                                            9
  103 FORMAT((I4,10D12.5))                                                10
  104 FORMAT(/8H ISTAT =,I6/)                                             10
  105 FORMAT(4D7.1)                                                       12
  106 FORMAT(//9X,I3,7(9X,I3)/)                                           13
  107 FORMAT((I4,8D12.5))                                                 14
  108 FORMAT(/40H   L   I   J   K          XSURF          YSURF/)         15
  109 FORMAT(/24H   L   I   J   K        ZSURF/)                          16
  110 FORMAT(4I3,2D16.9)                                                  17
  111 FORMAT(4I3,D16.9)                                                   18
  112 FORMAT(/17H LL   M          GPP/)                                   19
  113 FORMAT(I3,I4,D16.9)                                                 20
  114 FORMAT(23H POLE-POLE COEFFICIENTS/)                                 21
  115 FORMAT(1H1,3X,24HCHECK OF IDENTITY MATRIX/)                         22
  116 FORMAT(1H1,3X,89HDIPOLE-DIPOLE INVERSE MATRIX (H MATRIX) FOR A SUB  23
```

```
     1SURFACE GEOMETRY CONSISTING OF 16 BLOCKS/)
 117 FORMAT(1H1,2X,17HCOLUMN DEPENDENCE/)
 118 FORMAT(I7,F10.1)
 119 FORMAT(//9X,I3,6(9X,I3)/)
 120 FORMAT((I4,7D12.5))
 501 FORMAT(16D5.1)
 502 FORMAT(1H1,13H   TEST CASE -,I3//54H    BACKGROUND RESISTIVITY - 1.0
     1    SOURCE CURRENT - 1.0//22H    BLOCK RESISTIVITIES//61H    BLOCK
     2          MODEL               PREDICTED          PERCENT /62H   NUMBER
     3     RESISTIVITY          RESISTIVITY       DIFFERENCE/)
 503 FORMAT(I7,2X,2D19.9,F14.4)
 504 FORMAT(/21H    SURFACE POTENTIALS//96H     SOURCE   ELECTRODE      RECE
     1IVER   ELECTRODE         TOTAL SURFACE         PRIMARY             SECONDAR
     2Y/96H        COORDINATES               COORDINATES              POTENTIAL
     3          POTENTIAL           POTENTIAL/)
 505 FORMAT(4H    (,F3.1,1H,,F3.1,3H) (,F3.1,1H,,F3.1,5H)    (,F3.1,1H,,F
     13.1,3H) (,F3.1,1H,,F3.1,1H),3D18.9)
 506 FORMAT(1H1,59X,32HPERCENT SURFACE POTENTIAL CHANGE/56X,39HDUE TO T
     1HE FOLLOWING RESISTIVTY CHANGES//49X,39H4% IN        3% IN       2%
     2IN       1% IN/                                                  47X,42H1
     3ST LAYER   2ND LAYER   3RD LAYER   4TH LAYER/)
 507 FORMAT(4H    (,F3.1,1H,,F3.1,3H) (,F3.1,1H,,F3.1,5H)    (,F3.1,1H,,F
     13.1,3H) (,F3.1,1H,,F3.1,1H),4F11.4)
      WRITE(6,100)
      CALL PRTIME
      PI=3.14159265358979324D0
C          INTEGRATION CONSTANTS
      TEMP=.005D0/PI
      TEMP1=.01D0/PI
C          ESTABLISH PROBE COORDINATES
      XPP(1)=-1.0D0
      YPP(1)=-1.0D0
      XPP(2)=.956992776D0
      YPP(2)=.956992776D0
      YPP(3)=.939450777300
      XPP(3)=.1320311964D0
      YPP(4)=.8214674261D0
      XPP(4)=-.4185585595D0
      YPP(5)=.3059121160D0
      XPP(5)=-.8404866312700
      YPP(6)=-.2961981327D0
      XPP(6)=-.8137976813D0
      YPP(7)=-.7454695421D0
      XPP(7)=-.3798357035D0
      YPP(8)=-.8062257748D0
      XPP(8)=0.0D0
