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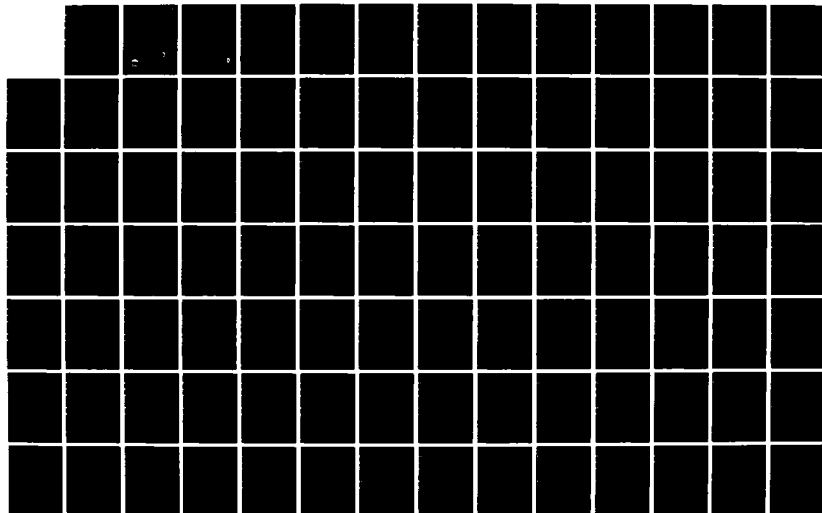
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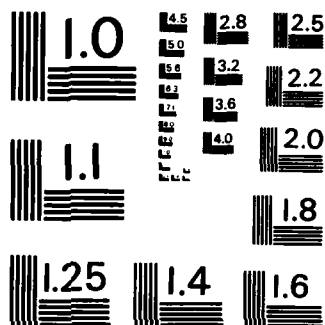
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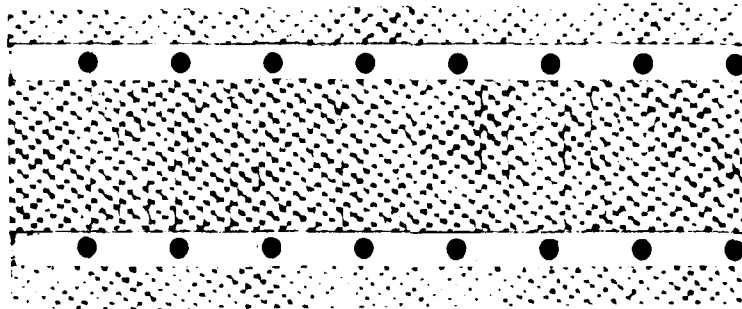


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Coupling of Airborne Sound
Into the Earth

H.E. Bass and L.N. Bolen
PARGUM Report 84-01

Final Report

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Physical Acoustics Research Group

The University of Mississippi
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Foreword

The work reported here was accomplished, to a large extent, by Mr. James Sabatier, a Ph.D. candidate. This report, modified in format, will serve as his Ph.D. dissertation and will be available as such with the same title. Much of the theoretical section is based upon unpublished work by Dr. Keith Attenborough, The Open University, England. The authors gratefully acknowledge his contributions and cooperation.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) As an acoustic wave propagates above the surface of the earth, part of the energy is transferred from motion of air to motion of the earth's surface which can be detected by a geophone. The purpose of the study described here was to establish the physical mechanisms responsible for this acoustic to seismic transfer of energy, to develop a mathematical formulation for quantitative predictions of the acoustic/seismic transfer function, and to collect data for comparison to the physical model.		

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➤ The physical model chosen to describe coupling of energy into the earth was developed by Biot and later extended by Stoll primarily for describing sound propagation in ocean sediments. The Biot-Stoll model describes sound propagation in a medium composed of fluid saturated pores and an elastic frame (matrix). The differential equations which arise from this formalism allow for a fast wave which propagates, primarily, in the frame and a slow wave which propagates, primarily, in the fluid. For our application we assume that the fluid is air and that the porous material is a layer between the air (an upper semi-infinite half space) and homogeneous clay (a lower semi-infinite half space). The resultant boundary value problem was solved for amplitude and phase of the acoustic wave above the surface, acoustic wave in the pores of the porous layer, seismic motion of the pore frame, and seismic motion of the lower clay half space. Shear motion was included for completeness. The incoming sound wave was assumed to be planar.

✓ Calculations suggest that the predicted transfer functions are not strongly affected by the flow resistance of the porous layer, the elastic properties of the clay, and the thickness of the porous layer. These three quantities were independently measured. The transfer function was measured for a microphone probe buried in the porous layer, and triaxial geophones in the porous layer and underlying clay. Measurements were made for acoustic frequencies between 30 and 300 Hz, for angles of incidence for the acoustic wave between 5° and 20° , and various depths for buried geophones and microphone probes.

Experimental values of the various transfer functions agree with predictions within a factor of two. The experimental results show fine structure not predicted which we attribute to multiple layers. Other quantities predicted by the model (attenuation of signal with depth, little dependence on angle of incidence, acoustic surface impedance) all agree equally well with experiment.

We conclude that the Biot-Stoll model is a good physical description of acoustic to seismic energy transfer. Additional avenues for future research are also discussed. Computer programs are included along with a representative sample of the experimental data.

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1. INTRODUCTION

The objective of this study was to establish the physical principles involved in coupling airborne sound into earth motion. The study was motivated by measurements made at the U.S. Army Corps Engineers Waterways Experiment Station (WES) in 1977. In these measurements, a speaker was suspended from a crane, the sound level in the far field was measured with a microphone above the surface, and geophone response was measured below the surface. The major findings^{1,2} were:

1. The geophone response had a magnitude 1000 times larger than one would expect from calculations based upon simple acoustic transmission through a boundary between two perfect fluids.

2. The magnitude of the geophone response is, within the accuracy of the measurements, independent of angle of incidence.

3. The transit time from speaker to microphone was approximately the same as from speaker to geophone and the speed of propagation was, within the accuracy of the measurements, the same as the speed of sound in air (343 m/sec).

4. The geophone signal varied in phase as one would expect of a Rayleigh Wave.

5. The geophone signal had well defined maxima and minima which could be accurately explained assuming interference in the upper boundary layer of the earth. The depth of this layer was defined by independent seismic refraction studies.

During the course of the study reported on here, a physical model consistent with these observations has been developed from which quantitative predictions can be made.

The first inquiry this laboratory received concerning this problem was from WES and was prompted by a field test during which airborne sound

sources had detonated smart mines. The first goal, then, was to develop an algorithm which would allow the sensor to discriminate against airborne sound. This was done by discriminating against geophone signals which correlate with above ground microphone signals. More recently, this correlation has been used to identify airborne sound source in a security system developed by Sandia Laboratories. The coupling between airborne and seismic signals, then, is not necessarily detrimental to military applications.

In the following sections several experiments and theoretical results will be presented which represent the progression of events leading to a physical model for the coupling process.

Initially, the theoretical approach was to treat the boundary as a separation between homogeneous half spaces and treat the shallow porous upper layer of the earth as an impedance matching layer.^{3,4,5} It was thought that this approach plus consideration of Rayleigh Waves in the earth instead of compressional waves would give the measured seismic amplitudes. Even with the relatively slow Rayleigh Wave velocity, however, the acoustic resistance (ρc) ratio between air and the earth is so small that most all the impinging energy would be reflected. This approach was abandoned after one year.

The initial experimental concerns were the extent to which the speaker was decoupled from the earth and the potential contributions of the geophone signal by direct airborne waves. Several experiments were conducted to insure direct coupling though speaker supports would not account for the geophone signal. Speakers were isolated from the ground using flexible cables and inner tubes with no effect on the measured seismic signal. Perhaps the most conclusive experiment was the firing of a freely falling blank pistol - the seismic/acoustic coupling remained unchanged.

At this stage in the research (about one year after beginning), it was concluded that airborne sound is, indeed, coupled into motion of the earth

frame with an amplitude larger than can be predicted from homogeneous layer theory.

A major breakthrough in the understanding of this problem came as a result of progress on another research project in this laboratory. To explain measurements of sound propagation through ocean sediments, it is common to use what is known as the Biot-Stoll Model.⁶ This model basically allows for two waves in the porous medium, one associated with the matrix, another associated with motion of the pore fluid relative to the matrix. At a meeting organized by this laboratory on the status of long range acoustic propagation research,⁷ the possibility of using the Biot-Stoll Model to explain coupling of airborne sound into the earth was explored. The physical principles were consistent with this problem, but the approximations used in underwater propagation codes were of concern. Following this meeting, Dr. Attenborough of the Open University of England agreed that this model offered most promise of explaining the seismic/acoustic coupling results. It was agreed that a joint effort would be fruitful, and cooperative measurements in this laboratory the following summer (1982) were arranged.

During the time Dr. Attenborough was visiting this laboratory it was agreed to address two major questions:

1. Is there an acoustic wave in the earth which can be attributed to motion of the pore fluid relative to the matrix?
2. If such an acoustic wave exists, is the velocity sufficiently low so that the acoustic resistance for this wave will allow for sufficient energy transfer? It was felt that if the wavelength of sound in the pores was much greater than a typical pore length (a few centimeters), transfer of energy to the pore walls by viscous drag would be quite small.

Both these questions were answered, to some degree, during the summer of 1982. Using a specially designed probe microphone (see Chapter 3) the

acoustic wave attributable to motion of air in the pores was detected, the attenuation of this wave with depth was measured and favorable comparisons with calculations made assuming a rigid porous medium were shown. These results were published in Reference 8. The same model used to compute attenuation was also used to predict the velocity of the acoustic wave in the earth. It was gratifying to find that the predicted speed decreases rapidly with decreasing frequency such that for a typical soil, the wavelength becomes independent of frequency below about 500 Hz with a wavelength of a few tens of centimeters. Measurements with the probe microphone illustrated that in the same medium, an acoustic signal could be observed down to depths of a few tens of centimeters. The pore depth is, in fact, comparable to the acoustic wavelength even at very low frequencies.

These results reinforced confidence in the Biot-Stoll Model and showed that previous knowledge in acoustic wave propagation in ocean sediments and above the surface of the earth could be applied directly to the seismic/acoustic coupling problem. The next step was to apply the Biot-Stoll Model quantitatively dropping the earlier assumption (commonly made in acoustics) that the frame is rigid. The result of that effort will be presented in Chapter 2.

2. THEORY

In this section application of the Biot-Stoll Model of sound propagation in a porous media to the air/earth boundary will be described. In the first section, the procedure for computing propagation coefficients in the media as developed by Attenborough^{9,10} will be presented. In the next section the boundary value problem for this case will set up and solved. This treatment is similar to that presented by Sides¹¹ except a shear wave term is also included. Finally measurable quantities will be defined and calculated.

Absent from this chapter are treatments of a spherically spreading source (plane waves are assumed), impulsive sources, and a soil with porosity varying with depth. The effect of spherical waves could be to introduce a sub-surface wave similar to the surface wave known in above ground propagation and which, above the ground, is dominant for certain source receiver geometries. By transforming from frequency to time domain, the current theory should be applicable to impulsive sounds but that process has not yet been developed. Varying porosity could improve coupling into the earth frame by providing a gradual change in the acoustic resistance with depth. These two extensions to the theory will probably be necessary before all experimental results can be explained.

The Biot-Stoll Model for wave propagation in a porous elastic medium was used to describe the coupling of an airborne acoustic wave into the porous elastic earth. The first layer or few tens of centimeters of the earth's surface is porous and will allow for the propagation of an acoustic wave, whether the surface is sand or grass covered soil. The porosity of a sand results from the packing of the sand particles. A grass covered soil's porosity might result from decaying organic matter and grass roots as well as the particle packing. This first layer was modeled as a two

dimensional homogeneous porous elastic medium characterized by a frame or matrix filled with air overlying a semi-infinite nonporous elastic clay.

From a plane wave analysis of the Biot-Stoll differential equations which govern the propagation of compressional waves, the attenuation coefficients and phase velocities of the allowed wave motions can be determined. After applying the boundary conditions at the boundaries of the air-sand-clay or air-soil-clay layer to solve for the amplitudes of the matrix and fluid motions, the specific normal acoustic surface impedance, the attenuation coefficients, and the surface transfer functions for the porous medium will be found.

Determination of Propagation Constants

The Biot-Stoll⁶ differential equations for compressional wave propagation are

$$\nabla^2 (He - C\xi) = \frac{\partial^2}{\partial t^2} (\rho e - \rho_f \xi) \quad (1a)$$

and

$$\nabla^2 (Ce - M\xi) = \frac{\partial^2}{\partial t^2} (\rho_f e - m\xi) - \frac{n}{\kappa} \frac{\partial \xi}{\partial t} \quad (1b)$$

The terms H, C and M are frequency dependent constants that characterize the porous elastic matrix and will be discussed later in this section. The quantity e represents the matrix dilatation, $e = \nabla \cdot \vec{u}$ where $\vec{u}$ is the matrix displacement. The dilatation of the fluid relative to the matrix is ξ and

$$\xi = \nabla \cdot \vec{w}$$

where

$$\vec{w} = \Omega(\vec{u} - \vec{U})$$

is the relative fluid velocity; $\vec{U}$ is the fluid displacement and Ω is the porosity. The density of the matrix and the fluid are identified with the

terms ρ and ρ_f while η and κ are the dynamic fluid viscosity and the permeability of the matrix. The term $\frac{\eta}{\kappa} \frac{\partial \xi}{\partial t}$ allows for damping through viscous drag as the fluid and matrix move relative to each other. The term m is a dimensionless parameter that accounts for the fact that not all the fluid moves in the direction of the macroscopic pressure gradient because the pores do not all run normal to the surface. This term is related to the Biot added mass term and allows for damping due to inertial drag between the fluid and matrix as they move relative to each other. This quantity is expressed as $q^2 \rho_f / \Omega$ where q^2 , the tortuosity, is a constant greater than or equal to one and has the particular value $1/\cos\theta$ when the pores are cylindrical and are inclined at θ to the surface normal.

The terms H , C , and M are complex constants that characterize the elastic response of the matrix. These constants are determined from the bulk and shear moduli of the solid material, the bulk modulus of the fluid and the bulk modulus of the matrix. The relationships are as follows

$$H = \frac{[K_r - K_b]^2}{[D - K_b]^2} + K_b + \frac{4}{3} \mu \quad (2a)$$

$$C = K_r \frac{K_r - K_b}{D - K_b} \quad (2b)$$

$$M = \frac{K_r^2}{D - K_b} \quad (2c)$$

with

$$D = K_r \left[1 + \Omega \left(\frac{K_r}{K_f} - 1 \right) \right]. \quad (2d)$$

In the above expressions, K_r is the bulk modulus of the solid material, K_f is the bulk modulus of the fluid and μ and K_b are the shear and bulk moduli of the matrix. The elastic constants can be made complex through a complex compressibility of the pore fluid. However, at this stage they were assumed to be real. The bulk and shear moduli were determined from the expressions for compressional and shear wave speeds in an elastic solid, which are

$$v_s = [G/\rho]^{1/2} \quad (3)$$

and

$$v_p = [(B + \frac{4}{3} G)/\rho]^{1/2} \quad (4)$$

In these expressions, B and G are the bulk and shear moduli and ρ is the density of the medium. For the porous soil, it was assumed B was the frame bulk modulus, G was the frame shear modulus and ρ was the frame density. In the non-porous clay, it was assumed the bulk modulus B was the bulk modulus of the solid material, and G was the shear modulus of the same. These assumptions imply that the porous medium is composed of the same material as the clay but that it has been made porous by some means, say weathering or cultivation.

In equation (1b), Stoll⁶ replaces the viscosity by a viscosity correction factor, $\eta F(\lambda)$, where λ is a dimensionless quantity that is related to the thickness of the viscous boundary layer at the pore wall. Biot¹¹ developed expressions for $F(\lambda)$ for cylindrical and parallel sided pores in terms of the fluid viscosity and pore diameter. Attenborough¹² suggested that the dimensionless parameter λ for an arbitrary pore shape is

$$\lambda = \frac{\sqrt{s}}{n} \frac{[8\rho_f \eta^2 \omega]^{1/2}}{\Omega \phi} \quad (5)$$

where $\frac{\sqrt{s}}{n}$ is a shape factor ratio, ϕ is the flow resistivity and ω is the angular frequency. The static shape factor, n, relates λ for an arbitrary pore cross section to that of a cylindrical pore cross section while the pore shape factor, s, accounts for the fact that the pores may have varying cross sections along their lengths. The ranges of n and s as suggested by Attenborough are $1.5 > s > 1 > n > 0.5$. The viscosity correction factor $F(\lambda)$ is a complex function and is written as

$$F(\lambda) = -\frac{1}{4} \cdot \frac{\sqrt{i}\lambda T[\sqrt{i}\lambda]}{1 - \frac{2}{\sqrt{i}\lambda} T[\sqrt{i}\lambda]} \quad (6)$$

with $T[\sqrt{i}\lambda] = J_1[\sqrt{i}\lambda]/J_0[\sqrt{i}\lambda]$, where J_0 and J_1 are the zero and first order Bessel functions of the first kind.

The Biot-Stoll equations of motion admit two plane wave solutions and thus two propagation constants or wave speeds. The waves are referred to as the type one and type two waves or simply as fast and slow waves. For each wave there is both fluid and solid displacement and each wave is distinguished by its propagation coefficients. In sands and soils the fast wave primarily moves in the matrix or solid component while the slow wave moves primarily in the fluid. The exact relationship between the fluid and solid displacement will be determined in a later paragraph. The slow wave is a diffusion wave and it is highly attenuated and very dispersive as it propagates. The fast wave is analogous to the compressional wave that propagates in a solid and it is relatively unattenuated and not dispersive.

From a plane wave analysis of equations (1a) and (1b) the frequency equation determining the propagation constants can be found. If the plane waves $e = A \exp[i(\ell x - \omega t)]$ and $\xi = B \exp[i(\ell x - \omega t)]$ are chosen as solutions to equations 1a and 1b, the following expressions

$$(H\ell^2 - \rho\omega^2)A + (\rho_f\omega^2 - C\ell^2)B = 0 \quad (7a)$$

and

$$(C\ell^2 - \rho_f\omega^2)A + (m\omega^2 - M\ell^2 - i\omega F(\lambda)\frac{\eta}{\kappa})B = 0 \quad (7b)$$

are found after substitution. The determinant of the coefficients must be zero so one can write

$$\begin{vmatrix} H\ell^2 - \rho\omega^2 & \rho_f\omega^2 - C\ell^2 \\ C\ell^2 - \rho_f\omega^2 & m\omega^2 - M\ell^2 - i\omega F(\lambda)\frac{\eta}{\kappa} \end{vmatrix} = 0. \quad (8)$$

There are two complex roots of this equation from which both the attenuation and phase velocities for the fast and slow waves can be found. The

solution to this expression must be done numerically because of the Bessel functions involved, and a routine is included in Appendix A.1.

From equation (7a) we can write down the relation between the fluid and matrix wave amplitudes for each wave type as

$$m_i = \frac{B}{A} = - \frac{(H\ell^2 - \rho\omega^2)}{(\rho_f\omega^2 - C\ell^2)}. \quad (9)$$

The Biot-Stoll differential equations which govern the propagation of shear waves are not included here but are found in Reference 6 along with the characteristic frequency equation for the propagation constants. In this work it was assumed that a shear wave is non-dispersive, and the wave number was determined from the measured shear wave velocity.

Now that the propagation coefficients are known the boundary value problem can be considered.

Boundary Value Problem

The first few tens of centimeters of the earth's surface was modeled as a two-dimensional porous elastic medium of depth d overlying a semi-infinite non-porous elastic medium. The intermediate medium was either a sand or soil and the lower medium was a non-porous clay. The air-soil or air-sand interface was assumed to be a free surface and the lower surface was assumed to be in welded contact with an impermeable membrane between the two media. The air is allowed to flow across the upper boundary, while it is not allowed to penetrate the elastic clay below the porous soil.

For this physical system, the boundary conditions have been developed by Deresiewicz and Sfalak.¹³ The boundary conditions at the upper interface are (1) continuity of normal particle velocity, (2) continuity of fluid pressure, (3) continuity of total normal stress, and (4) continuity of tangential stress. At the lower interface the boundary conditions are (5) continuity of normal frame velocity, (6) continuity of tangential frame

velocity, (7) continuity of fluid velocity, (8) continuity of total normal stress, and (9) continuity of tangential stress.

The pressure and stress-strain relations for a porous medium in the Biot-Stoll⁶ notation are:

$$\tau_{xx} = H e - 2\mu(e_y + e_z) - C\xi \quad (10)$$

$$\tau_{yy} = H e - 2\mu(e_z + e_x) - C\xi \quad (11)$$

$$\tau_{zz} = H e - 2\mu(e_x + e_y) - C\xi \quad (12)$$

$$\tau_{xy} = \mu\gamma_z \quad (13)$$

$$\tau_{yz} = \mu\gamma_x \quad (14)$$

$$\tau_{zx} = \mu\gamma_y \quad (15)$$

$$P_f = M\xi - C e \quad (16)$$

where τ_{ij} are the total stresses, and P_f is the pore fluid pressure. The terms e_x , e_y , e_z , γ_x , γ_y , and γ_z are defined as

$$e_x = \frac{\partial u_x}{\partial x} \quad (17)$$

$$e_y = \frac{\partial u_y}{\partial y} \quad (18)$$

$$e_z = \frac{\partial u_z}{\partial z} \quad (19)$$

$$\gamma_x = 1/2 \left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} \right) \quad (20)$$

$$\gamma_y = 1/2 \left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right) \quad (21)$$

$$\gamma_z = 1/2 \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) \quad (22)$$

It is informative to evaluate these relations in a medium which the porosity is either one or zero. If the porosity of the medium goes to one, $\Omega = 1$, then the medium is a fluid and the relation for the pressure reduces to

$$P_f = M\xi \quad (23)$$

because $e = \nabla \cdot \vec{u} = 0$ since there is no solid component present. In this last expression for P_f , the elastic constant, M , reduces to the bulk

modulus of the fluid. In the lowest medium, where the porosity is zero, the stress-strain relations reduce to that of an elastic solid. Specifically, the expression for τ_{zz} reduces to

$$\tau_{zz} = H e - 2\mu(e_x + e_z) \quad (24)$$

since there is no fluid component present. In this last expression, the elastic frame constant, H , reduces to

$$H = K_r + \frac{4}{3} \mu. \quad (25)$$

In the following M will be set equal to the bulk modulus when $\Omega = 1$ and, for a non-porous elastic material, $\Omega = 0$, H will be evaluated using equation (25).

Next the types of allowed wave motion are chosen and then the boundary conditions are applied at the appropriate interfaces. In the air, incident and reflected waves are allowed having wave vectors $\vec{k}_i$ and $\vec{k}_r$, with $|\vec{k}_i| = |\vec{k}_r|$. Type one and type two dilatational waves and a shear wave are transmitted into the porous medium with respective wave vectors, $\vec{k}_1$, $\vec{k}_2$, and $\vec{k}_3$. At the lower interface the three waves are reflected and have wave vectors $\vec{k}'_1$, $\vec{k}'_2$ and $\vec{k}'_3$ with $|\vec{k}_1| = |\vec{k}'_1|$, $|\vec{k}_2| = |\vec{k}'_2|$ and $|\vec{k}_3| = |\vec{k}'_3|$. In the clay only a shear wave and compressional wave are transmitted with wave vectors $\vec{k}_4$ and $\vec{k}_5$, respectively. Each allowed wave is associated with an angle of incidence, reflection, etc. as indicated in Figure 2.1. In the air the incident and reflected waves are

$$\vec{U}_i = \vec{k}_i B_i \exp[i(\vec{k}_i \cos \theta_i x + \vec{k}_i \sin \theta_i z - \omega t)] \quad (26)$$

and

$$\vec{U}_r = \vec{k}_r B_r \exp[i(\vec{k}_r \cos \theta_r x - \vec{k}_r \sin \theta_r z - \omega t)] \quad (27)$$

where B_i and B_r are the fluid displacement amplitudes. In the porous medium, the matrix compressional waves are

$$\vec{u}_1 = \hat{l}_1 A_1 \exp[i(l_1 \sin \theta_1 x + l_1 \cos \theta_1 z - \omega t)] \quad (28)$$

$$\vec{u}_2 = \hat{l}_2 A_2 \exp[i(l_2 \sin \theta_2 x + l_2 \cos \theta_2 z - \omega t)] \quad (29)$$

$$\vec{u}'_1 = \hat{l}'_1 A'_1 \exp[i(l'_1 \sin \theta'_1 x - l'_1 \cos \theta'_1 z - \omega t)] \quad (30)$$

$$\vec{u}'_2 = \hat{l}'_2 A'_2 \exp[i(l'_2 \sin \theta'_2 x - l'_2 \cos \theta'_2 z - \omega t)] \quad (31)$$

where $\vec{u}_1$ and $\vec{u}_2$ are the type one and two waves transmitted into the porous medium and $\vec{u}'_1$ and $\vec{u}'_2$ are the type one and two waves reflected at the lower boundary. The A_i are the matrix wave displacement amplitudes. Associated with each matrix wave in the porous medium is a relative fluid wave which is expressed as

$$\vec{w}_1 = \hat{l}_1 B_1 \exp[i(l_1 \sin \theta_1 x + l_1 \cos \theta_1 z - \omega t)] \quad (32)$$

$$\vec{w}_2 = \hat{l}_2 B_2 \exp[i(l_2 \sin \theta_2 x + l_2 \cos \theta_2 z - \omega t)] \quad (33)$$

$$\vec{w}'_1 = \hat{l}'_1 B'_1 \exp[i(l'_1 \sin \theta'_1 x - l'_1 \cos \theta'_1 z - \omega t)] \quad (34)$$

$$\vec{w}'_2 = \hat{l}'_2 B'_2 \exp[i(l'_2 \sin \theta'_2 x - l'_2 \cos \theta'_2 z - \omega t)] \quad (35)$$

where the B_i are the relative fluid wave amplitudes. In the porous medium there are also shear waves transmitted and reflected which are expressed as

$$\vec{u}_3 = \hat{e} E \exp[i(l_3 \sin \theta_3 x + l_3 \cos \theta_3 z - \omega t)] \quad (36)$$

$$\vec{u}'_3 = \hat{e}' E' \exp[i(l'_3 \sin \theta'_3 x - l'_3 \cos \theta'_3 z - \omega t)] \quad (37)$$

where E and E' are matrix displacement amplitudes. The transmitted compressional and shear waves in the clay are

$$\vec{u}_t^c = \hat{l}_5 A_t \exp[i(l_5 \sin \theta_5 x + l_5 \cos \theta_5 z - \omega t)] \quad (38)$$

$$\vec{u}_t^s = \hat{e}'' E_t \exp[i(l_4 \sin \theta_4 x + l_4 \cos \theta_4 z - \omega t)] \quad (39)$$

and A_t and E_t are again the displacement amplitudes. Using these plane waves, the boundary conditions at the two interfaces can be evaluated.

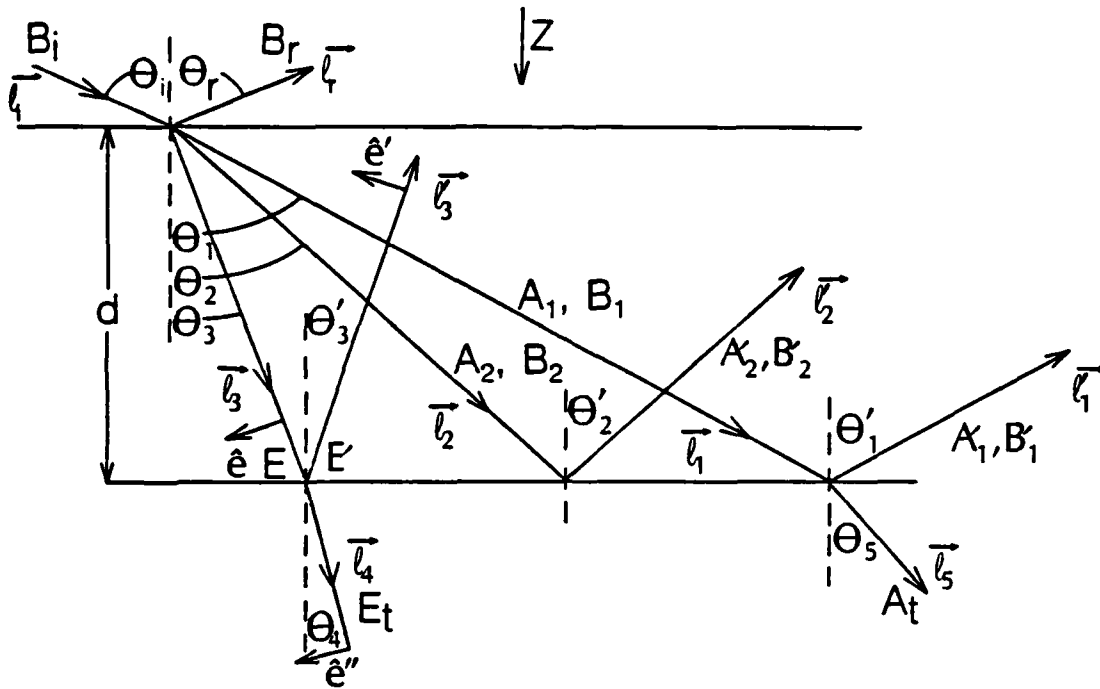


Figure 2.1. The layer model used indicating notation for angles of incidence, reflection and refraction, wave amplitudes, propagation vectors and polarizations.

At the upper boundary, the first boundary condition is continuity of normal particle velocity and is expressed as

$$\bar{U}_\perp = (1-\Omega)\dot{u}_\perp + \dot{U}_\perp \quad (40)$$

where a bar is used to indicate wave motion in the upper medium. Using $\vec{w} = \Omega(\vec{u} - \vec{U})$, $\dot{U}_\perp$ can be eliminated from the boundary condition to yield

$$\bar{U}_\perp = \dot{u}_\perp - \dot{w}_\perp. \quad (41)$$

Substituting in the appropriate waves yields the following equation

$$\begin{aligned} U_1 \cos \theta_1 - U_r \cos \theta_r &= u_1 \cos \theta_1 + u_2 \cos \theta_2 - u'_1 \cos \theta'_1 \\ &\quad - u'_2 \cos \theta'_2 - w_1 \cos \theta_1 - w_2 \cos \theta_2 \\ &\quad + w'_1 \cos \theta'_1 + w'_2 \cos \theta'_2 + u_3 \sin \theta_3 - u'_3 \sin \theta'_3. \end{aligned} \quad (42)$$

After substituting for $z = 0$, Snell's law is verified yielding:

$$\theta_i = \theta_r \quad (43)$$

$$\theta_1 = \theta'_1 \quad (44)$$

$$\theta_2 = \theta'_2 \quad (45)$$

$$\theta_3 = \theta'_3. \quad (46)$$

This boundary condition equation can be rewritten as

$$\begin{aligned} (B_1 - B_r) \cos \theta_1 &= A_1(1 - m_1) \cos \theta_1 + A_2(1 - m_2) \cos \theta_2 \\ &\quad - A'_1(1 - m_1) \cos \theta_1 - A'_2(1 - m_2) \cos \theta_2 \\ &\quad + E \sin \theta_3 - E' \sin \theta_3 \end{aligned} \quad (47)$$

where the relative wave amplitudes have been replaced by the matrix wave amplitudes, using $m_i = A_i/B_i$. The second boundary condition is continuity of fluid pressure. The expression for the pressure is

$$P_f = M\xi - Ce \quad (48)$$

which when evaluated at the boundary yields

$$\begin{aligned} K_f \ell_1 [B_1 + B_r] &= A_1 \ell_1 (C - m_1 M) + A_2 \ell_2 (C - m_2 M) + A'_1 \ell_1 (C - m_1 M) \\ &\quad + A'_2 \ell_2 (C - m_2 M). \end{aligned} \quad (49)$$

The continuity of total normal stress, τ_{zz} , is the third boundary condition and upon substitution yields the following at $z = 0$,

$$\begin{aligned} K_f \ell_1 (B_1 + B_r) &= A_1 \ell_1 [H - m_1 C - 2\mu \sin^2 \theta_1] + A_2 \ell_2 [H - m_2 C - 2\mu \sin^2 \theta_2] \\ &\quad + A'_1 \ell_1 [H - m_1 C - 2\mu \sin^2 \theta_1] + A'_2 \ell_2 [H - m_2 C - 2\mu \sin^2 \theta_2] \\ &\quad + 2E\mu \ell_3 \sin \theta_3 \cos \theta_3 + 2E'\mu \ell_3 \sin \theta_3 \cos \theta_3. \end{aligned} \quad (50)$$

In the fluid, τ_{zz} was set equal to the negative of the pressure. The last boundary condition to be evaluated at the upper interface is continuity of tangential stress,

$$\tau_{zx} = \frac{1}{2}\mu \left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} \right) \quad (51)$$

The fluid is assumed not to support any shears and thus τ_{zx} in the fluid was set equal to zero. This boundary condition results in

$$\begin{aligned} 0 = & 2A_1\ell_1\sin\theta_1\cos\theta_1 + 2A_2\ell_2\sin\theta_2\cos\theta_2 \\ & - 2A'_1\ell_1\sin\theta_1\cos\theta_1 - 2A'_2\ell_2\sin\theta_2\cos\theta_2 \\ & - E\ell_3(\cos^2\theta_3 - \sin^2\theta_3) + E'\ell_3(\cos^2\theta_3 - \sin^2\theta_3). \end{aligned} \quad (52)$$

Next, the five boundary conditions at the lower interface are evaluated. The fifth boundary condition is continuity of normal frame velocity,

$$\bar{u}_\perp = \dot{u}_\perp. \quad (53)$$

Substitution of the plane waves at the lower interface yields

$$\begin{aligned} u_1\cos\theta_1 + u_2\cos\theta_2 - u'_1\cos\theta_1 - u'_2\cos\theta_2 + u_3\sin\theta_3 \\ - u'_3\sin\theta_3 = u_t^c\cos\theta_5 + u_t^s\sin\theta_4 \end{aligned} \quad (54)$$

After setting $z = d$ in this expression, Snell's law is again verified and equation (54) may be written as

$$\begin{aligned} A_1\cos\theta_1\exp[i\ell_1\cos\theta_2d] + A_2\cos\theta_2\exp[i\ell_2\cos\theta_2d] \\ - A'_1\cos\theta_1\exp[-i\ell_1\cos\theta_1d] - A'_2\cos\theta_2\exp[i\ell_2\cos\theta_1d] \\ + E\sin\theta_3\exp[i\ell_3\cos\theta_3d] - E'\sin\theta_3\exp[-i\ell_3\cos\theta_3d] \\ = A_5\cos\theta_5\exp[i\ell_5\cos\theta_5d] + E_t\sin\theta_4\exp[i\ell_4\sin\theta_4d]. \end{aligned} \quad (55)$$

The sixth boundary condition is continuity of tangential frame velocity,

$$\bar{u}_t = \dot{u}_t. \quad (56)$$

This boundary condition yields

$$\begin{aligned} u_1\sin\theta_1 + u_2\sin\theta_2 + u'_1\sin\theta_2 + u'_2\sin\theta_2 - u_3\cos\theta_3 - u'_3\cos\theta_3 \\ = u_t^c\sin\theta_5 - u_t^s\cos\theta_4 \end{aligned} \quad (57)$$

and at $z = d$ reduces to

$$\begin{aligned}
& A_1 \sin \theta_1 \exp[i l_1 \cos \theta_1 d] + A_2 \sin \theta_2 \exp[i l_2 \cos \theta_2 d] \\
& + A'_1 \sin \theta_1 \exp[-i l_1 \cos \theta_1 d] + A'_2 \sin \theta_2 \exp[-i l_2 \cos \theta_2 d] \\
& - E \cos \theta_3 \exp[i l_3 \cos \theta_3 d] - E' \cos \theta_3 \exp[-i l_3 \cos \theta_3 d] \\
& = A_t \sin \theta_5 \exp[i l_5 \cos \theta_5 d] - E_t \cos \theta_4 \exp[i l_4 \cos \theta_4 d].
\end{aligned} \tag{58}$$

The seventh boundary condition is continuity of normal fluid velocity, however, since the fluid cannot penetrate the lower medium, the normal fluid velocity must go to zero at the boundary, $\dot{w}_\perp = 0$. Substitution in this expression yields

$$w_1 \cos \theta_1 + w_2 \cos \theta_2 - w'_1 \cos \theta_1 - w'_2 \cos \theta_2 = 0. \tag{59}$$

Using the relation between the relative wave amplitude and the matrix wave amplitude, equation (59) can be written as, at $z = d$,

$$\begin{aligned}
& A_1 m_1 \cos \theta_1 \exp[i l_1 \cos \theta_1 d] + A_2 m_2 \cos \theta_2 \exp[i l_2 \cos \theta_2 d] \\
& - A'_1 m_1 \cos \theta_1 \exp[-i l_1 \cos \theta_1 d] - A'_2 m_2 \cos \theta_2 \exp[-i l_2 \cos \theta_2 d] = 0.
\end{aligned} \tag{60}$$

Continuity of normal stress, τ_{zz} , is the eighth boundary condition and it yields, at $z = d$,

$$\begin{aligned}
& A_1 l_1 [H - m_1 C - 2\mu \sin^2 \theta_1] \exp(i l_1 \cos \theta_1 d) \\
& + A_2 l_2 [H - m_2 C - 2\mu \sin^2 \theta_2] \exp(i l_2 \cos \theta_2 d) \\
& + A'_1 l_1 [H - m_1 C - 2\mu \sin^2 \theta_1] \exp(-i l_1 \cos \theta_1 d) \\
& + A'_2 l_2 [H - m_1 C - 2\mu \sin^2 \theta_1] \exp(-i l_2 \cos \theta_2 d) \\
& + 2\mu l_3 E \sin \theta_3 \cos \theta_3 \exp(i l_3 \cos \theta_3 d) \\
& + 2\mu l_3 E' \sin \theta_3 \cos \theta_3 \exp(-i l_3 \cos \theta_3 d) \\
& = H' A_t l_5 \exp[i l_5 \cos \theta_5 d] - 2\mu' A_t l_5 \cos^2 \theta_5 \exp[i l_5 \cos \theta_5 d] \\
& - 2\mu' E_t l_4 \sin \theta_4 \cos \theta_4 \exp[i l_4 \cos \theta_4 d],
\end{aligned} \tag{61}$$

where H' and μ' are elastic constants in the clay. The last boundary condition is continuity of tangential stress, $\tau_{zx} = \tau'_{zx}$. Substitution in this expression yields, at $z=d$,

$$\begin{aligned}
& 2\mu A_1 l_1 \sin\theta_1 \cos\theta_1 \exp(il_1 \cos\theta_1 d) \\
& + 2\mu A_2 l_2 \sin\theta_2 \cos\theta_2 \exp(il_2 \cos\theta_2 d) \\
& - 2\mu A'_1 l_1 \sin\theta_2 \cos\theta_1 \exp(-il_1 \cos\theta_1 d) \\
& - 2\mu A'_2 l_2 \sin\theta_2 \cos\theta_2 \exp(-il_2 \cos\theta_2 d) \\
& - E\mu l_3 (\cos^2\theta_3 - \sin^2\theta_3) \exp(il_3 \cos\theta_3 d) \\
& + E'\mu l_3 (\cos^2\theta_3 - \sin^2\theta_3) \exp(-il_3 \cos\theta_3 d) \\
& = 2A_t \mu' l_5 \sin\theta_5 \cos\theta_5 \exp(il_5 \cos\theta_5 d) \\
& - E_t \mu' l_4 (\cos^2\theta_4 - \sin^2\theta_4) \exp(il_4 \cos\theta_4 d). \tag{62}
\end{aligned}$$

These nine boundary condition equations can be solved simultaneously to determine the amplitudes of the allowed types of wave motion relative to the incident wave amplitude. From these amplitudes, the acoustic propagation coefficients of the porous medium as well as the surface impedance and transfer functions for the upper boundary can be found. The routine, Ampl.Fortran, used to determine those amplitudes calls an IMSL subroutine. The main routine is included in Appendix A.2.

Measurable Quantities

Predictions of seismic/acoustic coupling in the field should, when possible, rely only upon quantities measurable in the field. Measurements of jacketed and unjacketed bulk moduli¹⁴ are interesting in the laboratory but not practical in the field. One goal of this study was to determine which quantities must be measured in order to predict seismic/acoustic coupling.

Acoustic measurements outdoors usually require that the acoustic impedance of the surface be known. Several techniques have been developed for

this purpose. It has been found, that for many surfaces, the acoustic impedance can be computed from the flow resistance. The flow resistance can be readily measured in the field or estimated by an on-site evaluation of the surface. During the course of these measurements, the ability to measure the attenuation of the acoustic wave with depth in the soil using a buried microphone was developed. The acoustic attenuation in the soil is, typically, easier to measure than the acoustic impedance yet, as will be shown later, carries the same information about the surface. The response of a buried geophone to an airborne acoustic wave and to seismic disturbances can be measured in the field. By comparing the geophone or probe microphone signal to the signal from a microphone above the surface, one can determine the transfer function for the boundary. Finally, by mechanically disturbing the surface, the seismic velocities can be measured as well as layer depths.

Of those quantities underlined above, flow resistance, seismic velocities, and layer depths must be experimentally measured. Experimental measurements of these quantities will be described in the next chapter. The other quantities can, in principle, be computed from flow resistance, seismic velocities, layer depths, and tabulated physical properties of the soil. In the following, a description of the calculations of the other underlined quantities will be given using the Biot-Stoll Model.

Acoustic Impedance of the Surface

The normal specific acoustic impedance of a surface is the ratio of the acoustic pressure to the particle velocity at the surface divided by the acoustic resistance of air, $\rho_0 c_0$. This is a complex quantity and is expressed as

$$z = z_{\text{real}} + z_{\text{imag}} \quad (63)$$

The surface pressure in terms of the incident and reflected wave amplitudes is

$$P_{\text{surface}}(\omega) = -iK_f \ell_1 [B_i + B_r] \quad (64)$$

and the velocity at the surface is

$$V_{(\text{surface})}(\omega) = -i\omega \cos \theta_1 [B_i - B_r]. \quad (65)$$

The normal surface impedance is then

$$z = \frac{P}{V} = \frac{K_f \ell_1}{\omega_0 \cos \theta_1} \frac{[B_r + B_i]}{[B_r - B_i]} \quad (66)$$

and

$$\frac{z}{z_{\text{air}}} = \frac{K_f}{\rho_0 c_0^2 \cos \theta_1} \frac{[B_i + B_r]}{[B_i - B_r]}. \quad (67)$$

In Appendix A.3 is a subroutine, Sufimp.Fortran, used to calculate the surface impedance.

Acoustic Attenuation in the Soil

The acoustic attenuation coefficients of the porous medium are found by determining the magnitude of the acoustic pressure at two different depths below the surface. The acoustic pressure below the surface is the sum of the fluid pressure due to the fast and slow waves. Using the fast wave amplitude and equation (9), for example, the amplitude of the fast relative fluid displacement at a depth z is

$$P_{\text{fast}} = iA_1 \ell_1 (C - m_1 M) \exp(i\ell_1 \cos \theta_1 z). \quad (68)$$

Expression for the fluid pressure due to the other waves in the porous medium are

$$P_{\text{slow}} = iA_2 \ell_2 (C - m_2 M) \exp(i\ell_2 \cos\theta_2 z) \quad (69)$$

$$P'_{\text{fast}} = iA'_1 \ell_1 (C - m_1 M) \exp(-i\ell_1 \cos\theta_1 z) \quad (70)$$

$$P'_{\text{slow}} = iA'_1 \ell_2 (C - m_2 M) \exp(-i\ell_2 \cos\theta_2 z) \quad (71)$$

where again the prime indicates a wave reflected from the lower boundary. The total fluid pressure at a depth z below the surface is the sum of the pressure due to the relative fluid waves and is expressed as

$$P_{\text{below}}(\omega, z) = P_{\text{fast}} + P_{\text{slow}} + P'_{\text{fast}} + P'_{\text{slow}}. \quad (72)$$

The attenuation coefficient in dB per unit depth is then

$$\alpha = [\ln|P_{\text{below}}(\omega, z)| - \ln|P_{\text{below}}(\omega, z_2)|] \cdot \frac{20.0 \log(e)}{(z_2 - z_1)}. \quad (73)$$

This calculation is done in the routine Ampl.Fortran.

Transfer Function of the Boundary

In this section the acoustic and seismic transfer function for the air-soil interface will be determined. The acoustic transfer function is the ratio of the acoustic pressures below and above the surface. This is a complex quantity and expressions for both the magnitude and phase will be included. The acoustic pressure at a height z above the surface is due to the incident and reflected wave amplitudes and is expressed as

$$P_{\text{above}}(\omega, z) = P_{\text{incident}}(\omega, z) + P_{\text{reflected}}(\omega, z) \quad (74)$$

where

$$P_{\text{incident}}(\omega, z) = -iK_f \ell_i B_i \exp(i\ell_i \cos\theta_i z) \quad (75)$$

and

$$P_{\text{reflected}}(\omega, z) = -iK_f \ell_r B_r \exp(-i\ell_r \cos\theta_r z). \quad (76)$$

Using the expression for the acoustic pressure below the surface, equation (72), the acoustic transfer function is expressed as

$$T(\omega, z, z') = \frac{P_{\text{below}}(\omega, z)}{P_{\text{above}}(\omega, z')} \quad (77)$$

The seismic transfer function is the ratio of the seismic velocity response of the matrix below the boundary to the acoustic pressure above the boundary. The total velocity response of the matrix will be the vector sum of the frame velocity of each of the allowed matrix waves. However, the total normal velocity response of the matrix will be determined so that it can be later compared to experimental results. The total normal velocity, V_n , at a depth z below the surface is

$$\begin{aligned} V_n &= \dot{u}_{1\perp} + \dot{u}_{2\perp} + \dot{u}'_{1\perp} + \dot{u}'_{2\perp} + \dot{u}_{3\perp} + \dot{u}'_{3\perp} \\ V_n &= -i\omega A_1 \cos\theta_1 \exp(i\ell_1 \cos\theta_1 z) + i\omega A'_1 \cos\theta_1 \exp(-i\ell_1 \cos\theta_1 z) \\ &\quad - i\omega A_2 \cos\theta_2 \exp(i\ell_2 \cos\theta_2 z) + i\omega A'_2 \cos\theta_2 \exp(-i\ell_2 \cos\theta_2 z) \\ &\quad + i\omega E \sin\theta_3 \exp(i\ell_3 \cos\theta_3 z) + i\omega E' \sin\theta_3 \exp(-i\ell_3 \cos\theta_3 z). \end{aligned} \quad (78)$$

An expression for the seismic transfer function is

$$T(\omega, z, z') = \frac{V_n(\omega, z)}{P_{\text{above}}(\omega, z')}. \quad (79)$$

The radial transfer function as well as an air-clay transfer function is a simple extension of this work. Routines for calculating these transfer functions are included in Appendix A.4, A.5, and A.6.

3. EXPERIMENTAL MEASUREMENTS

During the course of this study, a variety of experimental measurements were performed to define the mechanism responsible for seismic/acoustic coupling and insure that this quantity is measured. The individual experiments along with data analysis procedures will be described in the following. In many cases, the experiments were designed to answer specific experimental questions. In those cases the results and conclusions will be presented with the experimental procedure. The major measurements were of the transfer function. Interpretation of those results will be described Chapter 5.

Preliminary Measurements

Considerable effort was expended to make certain the sound system was mechanically decoupled from the surface of the earth to eliminate direct mechanical transfer of energy. The speaker systems were either suspended from a large A frame using various elastic straps, or supported on the bed of a 3/4-ton truck which was placed on inflated rubber bags.

In order to measure the degree of isolation, two types of tests were conducted. Impulses on the side of the speaker cabinet were generated and the resulting acoustic and seismic waves measured using a collocated geophone and microphone. As isolation systems were applied the magnitude of the seismic signal was observed on the geophone. The microphone provided a time scale to permit separation of a seismic wave generated mechanically at the source and an acoustically coupled wave. In all cases it was possible to reduce the mechanical coupling below the ambient background seismic noise level. Geophone response to sweep tones generated by the speaker were also measured as the decoupling was applied. The effectiveness of the decoupling as a function of frequency was observed in this way. It was possible to ascertain that no specific resonances existed in the isolation

system which would selectively pass low frequency energy to the earth and geophone.

A geophone isolated from the ground and suspended in air would respond to airborne acoustic energy. Measurements were made to determine if acoustic waves could generate a geophone response when the geophone was placed in a variety of porous materials, but still isolated from the earth and seismic energy sources. The airborne sound produced a geophone response when the geophone was covered in isolated containers of plastic beads, of sands and gravels with a variety of porosities. The overall response of the geophone varied with the surrounding materials, but in each case the results could be explained in terms of a vibrating mass loaded system driven by the airborne acoustic energy. The data indicated no measureable contribution to geophone response due to motion of the geophone relative to the matrix material when driven in this isolated system.

Measurements of the Acoustic Wave in the Earth

The measurements of the sound pressure below the surface of the earth were made with a specially designed probe as shown in Figure 3.1. It consists of an AKG microphone and preamplifier housed in a cylindrical brass tube. The inner cylinders shown were used to increase the mass of the probe and to seal any possible air leaks. The nose cone contains small holes to allow the active element of the microphone to sense the acoustic field. A rubber membrane was stretched over the microphone elements to protect it from any particles that penetrate the nose cone when the probe was inserted in a predrilled hole. A comparison of the probe microphone response to a standard AKG microphone is shown in Figure 3.2. The frequency response for the probe is essentially flat to 3kHz where it begins to roll off to a new, less sensitive, plateau near 7kHz. The frequency response of the probe is essentially unchanged when the probe is

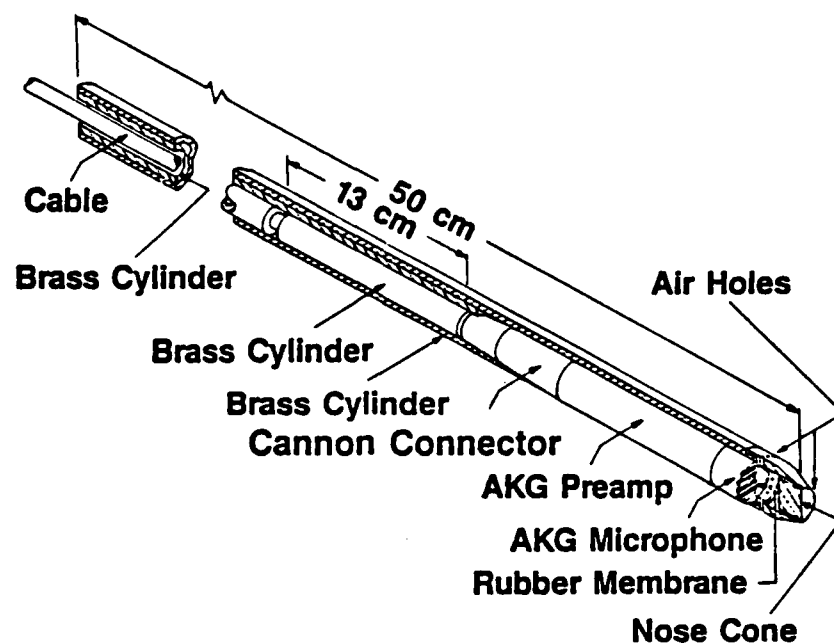


Figure 3.1. Specially designed probe microphone used to measure the acoustic sound field in the porous soil.

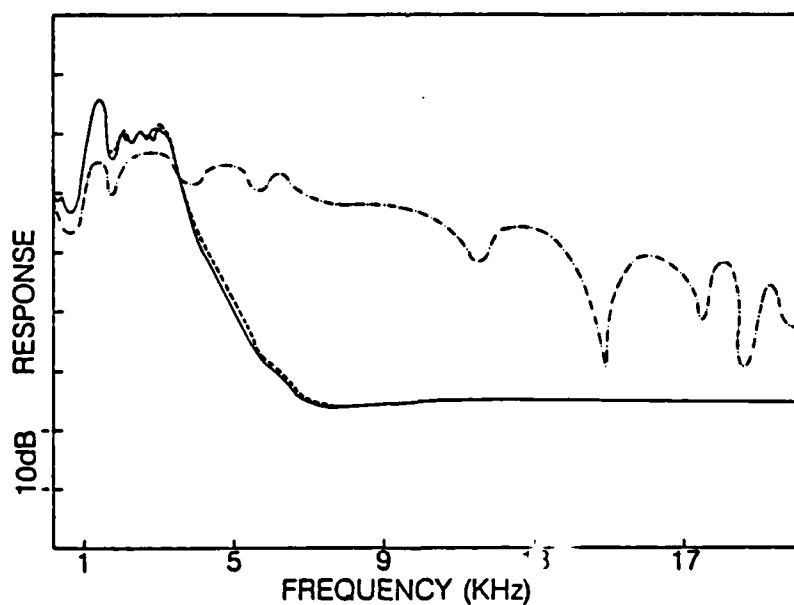


Figure 3.2. A comparison of probe microphone response (—) to a standard AKG microphone (---). Also shown is the response of the probe when pointed away from the sound source.

pointed away from the sound source, the normal geometry for measurements below the earth's surface.

Before the probe was inserted into the ground, a drill was used to bore a hole 1 inch in diameter to the desired depth. The probe was then forced into the hole and STP Oil Treatment was poured around the probe near ground level to further seal the probe entry. This procedure worked well giving reproducible results for sandy soil and loam. For clays, the soil in the vicinity of the probe would quite often crack providing air paths not previously available. This cracking gave results which differed from one attempt to the next. It was generally assumed that the measurement giving the smallest sound pressure at the probe was best.

Occasionally, the holes in the tip of the probe became filled with dirt when the probe was inserted. This occurrence could only be detected when the probe was removed and examined, so several data runs had to be rejected after the fact.

The results of an extensive series of probe microphone measurements are published in Reference 8. In subsequent measurements, the probe microphone output was recorded along with geophone response, but the microphone depth was not varied. Referring again to Figure 3.1, when the probe is inserted in the ground where the speed of sound is less than the speed in the air, the probe microphone response with frequency could be expected to differ. There is no clear theoretical relation to predict the microphone response when it is inserted into the earth since the surrounding medium is changed dramatically. One would expect, as a minimum, that the frequency at which the response begins to roll off should be related to the wavelength of sound in the pores which scales with wavelength. If the speed of sound in the pores is 10 m/sec, one would expect the microphone response to begin to roll off at about 100 Hz. This feature of the data will be demonstrated below.

The speed of sound in the pores was measured in a hemispherical dish formed in the ground with a radius of 0.5 m and filled with sand with a measured flow resistivity of 85 rayls/cm. Figure 3.3 shows the relative

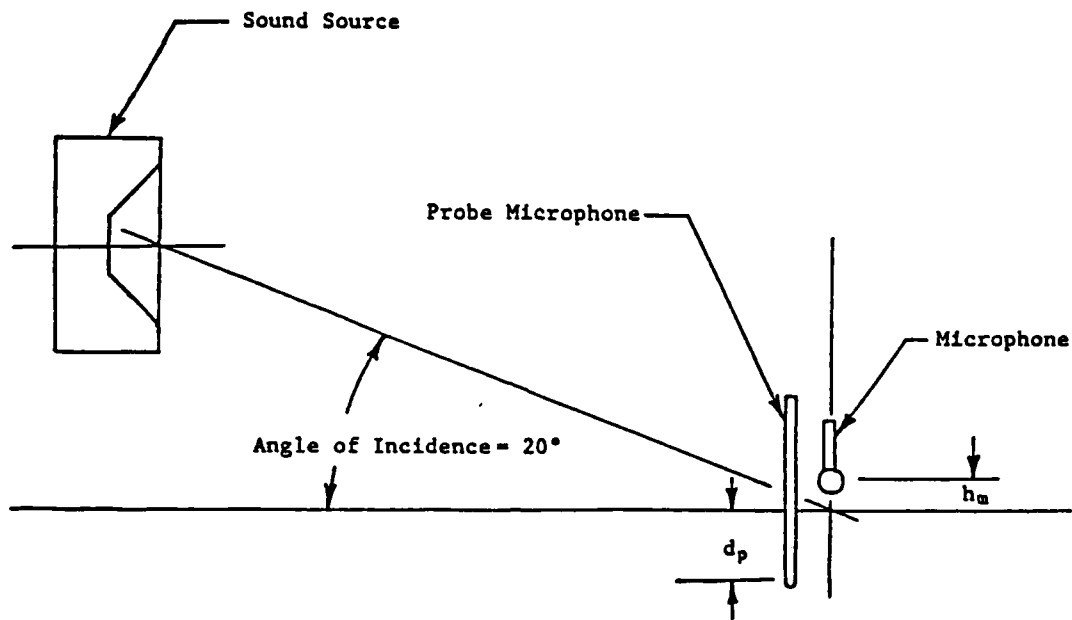


Figure 3.3. Relative positions of the sound source and sensors used to measure acoustic phase velocity and attenuation.

positions of the source and sensors used in the experiment. A reference AKG microphone was positioned approximately 5 cm above the sand and the probe microphone inserted to an approximate depth of five cm. A 50 Hz acoustic tone was broadcast at an angle of incidence of approximately 20° from the horizontal. The relative delay between the probe and reference microphone was recorded using a Nicolet 3091 digital oscilloscope. Next, the probe was pushed 2.0 cm further down in the sand and the relative delay again recorded. The sound speed in the pores is the ratio of the change in the probe depth to the change in the phase. The probe was pushed down in 2.0 cm increments to a depth of 11 cm and the phase difference recorded at each probe position. This experiment was repeated at several frequencies between 50 Hz and 500 Hz. Results of the average phase speed in the pores

are plotted in Fig. 3.4. The attenuation of the acoustic wave was measured in the same sand using sweep tones, results are shown in Figure 3.5. The solid line was calculated using equation (73).

Measurements of the Transfer Function

Experimental Configuration

The experimental data were collected at two different locations, the UM test field and Sardis beach. The UM test field is two miles south of Oxford, MS and a map showing the field size, relative elevations and tree lines is included in appendix C.1. Sardis beach is located at John W. Kyle state park which is located approximately ten miles west of Oxford and a map of the park is included in appendix C.2. Several experiments were performed at each site in order to characterize the physical properties necessary for theoretical calculations.

The flow resistivity was measured using an apparatus described by Leonard¹⁵. A cylindrical sample of earth was taken from the ground and the rate of air flow through the sample was measured as a function of differential pressure across the sample. Measurements of flow resistance were made of each soil sample using at least three differential pressures across the sample. Consistency of these results were always within 5%. However, it was found that there were inconsistencies in the measured flow resistances from multiple samples from the same site. Values of flow resistance varied as much as a factor of two at the UM test field, however, in sand these measurements were always within 10%. It was assumed that these discrepancies occurred because of variations in soil structure in the 10cm diameter plugs extracted for measurements and the effects of disturbing the soil. Results of these measurements are shown in Table 1. The density of the

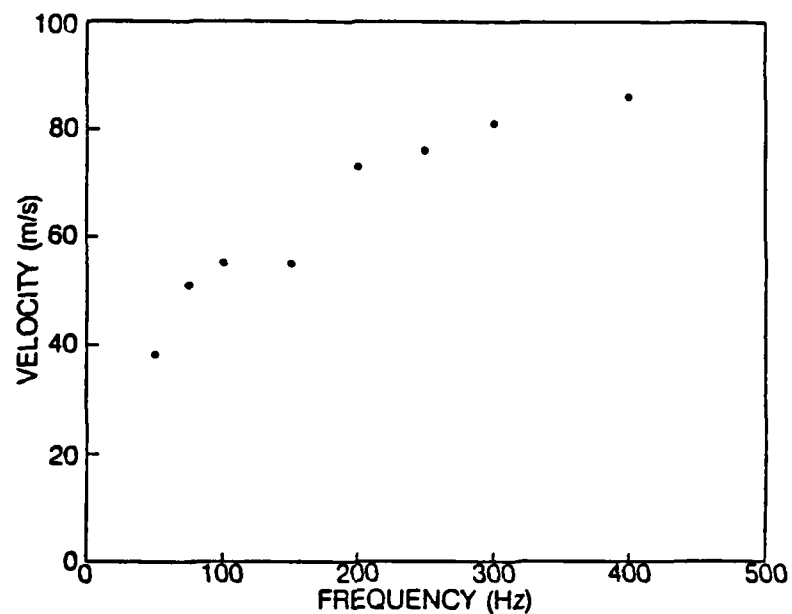


Figure 3.4. Acoustic phase velocity measured with the probe microphone in a sand with a flow resistivity of 85 rays/cm.

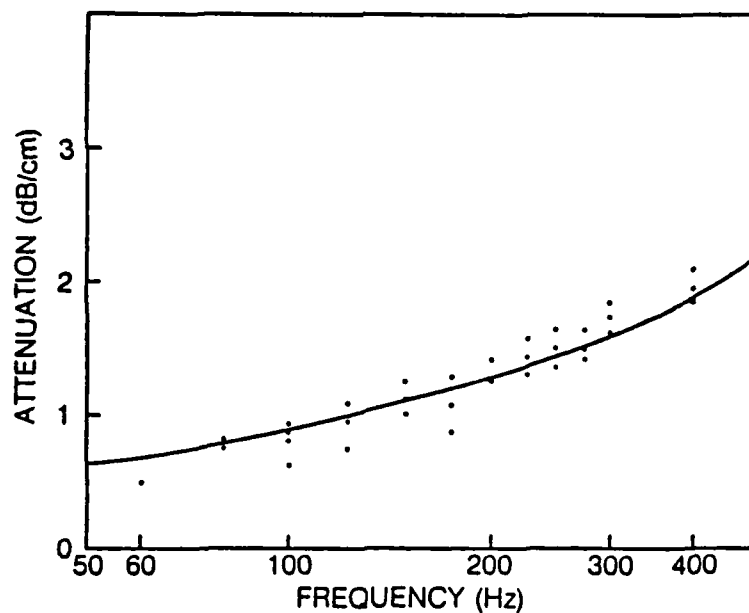


Figure 3.5. The acoustic attenuation measured with the probe microphone. The solid line was calculated using equation 73.

TABLE 1

Measured Values of Flow Resistance

<u>Site</u>	<u>Average (rayls/cm)</u>
Sardis	350
UM Test Field	550 to 1050

nonporous lower layer material at the UM test field was determined from a sample of clay extracted from approximately 0.5 meters below the surface. At Sardis beach, the density of the clay underlying the sand was assumed to be the same as at the UM test field, which was found to be 2.65g/cm^3 .

The shear and compressional wave speeds and the depth of the porous material were determined from a ray propagation model¹⁶ for a two layer system, see Figure 3.6. An impulse is created at x_0 by striking a metal block with a hammer. A seismic sensor is located at, say x_1 and is sensitive to both shear and compressional waves, and it is assumed that there are three possible paths to the sensor. Path one is along the surface at a wave speed of v_1 and is referred to as the direct path. The second path or reflected path is down towards the lower boundary and reflected in accordance with Snell's law. The third, the refracted path, is down towards the lower boundary, along the surface of the lower medium at a speed v_2 then back towards the upper boundary. When the seismic sensor is close to the source compared to the layer depth, the first arrival will be the direct pulse. As the seismic sensor is moved away from the source and the separation distance becomes greater than twice the layer depth, the first arrival will be the refracted pulse. A plot of arrival times versus source detector separation distance for the UM test field is plotted in Figure 3.7 and the wave velocities are the slopes of the lines drawn. From the geometry of the model, the layer depth can be expressed as

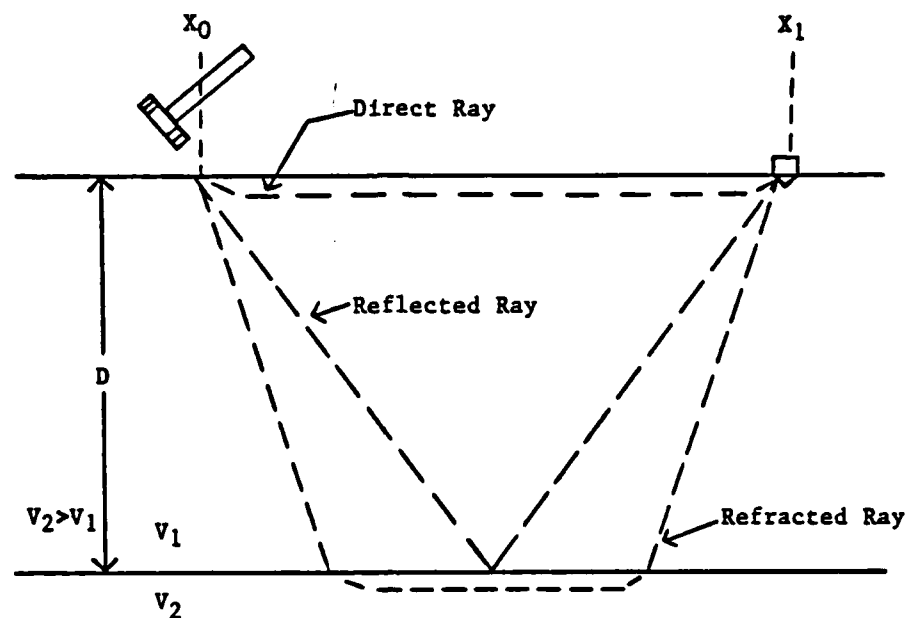


Figure 3.6. Ray propagation model used to calculate the layer depths at experimental sites.

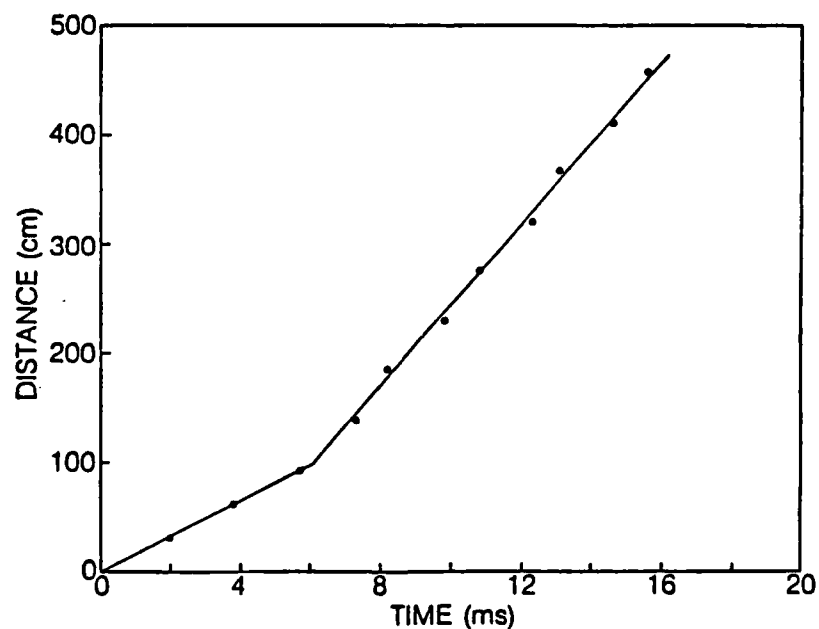


Figure 3.7. A plot of arrival times versus geophone position at the UM test field. The layer velocities are the slopes of the straight lines drawn.

$$d = \frac{x_c}{2} \frac{(V_1 - V_2)}{(V_1 + V_2)} \quad (80)$$

where x_c is the location of the intersection of the lines on the time-position graph. Physically, x_c is the distance from the source to the point at which the refracted pulse arrives at the same time as the direct pulse. The results of the wave speeds and the layer depths for both sites are recorded in Table 2.