      YPP(9)=-.6901706858D0
      XPP(9)=.3516595289D0
      YPP(10)=-.2536489269D0
      XPP(10)=.6968946992D0
      YPP(11)=.2418447626D0
      XPP(11)=.6544630243D0
      YPP(12)=.5977053469D0
      XPP(12)=.3045460855D0
      YPP(13)=.6324555320D0
      XPP(13)=0.0D0
      YPP(14)=.4183300132D0
```

```
      XPP(14)=-YPP(14)
      YPP(15)=0.0D0
      XPP(15)=-.5477225575D0
      YPP(16)=-.3535533905D0
      XPP(16)=YPP(16)
      YPP(17)=-.4428613435D0
      XPP(17)=-.0622401028700
      YPP(18)=-.3935291738D0
      XPP(18)=.0539015102D0
      YPP(19)=-.2236067977D0
      XPP(19)=-YPP(19)
      YPP(20)=0.0D0
      XPP(20)=.2236067977D0
      YPP(21)=.2633269333D0
      XPP(21)=.0370081866D0
      YPP(22)=.0685226827 3D0
      XPP(22)=-.1882645235D0
      YPP(23)=-.1575091888D0
      XPP(23)=-.0802549402 3D0
C          LOOP TO DEVELOP POLE-POLE PAIRS
      K=0
      DO 1 I=1,2
      DO 1 J=3,23
      K=K+1
      SXPP(K)=XPP(I)+2.0D0
      SYPP(K)=YPP(I)+2.0D0
      RXPP(K)=XPP(J)+2.0D0
    1 RYPP(K)=YPP(J)+2.0D0
      CALL PRTIME
      DO 60 L=1,42
      WRITE(6,108)
      LL=L
C          INTEGRATION OVER THE YZ PLANE (XSURF) AND THE XZ PLANE (YSURF)
      DO 20 I=1,3
      AI=I
      XP=AI
      YP=XP
      DO 20 J=1,2
      AJ=J
      DO 20 K=1,4
      AK=0.25D0+0.25D0*(K-1)
      SUM1=0.0D0
      SUM2=0.0D0
      DO 10 N=1,19,2
      YX=AJ+0.05D0*N
      XY=YX
      DO 10 M=1,9,2
      Z=AK+0.025D0*M
      SUM1=SUM1+FDOUB(XP,YX,Z,SXPP(L),SYPP(L),RXPP(L),RYPP(L),1)
   10 SUM2=SUM2+FDOUB(XY,YP,Z,SXPP(L),SYPP(L),RXPP(L),RYPP(L),2)
      XSURF(L,I,J,K)=TEMP*SUM1
      YSURF(L,I,J,K)=TEMP*SUM2
   20 WRITE(6,110) L,I,J,K,XSURF(L,I,J,K),YSURF(L,I,J,K)
      WRITE(6,109)
C          INTEGRATION OVER THE XY PLANE (ZSURF)
      DO 40 I=1,5
      AI=0.25D0+0.25D0*(I-1)
```

```
      Z=AI
      DO 40 J=1,2
      AJ=J
      DO 40 K=1,2
      AK=K
      SUM3=0.0D0
      DO 30 N=1,19,2
      X=AJ+0.05D0*N
      DO 30 M=1,19,2
      Y=AK+0.05D0*M
   30 SUM3=SUM3+FROUT(X,Y,Z,SXPP(L),SYPP(L),RXPP(L),RYPP(L),3)
      ZSURF(L,I,J,K)=TEMP1*SUM3
   40 WRITE(6,111) L,I,J,K,ZSURF(L,I,J,K)
      WRITE(6,112)
C        CALCULATION OF GEOMETRIC FACTORS FOR POLE-POLE PAIRS
      M=0
      DO 50 K=1,4
      KK=K+1
      DO 50 J=1,2
      JJ=J+1
      DO 50 I=1,2
      II=I+1
      M=M+1
      GPP(LL,M)=XSURF(L,II,J,K)-XSURF(L,I,J,K)+YSURF(L,JJ,I,K)-YSURF(L,J
     1,I,K)+ZSURF(L,KK,I,J)-ZSURF(L,K,I,J)
   50 WRITE(6,113) LL,M,GPP(LL,M)
      LT=MOD(L,2)
      IF (LT.EQ.0) CALL PRTIME
   60 CONTINUE
      CALL PRTIME
      WRITE(6,100)
      WRITE(6,114)
      DO 63 M1=1,9,8
      M2=M1+7
   63 WRITE(6,107) (L,(GPP(L,M),M=M1,M2),L=1,42)
C        CALCULATION OF GEOMETRIC FACTORS FOR DIPOLE-DIPOLE PAIRS
      DO 212 M=1,16
      DO 211 I=1,20
  211 GDP(I,M)=GPP(I,M)-GPP(I+1,M)-GPP(21+I,M)+GPP(22+I,M)
  212 CONTINUE
      WRITE(6,100)
      WRITE(6,101)
      DO 90 M1=1,9,8
      M2=M1+7
      WRITE(6,106) (M,M=M1,M2)
   90 WRITE(6,107) (L,(GDP(L,M),M=M1,M2),L=1,20)
      DO 91 I=1,20