TABLE 2

Seismic Wave Velocities (cm/s)

Layer depth (cm)

Sardis Beach

First Layer			Second Layer	
<u>Compressional</u>	<u>Shear</u>	<u>Layer Depth</u>	<u>Compressional</u>	<u>Shear</u>
1.6×10^4	1.5×10^4	26	4.6×10^4	2.6×10^4

UM Test Field

First Layer			Second Layer	
<u>Compressional</u>	<u>Shear</u>	<u>Layer Depth</u>	<u>Compressional</u>	<u>Shear</u>
1.6×10^4	$.95 \times 10^4$	30	3.7×10^4	2.2×10^4

Sources and Sensors

The sound source used to broadcast acoustic signals was constructed at the University of Mississippi Physics Department and a diagram of the speaker system is shown in Figure 3.8. The outer most material is 1/2 inch particle board which was nailed and glued to an internal framework constructed from two inch by two inch lumber. The speaker system consists of four independent vented boxes of which each has an internal volume of 725 liters and are each tuned to 20 hertz with a four inch diameter by six

inch depth cylindrical port. On the front face of each box is a modified Peavy 18 inch Black Widow driver. The speaker system was driven by two ADS Power Plate 100 watt amplifiers and was mounted on a truck so that it would be made mobile for field use.

A Hall Engineering acoustic signal generator was used to record two minute segments of pink noise at each one of the third octave bands from 25 Hz to 500 HZ. In the field experiments, this tape was broadcast using a Nakamichi 550 tape player. A block diagram of the acoustic broadcasting network is shown in Figure 3.9.

The seismic sensor used was a commercially available Mark Products L-4-3-D triaxial geophone. This geophone contains three coils which are sensitive to motion in the transverse, radial and vertical directions. A calibration factor supplied by the manufacturer enables the determination of the seismic velocity from the signal voltage. The calibration factor was $1.0 \text{ mV} = 3.57 \times 10^{-4} \text{ cm/sec}$. Using an auger, a cylindrical hole was dug slightly larger than the diameter of the geophone. The geophone was then placed in the hole, leveled, and then covered with the soil or sand that had been removed. In the transfer function experiment the geophones were buried to depths such that the top surface of the geophone was either 5 or 25 cm below the ground.

The probe microphone was of our own design and a cut-away view of the instrument is shown in Figure 3.1. At the UM test site the probe depth was 8cm and at Sardis beach the depth was 12cm. A reference AkG microphone, identical to the one in the probe, was positioned approximately 5 cm above the surface of the ground.

Figure 3.10 shows the relative positions of the sensors and sound source. Four different angles of incidence, in increments of 5° , were used during the experiment. At the largest angle, 20° , the separation distance between the source and sensors was 5.5 m while at the smallest incident

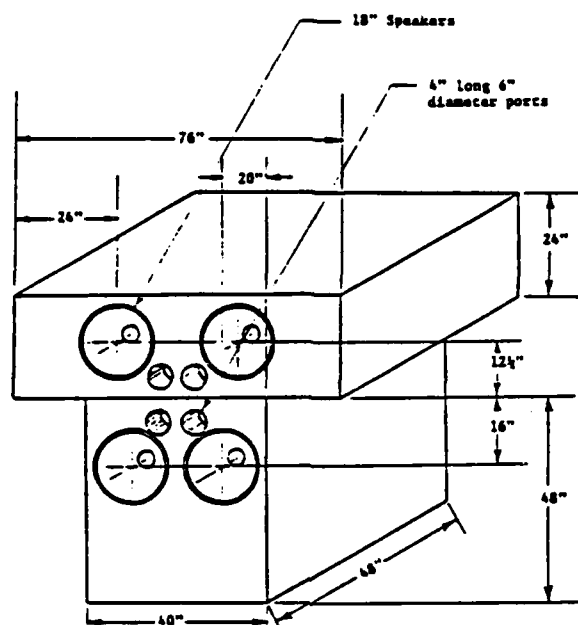


Figure 3.8. Speaker system built at the University of Mississippi Physics Department and used as a sound source in outdoor sound propagation measurements.

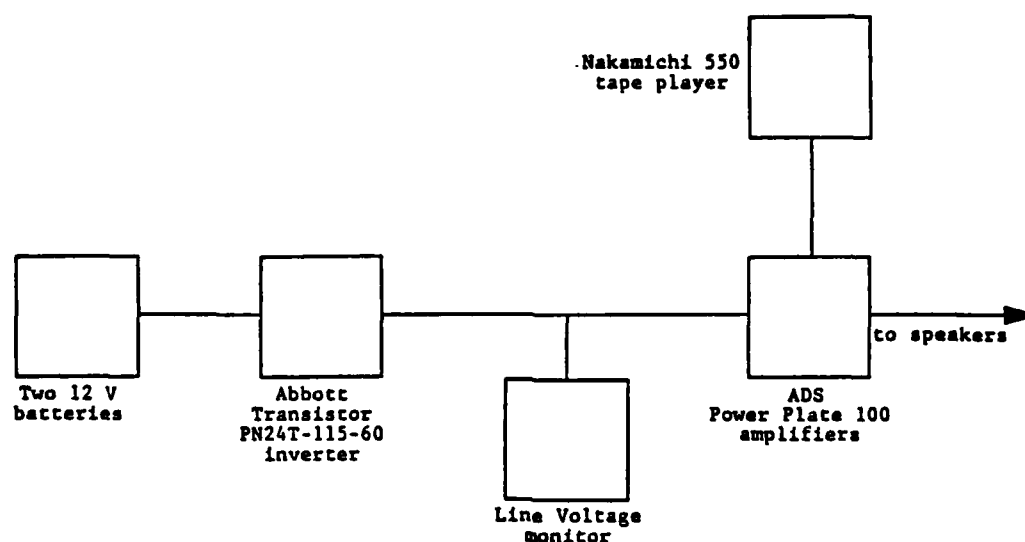


Figure 3.9. Block diagram of the acoustic broadcasting network used at experimental sites.

angle it was 23 m. The angle of incidence was changed by repositioning the truck upon which the speakers were mounted.

Each of the electronic signals from the sensors were amplified with a Tektronix AM 502 differential amplifier and then recorded on a Teac R-81 seven channel FM cassette recorder. A block diagram of the data recording system is shown in Figure 3.11. The amplifier gains were adjusted such that the most intense sound level broadcast did not overload the amplifiers. The gains of each of the coils of the geophone and the microphones along with the recorder channel assignments are in Table 3. The output voltage of

TABLE 3

UM Test Field

CH	SENSOR	GAIN
1	Vertical Triax	500
2	Longitudinal Triax	500
3	Transverse Triax	500
5	Above Ground Microphone	100
6	Probe Microphone	5000
7	Voice Memo & DC Trigger	

Sardis

CH	SENSOR	GAIN
1	Vertical Traix	500
2	Transverse Triax	500
3	Longitudinal Triax	500
5	Above Ground Microphone	100
6	Probe Microphone	500
7	Voice Memo & DC Trigger	

each amplifier was five volts and that was the maximum input voltage of the tape recorder, thus allowing the maximum dynamic range of the recorder, 40 dB, to be used. After the gains were set, a General Radio model 1986 sound level calibrator was used to record a 94 dB calibration tone on the reference microphone. The output voltage of this reference microphone was measured and then temporarily connected to each input of the geophone

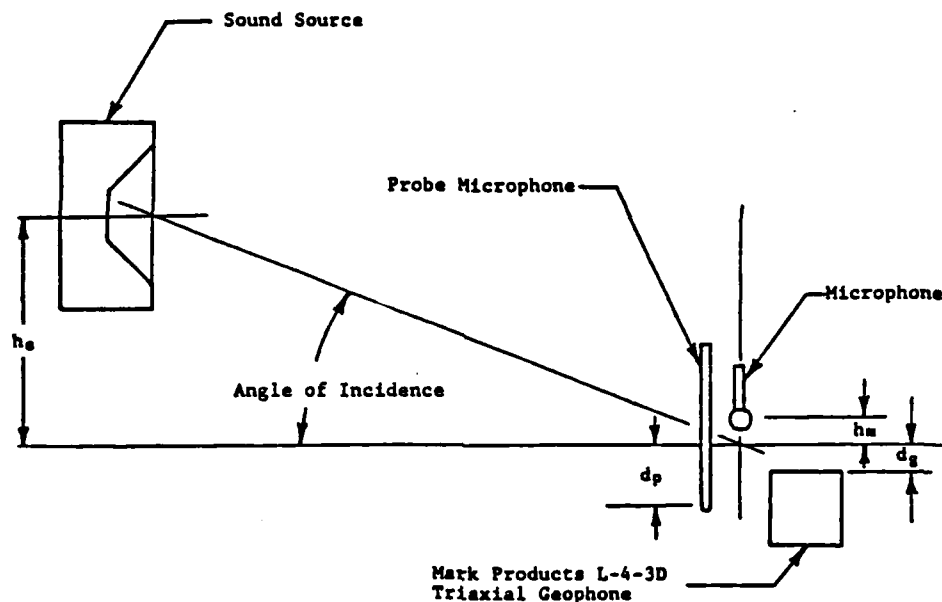


Figure 3.10. Diagram of source and sensor geometry indicating source height h_s , reference microphone position h_m , probe depth d_p and geophone depth d_g .

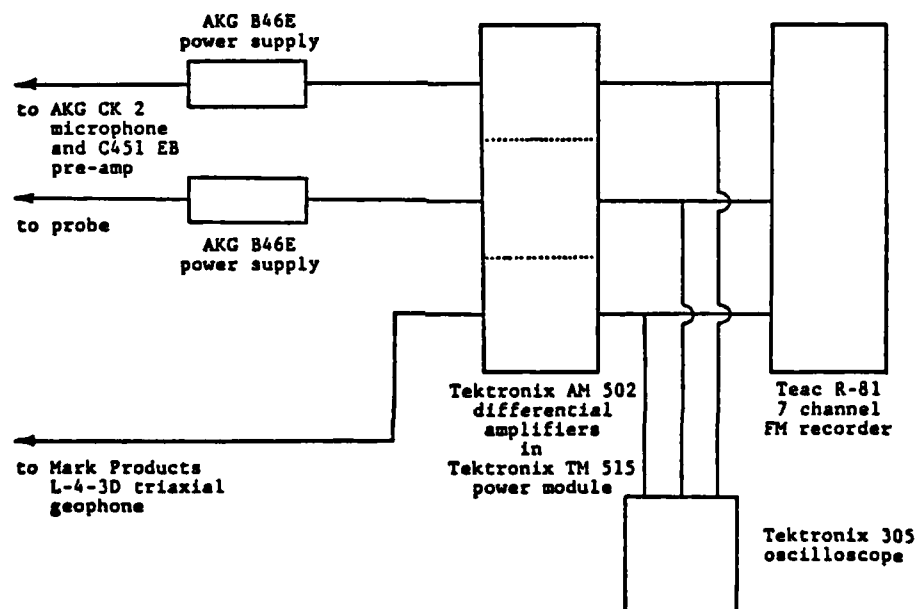


Figure 3.11. Data recording system used in the measurements of the transfer functions.

signal amplifiers, thus recording a calibration voltage for the seismic sensors. This procedure for calibration tones was repeated after the experiment was complete. Once the initial calibration tones were recorded, the test tape containing one-third octave bands of pink noise was broadcast. The geophone, probe and reference microphone responses were recorded on the assigned tape recorder channels. A five second 1.5 volt d.c. pulse was also recorded on its assigned channel (see Table 3) at the beginning of the broadcast of each one 1/3 octave band. This pulse was used as a trigger when the data were digitized. After the last 1/3 octave band was broadcast, the source tape was rewound, the truck repositioned and the broadcast repeated. This procedure was repeated at each of the remaining incident angles.

4. DATA ANALYSIS

The primary quantity of interest in this study was the transfer function defined by

$$T(f) = \frac{\text{Signal Below the Surface (Complex)}}{\text{Sound Pressure Above the Surface (Complex)}}.$$

The transfer function, $T(f)$, is a complex quantity which can be expressed in terms of a magnitude and phase. The data analysis procedure was designed to extract, from the FM tape records made in the field, this magnitude and phase.

Since we are concerned with the absolute magnitude of the transfer function, the first step in the analysis was to determine calibration levels of the two channels to be compared. Calibration tones were generated for each data channel used (except the probe microphone see experimental procedures). With the geophone and calibration levels used, a 1 bar acoustic sound pressure level and a geophone velocity of 1.754×10^{-4} cm/sec produced equal voltage levels at the input to the FM recorder.

The field records were digitized using a PDP 11/23 controlled A/D converter digitizing at 1000 Hz. No anti-aliasing filter was used. We assumed that the electronic and geophone frequency roll was sufficient to prevent aliasing.

The program used to analyze the data, called Tranff.Bas, is attached as Appendix A.7.

Representative results of the data analysis are given in Figures 4.1, 4.2, 4.3, and 4.4. The total amount of data precluded a complete presentation here but all data will be provided on request. A larger sample is included in Appendix B. Referring to Figure 4.2 note that the direction of phase change with frequency depends upon the sign convention chosen on

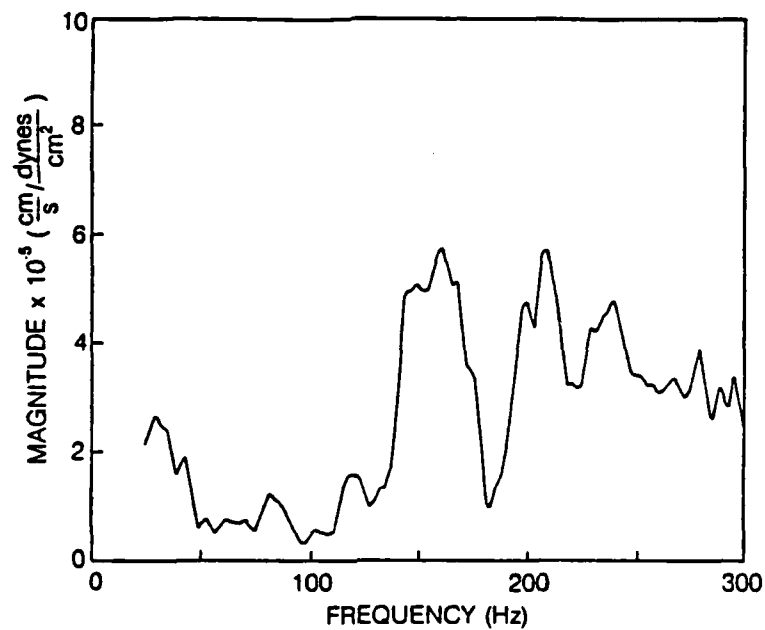


Figure 4.1. The experimental magnitude of the vertical seismic transfer function at a depth of 5cm and 20° angle of incidence at Sardis.

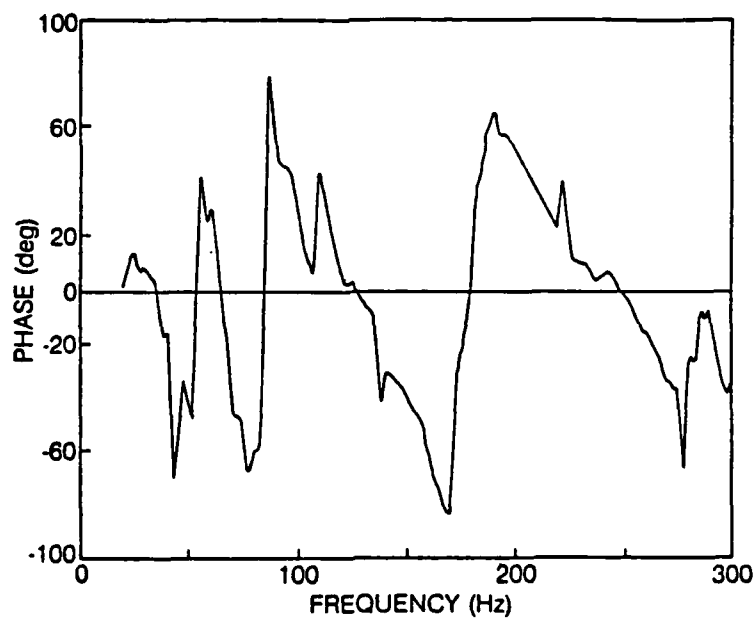


Figure 4.2. The experimental phase of the vertical seismic transfer function at a depth of 5cm and 10° angle of incidence for the UM test field.

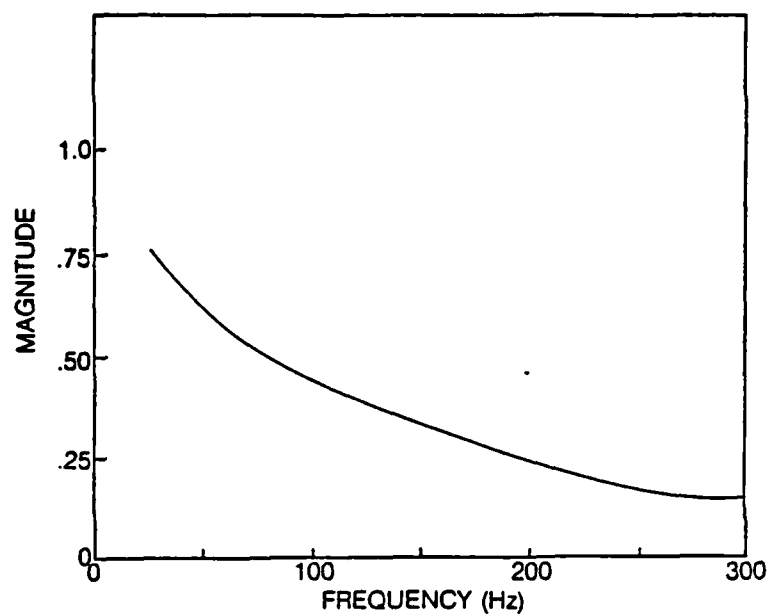


Figure 4.3. The experimental magnitude of the probe transfer function at a depth of 8cm and 20° angle of incidence for Sardis beach.

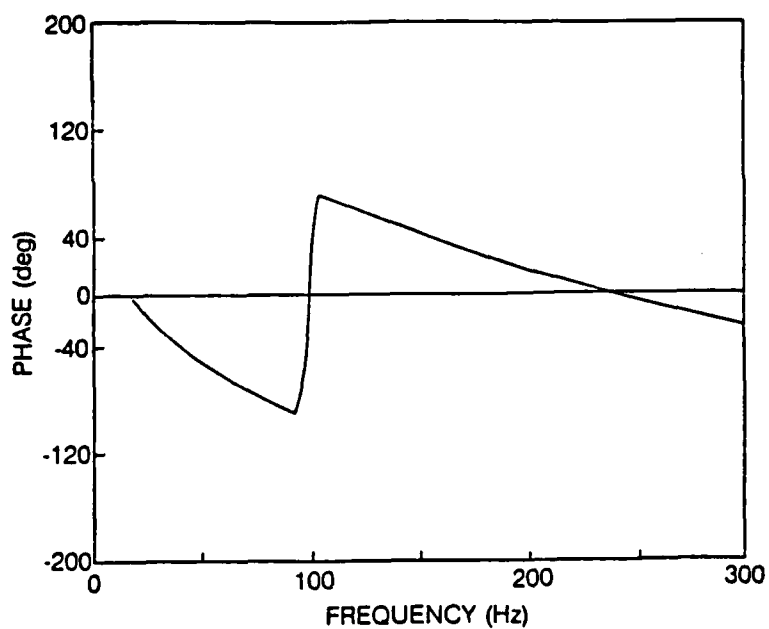


Figure 4.4. The experimental phase of the probe transfer function at a depth of 5cm and 15° angle of incidence for Sardis beach.

$\exp(i\omega t)$. Unfortunately, all data analysis was done independently of the theory development so the signs are reversed. In the data analysis program, the phase becomes more negative as the frequency increases (fixed path length difference, decreasing wavelength); in the theory program, this would result in a more positive phase. Also note, in figure 4.3 that the probe had no absolute calibration so we only measured the change in probe response as a function of frequency. For convenience in presentation, it was assumed that the probe microphone and the AKG microphone in the probe had the same sensitivity but this could be off by as much as a factor of two. Finally, note that all phases are limited between $\pm 90^\circ$ due to the ambiguity in the arctan routine. This accounts for occasional discontinuous jumps from -90° to $+90^\circ$. In fact, the phase is smoothly varying at this point through an angle greater than -90° .

Probe microphone data collected in the UM test field suffered from poor S/N due to the rapid attenuation of the sound field with depth at that site. The poor S/N ratio makes the phase measurements especially ragged through the trend is clear.

5. COMPARISON OF EXPERIMENTAL DATA TO THEORETICAL CALCULATION

This section provides a physical interpretation of selected experimental data and a comparison to theoretical predictions. The effects of the parameters which characterize the porous layer, viscosity, shape factor ratio, tortuosity, flow resistivity, porosity, angle of incidence, and layer depth, on the acoustic and seismic transfer functions are considered. Also, using measured values of flow resistivity, an acoustic surface impedance is calculated using a standard empirical form and compared to that which the Biot-Stoll Model (developed here) predicts and experiment.

Experimental Observations

At either depth at the UM test field, the phase of the seismic transfer function shows only a slight change when the incident angle is changed from 10° to 20° for frequencies above 100 Hz (See Figure 5.1 and 5.2). Similar observations can be made for the phase measurements at Sardis beach, but with less assurance due to the more rapid oscillation of the phase frequency (Figure 5.3 and 5.4). The phase of the seismic transfer function at the UM test field shows a $\frac{5}{2}\pi$ phase change over 300 Hz frequency range (Figure 5.1); at Sardis, for the same depth, there is a 3π to 4π phase change for the same frequency span (Figure 5.3). At a frequency of 100 Hz, there is approximately a 30° phase difference between the 5 cm and 25 cm depths for the seismic transfer functions at the UM test field, (Figure 5.1 and 5.4) (angle of incidence 20°) which would correspond to a seismic phase velocity of 2.4×10^4 cm/s. Table 2 shows values of measured wave speeds near this value.

The magnitude of the seismic transfer function is insensitive to angle of incidence at both depths at each experimental site. However, the magnitude of the acoustic transfer function at Sardis at the 12 cm depth shows an increase with decreasing angle of incidence. At 100 Hz, there is a 40%

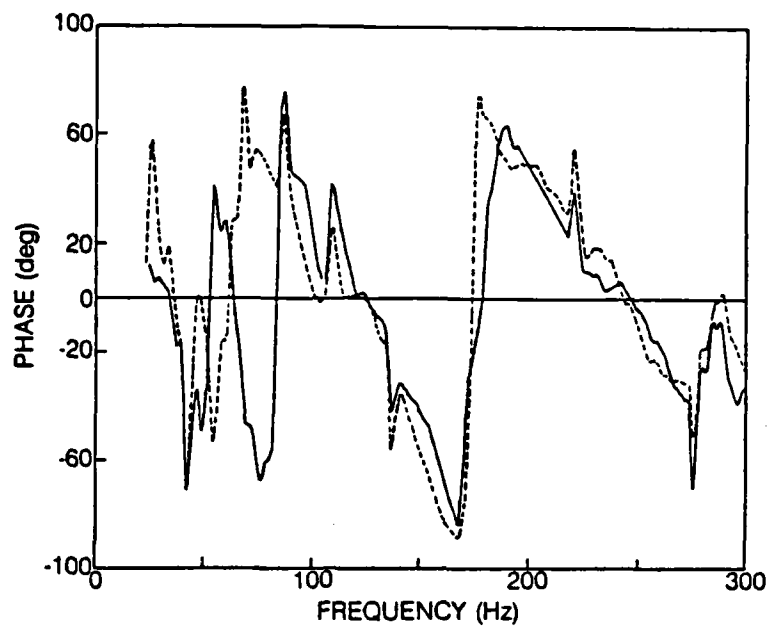


Figure 5.1. The phase of the experimental seismic transfer function at a 5cm depth at the UM test field for 10° (—) and 20° (---).

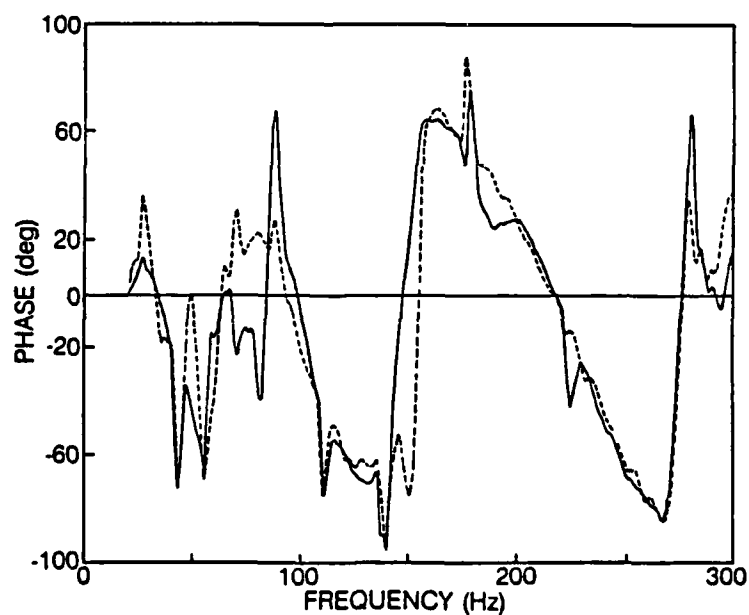


Figure 5.2. The phase of the experimental seismic transfer function at a 25cm depth at the UM test field for 10° (—) and 20° (---).

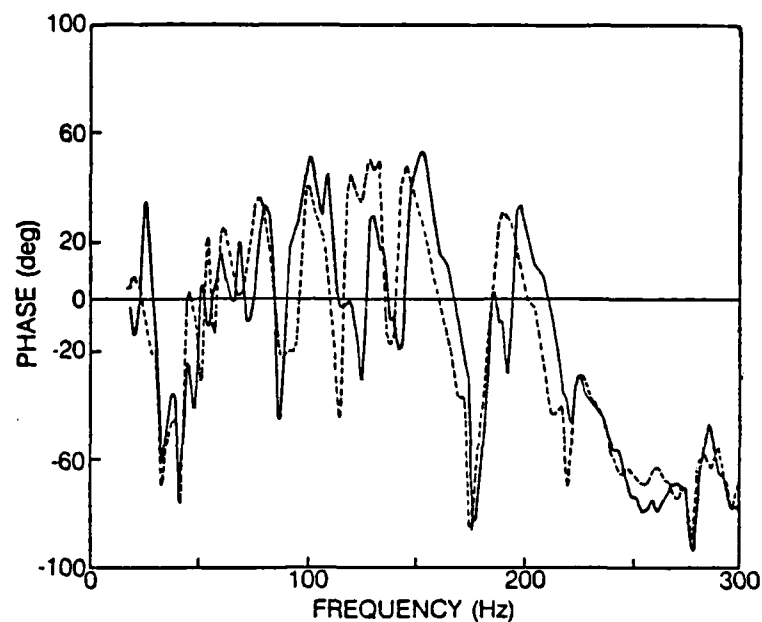


Figure 5.3. The phase of experimental seismic transfer function at a 5cm depth at Sardis beach for 10° (—) and 20° (---).

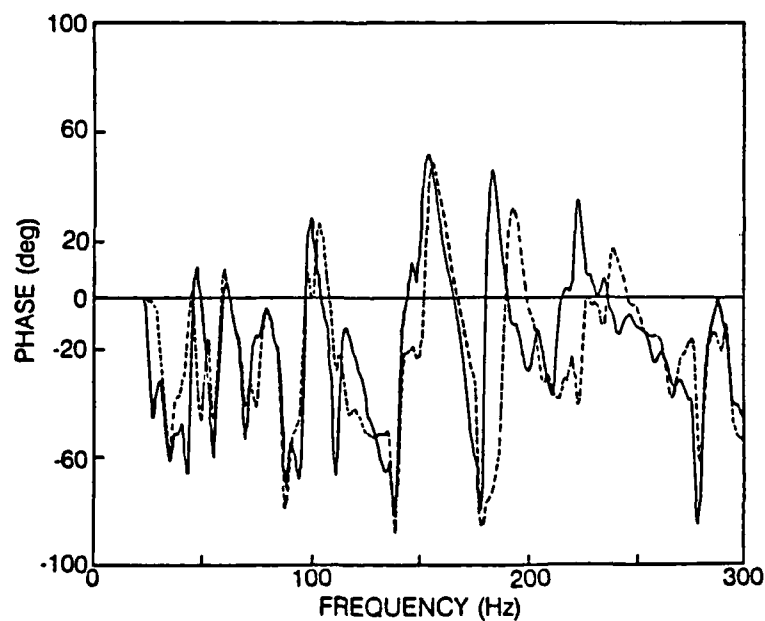


Figure 5.4. The phase of experimental transfer function at a 25cm depth at Sardis beach for 10° (—) and 20° (---).

increase in the magnitude when the angle of incidence is changed for 20° to 5° , (See Figure 5.5). This change is not observed at the UM test field.

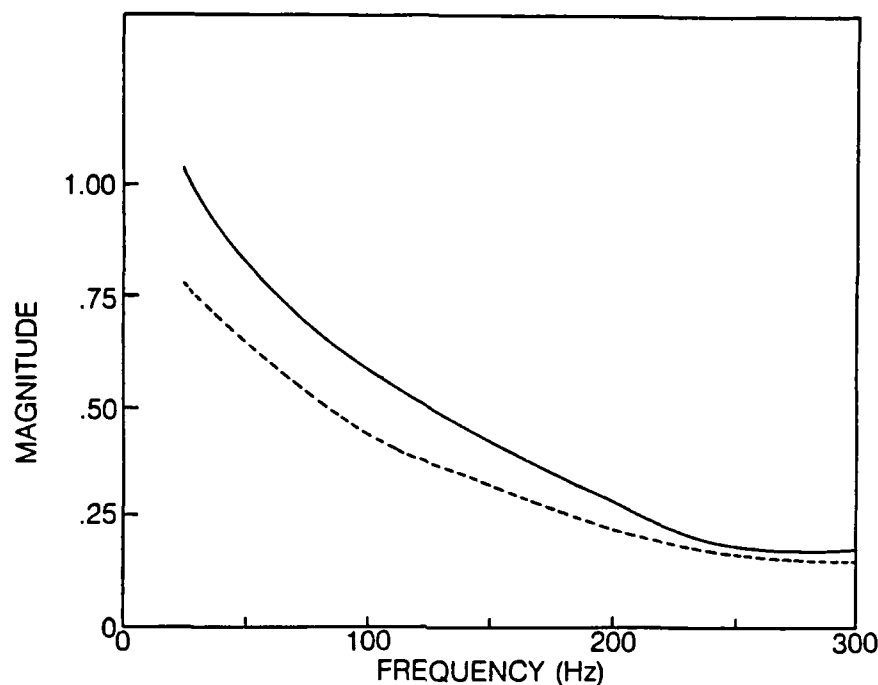


Figure 5.5. The magnitude of the experimental probe transfer function at 12cm at Sardis for 20° (—) and 5° (---).

The phase of the acoustic transfer function at Sardis is independent of angle of incidence. At the UM test field, the phase below 125 Hz is not affected by changes in the incident angle of incidence; above this frequency the S/N is so poor that a trend is not clear.

Sensitivity Analysis

In the field, only a finite number of surfaces can be studied. The theory developed in Chapter 2 can be used to determine the effects of the various physical properties required in the theory on the transfer functions.

Tortuosity and shape factor ratio have been shown by Attenborough⁸ to effect attenuation of an acoustic wave in some soils and sands, however these effects were not observed in this study. For ranges of the shape

factor ratio, $0.4 \leq \frac{n}{\sqrt{s}} \leq 1.0$, or tortuosity, $1.0 \leq q \leq 4.0$, the acoustic or seismic transfer functions are changed by less than 2%. The magnitude of the transfer functions are also insensitive to changes in both dynamic and kinematic viscosities of air when changed by factors up to five. The flow resistance and porosity do have a significant effect on the transfer functions.

The effect of increasing the porosity from .3 to .5 on the magnitude of the seismic transfer function is shown in Figure 5.6. Increasing porosity results in an increase in the seismic transfer function; the magnitude of the acoustic transfer function decreases for the same increases in porosity as indicated in Figure 5.7. The increase in the seismic transfer function results from a decrease in the mass density of the frame. For the same amount of incident acoustic energy when more is coupled into the frame, less must be available as transmitted acoustic energy, consequently the acoustic transfer function decreases with the increase in porosity. In the real world, the porosity cannot change without changing the flow resistivity. The argument here is offered only to aid physical interpretation.

The effect of changing the flow resistivity from 60 rayls/cm to 420 rayls/cm to 3000 rayls/cm on the magnitude of the seismic transfer functions is shown in Figure 5.8. Figure 5.9 shows the magnitude of the acoustic transfer function for flow resistivities of 60 rayls/cm, 150 rayls/cm and 420 rayls/cm. The magnitude of the acoustic transfer function decreases as the flow resistivity is increased. The magnitude of the seismic transfer function decreases with increasing flow resistivity for frequencies above 130 Hz and increases at the lower frequencies. If the flow resistivity were to go to infinity, the magnitude of the acoustic transfer function would tend to zero because acoustic energy could not be transmitted across the boundary as the pore fluid could not move. The

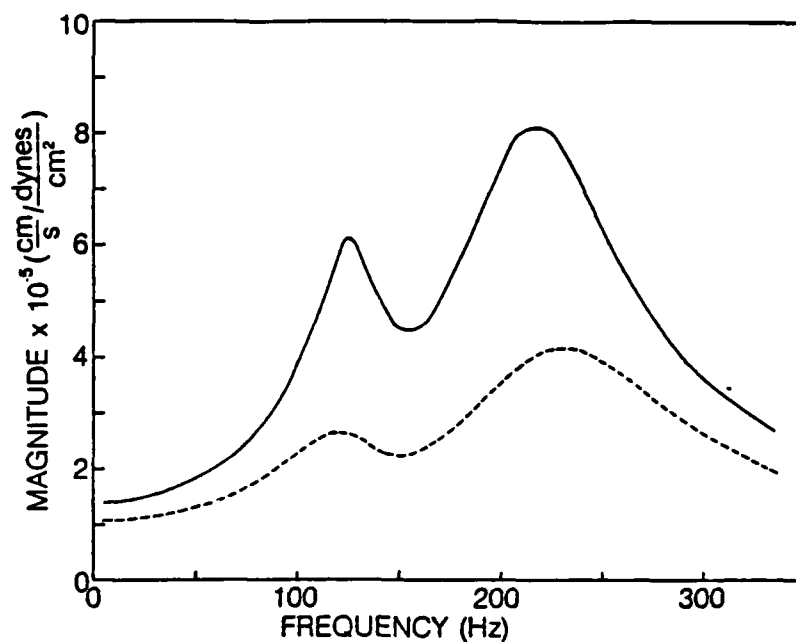


Figure 5.6. Magnitude of the calculated seismic transfer function for porosities of .3 (—) and .5 (---), 5 cm below the surface and 5° angle of incidence. All other parameters are set to values measured at Sardis.