C        CALCULATION OF THE INVERSE
      DO 91 J=1,16
   91 GDPI(I,J)=GDP(I,J)
      CALL PRTIME
      CALL GID(20,16,20,512,GDPI,U,AFLAG,ATEMP)
      CALL PRTIME
      WRITE(6,117)
      DO 308 I=1,16
  308 WRITE(6,118) I,AFLAG(I)
      CALL PRTIME
```

```
      DO 309 I=1,20
      DO 309 J=1,16
  309 HDP(J,I)=GDPI(I,J)
      CALL PRTIME
      DO 310 I=1,16
      DO 310 J=1,16
      CKI(I,J)=0.0D0
      DO 310 IJ=1,20
  310 CKI(I,J)=CKI(I,J)+HDP(I,IJ)*GDP(IJ,J)
      CALL PRTIME
      WRITE(6,115)
      DO 311 M1=1,9,8
      M2=M1+7
      WRITE(6,106) (M,M=M1,M2)
  311 WRITE(6,107) (L,(CKI(L,M),M=M1,M2),L=1,16)
      CALL PRTIME
      WRITE(6,116)
      DO 312 M1=1,11,10
      M2=M1+9
      WRITE(6,102) (M,M=M1,M2)
  312 WRITE(6,103) (L,(HDP(L,M),M=M1,M2),L=1,16)
C   DIPOLE-DIPOLE PAIR GENERATION
      K=0
      DO 3 J=3,22
      J1=J+1
      K=K+1
      SX1(K)=XPP(1)+2.D0
      SY1(K)=YPP(1)+2.D0
      SX2(K)=XPP(2)+2.D0
      SY2(K)=YPP(2)+2.D0
      RX1(K)=XPP(J)+2.D0
      RY1(K)=YPP(J)+2.D0
      RX2(K)=XPP(J1)+2.D0
    3 RY2(K)=YPP(J1)+2.D0
      TEMP=1.0D0/(2.0D0*PI)
      DO 2 I=1,20
      AM=DSQRT((SX1(I)-RX1(I))**2+(SY1(I)-RY1(I))**2)
      AN=DSQRT((SX1(I)-RX2(I))**2+(SY1(I)-RY2(I))**2)
      BN=DSQRT((SX2(I)-RX2(I))**2+(SY2(I)-RY2(I))**2)
      BM=DSQRT((SX2(I)-RX1(I))**2+(SY2(I)-RY1))**2)
    2 PHIP(I)=TEMP*(1.0D0/AM-1.0D0/AN-1.0D0/BM+1.0D0/BN)
      DO 19 L=1,73
      READ (5,501) RHOM
      DO 13 I=1,16
   13 FM(I)=3.6D0*((1.0D0-RHOM(I))/(1.0D0+2.0D0*RHOM(I)))
      DO 15 I=1,20
      PSI(I)=0.0D0
      DO 14 J=1,16
   14 PSI(I)=PSI(I)+GDP(I,J)*FM(J)
      PHIS(I)=TEMP*PSI(I)
   15 PHIT(I)=PHIP(I)-PHIS(I)
      DO 17 I=1,16
      FP(I)=0.0D0
      DO 16 J=1,20
   16 FP(I)=FP(I)+HDP(I,J)*PSI(J)
   17 RHOP(I)=(3.6D0-FP(I))/(2.0D0*FP(I)+3.6D0)
      WRITE(6,502) L
```

```
      DO 18 I=1,16
      T1=100.*SNGL((RHOM(I)-RHOP(I))/RHOM(I))
   18 WRITE(6,503) I,RHOM(I),RHOP(I),T1
      WRITE(6,504)
      DO 19 I=1,20
      SXX1=SNGL(SX1(I))
      SXX2=SNGL(SX2(I))
      SYY1=SNGL(SY1(I))
      SYY2=SNGL(SY2(I))
      RXX1=SNGL(RX1(I))
      RXX2=SNGL(RX2(I))
      RYY1=SNGL(RY1(I))
      RYY2=SNGL(RY2(I))
   19 WRITE(6,505) SXX1,SYY1,SXX2,SYY2,RXX1,RYY1,RXX2,RYY2,PHIT(I),PHIP(
     1I),PHIS(I)
      L=74
      DO 21 K=1,4
      JI=(K-1)*4+1
      JF=K*4
      DO 21 J=JI,JF
      IF (MOD(K,2).EQ.0) GO TO 420
      RHO (J)=(2**(K/2+2))
      GO TO 21
  420 RHO (J)=(2**(K/2))
   21 FM(J)=3.6D0*((1.0D0-RHOM(J))/(1.0D0+2.0D0*RHOM(J)))
      DO 23 I=1,20
      PSI(I)=0.0D0
      DO 22 J=1,16
   22 PSI(I)=PSI(I)+GDP(I,J)*FM(J)
      PHIS(I)=TEMP*PSI(I)
      PHIT(I)=PHIP(I)-PHIS(I)
   23 T2(I)=PHIT(I)
      DO 25 I=1,16
      FP(I)=0.0D0
      DO 24 J=1,20
   24 FP(I)=FP(I)+HDP(I,J)*PSI(J)
   25 RHOP(I)=(3.6D0-FP(I))/(2.0D0*FP(I)+3.6D0)
      WRITE(6,502) L
      DO 26 I=1,16
      T1=100.*SNGL((RHOM(I)-RHOP(I))/RHOM(I))
   26 WRITE(6,503) I,RHOM(I),RHOP(I),T1
      WRITE(6,504)
      DO 27 I=1,20
      SXX1=SNGL(SX1(I))
      SXX2=SNGL(SX2(I))
      SYY1=SNGL(SY1(I))
      SYY2=SNGL(SY2(I))