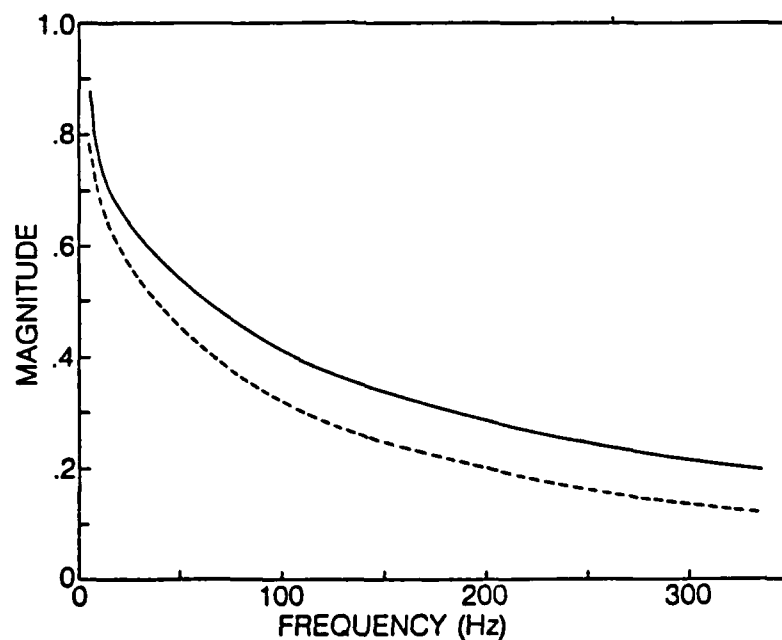


Figure 5.7. Magnitude of the calculated acoustic transfer function for porosities of .3 (—) and .5 (---), 5 cm below the surface and 5° angle of incidence. All other parameters are set to the values measured at Sardis.

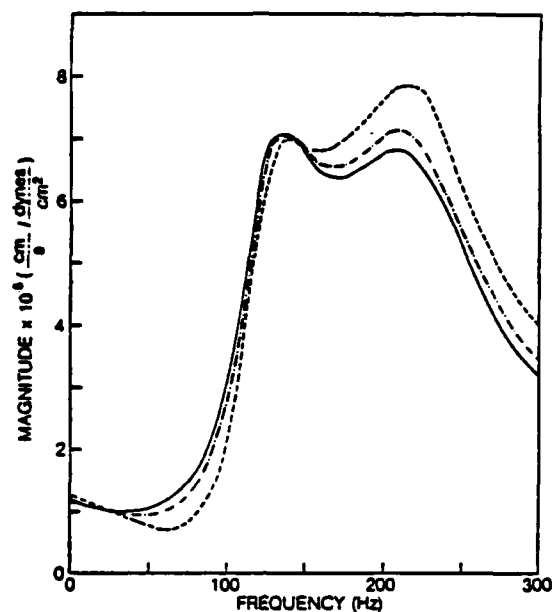


Figure 5.8. Magnitude of the calculated seismic transfer function for flow resistivities of 60 rayls/cm (—), 420 rayles/cm (---) and 3000 rayls/cm (— · —) at 23cm and 20°. The porosity is .4 and other parameters are set to the values measured at Sardis.

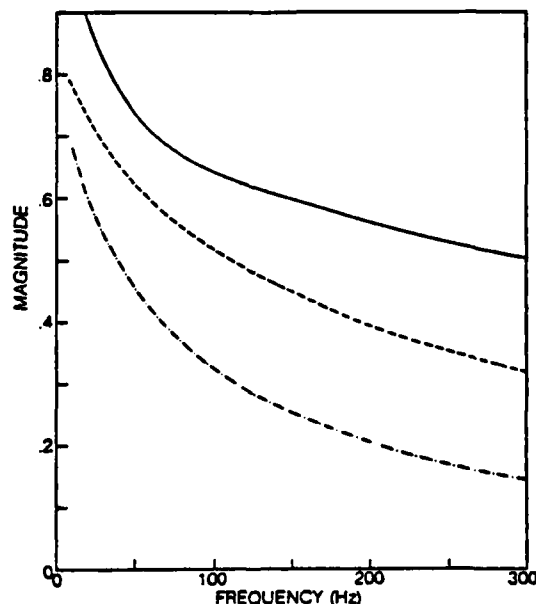


Figure 5.9. Magnitude of the calculated acoustic transfer function at 5cm for flow resistivities of 60 rayls/cm (—), 150 rayls/cm (— · —) and 420 rayls/cm (---), a porosity of .4 and angle of incidence of 5°. Other parameters are set to the values measured at Sardis.

seismic transfer function would approach zero since no acoustic energy could be coupled to motion of the frame through drag forces at the pore walls. If the flow resistivity went to zero, all the incident acoustic energy would pass through the upper boundary without attenuation but there would again be no seismic motion since there would be no frame.

By changing the layer depth, the effect of the measured wave speeds and consequently the elastic moduli on the transfer functions can be observed. Figure 5.10 shows the seismic transfer function for layer depths

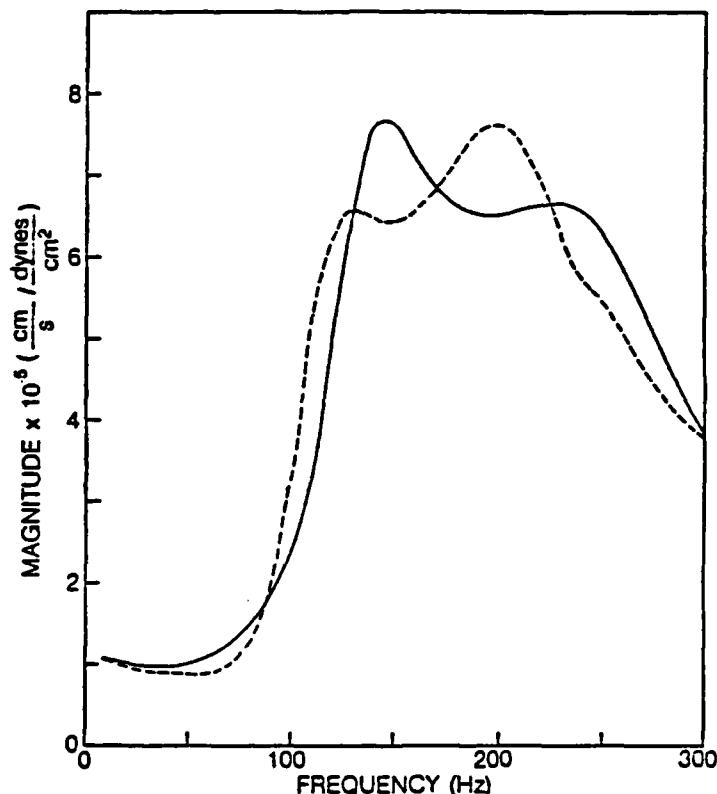


Figure 5.10. Magnitude of the calculated seismic transfer function at 23cm for layer depths of 28 cm (—) and 24 cm (---). Angle of incidence, porosity and flow resistance are 5° , .4, 350 rays/cm. Other parameters are set to those measured at Sardis.

of 28 and 24 cm. The acoustic transfer function for the same layer depths, not shown, is changed by less than 1%. The acoustic transfer function is insensitive to these changes but the seismic transfer function shows frequency shifts in the minimum and maximum indicating that some of the seismic energy is reflected from the lower boundary.

During the transfer function experiments, the angle of grazing incidence was varied from 5° to 20° . Figures 5.11 and 5.12 indicate the calculated effect of angle of incidence on the magnitude and phase of the seismic transfer function. The magnitude and phase of the acoustic transfer function is insensitive to the angle of incidence to less than 1 percent while the magnitude of the seismic transfer function decreases by as much as 25% at the maximum and the phase curve is shifted vertically by 4° to 5° .

Acoustic Transfer Function

Next, the experimental acoustic transfer function will be compared to the predicted transfer function using the measured values of flow resistivity (See Table 1) with the porosity set to 0.4 for both experimental sites. Figures 5.13 and 5.14 show the magnitude and phase of both the experimental and predicted acoustic transfer functions for the Sardis beach area at an incident angle of 20° and 12 cm below the surface. The theoretical phase plotted here is the negative of what was predicted for reasons previously explained. Comparisons of transfer functions for the UM test field are not shown. The agreement is no better or worse than at Sardis.

Even when the layer depth is theoretically changed from 26 cm to 6 cm the magnitude of the transfer function 5 cm below the surface does not show interference with waves reflected from the lower boundary because the acoustic wave in the pores is rapidly attenuated; it is not reflected from the lower boundary. By the time that the acoustic wave has propagated 4 cm through the pores almost all the acoustic energy has been transferred to motion of the frame at the pore walls. The effect of the porous layer acting as an impedance matching device coupling acoustic energy into the non-porous clay will be demonstrated in the next section of this report.

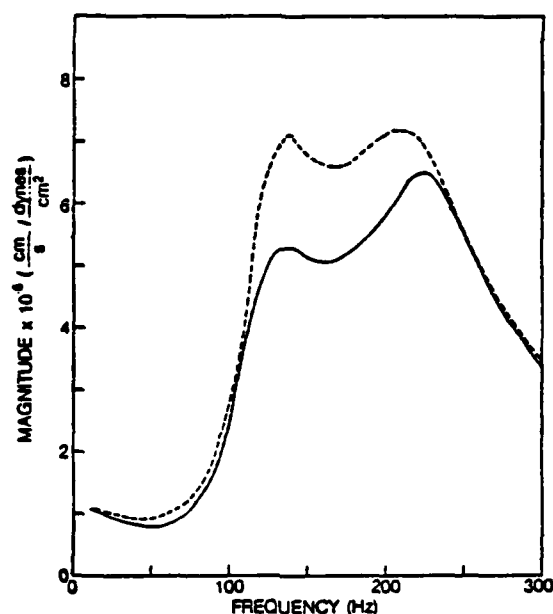


Figure 5.11. The calculated effect of angle of incidence on the magnitude of the seismic transfer function at 5° (---) and 20° (—) at a depth of 23cm. The porosity is 0.4 and other parameters are the values measured at Sardis.

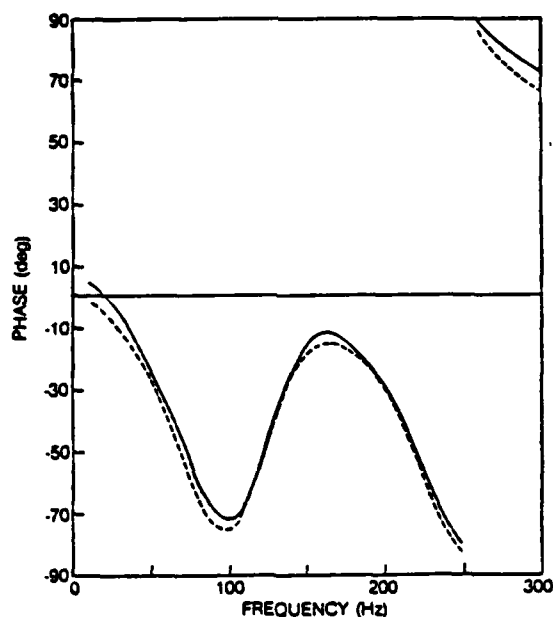


Figure 5.12. The calculated effect of angle of incidence on the phase of the seismic transfer function at 5° (---) and 20° (—) at a depth of 23cm. The porosity is 0.4 and other parameters are the values measured at Sardis.

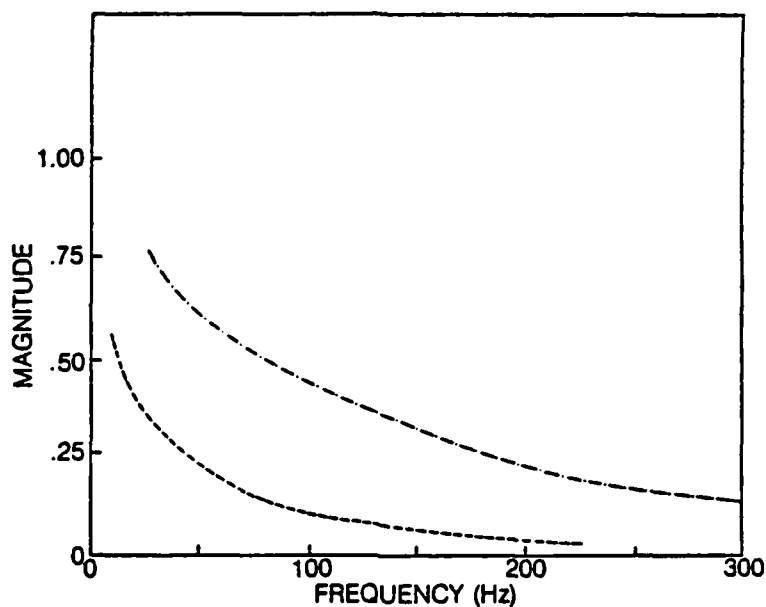


Figure 5.13. The calculated (—) and experimental (---) magnitudes of the acoustic transfer function at Sardis at 20° and 12 cm below the ground surface. Porosity is 0.4 and other parameters are the value measured at Sardis.

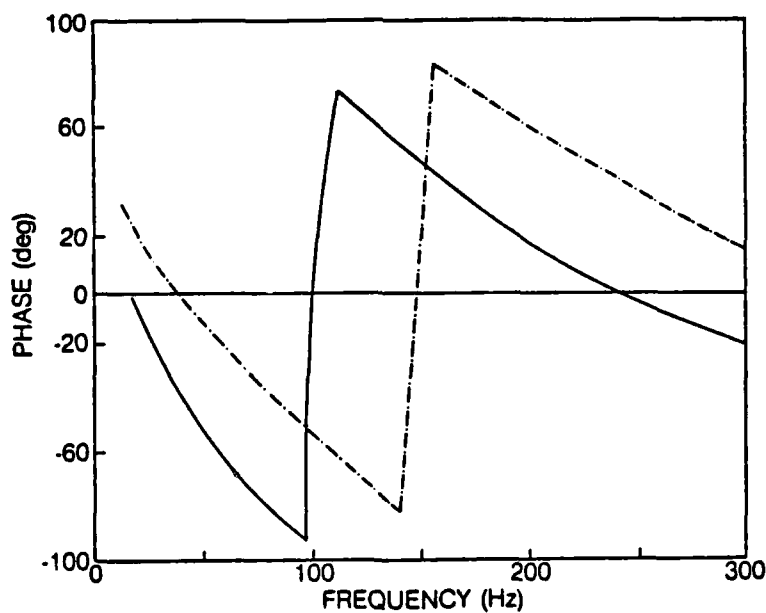


Figure 5.14. The calculated (---) and experimental (—) phases of the acoustic transfer function at Sardis.

Seismic Transfer Function

In the transfer function experiment, the seismic sensor was buried so that the top of the case was at depths of 5 and 25 cm. However, because of the physical size of the sensor (cylindrical, diameter = 20 cm, length = 18 cm), the transfer functions are calculated at 23 cm and 43 cm below the surface. At a depth of 43 cm, the lower clay layer is reached so we measure the seismic transfer function in both the porous soil and the non-porous clay. Figure 5.15, 5.16, 5.17 and 5.18 show the comparison of the magnitude and phase of the experimental and predicted seismic transfer function for both depths at Sardis. The experimental magnitude shows a strong minimum at 160 Hz and other fine structure which is not predicted by our single layer model. At Sardis the moisture content of the sand increased rapidly below 5 cm and became saturated at the depth of the clay layer. To predict the detailed structure of the seismic transfer functions in such a media it may be necessary to incorporate multiple layers in the physical model. In Figure 17, the UM test field measured seismic wave speeds for the clay were also used in the calculations along with a layer depth of 35 cm. Comparisons of the UM test field data to theory are not shown, but again the agreement is as good as at Sardis.

From the measured seismic wave speeds in the clay below the porous medium, the reflection coefficient for an air-clay boundary would be approximately .999 indicating almost no transmission into the surface. However, the measured magnitude of the seismic transfer function for the lower medium indicates as much seismic energy is transmitted into the clay as is coupled into the porous medium from the air. Theoretically, this is also seen. Transmission coefficients of .75 are computed at 200 Hz indicating that the porous layer acts as an impedance matching device for coupling acoustic energy into the non-porous clay below the porous medium.

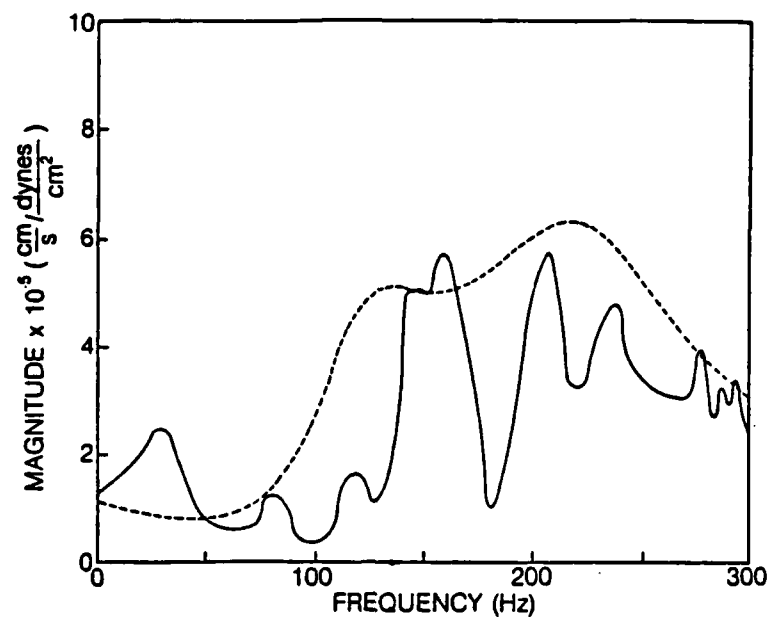


Figure 5.15. The magnitude of calculated (—) and experimental (---) seismic transfer function at Sardis at 20° and 23 cm.

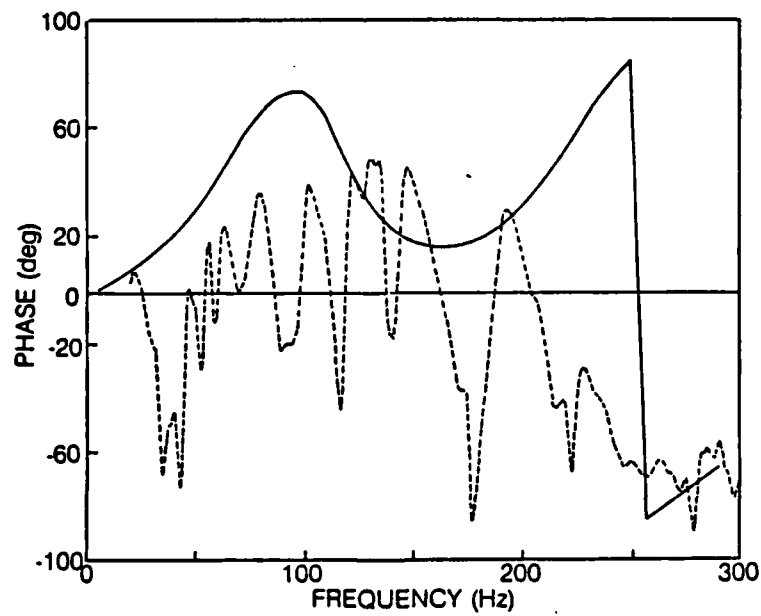


Figure 5.16. The phase of calculated (—) and experimental (---) seismic transfer function at Sardis at 20° and 23 cm.

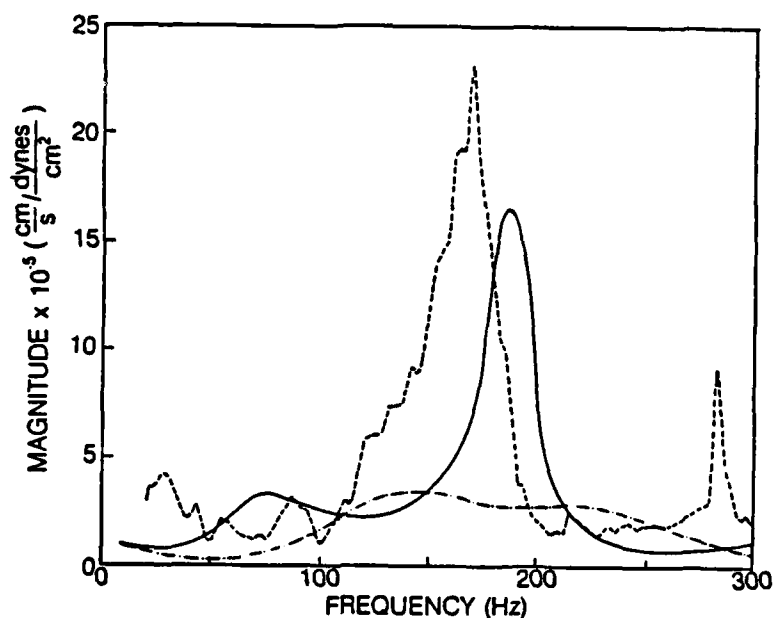


Figure 5.17. The magnitude of the calculated (---) and experimental (—) seismic transfer function at Sardis at 20° and 43 cm. The solid line is calculated with the UM test field clay velocities and a layer depth of 35cm substituted for the Sardis values.

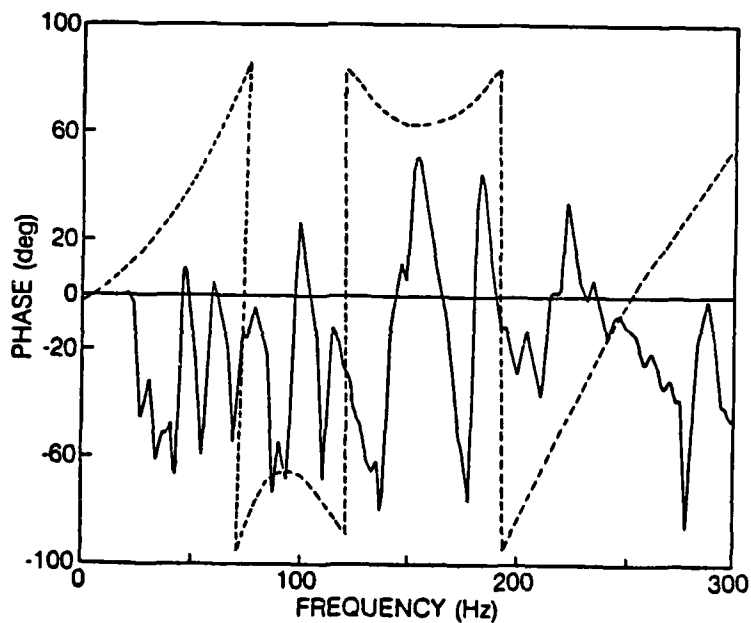


Figure 5.18. The phase of the calculated (---) and experimental (—) seismic transfer function at Sardis at 20° and 43 cm.

The very fact that the theoretical predictions come within a factor of 2 of the experimental data in all cases, compared to a factor of 1000 for a homogeneous layer theory, is remarkable considering that there are no empirical adjustments or parameters allowed.

Surface Impedance

The acoustic surface impedance at Sardis or the UM test field soil was not experimentally determined. However, Bolen and Bass have published normalized surface impedances for several ground covers which include a sand and two different soils. They compared experimentally measured values of surface impedance to that which is predicted from a single parameter model based on measured flow resistivity (see Reference 17). In each of the ground covers investigated, they found that the impedance necessary to reproduce the sound pressure level measured with above ground microphones required that they use a flow resistivity in the single parameter model approximately one-half the measured flow resistivity (see Figure 5.19, 5.20). This was referred to as the best fit to measured values. The theoretical normalized surface impedance predicted by the Biot-Stoll Model developed here is plotted on the Bolen and Bass impedance curves for their measured values of flow resistivity. Note that no empirical adjustment of the flow resistance is required. In fact, there are no adjustable parameters allowed.

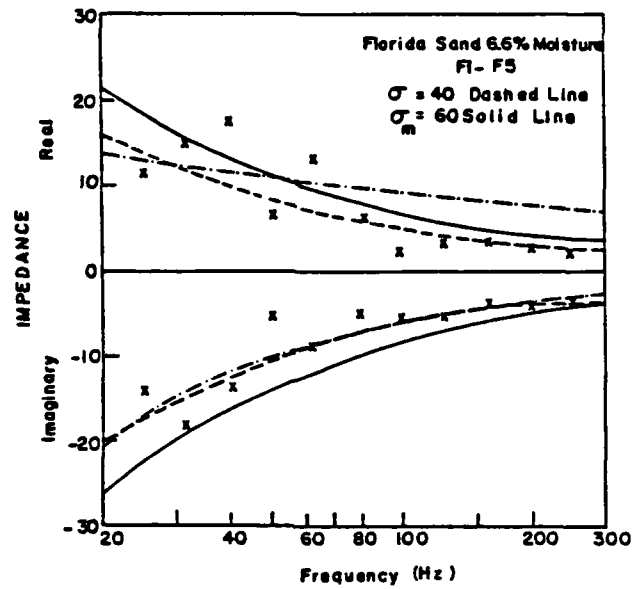


Figure 5.19. The real and imaginary impedance values for a Florida Sand determined by Bolen and Bass; experimental data (x), empirical Chessell model (—), the best fit (---). The dash dot line is calculated using the Biot-Stoll Model with the measured values of flow resistance, $\sigma_m = 60$ rayls/cm.

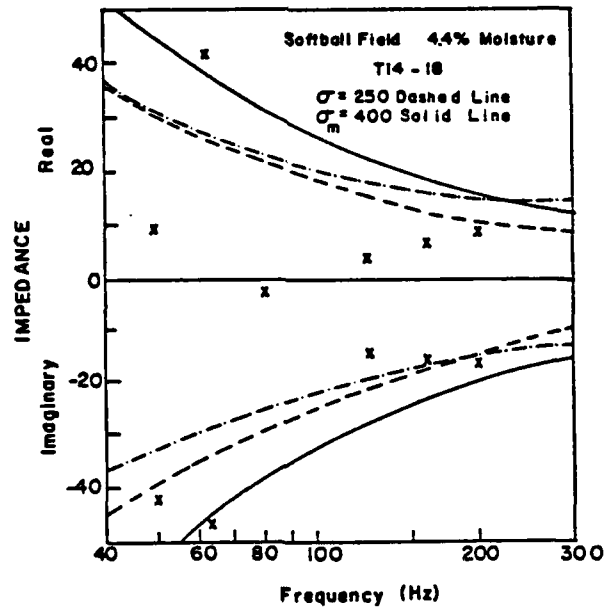


Figure 5.20. The real and imaginary impedance values for a Softball field determined by Bolen and Bass; experimental data (x), empirical Chessell model (—), the best fit (---). The dash dot line is calculated using the Biot-Stoll Model with the measured value of flow resistance, $\sigma_m = 400$ rayls/cm.

6. SUMMARY AND CONCLUSION

Using the Biot-Stoll Model of a porous elastic medium the compressional wave propagation constants have been numerically determined for a porous sand and a grass covered field. The earth's surface was modeled as a finite layer of porous material between two semi-infinite media, air and non-porous clay. The complex displacement amplitudes of compressional and shear waves in each medium were found using numerical techniques and a complex transfer function was defined in terms of these amplitudes. Compressional waves are emphasized here to clarify the physical properties. The surface impedance was also determined from the wave amplitudes. An outdoor experiment was performed in order to measure the transfer function so that theory could be compared to experiment.

A sensitivity analysis of the calculated transfer function revealed that the only physical quantities which significantly affect the computed transfer functions are the flow resistivity of the porous surface, the depth of the porous layer, and the compressional and shear wave velocities of the underlying clay. The magnitudes of the calculated acoustic/seismic transfer function using independently measured values of the physical properties typically agrees with the measured values of the transfer function within factors of two. The theory does not predict observed fine structure in the acoustic/seismic transfer function. It may be necessary to include multiple layers and flow resistivity gradients in the porous surface if the fine structure is required.

The Biot-Stoll Model allows for an acoustic wave in the pores of the porous surface. In a separate experiment, attenuation coefficients and phase velocities of this acoustic wave were measured in sand using a probe microphone. The phase velocity of the acoustic wave in the pores was only tens of m/s and the attenuation was one to two dB/cm. Predicted attenuation and wave velocity agree well with experiment.

The mechanism for the coupling of acoustic energy into the ground as seismic energy is understood in the light of these measurements. As the airborne acoustic wave impinges upon the porous surface, it forces motion of air in the surface pores. The oscillating air in the pores is subjected to viscous drag at the pore walls. As a result of this drag, energy is taken out pore fluid motion and appears as motion of the pore walls - motion of the soil matrix. This motion is detected with a seismic sensor - a geophone. An alternative way of viewing this coupling process is to consider the porous layer as an impedance matching network. Without the pores, the acoustic resistance (ρc) in air is much less than in the earth. The pore wave, however, is very slow bringing the effective ρc product for the earth's surface more near that of air.

This physical model also explains a result which has mystified outdoor acousticians for a number of years. Specifically, when one measures the impedance of the earth's surface it is found, in almost all cases, to be locally reacting. This means that energy is refracted so that it is almost normal to the surface. The impedance then becomes essentially independent of the angle of incidence and regions of the surface very far away from the point where the acoustic wave strikes do not contribute to the refracted or reflected acoustic fields. This is difficult to understand if the wave speed in the earth is taken to be hundreds of meters per second but follows readily from Snell's Law if the wave speed in the surface (in the pores) is only tens of meters per second. The empirical result that the earth's surface is almost always locally reacting can, then, be understood as a natural consequence of the porous upper layer of the earth.

In conclusion, the Biot-Stoll Model for a porous elastic medium as presented here provides a good physical description of the coupling of airborne acoustic energy into the ground where it appears as seismic motion and an acoustic wave in the pores. This model predicts the measured

attenuation of the acoustic wave in the pores, surface impedance, and acoustic and seismic transfer functions and their dependence upon angle of incidence and frequency within factors of two of measured values even when one assumes only one porous homogeneous layer. Earlier calculation based upon semi-infinite homogeneous fluids in contact were in error by a factor of 1000 and these calculations predicted a strong angle of incidence not observed experimentally, and predicted incorrect frequency dependence.

The theoretical results presented here need three refinements in order to make this procedure a useful engineering tool:

1. Only plane incident waves are included when, in fact, most sources are more nearly spherical. Dr. Attenborough¹⁸ has developed the mathematics necessary to treat the spherical case. His formalism needs to be included in our present computer programs and additional experiments need to be performed for angles of incidence less than 5° where Attenborough predicts a difference between plane and spherical wave results.

2. The theoretical expressions need to be simplified by searching for realistic approximations so that one can treat impulsive sources using Fourier Transform techniques. This refinement will require extensive calculations be made to verify that the approximate relations are valid for practical surfaces. This refinement will allow comparison between experiment and the large data base developed by van Hoof¹⁹ and co-workers for impulsive sources.

3. The model needs to be extended to allow for variation of flow resistance with depth and multiple porous layers. This refinement will be necessary before we can hope to predict the fine structure in the acoustic/seismic transfer functions. Experimentally, data is needed for a wider variety of surfaces as well as data with incident angles less than 5° . Specifically, surfaces with very low and very high flow resistivities would help explore the range of validity of this model.

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APPENDIX A.1

The subroutine PROP.FORTRAN is used to drive the routine SOAIR.FORTRAN which computes the compressional wave propagation constants using equation 8. The frequency, FR, is the input parameter and the propagation constants, ZSLOW1, ZFAST1 are the output. The routine is in CGS units. SOAIR computes the viscosity correction factor (equation 6) with IARGT=0 and the complex compressibility with ICOMP=1 (see Reference 12). Parameters not defined in SOAIR are as follows:

NVISC	Static Shape Factor (n)
STATSF	Dynamic Shape Factor (s)
NTHER	Same as NVISC
QSQ	Tortuosity
RHO	Bulk Density
CP	Specific Heat of Air
COFUIS	Same as ETA
THECON	Thermal Conductivity of Air
PRN	Prandtl's Number
SHFT	Shape Factor Ratio
SHF	Same as SHFT
GAMA	Ratio of Specific Heats of Air
COMP	Compressibility of Air
HBAR	See equation 2a
CBAR	See equation 2b
MBAR	See equation 2c
D	See equation 2d

The subroutines CBESJ.FORTRAN and CBJ.FORTRAN compute the Bessel functions required for the viscosity correction factor and complex compressibility.

C	DRIVE SR ROUTINE FOR PROPAGATION PROGRAMS	PRO00010
C	FOR DEFINITION OF CONSTANTS SEE APPROPRIATE	PRO00020
C	SUBPROGRAMS. SUBPROGRAM SOAIR COMPUTES THE	PRO00030
C	COMPLEX PROPAGATION CONSTANTS FOR THE POROUS	PRO00040
C	LAYER.	PRO00050
C		PRO00060
	SUBROUTINE PROP(FR,ZSLOW1,ZFAST1)	PRO00070
	IMPLICIT REAL *8 (A-H,O-Z)	PRO00080
	REAL *8 MU,KBAR,K,KR,NTHER,NVISC,NPRIME	PRO00090
	COMPLEX *16 ZSLOW1,ZFAST1,J,F	PRO00100
	COMMON /BLK2/ J,F,ETA,K,Q2	PRO00110
	COMMON /BLK4/ PHI	PRO00120
	COMMON /BLK/ DM,IARGT,ICOMP,MU,STATSF,NTHER,NVISC,NPRIME	PRO00130
	COMMON /BLK3/ RHOF,GB,KBAR,KR,RHOS,OMEGA	PRO00140

```

      ICOMP = 0
      MU=.1495D0
      ETA=1.81D-04
      K=ETA/PHI
      CALL SOAIR(FR,ZSLOW1,ZFAST1)
      RETURN
      END

```

```

PRO00150
PRO00160
PRO00170
PRO00180
PRO00190
PRO00200
PRO00210
PRO00220

```

```

      SUBROUTINE SOAIR(FR,ZSLOW1,ZFAST1)
      INPUTS          FR
      OUTPUTS         ZSLOW1,ZFAST1

```

```

SOA00010
SOA00020
SOA00030

```

```

      TO OBTAIN PROPAGATION CONSTANTS FOR DILITATIONAL WAVES.
      15TH NOV 82
      RECONSTRUCTED VERSION, 25TH APRIL 83.
      DATA TAKEN FROM STOLL'S PAPER JASA(1969) V 47, N 5,P1440-1447.

```

```

SOA00040
SOA00050
SOA00060
SOA00070
SOA00080

```

```

      SUBROUTINES USED

```

```

      CBESJ
      CBJ

```

```

SOA00090
SOA00100
SOA00110
SOA00120
SOA00130
SOA00140

```

```

      SUBROUTINE SOAIR(FR,ZSLOW1,ZFAST1)
      IMPLICIT REAL *8 (A-H,O-Z)

```

```

SOA00150
SOA00160

```

```

      DIMENSION AKBDB(6),FAT(6)
      DIMENSION DEP(6),AT(6)

```

```

SOA00170
SOA00180
SOA00190

```

```

      REAL *8      MU,KBAR,K,KR,NTHER,NVISC,NPRIME
      COMPLEX *16 J,ROOTJ,CAPB,CAPC,SDISC,ARG,Z1,Z2,DISC
      COMPLEX *16 XARG1,XJ0,XJ1,T1,COMP,KF
      COMPLEX *16 D,HBAR,CBAR,MBAR,CAPA
      COMPLEX *16 XARG2,RJ0,RJ1,T2,M
      COMPLEX *16 BJ0,BJ1,T,F,BBYA,BBYA2
      COMPLEX *16 ZKRB
      COMPLEX *16 ZFAST1,AKB1,ZKRB1,ZSLOW1
      COMPLEX *16 CPS,CPB,ZSLOW,ZFAST,SRAT1,SRAT2,FRAT1,FRAT2
      COMPLEX *16 XARG,AKB
      COMPLEX *16 EP,EQ,ER,TOWS,TOWF,RAFTOS

```

```

SOA00200
SOA00210
SOA00220
SOA00230
SOA00240
SOA00250
SOA00260
SOA00270
SOA00280
SOA00290
SOA00300
SOA00310
SOA00320

```

```

      COMMON /BLK/ DM,IARGT,ICOMP,MU,STATSF,NTHER,NVISC,NPRIME
      COMMON /BLK1/ EP,EQ,ER
      COMMON /BLK2/ J,F,ETA,K,QSQ
      COMMON /BLK3/ RHOF,GB,KBAR,KR,RHOS,OMEGA
      COMMON /BLK7/ HBAR,CBAR,MBAR

```

```

SOA00330
SOA00340
SOA00350
SOA00360
SOA00370
SOA00380
SOA00390
SOA00400
SOA00410
SOA00420
SOA00430

```

C	-----	SOA00440
C		SOA00450
	PI = 4.DO*DATAN(1.DO)	SOA00460
C	OMEGA=POROSITY(NO UNITS).	SOA00470
C	KR=BULK MODULUS OF GRAINS (DYNES/CM**2)	SOA00480
C		SOA00490
C	MU=KINEMATIC VISCOSITY (CM**2/SEC)	SOA00500
C	ETA=DYNAMIC FLUID VISCOSITY (DYNE-SEC/CM**2)	SOA00510
C	RHOS=DENSITY OF SOLID (GM/CM**3)	SOA00520
C	RHOF=DENSITY OF FLUID(GM/CM**3)	SOA00530
C		SOA00540
	RHO = (1.DO-OMEGA)*RHOS + OMEGA*RHOF	SOA00550
C	-----	SOA00560
C		SOA00570
C		SOA00580
C	COMPUTE PRANDTL NUMBER.	SOA00590
	CP = 1006.DO	SOA00600
	COFVIS = 1.81D-05	SOA00610
	THECON = 0.0257DO	SOA00620
	PRN = COFVIS*CP/THECON	SOA00630
	SPRN = DSQRT(PRN)	SOA00640
C		SOA00650
C	K=PERMEABILITY OF THE POROUS FRAME (CM**2)	SOA00660
C		SOA00670
	SHFT = DSQRT(STATSF)/NTHR	SOA00680
	SHF = DSQRT(STATSF)/NVISC	SOA00690
C		SOA00700
C		SOA00710
C	QSQ = (OMEGA)**(-NPRIME)	SOA00720
C		SOA00730
C	-----	SOA00740
C		SOA00750
	GAMA = 1.4DO	SOA00760
	STWO = DSQRT(2.DO)	SOA00770
	J = (0.DO,1.DO)	SOA00780
	ROOTJ = CDSQRT(J)	SOA00790
C	ROOTJ = CMPLX(REAL (ROOTJ),-AIMAG(ROOTJ))	SOA00800
	OM = 2.DO*PI*FR	SOA00810
	OM2 = OM*OM	SOA00820
	OM4 = OM2*OM2	SOA00830
C		SOA00840
C	-----	SOA00850
C		SOA00860
C	COMPUTE COMPLEX COMPRESSIBILITY.	SOA00870
	XLAM1 = (8.DO*QSQ*K)/(MU*OMEGA)	SOA00880
	XLAM1 = SHFT*DSQRT(XLAM1)	SOA00890
	XLAM1 = XLAM1*DSQRT(OM)	SOA00900
	XARG1 = ROOTJ*SPRN*XLAM1	SOA00910
	AXARG1= CDABS(XARG1)	SOA00920
	IF(AXARG1 .GT. 7.0) GO TO 60	SOA00930
	CALL CBESJ(XARG1,0,XJ0)	SOA00940
	CALL CBESJ(XARG1,1,XJ1)	SOA00950
60	IF(AXARG1 .LE. 7.0) GO TO 70	SOA00960
	CALL CBJ(XARG1,0,XJ0)	SOA00970
	CALL CBJ(XARG1,1,XJ1)	SOA00980
70	T1 = XJ1/XJ0	SOA00990

```

COMP = (1.DO+2.DO*(GAMA-1.DO)*T1/XARG1)/(GAMA*1.01325D06)
KF = 1.DO/COMP
IF( ICOMP.NE. 1 ) GO TO 80
    COMP = 9.86923D-07
    KF = 1.DO/COMP

```

```

CONTINUE

```

```

D = KR*(1.DO + OMEGA*(KR/KF - 1.DO))
HBAR = (KR-KBBAR)*(KR-KBBAR)/(D-KBBAR)
2 + KBBAR + (4.DO/3.DO)*GB
CBAR = KR*(KR-KBBAR)/(D-KBBAR)
MBAR = KR*KR/(D-KBBAR)
M = QSQ*(RHOF/OMEGA)
CAPA = -HBAR*MBAR + CBAR*CBAR

```

```

VISCOSITY CORRECTION

```

```

XARG = SHF*DSQRT((8.DO*QSQ*K)/(MU*OMEGA))
XX = XARG*DSQRT(OM)
ARG = ROOTJ*XX
OM2 = OM*OM
OM4 = OM2*OM2
IF( IARGT.NE. 1) GO TO 90
    ARG = ROOTJ*XX
90 IF( IARGT.NE.2) GO TO 100
    AP = SHF*DSQRT( 8.DO*QSQ*OMEGA)
    ARG = ROOTJ*DSQRT(OM/ETA)*AP
100 IF( IARGT.NE. 3) GO TO 110
    APhi = (DM/3.DO)*(OMEGA/(1.DO-OMEGA))
    ARG = ROOTJ*APhi*DSQRT(OM/ETA)
110 IF( IARGT.NE. 4) GO TO 120
    ARG = ARG/OMEGA

```

```

CONTINUE

```

```

IF( CDABS(ARG) .GT. 7.0) GO TO 130

```

```

CALL CBESJ(ARG,0,BJ0)

```

```

CALL CBESJ(ARG,1,BJ1)

```

```

130 IF( CDABS(ARG) .LE. 7.0) GO TO 140

```

```

CALL CBJ(ARG,0,BJ0)

```

```

CALL CBJ(ARG,1,BJ1)

```

```

WRITE(6,*)' BJ0 = ',BJ0,'BJ1 = ',BJ1

```

```

CONTINUE

```

```

T = BJ1/BJ0

```

```

WRITE(6,*)' T = ',T

```

```

F = (-0.25D0)*(ARG*T/(1.DO - 2.DO*T/ARG))

```

```

FREAL = DREAL(F)

```

```

FIMAG = DIMAG(F)

```

```

CAPB = OM2*(M*HBAR - 2.DO*CBAR*RHOF + RHO*MBAR)

```

```

2 +J*OM*F*ETA*HBAR/K

```

```

CAPC = OM4*(RHOF*RHOF - M*RHO)

```

```

2 - OM2*(RHO*J*OM*F*ETA/K)

```

```

BBYA = -CAPB/(2.DO*CAPA)

```

```

BBYA2 = BBYA*BBYA

```

SOA01000
 SOA01010
 SOA01020
 SOA01030
 SOA01040
 SOA01050
 SOA01060
 SOA01070
 SOA01080
 SOA01090
 SOA01100
 SOA01110
 SOA01120
 SOA01130
 SOA01140
 SOA01150
 SOA01160
 SOA01170
 SOA01180
 SOA01190
 SOA01200
 SOA01210
 SOA01220
 SOA01230
 SOA01240
 SOA01250
 SOA01260
 SOA01270
 SOA01280
 SOA01290
 SOA01300
 SOA01310
 SOA01320
 SOA01330
 SOA01340
 SOA01350
 SOA01360
 SOA01370
 SOA01380
 SOA01390
 SOA01400
 SOA01410
 SOA01420
 SOA01430
 SOA01440
 SOA01450
 SOA01460
 SOA01470
 SOA01480
 SOA01490
 SOA01500
 SOA01510
 SOA01520
 SOA01530

```

DISC = BBYA2 - CAPC/CAPA
SDISC= CDSQRT(DISC)
Z1  = BBYA + SDISC
Z2  = BBYA - SDISC
Z1  = CDSQRT(Z1)
Z2  = CDSQRT(Z2)

```

```

ZSLOW1 = Z1
ZFAST1 = Z2

```

```

RETURN
END

```

```

SUBROUTINE CBESJ(X,N,CBJ)
INPUTS      X,N
OUTPUTS     CBJ
ROUTINE TO COMPUTE COMPLEX BESSEL FUNCTION JN(X)
WHERE X IS A COMPLEX ARGUMENT

```

```

SUBROUTINE CBESJ(X,N,CBJ)
IMPLICIT REAL *8 (A-H,O-Z)
COMPLEX *16 X,CBJ,FM1,FM,BMK,ALPHA,CBPREV
CBPREV = (0.0,0.0)
D = 1.0E-4
AX = CDABS(X)
NTEST = 20.0 + 10.0*AX - AX**2/3
IF(AX.GT.15.0) NTEST = 90.0 + AX/2.0
IF(N.LT.NTEST) GO TO 20
WRITE(6,1001)
1001 FORMAT(1X,'RANGE OF X AND N IS INCORRECT')
RETURN
20  N1=N+1
MA = AX + 6.0
IF(AX.GE.5.0)MA = 1.40*AX + 60.0/AX
IX = AX
MB = N+ IX/4 + 2
MO = MAXO(MA,MB)
MMAX = NTEST
DO 90 M = MO,MMAX,3
FM1 = 1.0E-28
FM = 0.0
ALPHA = 0.D0
J1 = 1
IF(M.EQ.M/2*2) J1 = -1
M2 = M - 2
DO 160 K=1,M2
MK = M-K
XMK = MK + 2
BMK = XMK*FM1/X - FM
FM = FM1
FM1 = BMK
IF(MK-N-1.EQ.0.0) CBJ = BMK
J1 = -J1
S = 1 + J1

```

```

SOA01540
SOA01550
SOA01560
SOA01570
SOA01580
SOA01590
SOA01600
SOA01610
SOA01620
SOA01630
SOA01640
SOA01650
SOA01660
SOA01670

```

```

CBE00010
CBE00020
CBE00030
CBE00040
CBE00050
CBE00060
CBE00070
CBE00080
CBE00090
CBE00100
CBE00110
CBE00120
CBE00130
CBE00140
CBE00150
CBE00160
CBE00170
CBE00180
CBE00190
CBE00200
CBE00210
CBE00220
CBE00230
CBE00240
CBE00250
CBE00260
CBE00270
CBE00280
CBE00290
CBE00300
CBE00310
CBE00320
CBE00330
CBE00340
CBE00350
CBE00360
CBE00370
CBE00380
CBE00390
CBE00400
CBE00410
CBE00420

```

160	ALPHA = ALPHA + BMK*S	CBE00430
	BMK = 2.0*FM1/X - FM	CBE00440
	IF(N.EQ.0) CBJ = BMK	CBE00450
	ALPHA = ALPHA + BMK	CBE00460
	CBJ = CBJ/ALPHA	CBE00470
	IF(CDABS(CBJ-CBPREV).LT.(CDABS(D*CBJ)))GO TO 96	CBE00480
90	CBPREV = CBJ	CBE00490
96	RETURN	CBE00500
	END	CBE00510
C	SUBROUTINE CBJ(X,N,J)	TEM00010
C	INPUTS X,N	TEM00020
C	OUTPUT J	TEM00030
C		TEM00040
C	ROUTINE TO COMPUTE COMPLEX *16BESSEL FUNCTION JN(X)	TEM00050
C	WHERE X IS COMPLEX *16	TEM00060
C		TEM00070
C	THE ROUTINE CBESSEL (YBESS.FTP FROM SOUTHAMPTON IS USED	TEM00080
C	IF CABS(X) IS GREATER THAN 7.0, OTHERWISE CBESJ IS USED.	TEM00090
C		TEM00100
C	ZERO AND FIRST ORDER BESSEL FUNCTIONS OF COMPLEX *16ARGUMENTS	TEM00110
C	ARE COMPUTED.	TEM00120
C	N = 0; ZERO ORDER BESSEL FUNCTION.	TEM00130
C	N = 1; FIRST ORDER BESSEL FUNCTION.	TEM00140
C	*****	TEM00150
C		TEM00160
	SUBROUTINE CBJ(X,N,J)	TEM00170
	IMPLICIT REAL *8 (A-H,O-Z)	TEM00180
	COMPLEX *16 X,J,FM1,FM,BMK,ALPHA,CBPREV	TEM00190
	COMPLEX *16 Z,CHI,EZ,T0,T1,T2,T3,T4,T5,T6,T7,P0,Q0	TEM00200
	REAL *8 JR,JI	TEM00210
	AX = CDABS(X)	TEM00220
	IF(AX.GT.7.0) GO TO 100	TEM00230
	CBPREV = (0.0,0.0)	TEM00240
	D = 1.0E-04	TEM00250
	NTEST = 20.0 + 10.0*AX - AX**2/3	TEM00260
	IF(AX.GT.15.0) NTEST = 90.0 + AX/2.0	TEM00270
	IF(N.LT.NTEST) GO TO 20	TEM00280
	WRITE(6,1001)	TEM00290
1001	FORMAT(1X,'RANGE OF X AND N IS INCORRECT')	TEM00300
	RETURN	TEM00310
20	N1 = N + 1	TEM00320
	MA = AX + 6.0	TEM00330
	IF(AX.GE.5.0) MA = 1.4D0*AX + 60.D0/AX	TEM00340
	IX = AX	TEM00350
	MB = N + IX/4 + 2	TEM00360
	MO = MAX0(MA,MB)	TEM00370
	MMAX = NTEST	TEM00380
	DO 90 M = MO,MMAX,3	TEM00390
	FM1 = 1.0E-28	TEM00400
	FM = 0.0	TEM00410
	ALPHA = 0.0	TEM00420
	J1 = 1	TEM00430
	IF(M.EQ.M/2*2) J1 = -1	TEM00440
	M2 = M - 2	TEM00450

	DO 160 K=1,M2	TEM00460
	MK = M - K	TEM00470
	XMK = MK*2	TEM00480
	BMK = XMK*FM1/X - FM	TEM00490
	FM = FM1	TEM00500
	FM1 = BMK	TEM00510
	IF(MK-N-1.EQ.0) J = BMK	TEM00520
	J1 = -J1	TEM00530
	S = 1 + J1	TEM00540
160	ALPHA = ALPHA + BMK*S	TEM00550
	BMK = 2.0*FM1/X - FM	TEM00560
	IF(N.EQ.0) J = BMK	TEM00570
	ALPHA = ALPHA + BMK	TEM00580
	J = J/ALPHA	TEM00590
	IF(CDABS(J-CBPREV).LT.(CDABS(D*J))) GO TO 200	TEM00600
90	CBPREV = J	TEM00610
	GO TO 200	TEM00620
C	BEGIN CALCULATION USING LARGE ARGUMENT SERIES	TEM00630
C	A.ANDS.EQU.9.2.5 (8 TERMS ARE USED)	TEM00640
100	Z = X	TEM00650
	EZ = 8.0*Z	TEM00660
	IF(N.EQ.0) GO TO 189	TEM00670
C		TEM00680
C	FIRST ORDER CALCULATIONS	TEM00690
C		TEM00700
	CHI = Z - 3.0*3.14159265/4.0	TEM00710
C		TEM00720
C	TERMS IN P0 AND Q0 SERIES ARE FORMED BY	TEM00730
C	CHAIN MULTIPLICATION	TEM00740
C		TEM00750
	T0 = 1.0	TEM00760
	T1 = T0*(3.0/EZ)	TEM00770
	T2 = T1*(5.0/(2.0*EZ))	TEM00780
	T3 = T2*(21.0/(3.0*EZ))	TEM00790
	T4 = T3*(45.0/(4.0*EZ))	TEM00800
	T5 = T4*(77.0/(5.0*EZ))	TEM00810
	T6 = T5*(117.0/(6.0*EZ))	TEM00820
	T7 = T6*(165.0/(7.0*EZ))	TEM00830
C		TEM00840
C	FORM P0 = 1.0+T2-T4+T6	TEM00850
C		TEM00860
	P0 = T6 - T4	TEM00870
	PC = P0 + T2	TEM00880
	PO = P0 +T0	TEM00890
C		TEM00900
C	FORM Q0 = T1-T3+T5-T7	TEM00910
C		TEM00920
	Q0 = T5 - T7	TEM00930
	Q0 = Q0 - T3	TEM00940
	Q0 = Q0 + T1	TEM00950
	GO TO 199	TEM00960
C		TEM00970
C	ZERO ORDER CALCULATION	TEM00980
C		TEM00990
189	CHI = Z - 3.14159265359/4.0	TEM01000

TERMS IN P0 AND Q0 SERIES ARE FORMED BY
CHAIN MULTIPLICATION.

T0 = 1.0
T1 = T0/EZ
T2 = T1*(9.0/(2.0*EZ))
T3 = T2*(25.0/(3.0*EZ))
T4 = T3*(49.0/(4.0*EZ))
T5 = T4*(81.0/(5.0*EZ))
T6 = T5*(121.0/(6.0*EZ))
T7 = T6*(169.0/(7.0*EZ))

FORM P0 = 1.0 - T2 + T4 - T6

P0 = T4 - T6
P0 = P0 - T2
P0 = P0 + T0

FORM Q0 = -T1+T3-T5+T7

Q0 = T7 - T5
Q0 = Q0 + T3
Q0 = Q0 - T1

CONTINUE

J = CDSQRT(2.0/(3.14159265359*Z))*(P0*CDCOS(CHI)-
Q0*CDSIN(CHI))

END OF CALCULATION USING SERIES EXPRESSION.

CONTINUE

XR = DREAL (X)
XI = DIMAG(X)
JR = DREAL (J)
JI = DIMAG(J)

FOR ZEROth ORDER FUNCTION:

- IF XR=0.0 OR XI=0.0 THEN J IS REAL .
- THUS SET IMAG. RESULT TO ZERO.

IF(((XR.EQ.0.0).OR.(XI.EQ.0.0)).AND.(N.EQ.0)) JI = 0.0

FOR FIRST ORDER FUNCTION

- IF XI = 0.0 THEN J IS REAL
- THUS SET IMAG. RESULT TO ZERO

- IF XR = 0.0 THEN J IS IMAGINARY
- THUS SET REAL *8 RESULT TO ZERO

IF((XI.EQ.0.0).AND.(N.EQ.1)) JI = 0.0

IF((XR.EQ.0.0).AND.(N.EQ.1)) JR = 0.0

J = DCMLX(JR,JI)

RETURN

END

TEM01010
TEM01020
TEM01030
TEM01040
TEM01050
TEM01060
TEM01070
TEM01080
TEM01090
TEM01100
TEM01110
TEM01120
TEM01130
TEM01140
TEM01150
TEM01160
TEM01170
TEM01180
TEM01190
TEM01200
TEM01210
TEM01220
TEM01230
TEM01240
TEM01250
TEM01260
TEM01270
TEM01280
TEM01290
TEM01300
TEM01310
TEM01320
TEM01330
TEM01340
TEM01350
TEM01360
TEM01370
TEM01380
TEM01390
TEM01400
TEM01410
TEM01420
TEM01430
TEM01440
TEM01450
TEM01460
TEM01470
TEM01480
TEM01490
TEM01500
TEM01510

APPENDIX A.2

AMPL.FORTTRAN solves for the amplitudes of the wave motion developed in the section Boundary Value Problem. This routine calls the subroutines PROP, SURIMP, LTRANR, TRANSF and RTRANS which are discussed in additional appendices. AMPL reads the following input from a data file:

VP1	p-wave Velocity in Sand
VP2	p-wave Velocity in Clay
VS1	s-wave Velocity in Sand
VS2	s-wave Velocity in Clay
OMEGA	Porosity
THETO	Incidence Angle from Normal
D	Propagation Depth
RHOS	Clay Density
PHI	Flow Resistivity
QSQ	Tortuosity
STATSF	Dynamic Shape Factor (s)
NTHER	Static Shape Factor (n)
NVISC	Same as NTHER
IARGT	Set to ϕ for this work
DM	Not used for IARGT = ϕ
DEP	Layer Thickness
D1	Propagation Height

For each frequency, AMPL calls PROP which returns the fast and slow wave propagation constants, then the constants in the nine boundary condition equations are computed. The IMSL routine LEQTIC is called and returns the wave amplitudes. Originally AMPL calculated attenuation coefficients, equation 73, but these lines (4710-4920) are no longer used.

*****	AMP00010
NUMERICAL SOLUTION FOR WAVE AMPL. OF A BIOT LAYER	AMP00020
*****	AMP00030
	AMP00040
	AMP00050
IMPLICIT REAL * 8 (A-H,O-Z)	AMP00060
DIMENSION WK(9)	AMP00070
DIMENSION ZREAL(12),ZIMAG(12),FRQ(12),PHSGEO(12),PHSPRB(12)	AMP00080
REAL *8 ATDBG(12),ATDBF(12),MAGG2(12),MAGG1(12),MAGP1(12)	AMP00090
REAL *8 MAGP2(12),MAGGEO(12),MAGPRB(12)	AMP00100
COMPLEX *16 HH1,CC1,MM1	AMP00110
COMPLEX *16 WA(99)	AMP00120
DIMENSION WA(9)	AMP00130
COMPLEX *16 TEMP1,TEMP2,TEMP3,TEMP4,TEMP5	AMP00140
COMPLEX *16 Q3,Q4,Q5,C3,C4,C5	AMP00150
COMPLEX *16 J,L1,L2,L1S,L2S,C1,C2,S1,S2,Q1,Q2	AMP00160
COMPLEX *16 EXP1,EXP2,EXP3,EXP4,EXP5,EXP11,EXP12	AMP00170

	COMPLEX *16 EXP13,EXP14,EXP15	AMP00180
	COMPLEX *16 V1,V2,Z1,Z2,M1,M2,F	AMP00190
	REAL *8 OMEGA,KR,KF,KBBAR,K	AMP00200
	REAL *8 MAGGO,MAGPB	AMP00210
	REAL *8 MU,STATSF,NTHER,NVISC,NPRIME	AMP00220
	REAL *8 GB,GB2,LAM2	AMP00230
	COMPLEX *16 A(9,9),B(9)	AMP00240
	REAL *8 LO,L3,L4,L5,LOS,L3S,L4S,L5S,LOSO	AMP00250
	COMMON /BLK3/ RHOF,GB,KBBAR,KR,RHOS,OMEGA,KF	AMP00260
	COMMON /BLK2/ J,F,ETA,K,QSQ	AMP00270
	COMMON /BLK5/ VO,CO,SO,C1,LO,L1,C2,L2,S3,L3,C3	AMP00280
	COMMON /BLK4/ PHI	AMP00290
	COMMON /BLK/ DM,IARGT,ICOMP,MU,STATSF,NTHER,NVISC,NPRIME	AMP00300
	COMMON /BLK7/ HH1,CC1,MM1	AMP00310
	COMMON /BLK8/ S1,S2	AMP00320
	COMMON /BLK8/ C4,S4,C5,L4,L5	AMP00330
	J=(0.DO,1.DO)	AMP00340
	E=DEXP(1.DO)	AMP00350
	TWOPI=4.DO*DARSIN(1.DO)	AMP00360
C		AMP00370
C		AMP00380
C	DEP IS LAYER THICKNESS	AMP00390
C	D IS PROPAGATION DEPTH	AMP00400
C	D1 IS A PROPAGATION HEIGHT	AMP00410
C		AMP00420
C	*****	AMP00430
C		AMP00440
	WRITE(6,20)	AMP00450
20	FORMAT(1X,'INPUT 1 FOR SARDIS, 2 FOR AUDI ACRES.')	AMP00460
	READ(5,*)NTYPE	AMP00470
	IF(NTYPE .GT. 2)GO TO 9997	AMP00480
	READ(2,10,END=99)VP1,VP2,VS1,VS2,OMEGA,THETO,D,RHOS,PHI,QSQ,STATSF	AMP00490
	2 ,NTHER,NVISC,IARGT,DM,DEP,D1	AMP00500
99	IF(NTYPE .NE. 1)GO TO 409	AMP00510
	READ(1,10,END=409)VP1,VP2,VS1,VS2,OMEGA,THETO,D,RHOS,PHI,QSQ,	AMP00520
	2 STATSF,NTHER,NVISC,IARGT,DM,DEP,D1	AMP00530
10	FORMAT(/,1X,7(E10.3,1X),///,1X,6(E10.3,1X),I3,/,1X,3(E10.3,1X))	AMP00540
409	WRITE(11,21)VP1,VP2,VS1,VS2,OMEGA,THETO,D,PHI,QSQ,STATSF,	AMP00550
	2 NTHER,NVISC,IARGT,DM,D1,DEP	AMP00560
21	FORMAT(1X,'VP1 = ',E10.3,2X,'VP2 = ',E10.3,2X,'VS1 = '	AMP00570
2	,E10.3,3X,'VS2 = ',E10.3,/,1X,'OMEGA = ',E10.3,3X,	AMP00580
2	'THETO = ',E10.3,3X,'+Z = ',E10.3,/,1X,'FLOW RESIST = '	AMP00590
2	,E10.3,3X,'TORTUOSITY = ',E10.3,3X,'STATSF = '	AMP00600
2	,E10.3,/,1X,'NTHER = ',E10.3,3X,'NVISC = ',	AMP00610
2	E10.3,3X,'IARGT = ',I2,3X,'DM = ',E10.3,3X,/,1X,'-Z = ',E10.3,3X	AMP00620
2	, 'LAYER THICKNESS = ',E10.3)	AMP00630
C	*****	AMP00640
C	FR IS FREQUENCY	AMP00650
C	THETO IS INCIDENT ANGLE	AMP00660
C		AMP00670
	DO 9 I=1,300	AMP00680
	FRQ(I)=I	AMP00690
9	CONTINUE	AMP00700
	FR=10.DO	AMP00710

LTHETI=THETO
 THETO=TWOPI*THETO/360.D0
 D3=D

D IS PROPAGATION DEPTH BELOW SURFACE.
 D1 IS PROPAGATION DEPTH ABOVE SURFACE/

WAVE NUMBERS: 0 INCIDENT WAVE IN AIR AT THETO.
 1 FAST WAVE IN POROUS MEDIUM
 2 SLOW WAVE IN POROUS MEDIUM
 3 SHEAR WAVE IN POROUS MEDIUM
 4 SHEAR WAVE IN 3RD MEDIUM
 5 FAST WAVE IN 3RD MEDIUM

V0 TO V5 ARE THE WAVE VELOCITIES IN CGS UNITS

V0= SOUND SPEED IN AIR
 V1= BIOT FAST WAVE VELOCITY
 V2= BIOT SLOW WAVE VELOCITY
 V3= SHEAR WAVE VELOCITY IN LAYER
 V4= SHEAR WAVE VELOCITY IN LOWER MEDIUM
 V5= COMPRESSIONAL WAVE VELOCITY IN LOWER MEDIUM

DENSITIES OF MATERIALS FOR THE SYSTEM:

DENSITY OF AIR, RHOF (CGS UNITS)

RHOF=1.204D-03

DENSITY OF CLAY, RHOS AND MEAS VAL. = 2.65 GCM**3

DENSITY OF POROUS LAYER, RHO

RHO=RHOS+OMEGA*(RHOF-RHOS)

GB AND GB2 ARE THE SHEAR MODULI FOR THE LAYER AND CLAY

GB = VS1*VS1*RHO

GB2 = VS2*VS2*RHOS

AMP00720
 AMP00730
 AMP00740
 AMP00750
 AMP00760
 AMP00770
 AMP00780
 AMP00790
 AMP00800
 AMP00810
 AMP00820
 AMP00830
 AMP00840
 AMP00850
 AMP00860
 AMP00870
 AMP00880
 AMP00890
 AMP00900
 AMP00910
 AMP00920
 AMP00930
 AMP00940
 AMP00950
 AMP00960
 AMP00970
 AMP00980
 AMP00990
 AMP01000
 AMP01010
 AMP01020
 AMP01030
 AMP01040
 AMP01050
 AMP01060
 AMP01070
 AMP01080
 AMP01090
 AMP01100
 AMP01110
 AMP01120
 AMP01130
 AMP01140
 AMP01150
 AMP01160
 AMP01170
 AMP01180
 AMP01190
 AMP01200
 AMP01210
 AMP01220
 AMP01230
 AMP01240

C		AMP01250
	KBBAR = VP1*VP1*RHO - 4.DO/3.DO*GB	AMP01260
C		AMP01270
	KR = VP2*VP2*RHOS - 4.DO/3.DO*GB2	AMP01280
C		AMP01290
C		AMP01300
C	*****	AMP01310
C	EQUATIONS TO CALCULATE H,C,M FOR THE POROUS MEDIUM	AMP01320
C	ARE TAKEN FROM STEVE ADDISONS SEMINAR.	AMP01330
C	H IS HH1,C IS CC1, M IS MM1	AMP01340
C		AMP01350
C		AMP01360
C	FOR THE LAYER: BULK MOD FOR THE GRAINS IS SAME AS CLAY, KR	AMP01370
C	BULK MOD FOR THE FRAME IS INPUT, KBBAR	AMP01380
C	BULK MOD OF FLUID =ATM. PRES. 1.01E6 KF	AMP01390
C	KF=1.01D06	AMP01400
C		AMP01410
C		AMP01420
C	TEMP=KR*(1.DO+OMEGA*(KR/KF-1.DO))	AMP01430
C		AMP01440
C	HH1=(KR-KBBAR)**2.DO/(TEMP-KBBAR)+KBBAR+GB*4.DO/3.DO	AMP01450
C		AMP01460
C	CC1=KR*(KR-KBBAR)/(TEMP-KBBAR)	AMP01470
C		AMP01480
C	MM1=KR**2.DO/(TEMP-KBBAR)	AMP01490
C		AMP01500
C		AMP01510
CC	WRITE(6,30)HH1,CC1,MM1	AMP01520
30	FORMAT(1X,'H=',2E13.6,2X,'C=',2E13.6,2X,'M=',2E13.6)	AMP01530
C		AMP01540
C	*****	AMP01550
C		AMP01560
C	DO 101 J1=5,10,5	AMP01570
	DO 201 I=1,30	AMP01580
11	CALL PROP(FR,L2,L1)	AMP01590
C		AMP01600
C		AMP01610
C	WRITE(6,30)HH1,CC1,MM1	AMP01620
C		AMP01630
	V1=TWOPI*FR/L1	AMP01640
	V2=TWOPI*FR/L2	AMP01650
C	WRITE(11,50) L2,L1	AMP01660
50	FORMAT(5X,'BIOT WAVE CONSTANTS',/	AMP01670
2	,10X,'SLOW WAVE CON. = ',E13.6,',',E13.6,	AMP01680
2	/,10X,'FAST WAVE CON. = ',E13.6,',',E13.6,/)	AMP01690
C		AMP01700
	V0=3.43D4	AMP01710
C		AMP01720
C		AMP01730
C		AMP01740
C		AMP01750
C	WRITE(6,65)KBBAR,KR,GB,GB2	AMP01760
65	FORMAT(1X,'KBBAR=',E13.2,2X,'KR=',E13.2,2X,'GB=',E13.2,2X	AMP01770
2	, 'GB2=',E13.2,///)	AMP01780