      RXX1=SNGL(RX1(I))
      RXX2=SNGL(RX2(I))
      RYY1=SNGL(RY1(I))
      RYY2=SNGL(RY2(I))
   27 WRITE(6,505) SXX1,SYY1,SXX2,SYY2,RXX1,RYY1,RXX2,RYY2,PHIT(I),PHIP(
     1I),PHIS(I)
      DO 31 L=1,4
      T4=1.0D0+0.01D0*(5-L)
      JI=(L-1)*4+1
      JF=L*4
```

```
      DO 28 J=JI,JF
      RHOM(J)=T4*RHOM(J)
   28 FM(J)=3.6D0*((1.0D0-RHOM(J))/(1.0D0+2.0D0*RHOM(J)))
      DO 33 I=1,20
      PSI(I)=0.0D0
      DO 29 J=1,16
   29 PSI(I)=PSI(I)+GDP(I,J)*FM(J)
      PHIS(I)=TEMP*PSI(I)
      PHIT(I)=PHIP(I)-PHIS(I)
   33 T3(L,I)=100.*SNGL((T2(I)-PHIT(I))/T2(I))
      DO 31 J=JI,JF
      RHOM(J)=RHOM(J)/T4
   31 FM(J)=3.6D0*((1.0D0-RHOM(J))/(1.0D0+2.0D0*RHOM(J)))
      WRITE(6,506)
      DO 32 I=1,20
   32 WRITE(6,507) SX1(I),SY1(I),SX2(I),SY2(I),RX1(I),RY1(I),RX2(I),RY2(
     1I),(T3(L,I),L=1,4)
      CALL PRTIME
      GO TO 99
   98 WRITE(6,104) ISTAT
      STOP
   99 END
@SYSTEM**LTPRO.FOR7C,IS  FCN1
      DOUBLE PRECISION FUNCTION FDOUB(X,Y,Z,SX,SY,RX,RY,NS)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      RRP2=(X-RX)**2+(Y-RY)**2+Z**2
      RSP2=(X-SX)**2+(Y-SY)**2+Z**2
      RRP3=(RRP2)**1.5
      RSP3=(RSP2)**1.5
      GO TO (10,20,30),NS
   10 FDOUB=(RRP2*(X-SX)+RSP2*(X-RX))/(RRP3*RSP3)
      GO TO 40
   20 FDOUB=(RRP2*(Y-SY)+RSP2*(Y-RY))/(RRP3*RSP3)
      GO TO 40
   30 FDOUB=(Z*(RRP2+RSP2))/(RRP3*RSP3)
   40 RETURN
      END
@FOR,IS PRTIME
      SUBROUTINE PRTIME
      DIMENSION A(10)
      J=-1
      GO TO 1
      ENTRY SETIME(IT1)
      J=0
      GO TO 1
      ENTRY TIMINC(IT2)
      J=1
    1 CALL TIME(I1,I2)
      T=2.E-4*I2
      IHR=T/3600.
      I3=AMOD(T,3600.)
      IMIN=I3/60.
      SEC=AMOD(T,60.)
      WRITE(6,20) IHR,IMIN,SEC
   20 FORMAT(20H0  REAL TIME CLOCK  ,I2,3H : ,I2,3H : ,F7.4)
      IF (J) 5,2,3
    2 A(IT1)=T
```

```
      WRITE(6,21) IT1                                                   PT21
   21 FORMAT(1H+,46X,18HTIME OF SET POINT ,I2)                          PT22
      GO TO 5                                                           PT23
    3 T=T-A(IT2)                                                        PT24
      WRITE(6,22) IT2,T                                                 PT25
   22 FORMAT(1H+,46X,20HTIME FROM SET POINT ,I2,3H : ,F9.4,4H SEC)      PT26
    5 RETURN                                                            PT27
      END                                                               PT28
@SYSTEM$*ALTPRO.FOR7C,IS  GID
      SUBROUTINE GID(NR,NC,MR,MM,A,U,AFLAG,ATEMP)
C THE GENERALIZED UNIQUE INVERSE OF DOUBLE PRECISION MATRIX A          GIDH
C          IS COMPUTED WITH TRANSPOSE OF THIS INVERSE REPLACING MATRIX A GIDH
C          IN STORAGE.  ORIGINAL MATRIX A MUST NOT HAVE A COMPLETELY    GIDH
C          NULL INITIAL COLUMN VECTOR.  SUBROUTINES GIP, GID, AND GIC   GIDH
C          HANDLE REAL, DOUBLE PRECISION, AND COMPLEX MATRICES.  THE    GIDH
C          GENERALIZED UNIQUE INVERSE OF A REAL SQUARE NONSINGULAR MATRIXGIDH
C          WITH RANK EQUAL TO ORDER IS THE SAME AS THE CONVENTIONAL     GIDH