C		AMP01790
C		AMP01800
C	*****	AMP01810
C		AMP01820
C	M1 AND M2 ARE THE RATIOS OF THE RELATIVE WAVE TO THE	AMP01830
C	MATRIX WAVE(FAST, SLOW)	AMP01840
C		AMP01850
C	EQUATIONS FOR M1 AND M2 TAKEN FROM GEERTSMA AND SMIT	AMP01860
C	GEOPHYSICS V.26 APR 1961	AMP01870
C	ASPECTS OG ELASTIC WAVE PROG. IN FLD. SAT. POROUS SOLIDS.	AMP01880
C		AMP01890
C	*****	AMP01900
C		AMP01910
C	Z1= HH1*L1*L1/(RHO*TWOPI*TWOPI*FR*FR)	AMP01920
C		AMP01930
C	Z2= HH1*L2*L2/(RHO*TWOPI*TWOPI*FR*FR)	AMP01940
C		AMP01950
C	M1= (HH1*(Z1-1.D0))/(Z1*CC1-RHOF*HH1/RHO)	AMP01960
C		AMP01970
C	M2= (HH1*(Z2-1.D0))/(Z2*CC1-RHOF*HH1/RHO)	AMP01980
C		AMP01990
C	WRITE(11,40)M1,M2	AMP02000
40	FORMAT(1X,'M1=',E13.6,E13.6,2X,'M2=',E13.6,E13.6,///)	AMP02010
C		AMP02020
C	*****	AMP02030
C		AMP02040
C	LAME'S CONSTANTS FOR THE LOWER MEDIUM ARE LAM2,GB2	AMP02050
C		AMP02060
C	LAM2=KR + (4.D0/3.D0)*GB2	AMP02070
C		AMP02080
C		AMP02090
C		AMP02100
C		AMP02110
C	*****	AMP02120
C		AMP02130
C	L0 - L5 ARE THE WAVE NUMBERS	AMP02140
C		AMP02150
C		AMP02160
C	L0=TWOPI*FR/V0	AMP02170
C	L3=TWOPI*FR/VS1	AMP02180
C	L4=TWOPI*FR/VS2	AMP02190
C	L5=TWOPI*FR/VP2	AMP02200
C		AMP02210
C		AMP02220
C	L0S=L0*L0	AMP02230
C	L1S=L1*L1	AMP02240
C	L2S=L2*L2	AMP02250
C	L3S=L3*L3	AMP02260
C	L4S=L4*L4	AMP02270
C	L5S=L5*L5	AMP02280
C	*****	AMP02290
C		AMP02300
C	SO,S1,C0,C1, ETC ATE THE SINES AND COSINES OF THE	AMP02310
C	INCIDENT, REFLECTED AND REFRACTED ANGLES.	AMP02320
C		

C	*****	AMP02330
	S0=DSIN(THETO)	AMP02340
	C0=DCOS(THETO)	AMP02350
	SSQ=S0*S0	AMP02360
	C1=CDSQRT(1.D0-L0S*SSQ/L1S)	AMP02370
	C2=CDSQRT(1.D0-L0S*SSQ/L2S)	AMP02380
	TEMP3=1.D0-L0S*SSQ/L3S	AMP02390
	TEMP4=1.D0-L0S*SSQ/L4S	AMP02400
	TEMP5=1.D0-L0S*SSQ/L5S	AMP02410
	C3=CDSQRT(TEMP3)	AMP02420
	C4=CDSQRT(TEMP4)	AMP02430
	C5=CDSQRT(TEMP5)	AMP02440
	L0S0=L0*S0	AMP02450
	S1=L0S0/L1	AMP02460
	S2=L0S0/L2	AMP02470
	S3=L0S0/L3	AMP02480
	S4=L0S0/L4	AMP02490
	S5=L0S0/L5	AMP02500
C	*****	AMP02510
C		AMP02520
C	Q1 - Q5 IS THE WAVE NUMBER * COS(ANGLE) * LAYER THICKNESS	AMP02530
C		AMP02540
C	DEP IS THE DEPTH OF LAYER	AMP02550
C		AMP02560
	Q1=L1*C1*DEP	AMP02570
	Q2=L2*C2*DEP	AMP02580
	Q3=L3*C3*DEP	AMP02590
	Q4=L4*C4*DEP	AMP02600
	Q5=L5*C5*DEP	AMP02610
	WRITE(6,*)Q1,Q2,Q3,Q4,Q5	AMP02620
C	*****	AMP02630
C		AMP02640
C	EXPI OR EXP11 ARE THE EXPONENTIALS IN THE B. C. EQUATIONS	AMP02650
C		AMP02660
C		AMP02670
C	EXP11 =CDEXP(-J*Q1)	AMP02680
	EXP1=CDEXP(J*Q1)	AMP02690
	EXP12=CDEXP(-J*Q2)	AMP02700
	EXP2=CDEXP(J*Q2)	AMP02710
	EXP3=CDEXP(J*Q3)	AMP02720
	EXP13=CDEXP(-J*Q3)	AMP02730
	EXP4=CDEXP(J*Q4)	AMP02740
	EXP14=CDEXP(-J*Q4)	AMP02750
	EXP5=CDEXP(J*Q5)	AMP02760
	EXP15=CDEXP(-J*Q5)	AMP02770
C	*****	AMP02780
C		AMP02790
C	THE A SUB II'S ARE THE COEF. IN THE B. C. EQUATIONS.	AMP02800
C		AMP02810
C		AMP02820
C		AMP02830
C		AMP02840
C		AMP02850
		AMP02860

A(1,1)=(1.D0-M1)*C1	AMP02870
A(1,2)=-A(1,1)	AMP02880
A(1,3)=(1.D0-M2)*C2	AMP02890
A(1,4)=-A(1,3)	AMP02900
A(1,5)=S3	AMP02910
A(1,6)=-S3	AMP02920
A(1,7)=(0.D0,0.D0)	AMP02930
A(1,8)=(0.D0,0.D0)	AMP02940
A(1,9)=C0	AMP02950
A(2,1)=2.D0*L1*S1*C1	AMP02960
A(2,2)=-A(2,1)	AMP02970
A(2,3)=2.D0*L2*C2*S2	AMP02980
A(2,4)=-A(2,3)	AMP02990
A(2,5)=-L3*C3*C3-L3*S3*S3)	AMP03000
A(2,6)=-A(2,5)	AMP03010
A(2,7)=(0.D0,0.D0)	AMP03020
A(2,8)=(0.D0,0.D0)	AMP03030
A(2,9)=(0.D0,0.D0)	AMP03040
A(3,1)=L1*(HH1-M1*CC1-2.D0*GB*S1*S1)	AMP03050
A(3,2)=A(3,1)	AMP03060
A(3,3)=L2*(HH1-M2*CC1-2.D0*GB*S2*S2)	AMP03070
A(3,4)=A(3,3)	AMP03080
A(3,5)=2.D0*GB*L3*S3*C3	AMP03090
A(3,6)=A(3,5)	AMP03100
A(3,7)=(0.D0,0.D0)	AMP03110
A(3,8)=(0.D0,0.D0)	AMP03120
A(3,9)=-KF*L0	AMP03130
A(4,1)=L1*(CC1-M1*MM1)	AMP03140
A(4,2)=A(4,1)	AMP03150
A(4,3)=L2*(CC1-M2*MM1)	AMP03160
A(4,4)=A(4,3)	AMP03170
A(4,5)=(0.D0,0.D0)	AMP03180
A(4,6)=(0.D0,0.D0)	AMP03190
A(4,7)=(0.D0,0.D0)	AMP03200
A(4,8)=(0.D0,0.D0)	AMP03210
A(4,9)=-KF*L0	AMP03220
A(5,1)=C1*EXP1	AMP03230
A(5,2)=-C1*EXP11	AMP03240
A(5,3)=C2*EXP2	AMP03250
A(5,4)=-C2*EXP12	AMP03260
A(5,5)=S3*EXP3	AMP03270
A(5,6)=-S3*EXP13	AMP03280
A(5,7)=-C5*EXP5	AMP03290
A(5,8)=-S4*EXP4	AMP03300
A(5,9)=(0.D0,0.D0)	AMP03310
A(6,1)=S1*EXP1	AMP03320
A(6,2)=S1*EXP11	AMP03330
A(6,3)=S2*EXP2	AMP03340
A(6,4)=S2*EXP12	AMP03350
A(6,5)=-C3*EXP3	AMP03360
A(6,6)=-C3*EXP13	AMP03370
A(6,7)=-S5*EXP5	AMP03380
A(6,8)=C4*EXP4	AMP03390
A(6,9)=(0.D0,0.D0)	AMP03400
A(7,1)=A(3,1)*EXP1	AMP03410

C
C
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C		AMP03950
C	SUBROUTINE LEQTIC	AMP03960
C		AMP03970
C	SOLVES SIMULTANEOUS ALGEBRAIC EQUATIONC	AMP03980
C		AMP03990
C		AMP04000
C	*****	AMP04010
	IA=9	AMP04020
	IB=9	AMP04030
	N=9	AMP04040
	IJOB=0	AMP04050
	M=1	AMP04060
	CALL LEQ2C(A, N, IA, B, M, IB, IJOB, WA, WK, IER)	AMP04070
C		AMP04080
C		AMP04090
C	*****	AMP04100
C		AMP04110
C		AMP04120
C	IFREQ=FR	AMP04130
C204	WRITE(11,205)	AMP04140
205	FORMAT(5X, 'FREQUENCY', 5X 'INCIDENT ANGLE')	AMP04150
C	WRITE(11,210)IFREQ, LTHETI	AMP04160
210	FORMAT(6X, I4, 15X, I2, //)	AMP04170
C	WRITE(11,300)	AMP04180
300	FORMAT(9X, 'FAST WAVE (DOWN)', 20X, 'FAST WAVE (UP)')	AMP04190
C	WRITE(11,305)B(1), B(2)	AMP04200
305	FORMAT(1X, E14.8, 1X, ' ', 1X, E14.8, 5X, E14.8, 1X, ' ', 1X, E14.8, //)	AMP04210
C	WRITE(11,310)	AMP04220
310	FORMAT(9X, 'SLOW WAVE (DOWN)', 21X, 'SLOW WAVE (UP)')	AMP04230
C	WRITE(11,305)B(3), B(4)	AMP04240
C	WRITE(11,320)	AMP04250
320	FORMAT(9X, 'SHEAR WAVE (DOWN)', 20X, 'SHEAR WAVE (UP)')	AMP04260
C	WRITE(11,305)B(5), B(6)	AMP04270
C	WRITE(11,330)	AMP04280
330	FORMAT(9X, 'TRANS. COMP. WAVE', 20X, 'TRANS. SHEAR WAVE')	AMP04290
C	WRITE(11,305)B(7), B(8)	AMP04300
	WRITE(6,340)	AMP04310
340	FORMAT(9X, 'REFL WAVE')	AMP04320
	WRITE(6,305)B(9)	AMP04330
C	WRITE(6,*)(B(I), I=1,9)	AMP04340
C		AMP04350
C	*****	AMP04360
	CALL SUFIMP(B, LO, KF, RHOF, VO, CO, FR, ZREAL1, ZIMAG1)	AMP04370
	ZREAL(I)=ZREAL1	AMP04380
	ZIMAG(I)=ZIMAG1	AMP04390
C	IF(D.GT.DEP) GO TO 1090	AMP04400
C	CALL TRANSF(B, M1, M2, FR, D, D1, MAGGO, MAGPB, PHSGO, PHSPB)	AMP04410
C	CALL RTRANS(B, FR, D, D1, RMAG, RPHAS)	AMP04420
	GO TO 1095	AMP04430
C1090	CALL LTRANSF(B, LO, RHOF, KF, FR, DPRIME, MAGGO, PHSGO)	AMP04440
1095	CONTINUE	AMP04450
	MAGGEO(I)=MAGGO	AMP04460
C	WRITE(6,13)FR, MAGGO, MAGPB	AMP04470
C13	FORMAT(1X,3(E14.3))	AMP04480

MAGPRB(I)=MAGPB	AMP04490
PHSGEO(I)=PHSGO	AMP04500
PHSPRB(I)=PHSPB	AMP04510
C	AMP04520
C WRITING VALUES FOR TRANSFER FUNCTION AND SURFACE IMPEDANCE.	AMP04530
C	AMP04540
C WRITE(6,256)MAGGEO(I),PHSGEO(I),MAGPRB(I),PHSPRB(I),ZREAL(I)	AMP04550
C 2 ,ZIMAG(I),RMAG,RPHAS	AMP04560
256 FORMAT(1X,8E12.4)	AMP04570
WRITE(6,257)ZREAL(I),ZIMAG(I)	AMP04580
257 FORMAT(1X,2E12.4)	AMP04590
505 FORMAT(1X,'MAD FOR VERT GEO. = ',E14.8,/'	AMP04600
2 ,1X,'PHAS FOR VERT GEO. = ',E14.8,/'	AMP04610
2 ,1X,'MAG FOR PROBE = ',E14.8,/'	AMP04620
2 1X,'PHAS FOR PROBE = ',E14.8,/'	AMP04630
2 ,1X,'REAL PART OF IMPEDANCE = ',E14.8,/'	AMP04640
2 1X,'IMAG PART OF IMPEDANCE = ',E14.8,/'	AMP04650
C	AMP04660
C MAGG2(I)=MAGGEO(I)	AMP04670
C MAGP2(I)=MAGPRB(I)	AMP04680
FR = FR + 10.0D0	AMP04690
201 CONTINUE	AMP04700
C IF(J1.GE.10)GO TO 1100	AMP04710
C DO 301 I1=1,12	AMP04720
C MAGG1(I1)=MAGG2(I1)	AMP04730
C MAGP1(I1)=MAGP2(I1)	AMP04740
C301 CONTINUE	AMP04750
C D = D + 1.D0	AMP04760
C FR = 25.D0	AMP04770
C101 CONTINUE	AMP04780
1100 CONTINUE	AMP04790
C FR = 25.	AMP04800
C DELD = D - D3	AMP04810
C DO 401 I=1,12	AMP04820
C ATDBG(I)=(-1.D0)*(DLOG(MAGG2(I))-DLOG(MAGG1(I)))*20.D0*DLOG10(E)/	AMP04830
C 2 DELD	AMP04840
C ATDBP(I)=(-1.D0)*(DLOG(MAGP2(I))-DLOG(MAGP1(I)))*20.D0*DLOG10(E)/	AMP04850
C 2 DELD	AMP04860
C FR = FR + 25.D0	AMP04870
C401 CONTINUE	AMP04880
C WRITE(11,203)	AMP04890
203 FORMAT(1X,'FREQ, ATTENUATION IN DB OF PROBE AND VERT. GEO.')	AMP04900
C WRITE(11,506)(FRQ(I),ATDBP(I),ATDBG(I),I=1,12)	AMP04910
506 FORMAT(1X,3(E14.8,1X))	AMP04920
9997 STOP	AMP04930
END	AMP04940

APPENDIX A.3

The routine SUFIMP.FORTRAN computes the real (ZREAL) and imaginary (ZIMAG) parts of the acoustic surface impedance relative to air using equation 67. The input arguments passed are all defined in AMPL.FORTRAN (see Appendix A.2).

C	SUBROUTINE TO CALCULATE THE	SUF00010
C	REAL AND IMAGINARY PARTS OF	SUF00020
C	THE SURFACE IMPEDANCE.	SUF00030
	SUBROUTINE SUFIMP(B,LO,KF,RHOF,VO,CO,FR,ZREAL,ZIMAG)	SUF00040
	IMPLICIT REAL *8 (A-H,O-Z)	SUF00050
	COMPLEX *16 B(9)	SUF00060
	COMPLEX *16 J,PRES,VEL,ZNOT	SUF00070
	REAL *8 KF,LO	SUF00080
C	CALCULATE PRESSURE AND VELOCITY AT THE SURFACE.	SUF00090
	J=(0.D0,1.D0)	SUF00100
	TWOPI=4.D0*DARSIN(1.D0)	SUF00110
C	PRES = RHOF*VO*CO*(1.D0+B(9))*(-J*TWOPI*FR)	SUF00120
	PRES = -J*KF*LO*(1.D0+B(9))	SUF00130
	VEL=CO*(1.D0-B(9))*(-J*TWOPI*FR)	SUF00140
	ZNOT= PRES/VEL	SUF00150
	ZREAL=DREAL(ZNOT)/(RHOF*VO)	SUF00160
	ZIMAG=DIMAG(ZNOT)/(RHOF*VO)	SUF00170
C	WRITE(6,13)ZREAL,ZIMAG	SUF00180
13	FORMAT(1X,'IMPEDANCE = ',2(E14.3))	SUF00190
	RETURN	SUF00200
	END	SUF00210

APPENDIX A.4

The subroutine TRANSF.FORTRAN computes the acoustic and vertical seismic transfer functions for the porous sand using equations 77 and 79, respectively. TRANSF returns the magnitudes (DMAG, DMMAG) and phases (PHAS, PHAS2) of these transfer functions. Input parameters are defined in AMPL.FORTRAN.

C*****	TRA00010
C	TRA00020
C	TRA00030
C	TRA00040
C	TRA00050
LET WAVES PROPAGATE AND CALCULATE VERTICAL TRANSFER FUNCTION	TRA00060
FOR MIC AND VERT GEOPHONE	TRA00070
SUBROUTINE TRANSF(B,M1,M2,FR,DPRIME,D1,DMAG,DMMAG,PHAS,PHAS2)	TRA00080
IMPLICIT REAL *8 (A-H,O-Z)	TRA00090
COMPLEX *16 J,L1,L2,C1,C2,C3	TRA00100
COMPLEX *16 TEMP4,TPRES,M1,M2,TEMP6	TRA00110
COMPLEX *16 MOVFM,T1,T2,P1,P2,P3,P4	TRA00120
COMPLEX *16 PRES,NVEL1,NVEL2,NVEL3,NVEL4,NVEL5,NVEL6	TRA00130
COMPLEX *16 TNVEL,GOVRM	TRA00140
COMPLEX *16 B(9)	TRA00150
REAL *8 M,KF,KBBAR,KR,L0,L3	TRA00160
COMMON /BLK7/ H,C,M	TRA00170
COMMON /BLK5/ V0,C0,S0,C1,L0,L1,C2,L2,S3,L3,C3	TRA00180
COMMON /BLK3/ RHOF,GB,KBBAR,KR,RHOS,OMEGA,KF	TRA00190
J = (0.D0,1.D0)	TRA00200
TWOPI = 4.D0*DARSIN(1.D0)	TRA00210
DPRIME IS PROPAGATION DEPTH	TRA00220
D1 IS PROPAGATION HEIGHT	TRA00230
CALCULATE PRESSURE AT ABOVE GROUND MIC	TRA00240
PRES = -J*KF*L0*(1.D0+B(9))	TRA00250
CALCULATE NORMAL COMPONENTS OF PARTICLE VELOCITY	TRA00260
NVEL1 = -J*TWOPI*FR*B(1)*C1*CDEXP(J*L1*C1*DPRIME)	TRA00270
NVEL2 = J*TWOPI*FR*B(2)*C1*CDEXP(-J*L1*C1*DPRIME)	TRA00280
NVEL3 = -J*TWOPI*FR*B(3)*C2*CDEXP(J*L2*C2*DPRIME)	TRA00290
NVEL4 = J*TWOPI*FR*B(4)*C2*CDEXP(-J*L2*C2*DPRIME)	TRA00300
NVEL5 = J*TWOPI*FR*B(5)*S3*CDEXP(J*L3*C3*DPRIME)	TRA00310
NVEL6 = J*TWOPI*FR*B(6)*S3*CDEXP(-J*L3*C3*DPRIME)	TRA00320
TNVEL = NVEL1 + NVEL2 + NVEL3 + NVEL4 + NVEL5 + NVEL6	TRA00330
T1 = (C - M1*M)	TRA00340
T2 = (C - M2*M)	TRA00350
P1 = B(1)*L1*T1*CDEXP(J*L1*C1*DPRIME)	TRA00360
P2 = B(2)*L1*T1*CDEXP(-J*L1*C1*DPRIME)	TRA00370
P3 = B(3)*L2*T2*CDEXP(J*L2*C2*DPRIME)	TRA00380
P4 = B(4)*L2*T2*CDEXP(-J*L2*C2*DPRIME)	TRA00390
TPRES = P1 + P2 + P3 + P4	TRA00400
	TRA00410
	TRA00420
	TRA00430
	TRA00440

```

C      WRITE(6,13) PRES, TPRES
13      FORMAT(1X,4(E8.2,2X))
        MOV RM = TPRES/PRES
        GOV RM = TNVEL/PRES
        TEMP4 = DCONJG(GOV RM)
        TEMP6 = DCONJG(MOV RM)
        TEMP5 = GOV RM*TEMP4
        TEMP7 = MOV RM*TEMP6
        DMAG  = DSQ RT(TEMP5)
        DMMAG = DSQ RT(TEMP7)
        TEMP1 = DIMAG(GOV RM)
        TEMP8 = DIMAG(MOV RM)
        TEMP2 = DREAL(GOV RM)
        TEMP9 = DREAL(MOV RM)
        ARG   = TEMP1/TEMP2
        ARG2  = TEMP8/TEMP9
        PHAS  = DATAN(ARG)*360.D0/TWOPI
        PHAS2 = DATAN(ARG2)*360.D0/TWOPI
        RETURN
        END

```

```

TRA00450
TRA00460
TRA00470
TRA00480
TRA00490
TRA00500
TRA00510
TRA00520
TRA00530
TRA00540
TRA00550
TRA00560
TRA00570
TRA00580
TRA00590
TRA00600
TRA00610
TRA00620
TRA00630
TRA00640

```

APPENDIX A.5

The subroutine LTRANF.FORTRAN computes the vertical seismic transfer function in the clay by taking the ratio of the normal seismic response to the acoustic pressure at the surface. LTRANF then returns the magnitude (DMAG) and phase (PHAS) of the transfer function. Input arguments are all defined in the main routine AMPL.FORTRAN.

C*****	LTR00010
C	LTR00020
C	LTR00030
C	LTR00040
C	LTR00050
	LTR00060
LET WAVES PROPAGATE AND CALCULATE VERTICAL TRANSFER FUNCTION	LTR00070
FOR MIC AND VERT GEOPHONE IN CLAY	LTR00080
	LTR00090
SUBROUTINE LTRANF(B,L0,RHOF,KF,FR,DPRIME,DMAG,PHAS)	LTR00100
IMPLICIT REAL *8 (A-H,O-Z)	LTR00110
COMPLEX *16 J	LTR00120
COMPLEX *16 TEMP4,NVEL1,NVEL2	LTR00130
COMPLEX *16 TNVEL,GOVRM,PRES	LTR00140
COMPLEX *16 B(9),C4,C5	LTR00150
REAL *8 L0,KF,L4,L5	LTR00160
COMMON /BLK8/ C4,S4,C5,L4,L5	LTR00170
J = (0.D0,1.D0)	LTR00180
TWOPI = 4.D0*DARSIN(1.D0)	LTR00190
	LTR00200
DPRIME IS PROPAGATION DEPTH	LTR00210
D1 IS PROPAGATION HEIGHT	LTR00220
	LTR00230
	LTR00240
CALCULATE PRESSURE AT ABOVE GROUND MIC	LTR00250
	LTR00260
PRES = -J*KF*L0*(1.D0+B(9))	LTR00270
	LTR00280
	LTR00290
CALCULATE NORMAL COMPONENTS OF PARTICLE VELOCITY	LTR00300
	LTR00310
NVEL1 = -J*TWOPI*FR*B(8)*S4*CDEXP(J*L4*C4*DPRIME)	LTR00320
NVEL2 = -J*TWOPI*FR*B(7)*C5*CDEXP(J*L5*C5*DPRIME)	LTR00330
TNVEL = NVEL1 + NVEL2	LTR00340
GOVRM = TNVEL/PRES	LTR00350
TEMP4 = DCONJG(GOVRM)	LTR00360
TEMP5 = GOVRM*TEMP4	LTR00370
DMAG = DSQRT(TEMP5)	LTR00380
TEMP1 = DIMAG(GOVRM)	LTR00390
TEMP2 = DREAL(GOVRM)	
ARG = TEMP1/TEMP2	
PHAS = DATAN(ARG)*360.D0/TWOPI	
RETURN	
END	

APPENDIX A.6

RTRANS.FORTRAN returns the manitude (DMAG) and phase (PHAS) of the radial seismic transfer function for the porous sand. The routine is the same as TRANSF except that the radial component is taken as opposed to the normal component. The arguments in the call statement are defined in the calling routine, AMPL.FORTRAN.

```

C*****
C
C      LET WAVES PROPAGATE AND CALCULATE RADIAL TRANSFER FUNCTION
C
      SUBROUTINE RTRANS(B,FR,DPRIME,D1,DMAG,PHAS)
      IMPLICIT REAL *8 (A-H,O-Z)
      COMPLEX *16 J,L1,L2,C1,C2,C3,S1,S2
      COMPLEX *16 TEMP4,TPRES,M1,M2,TEMP6
      COMPLEX *16 PRES,NVEL1,NVEL2,NVEL3,NVEL4,NVEL5,NVEL6
      COMPLEX *16 TNVEL,GOVRM
      COMPLEX *16 B(9)
      REAL *8 M,KF,KBBAR,KR,LO,L3
      COMMON /BLK8/ S1,S2
      COMMON /BLK7/ H,C,M
      COMMON /BLK5/ V0,C0,S0,C1,LO,L1,C2,L2,S3,L3,C3
      COMMON /BLK3/ RHOF,GB,KBBAR,KR,RHOS,OMEGA,KF
      J = (0.DO,1.DO)
      TWOPI = 4.DO*DARSIN(1.DO)

      DPRIME IS PROPAGATION DEPTH
      D1 IS PROPAGATION HEIGHT

      CALCULATE PRESSURE AT ABOVE GROUND MIC

      PRES = -J*KF*LO*(1.DO+B(9))

      CALCULATE RADIAL COMPONENTS OF PARTICLE VELOCITY

      NVEL1 = -J*TWOPI*FR*B(1)*S1*CDEXP(J*L1*C1*DPRIME)
      NVEL2 = J*TWOPI*FR*B(2)*S1*CDEXP(-J*L1*C1*DPRIME)
      NVEL3 = -J*TWOPI*FR*B(3)*S2*CDEXP(J*L2*C2*DPRIME)
      NVEL4 = J*TWOPI*FR*B(4)*S2*CDEXP(-J*L2*C2*DPRIME)
      NVEL5 = J*TWOPI*FR*B(5)*C3*CDEXP(J*L3*C3*DPRIME)
      NVEL6 = J*TWOPI*FR*B(6)*C3*CDEXP(-J*L3*C3*DPRIME)
      TNVEL = NVEL1 + NVEL2 + NVEL3 + NVEL4 + NVEL5 + NVEL6
      GOVRM = TNVEL/PRES
      TEMP4 = DCONJG(GOVRM)
      TEMP5 = GOVRM*TEMP4
      DMAG = DSQRT(TEMP5)
      TEMP1 = DIMAG(GOVRM)
      TEMP2 = DREAL(GOVRM)
      ARG = TEMP1/TEMP2
      PHAS = DATAN(ARG)*360.DO/TWOPI
      RETURN
      END
RTR00010
RTR00020
RTR00030
RTR00040
RTR00050
RTR00060
RTR00070
RTR00080
RTR00090
RTR00100
RTR00110
RTR00120
RTR00130
RTR00140
RTR00150
RTR00160
RTR00170
RTR00180
RTR00190
RTR00200
RTR00210
RTR00220
RTR00230
RTR00240
RTR00250
RTR00260
RTR00270
RTR00280
RTR00290
RTR00300
RTR00310
RTR00320
RTR00330
RTR00340
RTR00350
RTR00360
RTR00370
RTR00380
RTR00390
RTR00400
RTR00410
RTR00420
RTR00430
RTR00440
RTR00450
RTR00460

```

APPENDIX A.7

This routine was used to compute the magnitude and phase of the experimental transfer function. Tranff.Bas program first accepts the calibrations (typically 10-15 seconds depending on the length of data record to be analyzed) on channel 0 (always the reference microphone above the ground). The digitized record is always collected in blocks of 1024 points. Due to finite transfer rates, a few points could be dropped between successive 1024 point records. After the calibration tone is digitized, each 1024 point record is Fourier transformed. The magnitudes of the transform at each frequency (512 of these) are added together and these are added to the magnitude determined from each successive 1024 point data record. The total sum is then divided by the number of data records - this is referred to as the calibration level for channel 0. The tape is then moved to the calibration tone on the channel to be analyzed and this process is repeated to give the calibration level for channel 1.

Next the tape is moved to the data for the first third octave band (31.5 Hz). At this point, the data from the reference microphone and channel of interest are simultaneously digitized. Actually channel 0 is sampled first; channel one is sampled a few hundred microseconds later. This small delay gives a small phase difference which must be corrected for later. Once the data is all digitized and stored in memory, each 1024 point data record from channel 0 is Fourier transformed. The simultaneous 1024 point record from channel 1 is next Fourier transformed and the transfer function for these 1024 points is computed giving the transfer function at 512 frequencies. Only those frequencies within the third octave band being considered are kept. The next pair of 1024 point records is transformed and the transfer function computed is added to the first. This process is continued for all the data records for that third octave band.

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COUPLING OF AIRBORNE SOUND INTO THE EARTH(U)
MISSISSIPPI UNIV UNIVERSITY PHYSICAL ACOUSTICS RESEARCH
LAB H E BASS ET AL. 01 AUG 84 PARGUM-84-01
ARO-17560 2-GS DAAG29-81-K-0078 F/G 17/1

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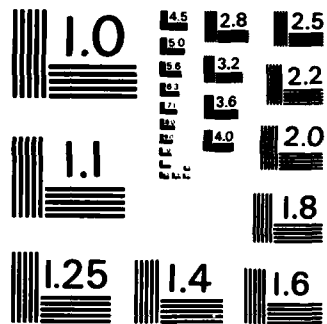
F/G 17/1

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END

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OTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Next, the tape is advanced to the next third octave band and the process is repeated.

The raw transfer function at each frequency is divided by the calibration levels to get absolute values for the real and imaginary parts of the transfer function. Finally, the real and imaginary parts are converted to a magnitude and phase at each frequency; the results are plotted on an X-Y plotter (program Plotff.Bas, Appendix A.8) and stored on disks.

The plotted transfer function was, in many cases, quite noisy (many sharp spikes). For comparison to theory, sometimes smoothed this data. A seven point averaging routine was used, twice, to smooth the data which was then replotted. The smoothing routine (Program Smooth.Bas, Appendix A.9) computed:

$$Y(0) = \{[Y(-3)+Y(3)]+4[Y(-2)+Y(2)]+11[Y(-1)+Y(1)]+14Y(0)\}/42$$

which replaced $Y(0)$. This procedure was executed twice to result in graphs referred to later as smoothed curves.

As noted earlier, samples from the two channels are actually taken sequentially which means that there is a small time delay between samples on the two channels. This delay was determined experimentally. An oscillator generating a sine wave at one of the 1/3 octave band center frequencies was coupled directly into channel 0 of the computer and the same signal was put through an RC filter (time constant .002 sec) into channel 1. Through such a circuit, the amplitude should vary between 0 (at 0 Hz) and 1 (well above 80 Hz, where $\omega = 1/RC$). The phase should decrease from 90° at 0 Hz to 0° well above 80 Hz. When the amplitude of channel 1 is 0.707 times the amplitude of channel 0, the phase difference should be $+45^\circ$. Experimentally, the phase was found to be slightly larger than 45° requiring that we introduce a phase correction of $.06 \times \text{frequency}$. Note that at a frequency of 6 kHz, the phase corrections would be 360° implying

a channel to channel delay of 167 sec which is close to the manufacturer's (DEC) specifications. This correction appears on line 5297 of program Tranff.

```
20 OPEN "VM:FILE1.DAT" AS FILE #1
30 OPEN "VM:FILE2.DAT" AS FILE #2
40 OPEN "VM:FILE3.DAT" AS FILE #3
45 OPEN "VM:FILE4.DAT" AS FILE #4
47 OPEN "LP:" FOR OUTPUT AS FILE #7
50 DIM #1,A1%(33768)
60 DIM #2,D1(1024)
70 DIM #3,F1(1024)
75 DIM #4,O(14)
78 DIM CZ(1024)
80 COMMON AZ(2048)
85 VZ=0
100 PRINT "NUMBER OF SECONDS TO BE DIGITIZED?";
110 INPUT S3%
120 S4=S3%-1
130 PRINT "LISTEN FOR CAL. TONE ON CH."VZ", PUSH RETURN";
140 INPUT Z$
160 FOR IX=0 TO S4
170 AIN(AZ(),1024,1/1000,VZ,1)
180 BLOCK MOVE(AZ(0),A1%(IX*1024),1024)
190 NEXT IX
210 PRINT "STOP TAPE"
230 S2=0
240 FOR IX=1 TO 512
250 D1(IX)=0
260 F1(IX)=0
270 NEXT IX
280 FOR IX=0 TO S3%-1
290 N1=1024*IX \ N2=N1+1023 \ S9%=1
300 GOSUB 7370
310 FFT(,1024,AZ(),CZ(),S%)
320 FOR JZ=1 TO 512
330 D1(JZ)=D1(JZ)+SQR((AZ(JZ)*2^S%)^2+(CZ(JZ)*2^S%)^2)
350 NEXT JZ
360 NEXT IX
370 FOR IX=1 TO 512
380 S2=S2+D1(IX)
390 NEXT IX
400 S2=S2/S3%
410 IF VZ=1 THEN 460
420 VZ=VZ+1
430 S1=S2
440 GO TO 130
460 JZ=0
470 PRINT S1,S2
570 O(0)=20 \ O(1)=25 \ O(2)=31.5 \ O(3)=40 \ O(4)=50 \ O(5)=63 \ O(6)=80
```

```

670 O(7)=100 \ O(8)=125 \ O(9)=160 \ O(10)=200 \ O(11)=250 \ O(12)=315
870 FO=1000/1024
880 FOR IZ=1 TO 1024
900 D1(IZ)=0
910 F1(IZ)=0
920 NEXT IZ
930 S4=S3%-1
970 FOR LZ=1 TO 12
1070 CLOSE #1
1170 OPEN "VM:FILE1.DAT" AS FILE #1
1270 Q8%=53
1370 F1=(2^.1667)*O(LZ-1)
1470 F2=(2^.1667)*O(LZ)
1570 I1%=F1/FO
1670 I2%=F2/FO
1770 PRINT "START TAPE ";O(LZ);" HZ AND PRESS RETURN.";
1870 INPUT D9$

```

```

1970 SCHMITT(1,8070)
2070 IF Q8%<>-999 THEN 2070
2170 SCHMITT
2370 FOR IZ=0 TO S4
2470 AIN(AZ(),2048,1/1000,0,2)
2570 BLOCK MOVE(AZ(0),A1Z(IZ*2048),2048)
2670 NEXT IZ
2870 PRINT "STOP TAPE!!!!!!!!!!!!!! "
3370 FOR IZ=0 TO S3%-1
3470 N1=2*1024*IZ \ N2=N1+2046 \ S9%=2
3570 GOSUB 7370
3670 FFT(,1024,AZ(),CZ(),SZ)
3770 FOR MZ=I1% TO I2%
3870 JZ=MZ+512
3970 D1(MZ)=(AZ(MZ)*2^SZ)/S1
4070 D1(JZ)=(CZ(MZ)*2^SZ)/S1
4170 NEXT MZ
4470 N1=2*1024*IZ+1 \ N2=N1+2046 \ S9%=2
4570 GOSUB 7370
4670 FFT(,1024,AZ(),CZ(),SZ)
4770 FOR MZ=I1% TO I2%
4870 JZ=MZ+512
4880 M=D1(MZ)^2+D1(JZ)^2
4890 R=(AZ(MZ)*D1(MZ)+CZ(MZ)*D1(JZ))*2^SZ/S2
4900 I2=(D1(MZ)*CZ(MZ)-AZ(MZ)*D1(JZ))*2^SZ/S2
4970 F1(MZ)=F1(MZ)+SQR((R^2+I2^2)/M^2)
5070 F1(JZ)=F1(JZ)+ATN(I2/R)
5170 NEXT MZ
5270 NEXT IZ
5280 FOR IZ=I1% TO I2%
5290 MZ=IZ+512
5291 D1(IZ)=IZ*FO
5293 F1(IZ)=F1(IZ)/S3%

```

```

5297 F1(MZ)=180*((F1(MZ)/S3%)/3.14159)-D1(IZ)*60/1000
5310 NEXT IZ
5370 NEXT LZ
5870 I1Z=(2^.1667)*O(0)/FO
5970 I2Z=(2^.1667)*O(13)/FO
6070 FOR IZ=I1Z TO I2Z
6170 MZ=IZ+512
6780 PRINT #7,"FREQ="D1(IZ),"MAG="F1(IZ),"PHASE="F1(MZ)
6970 NEXT IZ
7229 CLOSE
7250 CHAIN "PLOTFF.BAS"
7270 STOP
7370 JZ=0
7380 FOR I3Z=N1 TO N2 STEP S9Z
7470 JZ=JZ+1
7570 CZ(JZ)=0
7670 AZ(JZ)=A1Z(I3Z)
7770 NEXT I3Z
7870 RETURN
7970 END
8070 Q8Z=-999
8170 RETURN

```

APPENDIX A.8

PLOTFF.BAS was written to plot the output of TRANFF.BAS on an HP 7470A digital plotter.

```

60 OPEN "VM:FILE2.DAT" AS FILE #2
70 OPEN "VM:FILE3.DAT" AS FILE #3
80 DIM #2,D1(1024)
90 DIM #3,F1(1024)
100 L9=2 \ O=1 \ O1=1 \ Q=1
200 DISPLAY CLEAR
1400 PRINT "input the size of plot (1) full page, and (2) quarter page ? ";
1500 INPUT AZ
1600 X9=0 \ X8=0
3400 FOR I=1 TO 2
3450 PRINT "PLEASE PUT PAPER IN H.P. PLOTTER AND PRESS RETURN"; \ INPUT E7$
3475 Y9=0 \ Y8=0 \ L9=2 \ O=1 \ O1=1 \ Q=1
3500 FOR J=1 TO 362
3600 IF I=1 THEN IF Y9<F1(J) THEN Y9=F1(J)
3700 IF I=1 THEN IF Y8>F1(J) THEN Y8=F1(J)
3800 IF I=2 THEN IF Y9<F1(J+512) THEN Y9=F1(J+512)
3900 IF I=2 THEN IF Y8>F1(J+512) THEN Y8=F1(J+512)
3950 IF I=2 THEN 4500
4000 IF X9<D1(J) THEN X9=D1(J)
4100 IF X8>D1(J) THEN X8=D1(J)
4500 NEXT J
4600 IF Y9<3 THEN O1=10000
4700 IF X9<3 THEN O=10000
5100 PAUSE(3)
5200 IF Y9*O1<0 THEN P1=-1
5300 IF Y9*O1>=0 THEN P1=1
5400 Y2=INT(LOG10(ABS(Y9*O1)))
5500 IF Y2<0 THEN Y2=Y2-1
5600 Y3=Y9*O1/10^Y2
5700 IF ABS(Y3)=1 THEN S1=1
5800 IF ABS(Y3)>1 THEN S1=2
5900 IF ABS(Y3)>2 THEN S1=2.5
6000 IF ABS(Y3)>2.5 THEN S1=5
6100 IF ABS(Y3)>5 THEN S1=10
6200 U1=(S1*10^Y2)*P1
6300 IF ABS(Y8*O1)<(1.00000E-03*(Y9*O1)) THEN 7600
6400 IF Y8*O1<0 THEN P2=-1
6500 IF Y8*O1>=0 THEN P2=1
6600 Y4=INT(LOG10(ABS(Y8*O1)))
6700 IF Y4<0 THEN Y4=Y4-1
6800 Y5=Y8*O1/10^Y4
6900 IF ABS(Y5)=1 THEN S2=1
7000 IF ABS(Y5)>1 THEN S2=2
7100 IF ABS(Y5)>2 THEN S2=2.5
7200 IF ABS(Y5)>2.5 THEN S2=5
7300 IF ABS(Y5)>5 THEN S2=10
7400 L1=(S2*10^Y4)*P2
7500 GO TO 8300
7600 L1=0

```

```

8200 PAUSE(3)
8300 IF AZ=1 THEN X6=9200 \ Y6=7560
8400 IF AZ=2 THEN X6=5150 \ Y6=4180
8410 IF ABS(U1)>30000 THEN Q=100
8420 IF ABS(L1)>30000 THEN Q=100
8500 COUT("IN;SP1;",,1)
8600 MS="IP 1100,1600,"+STR$(X6)+", "+STR$(Y6)+";"
8700 COUT(,MS,,1)
8800 MS="SC "+STR$(X8*O)+", "+STR$(X9*O)+", "+STR$(L1/Q)+", "+STR$(U1/Q)+";"
8900 COUT(,MS,,1)
9000 MS="PA "+STR$(X8*O)+", "+STR$(L1/Q)+", PD, "+STR$(X9*O)+", "+STR$(L1/Q)+", "
9100 MS=MS+STR$(X9*O)+", "+STR$(U1/Q)+", "+STR$(X8*O)+", "+STR$(U1/Q)+",
      "+STR$(X8*O)+", "+STR$(L1/Q)+", PU;"
9200 COUT(,MS,,1)
9300 PAUSE(2)

```

```

9900 COUT("SR 1,2;",,1)
10000 T1=(ABS(X9*O)+ABS(X8*O))/5
10100 T2=(ABS(L1/Q)+ABS(U1/Q))/5
10200 C=X8*O
10300 FOR J=1 TO 6
10400 MS="PA "+STR$(C)+", "+STR$(L1/Q)+";XT;"
10500 COUT(,MS,,1)
10600 MS="PR "+STR$(-(T1*.15))+", "+STR$(-(T2*.2))+";"
10700 COUT(,MS,,1)
10800 MS="LB"+STR$(C/O)+CHR$(3)
10900 COUT(,MS,,1)
10950 PAUSE(2)
11000 C=C+T1
11100 NEXT J
11200 PAUSE(4)
11300 C=L1/Q
11400 FOR J=1 TO 6
11500 MS="PA "+STR$(X8*O)+", "+STR$(C)+";YT;"
11600 COUT(,MS,,1)
11700 MS="PR "+STR$(-(T1*.4))+", 0;LB"+STR$((C/O1)*Q)+CHR$(3)
11800 COUT(,MS,,1)
11900 C=C+T2
12000 NEXT J
12050 PAUSE(5)
12600 MS="PA "+STR$(X8*O)+", 0;PR "+STR$(-(T1*.4))+", 0;LBO "+CHR$(3)
12700 COUT(,MS,,1)
12800 MS="PA "+STR$(X8*O)+", 0,PD, "+STR$(X9*O)+", 0,PU;"
12900 COUT(,MS,,1)
13000 PAUSE(5)
13100 IF I=1 THEN A2$="MAGNITUDE"
13200 IF I=2 THEN A2$="PHASE"
13300 A1$="FREQUENCY"
14000 Z1=LEN(A1$)
14100 Z2=LEN(A2$)
14200 MS="PA "+STR$(((X8*O)+(X9*O))/2)+", "+STR$(L1/Q)+";"

```

```

14300 COUT(,MS,,1)
14400 M$="PR 0,"+STR$(-(T2*.4))+",";
14500 COUT(,MS,,1)
14600 PAUSE(1)
14700 M$="PR "+STR$(-(T1*.05)*(Z1/2))+",0;LB"+A1$+CHR$(3)
14800 COUT(,MS,,1)
14900 PAUSE(2)
15000 M$="PA "+STR$(X8*0)+","+STR$(((L1/Q)+(U1/Q))/2)+",";
15100 COUT(,MS,,1)
15200 M$="PR "+STR$(-(T1*.6))+",0;"
15300 COUT(,MS,,1)
15400 M$="PR 0,"+STR$(-(T2*.06)*(Z2/2))+";DR 0,1;LB"+A2$+CHR$(3)
15500 COUT(,MS,,1)
15550 COUT("SP2;",,1)
16200 PAUSE(20)
17200 M$="PA "+STR$(D1(1)*0)+","+STR$((F1((I-1)*512+1)*01)/Q)+";PD;"
17300 COUT(,MS,,1)
17400 FOR J=2 TO 362
17450 IF INT(J/100)=J/100 THEN PAUSE(1)
17600 M$="PA "+STR$(D1(J)*0)+","+STR$((F1(((I-1)*512)+J)*01)/Q)+";"
17700 COUT(,MS,,1)
17800 NEXT J
18000 COUT("PU;",,1)
18100 PAUSE(3)
18200 NEXT I
18210 PRINT "WOULD YOU LIKE TO SAVE THESE NUMBERS ON DISK? IF SO TYPE A FILE"
18220 PRINT "NAME IN. IF YOU DON'T WANT TO SAVE THESE NUMBER JUST PRESS RETURN"
18230 PRINT "INPUT FILE NAME"; \ INPUT F4$

18240 IF F4$="" THEN 18300
18250 OPEN "DY1:"+F4$+".XYZ" AS FILE #1
18260 FOR LZ=1% TO 362%
18270 PRINT #1,D1(LZ),"F1(LZ)","F1(LZ+512%)"
18280 NEXT LZ
18290 CLOSE
18300 END

```

APPENDIX A.9

SMOOTH.BAS is a seven point smoothing routine used to smooth the output of TRANFF.BAS and is discussed in Chapter 4 of this report.

```

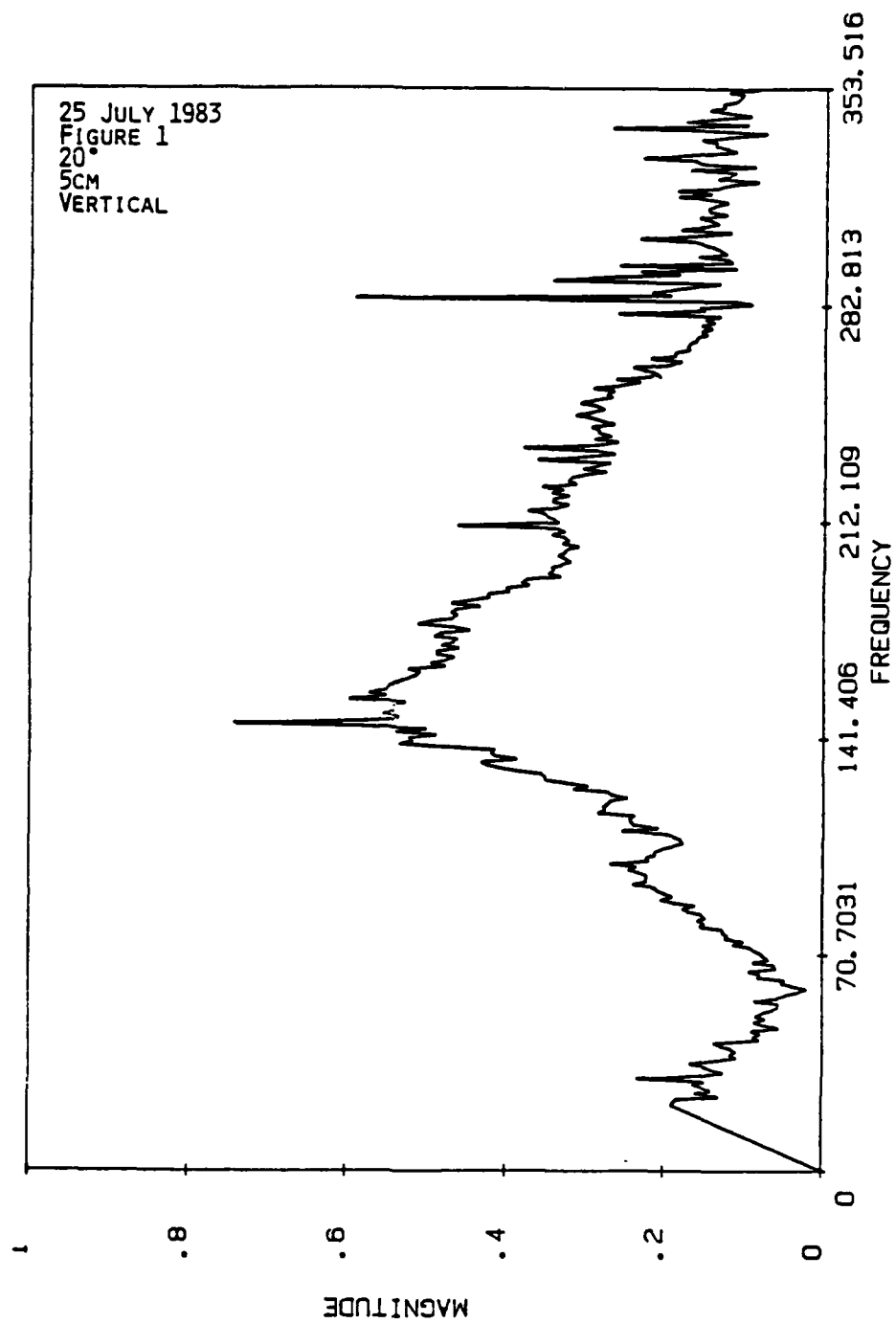
10 OPEN "VM:FILE2.DAT" AS FILE #2
20 OPEN "VM:FILE3.DAT" AS FILE #3
30 DIM #2,D1(1024)
40 DIM #3,F1(1024)
50 DIM X(512),Y(512),Z(512)
60 PRINT "INPUT FILE NAME"; \ INPUT A1$
70 OPEN "DY1:"+A1$+".XYZ" AS FILE #1
80 FOR IZ=1 TO 353
90 INPUT #1,X(IZ),Y(IZ),Z(IZ)
100 NEXT IZ
110 NZ=0
120 FOR IZ=4 TO 350
130 Y(IZ)=Y(IZ)*14+11*(Y(IZ-1)+Y(IZ+1))+4*(Y(IZ-2)+Y(IZ+2))
140 Y(IZ)=(Y(IZ)-(Y(IZ-3)+Y(IZ+3)))/42
141 IF Z(IZ)<90 GO TO 143
142 Z(IZ)=90
143 IF Z(IZ)>-90 GO TO 150
144 Z(IZ)=-90
150 Z(IZ)=Z(IZ)*14+11*(Z(IZ-1)+Z(IZ+1))+4*(Z(IZ-2)+Z(IZ+2))
160 Z(IZ)=(Z(IZ)-(Z(IZ-3)+Z(IZ+3)))/42
170 NEXT IZ
171 Y(350)=0
172 Z(350)=0
180 NZ=NZ+1
190 IF NZ=1 GO TO 120
200 BLOCK_MOVE(X(0),D1(0),512)
210 BLOCK_MOVE(Y(0),F1(0),512)
220 BLOCK_MOVE(Z(0),F1(513),512)
230 CLOSE
240 CHAIN "PLOTFF.BAS"
250 END

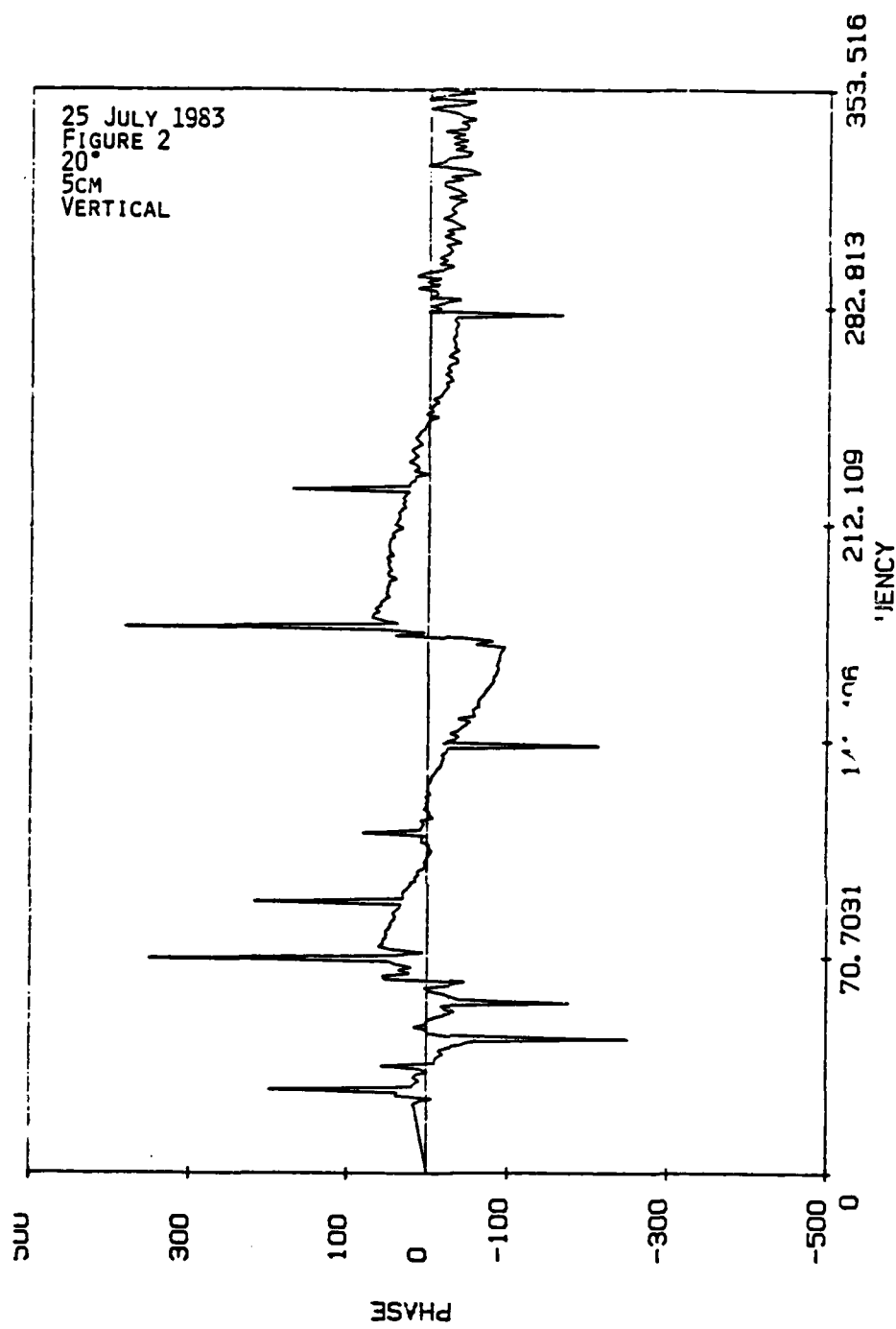
```

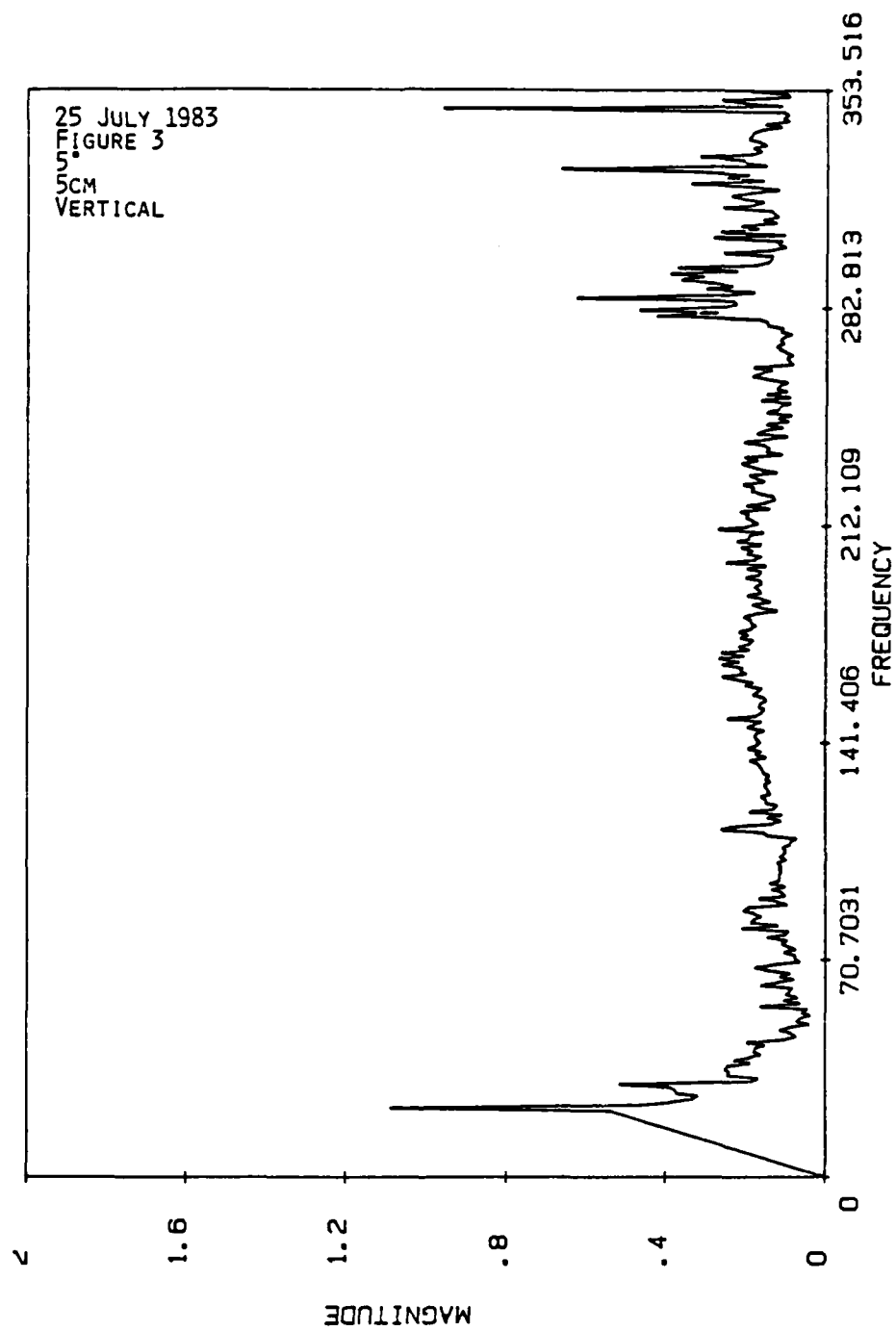
APPENDIX B

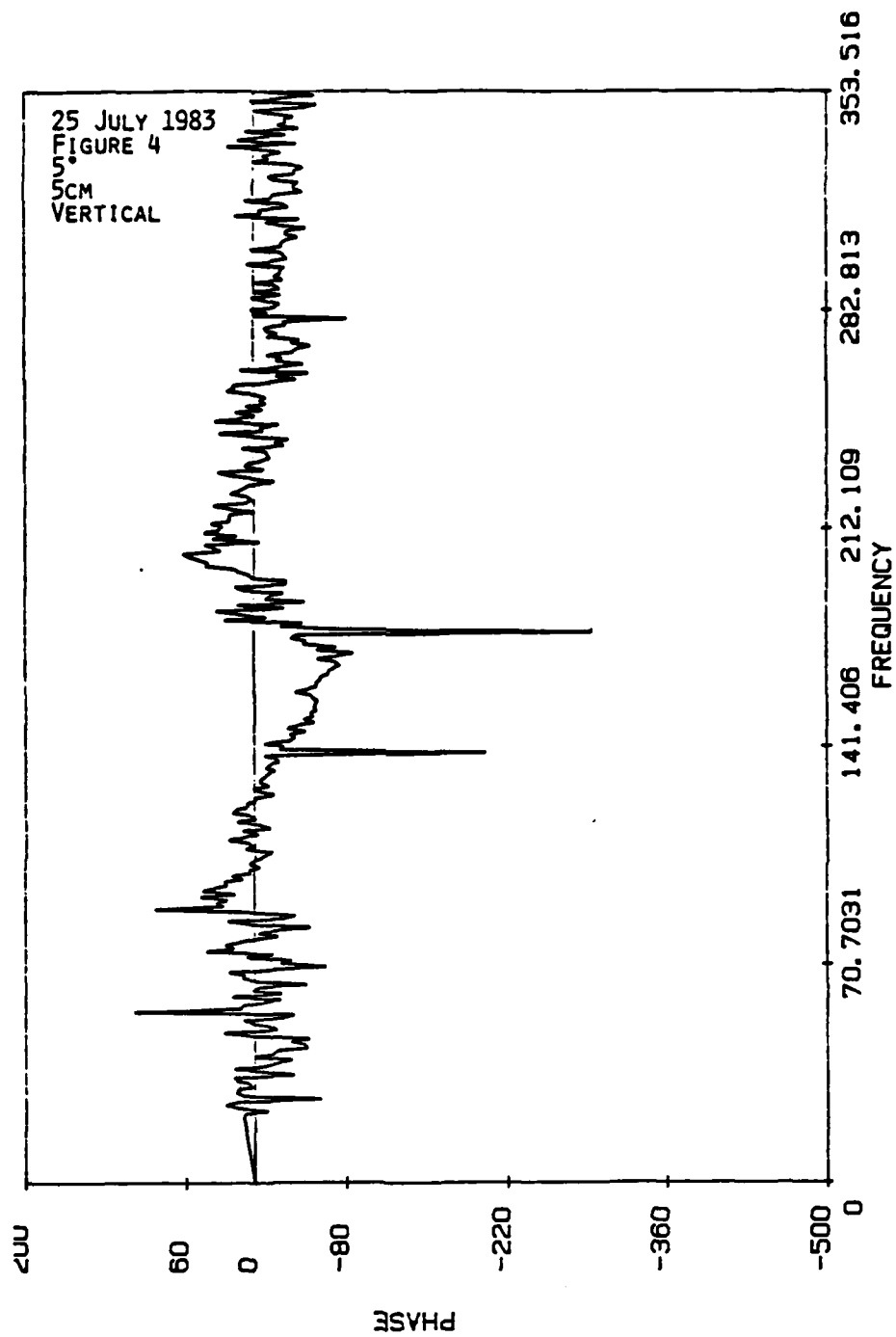
Included here is a larger and more complete sample of the experimental data collected. The purpose is twofold; one, to present a sample of the raw data before smoothing calculations were done and two, to make available samples of the radial and transverse seismic transfer function which were not included in the body of the report. The data chosen for presentation were collected at the UM test field and have not been scaled. The units have been left off the axes, however, they are the same as on earlier graphs. On each figure is a legend which includes the date, angle of incidence, depth of the sensor and the axis of the geophone or probe.

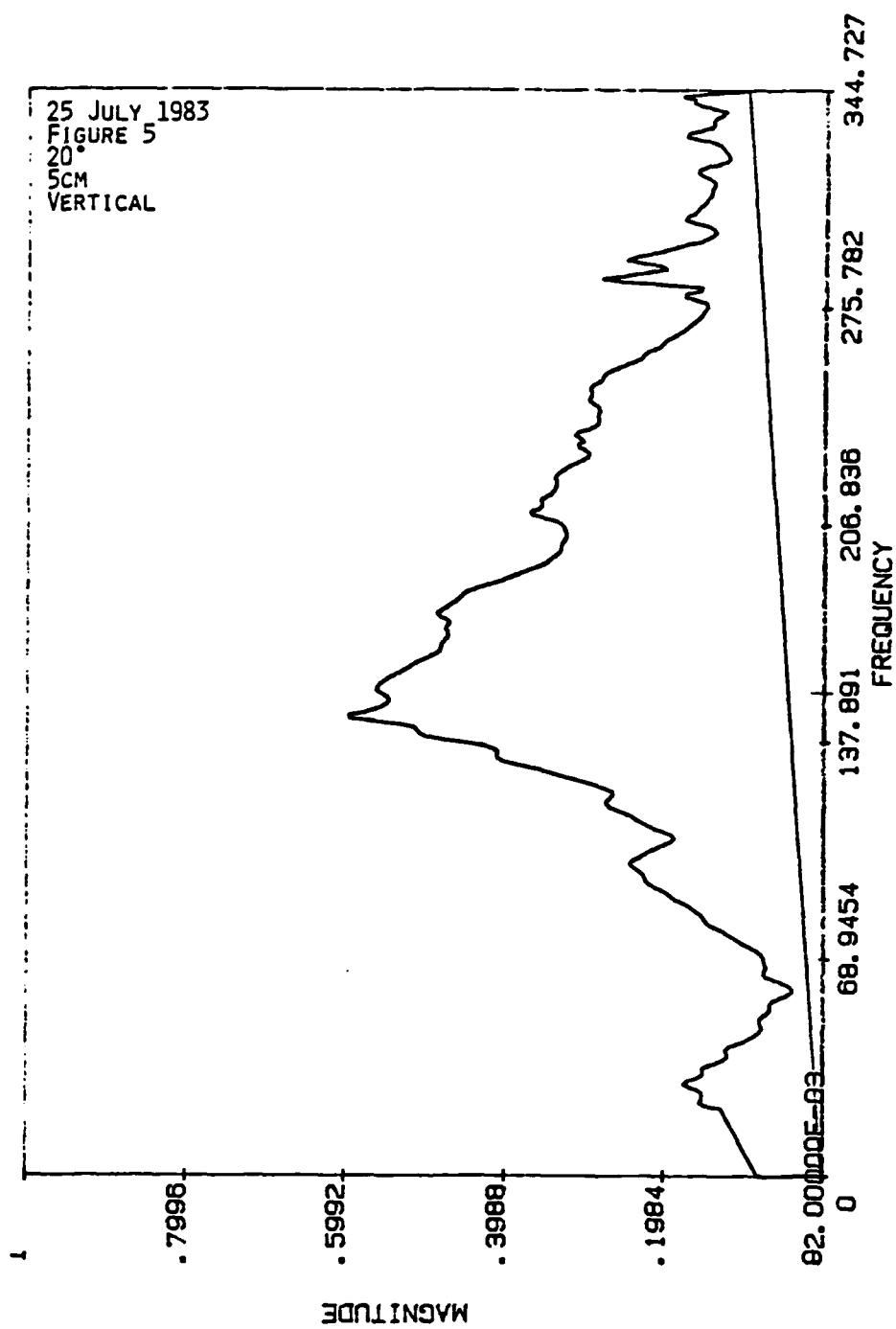
Figures 1-4 indicate the poor signal to noise ratio obtained as the angle of incidence was changed from 20° to 5° . The remaining eight figures are the magnitudes and phases of the vertical, radial and transverse seismic transfer function and the probe transfer function.