C          INVERSE.  THE CONJUGATE TRANSPOSE OF THE GENERALIZED UNIQUE  GIDH
C          INVERSE OF MATRIX A IS IDENTICAL WITH THE GENERALIZED UNIQUE GIDH
C          INVERSE OF THE CONJUGATE TRANSPOSE OF MATRIX A.              GIDH
C                                                                       GIDH
C THIS IS L. R. GROSENBAUGH'S 08-16-66 MODIFICATION OF GINV2 BY B. RUST,GIDH
C          W. R. BURRUS, AND C. SCHNEEBERGER WHICH APPEARED IN MAY 1966 GIDH
C          COMMUNICATIONS OF THE ACM 9, PAGES 381-385,387.              GIDH
C                                                                       GIDH
C COLUMNS OF THE ORIGINAL MATRIX ARE SUCCESSIVELY ORTHOGONALIZED BY     GIDH
C          DOUBLE APPLICATION OF THE GRAM-SCHMIDT PROCESS.  THIS        GIDH
C          TRANSFORMS ANY COLUMN THAT LINEARLY DEPENDS ON PRECEDING     GIDH
C          COLUMNS INTO A NULL VECTOR, AND ANY NULL VECTOR IS IMMEDIATELYGIDH
C          REPLACED BY A NONNULL VECTOR APPROPRIATELY DERIVED FROM THE  GIDH
C          BOOKKEEPING MATRIX.  THE ORTHOGONALIZED MATRIX A (WITH NULL  GIDH
C          VECTOR REPLACEMENTS FLAGGED BY ZEROS IN VECTOR AFLAG) COULD  GIDH
C          BE PRESERVED BY RETURN AT STATEMENT 100.                     GIDH
C                                                                       GIDH
C  A IS ORIGINALLY THE INPUT MATRIX, ULTIMATELY REPLACED BY             GIDH
C          THE TRANSPOSE (NOT THE CONJUGATE TRANSPOSE) OF ITS COMPUTED  GIDH
C          GENERALIZED UNIQUE INVERSE.                                  GIDH
C                                                                       GIDH
C  AFLAG IS COMPUTED OUTPUT VECTOR WITH ELEMENT 0.0 FOR EACH COLUMN OF  GIDH
C          THE ORIGINAL INPUT MATRIX THAT WAS LINEARLY DEPENDENT OR NULL,GIDH
C          AND ELEMENT 1.0 FOR EACH LINEARLY INDEPENDENT NONNULL COLUMN, GIDH
C          SO THAT SUM OF NC ELEMENTS GIVES RANK OF ORIGINAL MATRIX AND GIDH
C          ZEROS IDENTIFY ORIGINALLY DEPENDENT OR NULL COLUMNS.         GIDH
C                                                                       GIDH
C  U IS MERELY THE UPPER TRIANGULAR BOOKKEEPING MATRIX OBTAINED BY      GIDH
C          POST-MULTIPLYING IDENTITY MATRIX BY APPROPRIATE ELEMENTARY   GIDH
C          COLUMNAR OPERATOR MATRICES.                                  GIDH
C                                                                       GIDH
C  ATEMP IS MERELY THE VECTOR USED FOR TEMPORARY WORKING STORAGE.       GIDH
C                                                                       GIDH
C  NR IS THE ACTUAL NUMBER OF ROWS IN A PARTICULAR MATRIX A, DETERMINED GIDH
C          AT OBJECT TIME.  IT WILL BE SET NEGATIVE AND CONTROL WILL BE GIDH
C          RETURNED TO THE CALLING PROGRAM IF NR OR NC IS LESS THAN     GIDH
C          1 OR GREATER THAN MR, OR IF THE INITIAL VECTOR IS NULL.      GIDH
C                                                                       GIDH
C  NC IS THE ACTUAL NUMBER OF COLUMNS IN MATRIX A, ALSO AT OBJECT TIME, GIDH
C                                                                       GIDH
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C   MR IS THE ORDER (I.E., THE MAXIMUM NUMBER OF ROWS OR COLUMNS) OF THE GTDH
C          LARGEST SQUARE MATRIX THAT CAN BE HANDLED BY THE SUBROUTINE.  GTDH
C          PRIOR TO COMPILATION, CALLING PROGRAM MUST ASSIGN A NUMERICAL GTDH
C          VALUE TO THIS PARAMETER, AND THE SAME VALUE MUST BE USED IN   GTDH
C          APPROPRIATE DIMENSION SPECIFICATION STATEMENTS IN THE CALLING GTDH
C          PROGRAM (DIMENSION, COMMON, REAL, DOUBLE PRECISION, COMPLEX,  GTDH
C          ETC.) FOR SQUARE ARRAYS A, U AND FOR VECTORS AFLAG, ATEMP.    GTDH
C                                                                        GTDH
C   N IS THE TOLERANCE THRESHHOLD FOR DETECTING NON-INDEPENDENT COLUMNS, GTDH
C          AND SHOULD BE SET IN SUBROUTINE GIS (EQUAL TO THE NUMBER OF   GTDH
C          BINARY BITS IN THE FLOATING POINT MANTISSA OF THE REAL PART   GTDH
C          OF AN ELEMENT OF MATRIX A).                                   GTDH
      DIMENSION AFLAG(MR)                                                GTDH
      DOUBLE PRECISION A(MR,NC),U(MM),ATEMP(MR)                          GTDH
      DOUBLE PRECISION FAC,DOT1,DOT2,ZER,UNI,TOL,TEN,HAF                 GTDH
      LAD(I,J)=I+(J*(J-1))/2                                             GTDH A
      DATA ZER/0.0D0/,UNI/1.0D0/,TEN/10.0D0/,HAF/.5D0/                   GTDH
      IF ((NR .LT. 1) .OR. (NR .GT. MR))  GO TO 3                        GTDH 6
      IF ((NC .LT. 1) .OR. (NC .GT. MR))  GO TO 3                        GTDH
      GO TO 4                                                            GTDH
    3 NR=-NR                                                             GTDH
      RETURN                                                             GTDH
    4 N=54                                                               GTDH
      TOL=(TEN*HAF**N)**2                                                GTDH
      DO 10 I=1,NC                                                       GTDH
      DO  5 J=I,NC                                                       GTDH
      IJ=LAD(I,J)                                                        GTD  A
    5 U( IJ)=ZER                                                         GTD
      II=LAD(I,I)                                                        GTD  A
   10 U( II)=UNI                                                         GTD
      FAC=ZER                                                            GTDH
      DO 11 I=1,NR                                                       GTDH
   11 FAC=FAC+       (A(I,1))*A(I,1)                                     GTDH
      IF (FAC .LT. TOL) GO TO 3                                          GTDH
      FAC=UNI/DSQRT(FAC)                                                 GTDH
      DO 15 I=1,NR                                                       GTDH
   15 A(I,1)=A(I,1)*FAC                                                  GTDH