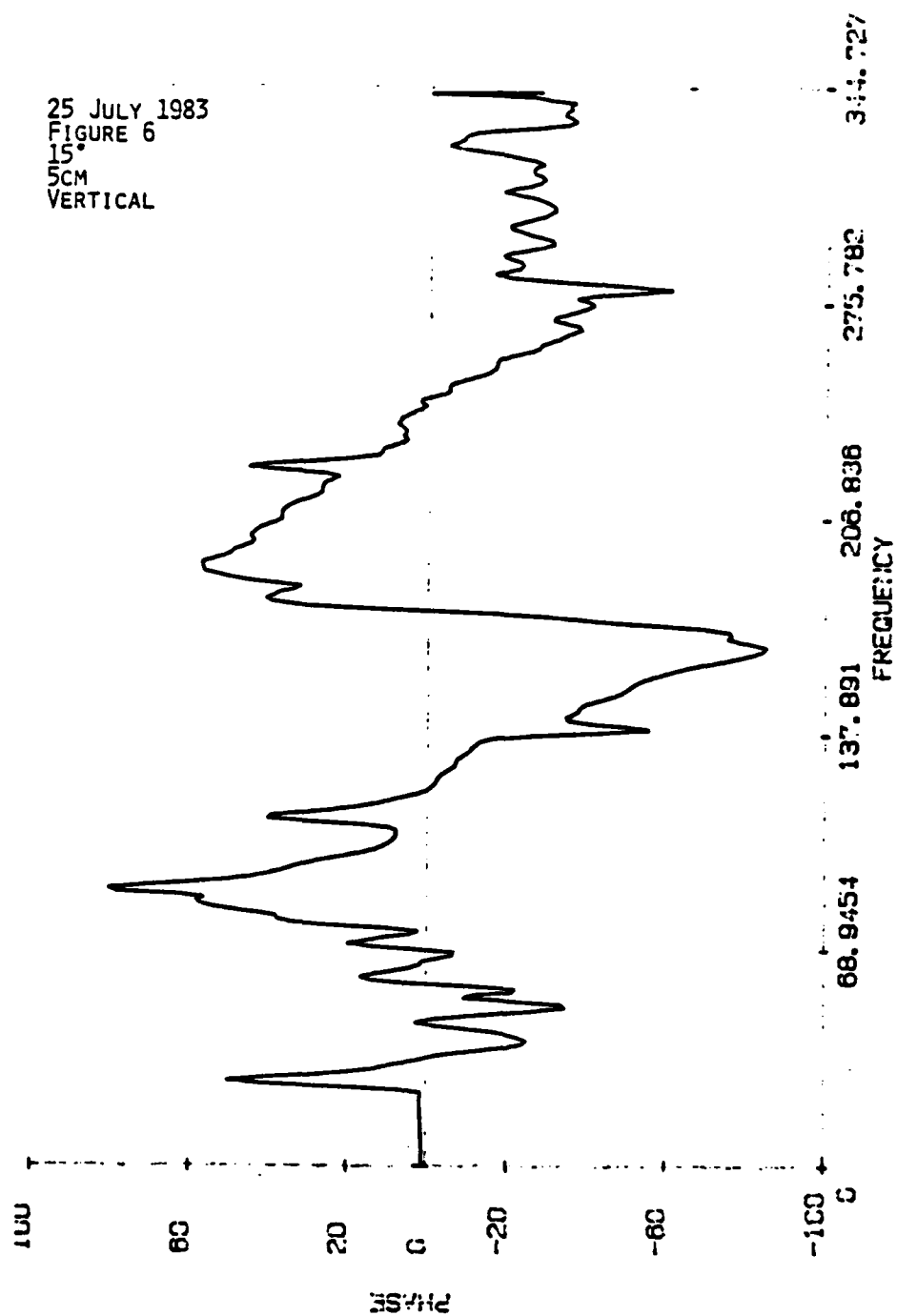


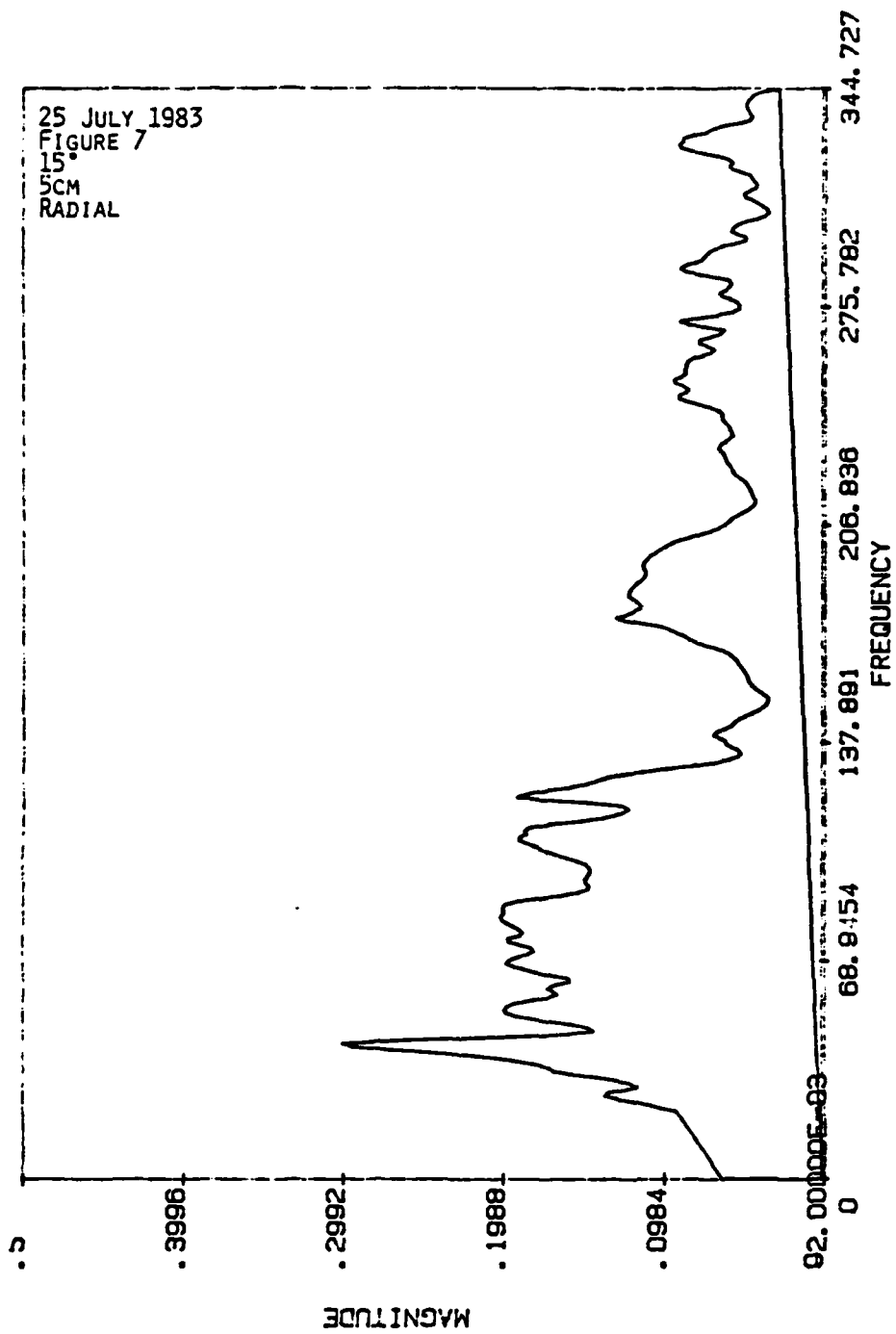


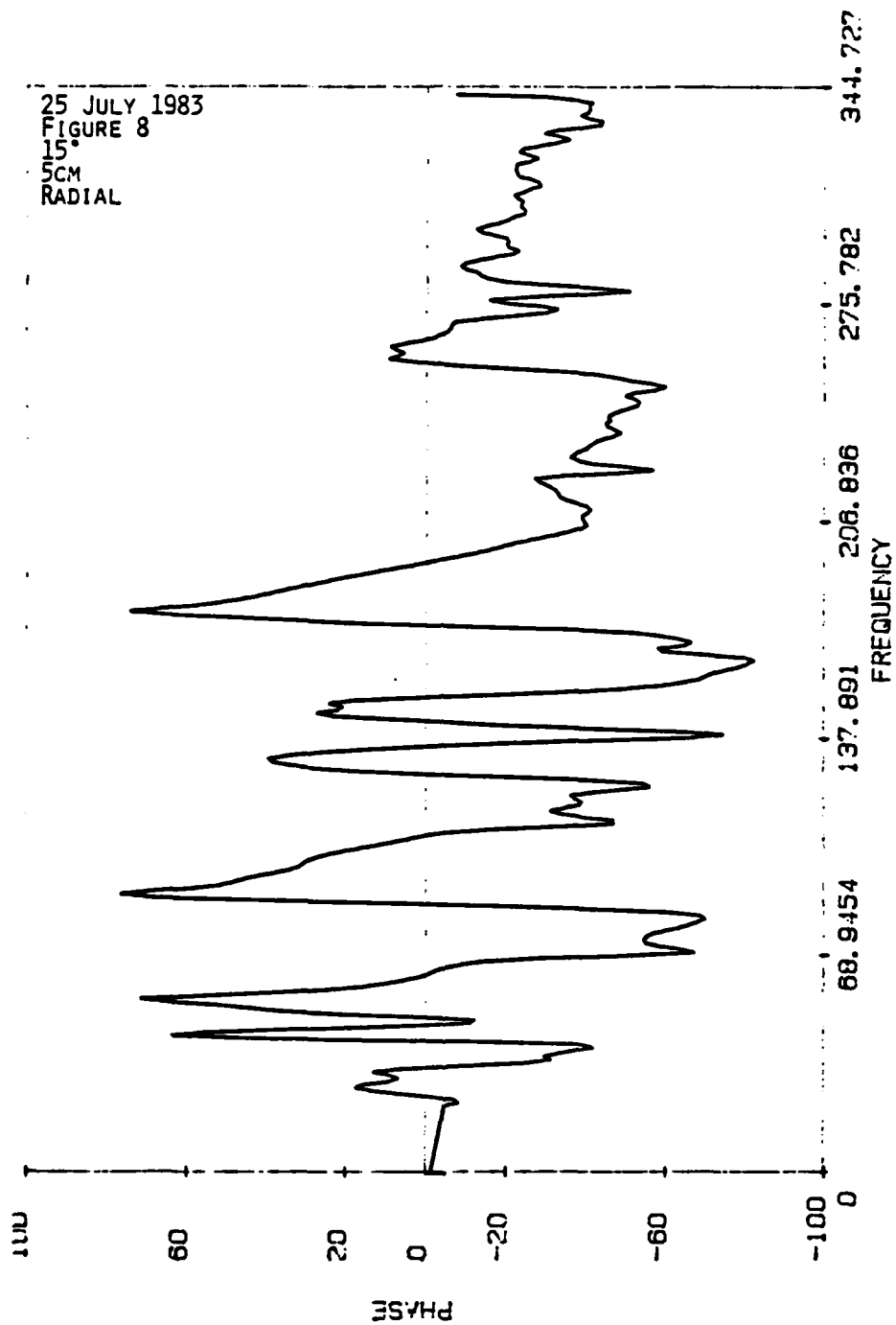


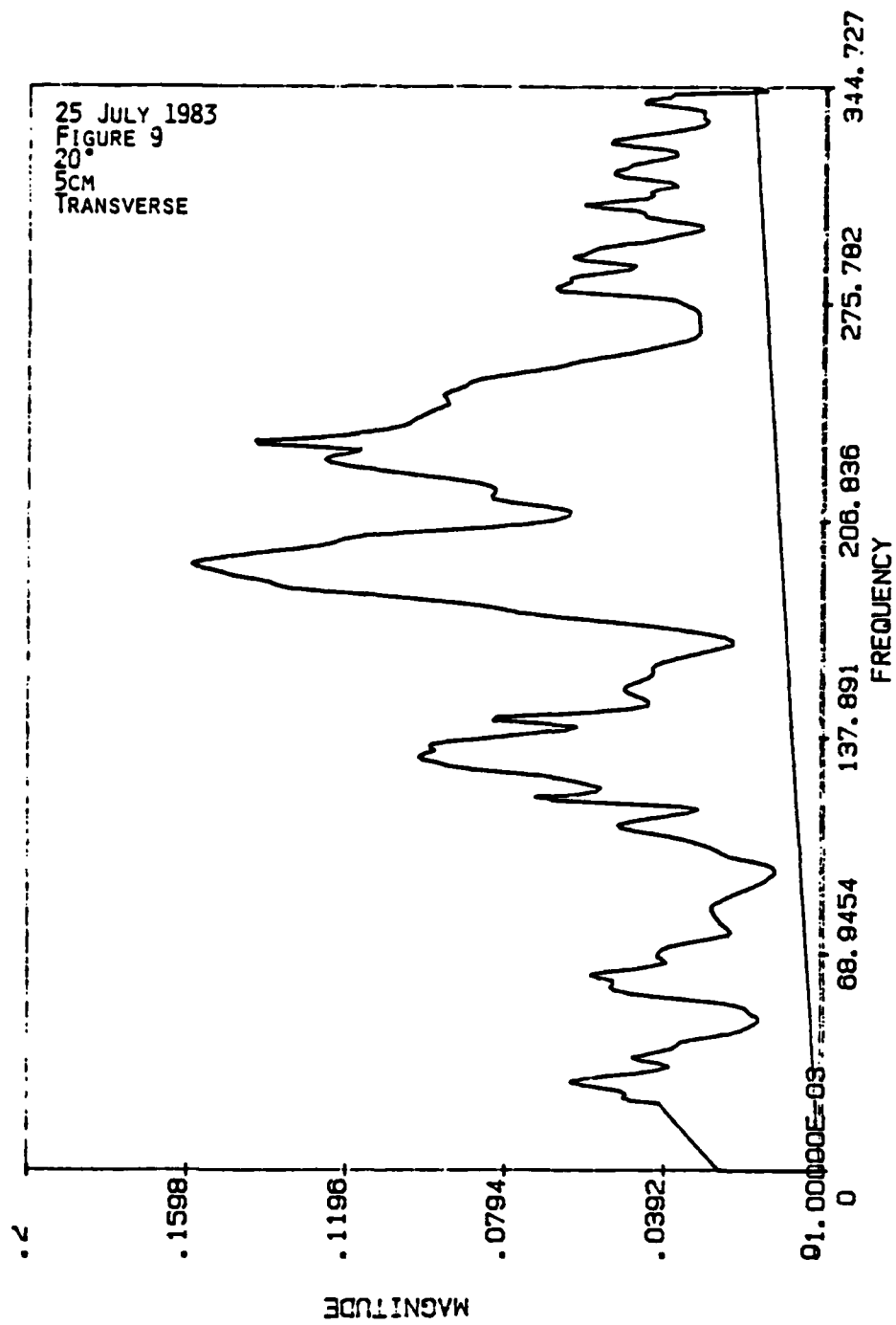


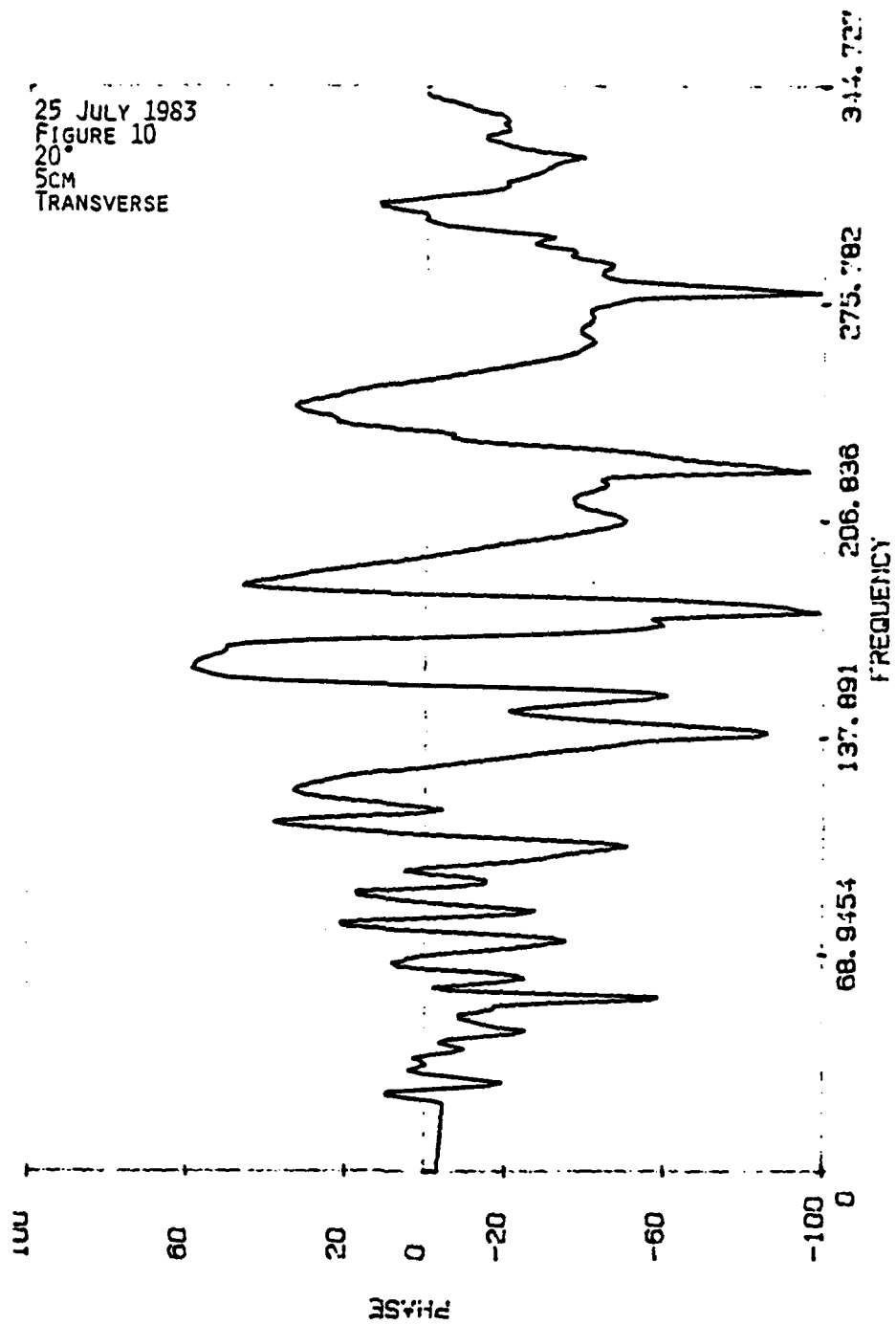
25 JULY 1983
 FIGURE 6
 15°
 5CM
 VERTICAL

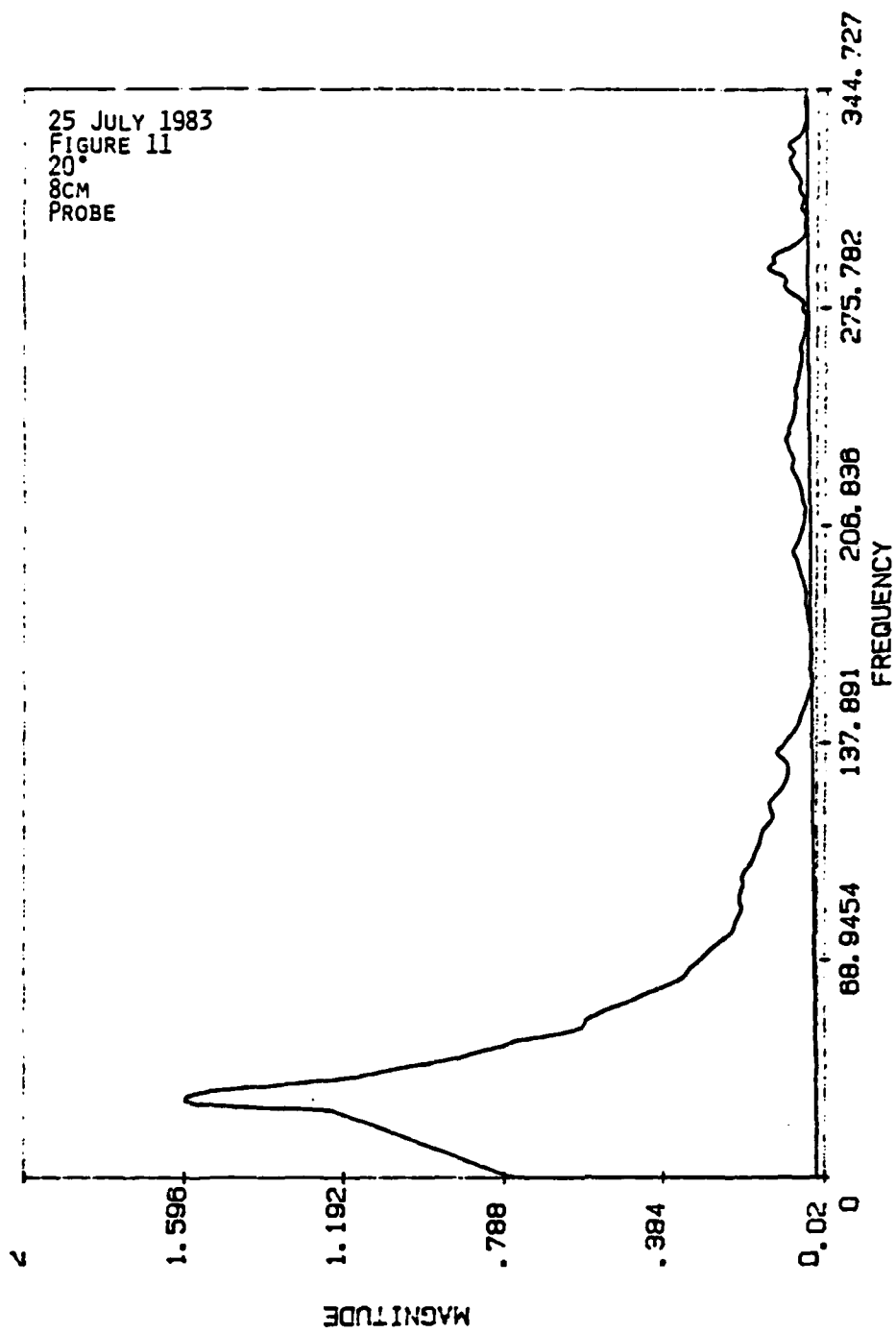


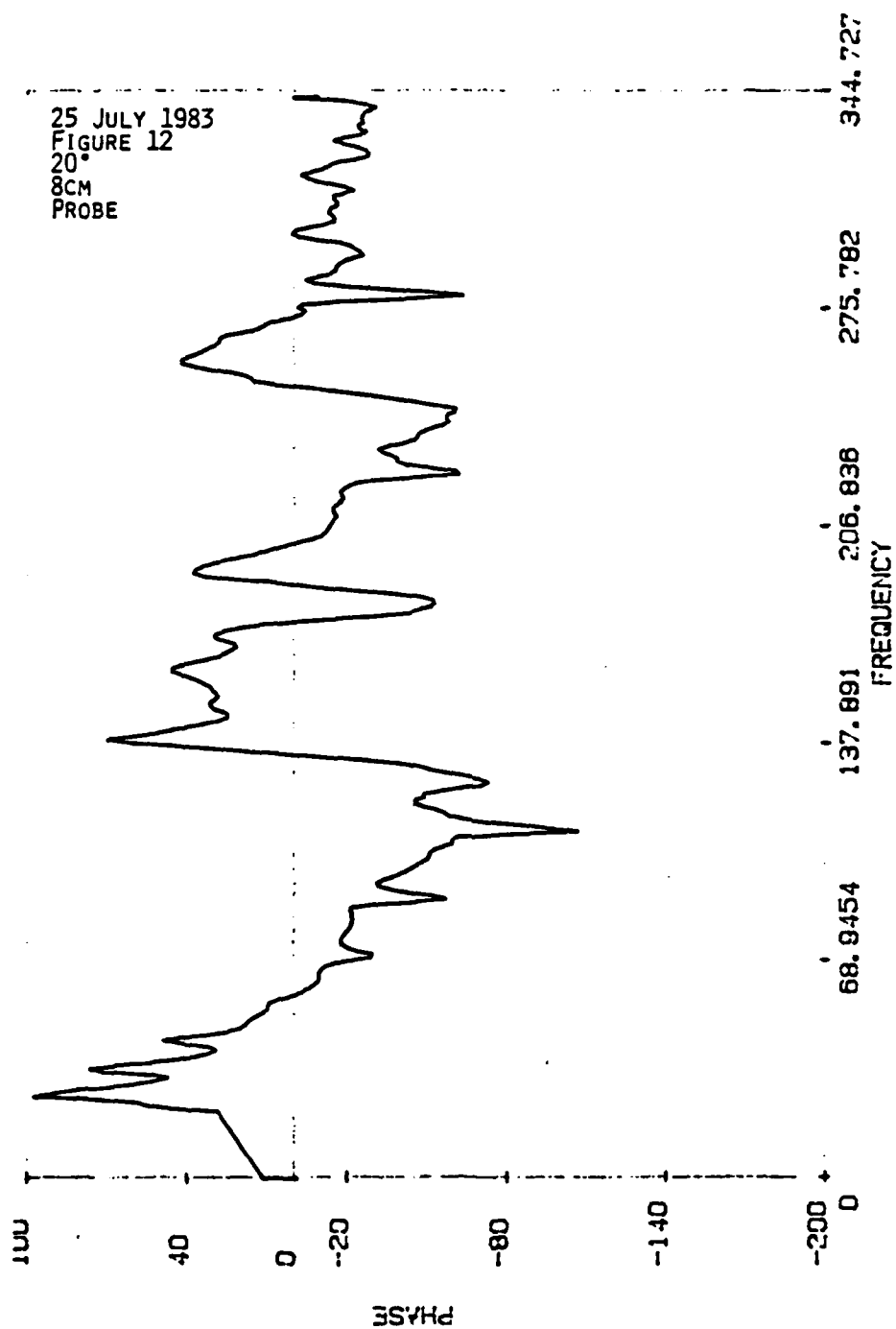






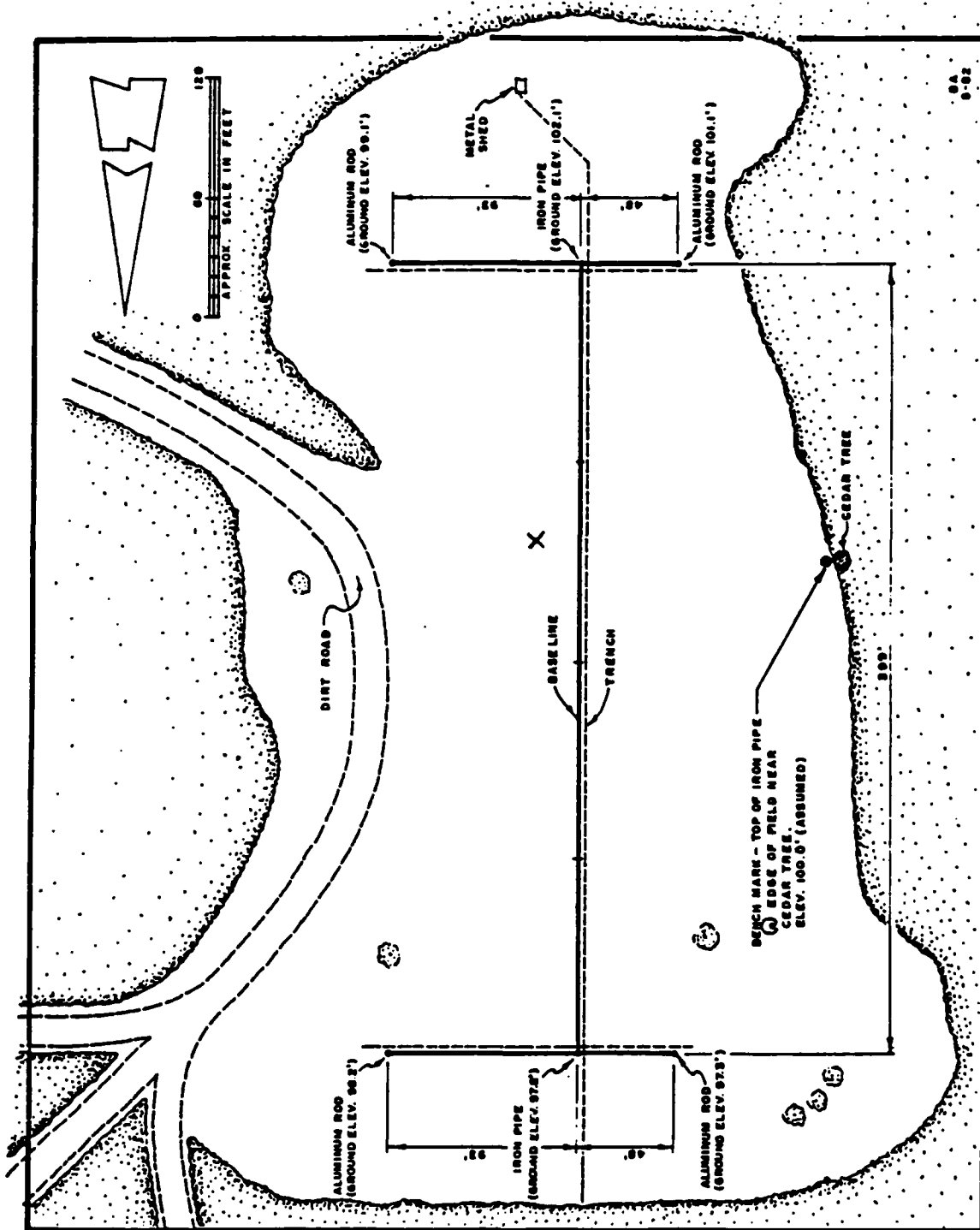






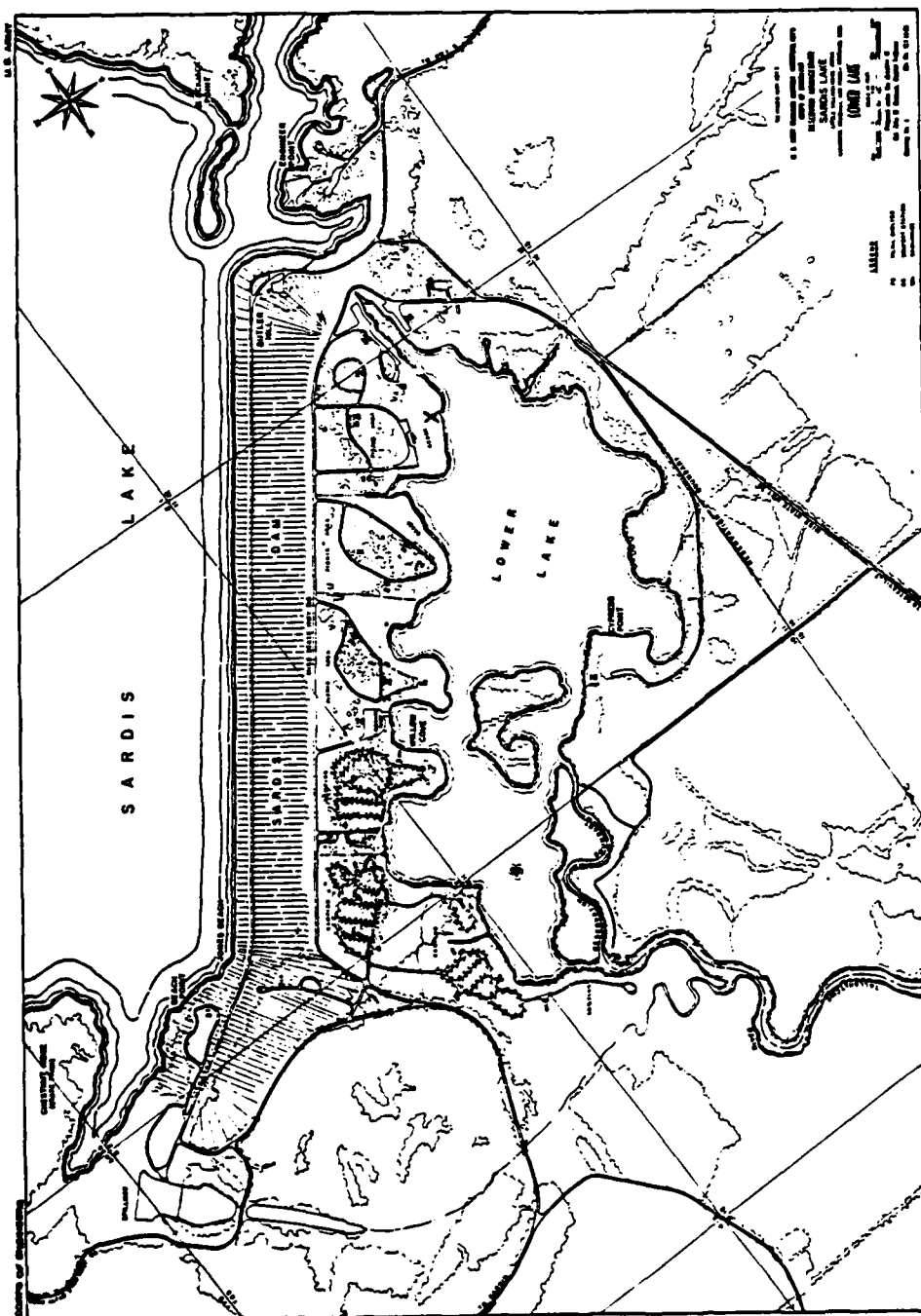
APPENDIX C.1

The UM test field is located two miles south of Oxford, Mississippi and a map of the site is shown below. The experiment was carried out near the center of the field and the experimental site is marked with an X.



APPENDIX C.2

Sardis beach is located in the John W. Kyle State Park which is approximately 10 miles west of Oxford, Mississippi. The experiment was carried out on the lower lake beach immediately below the eastern most end of the dam. The experimental site is marked with an X.



APPENDIX D

Participating Scientific Personnel

Bass, Henry E.	Co-Principal Investigator
Bolen, Lee N.	Co-Principal Investigator
Attenborough, Keith	Research Scientist
Sabatier, James	Ph.D. - Sept. 1984 (estimated)
Rish, Jeff	Ph.D. Candidate
Fortenberry, Rance M.	B.S. - May 1981
Sisler, Peter H.	M.S. - May 1982
Ezell, Jean E.	B.S. - May 1983
Horsburgh, Steven D.	M.S. - Aug. 1984
Wittchen, Bruce D.	B.S.E. - Dec. 1983
Logue, Lawrence C.	B.S. - May 1983
Fisher, Donald	B.S. Candidate
Rogers, Richard	M.S. Candidate
Givens, William J.	M.S. Candidate
Fortenberry, Steven D.	B.S. Candidate
McGee, Brenda Jo	B.A. Candidate