   20 U(  1)=FAC                                                         GTD
      AFLAG(1)=1.0                                                       GTDH
      IF (NC .EQ. 1)  GO TO 100                                          GTDH
      DO  85 J=2,NC                                                      GTDH
      DOT1=ZER                                                           GTDH
      DO 29 I=1,NR                                                       GTDH
   29 DOT1=DOT1+       (A(I,J))*A(I,J)                                   GTDH
      JM1=J-1                                                            GTDH
      IF (DOT1 .LT. TOL)  GO TO 55                                       GTDH
      DO 40 L=1,2                                                        GTDH
      DO 30 K=1,JM1                                                      GTDH
      ATEMP(K)=ZER                                                       GTDH
      DO 30 I=1,NR                                                       GTDH
   30 ATEMP(K)=ATEMP(K)+       (A(I,K))*A(I,J)                           GTDH
      DO 40 K=1,JM1                                                      GTDH
      DO 35 I=1,NR                                                       GTDH 1
   35 A(I,J)=A(I,J)-ATEMP(K)*A(I,K)*AFLAG(K)                             GTDH 1
      DO 40 I=1,K                                                        GTDH 1
      IJ=LAD(I,J)                                                        GTD A1
      IK=LAD(I,K)                                                        GTD B1
```

```
45  U( IJ)=U( IJ)-ATEMP(K)*U( IK)                                    GTD   1
    DOT2=ZER                                                         GTDH  1
    DO 49 I=1,NR                                                     GTDH  1
49  DOT2=DOT2+        (A(I,J))*A(I,J)                                GTDH  1
C                                                                    GTDH  1
    IF (DOT2 .LT. TOL)  GO TO 55                                     GTDH  1
    IF (DOT2/DOT1 .GT. TOL)  GO TO 70                                GTDH  1
55  DO 60 I=1,JM1                                                    GTDH  1
    ATEMP(I)=ZER                                                     GTDH  1
    DO 60 K=1,I                                                      GTDH  1
    KI=LAD(K,I)                                                      GTD  A1
    KJ=LAD(K,J)                                                      GTD  B1
60  ATEMP(I)=ATEMP(I)+       (U( KI))*U( KJ)                         GTD   1
    DO 65 I=1,NR                                                     GTDH  1
    A(I,J)=ZER                                                       GTDH  1
    DO 65 K=1,JM1                                                    GTDH  1
65  A(I,J)=A(I,J)-ATEMP(K)*A(I,K)*AFLAG(K)                           GTDH  1
    AFLAG(J)=0.0                                                     GTDH  1
    FAC=ZER                                                          GTDH  1
    DO 69 I=1,J                                                      GTDH  1
    IJ=LAD(I,J)                                                      GTD  A1
69  FAC =FAC +        (U( IJ))*U( IJ)                                GTD   1
    FAC=UNI/DSQRT(FAC)                                               GTDH  1
    GO TO 75                                                         GTDH  1
70  AFLAG(J)=1.0                                                     GTDH  1
    FAC=UNI/DSQRT(DOT2)                                              GTDH  1
75  DO 80 I=1,NR                                                     GTDH  1
80  A(I,J)=A(I,J)*FAC                                                GTDH  1
    DO 85 I=1,J                                                      GTDH  1
    IJ=LAD(I,J)                                                      GTD  A1
85  U( IJ)=U( IJ)*FAC                                                GTD   1
100 CONTINUE                                                         GTDH  1
    DO 130 J=1,NC                                                    GTDH  1
    DO 130 I=1,NR                                                    GTDH  1
    FAC =ZER                                                         GTDH  1
    DO 120 K=J,NC                                                    GTDH  1
    JK=LAD(J,K)                                                      GTD  A1
120 FAC =FAC +        (A(I,K))*U( JK)                                GTDH  1
130 A(I,J)=FAC                                                       GTDH  1
    RETURN                                                           GTDH  1
    END                                                              GTDH  1
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A numerical inversion technique was developed for resistivity data but found to be unsuitable for application to data with large errors or data which does not conform closely to the assumptions in the technique. The theoretical development is included since it contains some innovations concerning the modeling of the electrical response of a media with variable resistivity. (U).

A field program was carried out to test the feasibility of the measurement of the electroseismic effect. The electroseismic effect is defined in this report as the change in resistivity induced during the passage of seismic waves. Measurements were made in the Wenner configuration at a single location in recent coastal plane sediments of central Georgia. Voltage variations were recorded which could be correlated with the seismic arrivals from two pounds of explosives at about 250 feet. Using the theory developed in this report for its interpretation, the electrical response could be used to infer changes in resistivity at depth induced by seismic waves. Measurement of the electroseismic phenomenon is feasible but more research is needed to develop the interpretation theory and test the electroseismic response of different types of rocks. (U).

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